Coastal Defense in an Era of Sea-Level Rise:
science, politics, and decision making

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Abstract

Rising mean sea levels due to global warming and other factors are increasing the frequency of coastal flood events. This trend poses a formidable public policy challenge for governments tasked with managing the coastline. Failure to address this issue would continue to put millions of vulnerable people at risk from both cumulative economic losses from minor floods (e.g., high tides) and acute losses from costly and deadly events (e.g., major coastal storms).

Governments up to the task of coastal flood management are confronted with numerous challenges when 1) quantifying future flood risk, 2) designing solutions, and 3) implementing them. Quantifying future uncertainties in relevant physical science parameters, including those that are "deeply uncertain" (either ignorance or disagreement over models used to describe key system processes and probability distributions used to characterize the uncertainty of key variables and parameters) can challenge efforts to quantify present and future risk from coastal floods and can also complicate legacy engineering decision-making for choosing the design heights of coastal flood protection strategies. The latter includes how high to build levees or what elevation to retreat to in order to attain a desired margin of safety. Those pursuing public works to manage coastal floods must also contend with processes constrained by laws and institutions and replete with social conflict between diverse groups, organizations, and communities with heterogenous values, beliefs, interests, and influence. This dissertation examines both of these physical and social science issues across five chapters, each standing alone as its own unique research endeavor.

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[1] Acknowledgements specific to each chapter also appear throughout the dissertation

New Jersey. At GFDL (as it is more affectionately known), I was blessed to have shared a work environment full of world class scientists, some even carrying a celebrity status of sorts among climate nerds like myself. In particular, I was fortunate to have worked as a research assistant to Arlene Fiore (now a professor at Columbia University). Arlene furthered my interest in academic research and even somehow got me thinking about one day starting a PhD, something never imagined by a skiing-and-cycling-obsessed college student with a remarkably unremarkable academic record. The support from both Tracey and Arlene in the years between undergrad and starting my PhD has been indispensable.

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Last but not least, I'd like to thank my parents and family for continuing to support my "adventures" in academia. I am sure you're all still wondering what the hell it is that I actually do, and I know you're still waiting for me to somehow lower your flood insurance bills...still working on that.

Stay curious. Don't be afraid to feel foolish. And never stop having fun.

D.J.

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Contents

Chapter 1

Introduction

Deltas, estuaries, and the coastal zone continue to attract humans and wealth due to its inherent natural beauty, space for recreational or cultural activities, source of subsistence resources (e.g., fish and other seafood), and strategic importance for trade and maritime travel. However, extreme sea levels pose a threat to those living and/or working in these areas, particularly to human health and well-being, economies, infrastructure, and cultural heritage. For as long as human civilization has lived by the sea, communities have sought preemptive strategies to protect themselves from extreme sea levels generated by tropical cyclones, winter storms, tsunamis, and other meteorological phenomena. For thousands of years the Calusa Indians of present-day Southwest Florida built elevated mounds using collected sea shells, in part, as a strategy to protect tribal elites from high water brought by hurricanes (Widmer, 1988). In Japan, hundreds of so-called tsunami stones, some more than six centuries old, dot the coastline serving as warnings from past generations to present-day residents to not build below them (Fackler, 2011), and in Europe, Pliny, the first-century Roman author, observed people in the present-day region of the Netherlands living in fabricated platforms that were built to a height above the highest high tide (Devoldere, 2019).

Today, it is estimated that 110 million people around the world live on land below the high tide line[1] (Kulp and Strauss, 2019). Over the next century, populations in low lying coastal areas are projected to grow (Neumann et al, 2015; Hauer et al, 2016; Hauer,

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[1] Many of these people live in stilted dwellings or have implemented some other type of adaptation.

2017; Crossett et al, 2013), encouraging increased development on lands exposed to extreme sea levels. Simultaneously, global warming is causing global mean sea levels to rise at an increasing rate (Church and White, 2011; Hay et al, 2015; Dangendorf et al, 2017; Kopp et al, 2016), as a result of thermal expansion of ocean water, melting of land ice (e.g., glaciers and ice caps), and–to a smaller extent–groundwater withdrawal (Church et al, 2013; M. Oppenheimer et al, in press). As a result of this global trend, land subsidence, and other factors, the frequency of extreme sea levels for many coastal communities around the world is increasing (Menéndez and Woodworth, 2010; Buchanan et al, 2017; Sweet and Park, 2014; Frederikse et al, 2020). Global warming is also expected to increase the intensity of tropical cyclones (Sobel et al, 2016), although it is unclear if the overall number of tropical cyclones will change (Walsh et al, 2016). This collision course of 1) increasing coastal population and wealth and 2) a rapidly changing global environment poses a grand public policy challenge for both now and the future.

1.1 Decision-making in an era of sea-level change

Over the past few centuries, governments have increasingly taken on the responsibility of planning, funding, and implementing coastal flood risk[2] reduction strategies that aim to generate significant benefits to their societies by attempting to save lives and reduce flood damage to both the built environment and natural ecosystems. This including shifting from coastal risk reduction policies that take a predominantly piecemeal and reactive approach to dealing with coastal disasters to those that take a more systematic and proactive approach. Examples of flood risk reduction strategies include those that change flood hazards (e.g., building coastal defenses such as levees, storm surge barriers, oyster beds, sand dunes, and wetland restoration) and those that reduce their consequences (e.g., government-backed flood insurance programs, government-funded buyouts of structures in the flood plain, informed land-use planning to prevent future development in exposed areas, building codes that require flood accommodation, accurate forecasts, and early warning systems). In all cases, effective flood management strategies must consider both cumulative impacts from

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[2] "Risk" is used here to mean the potential for coastal flood hazards to cause adverse effects on human and natural systems.

minor flood events (e.g., high-tide flooding) and acute losses from major, but rare, events (e.g., Hurricanes Harvey, Katrina, Irma, Sandy).

A key dilemma for a coastal manager is whether a particular investment in a risk reduction strategy is justified, and if so, what particular approach(es) should be taken. Rarely is there a single, readily available solution applicable to all cities. In most democracies, coastal flood risk reduction decisions occur at every level of government and involve input from a diverse set of stakeholders, including elected officials, technical experts, and citizens that may be affected by a particular risk reduction strategy. Each strategy comes with different risk reduction costs and benefits (both monetized and non-monetized), including different levels of impact on ecosystems and the natural environment.

No longer should coastal flood management decisions be limited to the current climate. Changing mean sea levels impact coastal flood hazards by shifting the baseline from which extreme sea levels occur and also by permanently submerging lands. Prior to the mid 21st century, uncertainty in future sea level change is relatively small, providing a reliable foundation for making adaptation decisions today (in 2020) with roughly 30-year lifetimes. Beyond midcentury, uncertainty in future sea level change grows significantly due to 1) multiple plausible scenarios of anthropogenic greenhouse-gas emissions that govern how much global warming will occur and 2) physical uncertainty, especially in how the Antarctic and Greenland ice sheets will respond to a given amount of warming. These uncertainties, along with many others (e.g. potential changes in tropical cyclone frequency and severity), challenge long-lived decisions regarding coastal risk reduction. Legacy decision-making frameworks, such as benefit-cost analysis and risk protection standards that seek to provide a specified margin of safety (e.g., protection against extreme sea levels that are expected to occur once in a thousand years), must account for these uncertainties. However, one can never predict how exactly the future will unfold and what measures will be needed. New decision-making frameworks will be required to formulate adequate adaptation responses under uncertainty. This includes taking flexible approaches that implement tactics that aim keep future options open.

1.2 Politics adds a layer of complexity to coastal risk reduction efforts

While new decision-making frameworks can inform coastal risk reduction strategies, in practice these approaches are likely to encounter political limitations that may delay or block the deployment of coastal risk reduction. In democracies, the deployment of coastal risk reduction is not simply a matter of closed-door decisions informed by technoeconomic analyses that suggests projects are technically feasible and economically justified (e.g., the discounted expected benefits resulting from the project exceed the costs associated with construction, operation, and maintenance). Politics and social conflict inevitably result from interactions between diverse groups, organizations, and communities with differing values, beliefs, interests, and influence. Because of their inherently large scope, coastal flood protection megastructures, such as storm surge barriers and levees, provide an especially fruitful example for exploring how these factors play a role in the planning and implementation of coastal risk reduction strategies.

Several major coastal cities in the U.S. are investigating the use of coastal flood protection megaprojects to protect against coastal storms and rising sea levels. Most of these projects have been conceived by the Civil Works program of the U.S. Army Corps of Engineers, the principal federal agency responsible for studying and designing coastal flood protection infrastructure. Army Corps projects are guided by an extensive body of laws, regulations, and polices and involve coordination and cooperation between elected officials at all levels of government, federal agencies (e.g., the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service), and a variety of stakeholders that may be inherently biased in supporting (e.g., contractors, professional associations, academics) or opposing projects (e.g., environmental NGOs, seafood industry, recreational and commercial boaters, and academics).

1.3 Overview of the dissertation

As a field of inquiry, coastal flood risk reduction is widely interdisciplinary. This dissertation presents four original research studies and one review that examine just a few unanswered questions in the disciplines of geoscience, engineering, political science, and public policy. While much remains to be studied and understood, my hope is that these five chapters will, at least incrementally, better inform those tasked with managing increasingly crowded coastlines in an era of sea-level rise.

Part I (Geoscience and Public Policy)

In Part I, two original studies are presented that project both future coastal flood hazards and current societal exposure to future flood hazards. In the first of these studies (Chapter 2), I generate new local sea level projections that consider future climate stabilization targets in line with the United Nations Paris Climate Agreement. Using these sea level projections, I assess differences in 1) projected extreme sea level frequency and 2) current population exposure to future permanent sea level inundation. In the second study (Chapter 3), I argue why extreme sea level metrics (such as those used in Chapter 2) should not be used as surrogates for future flood risk (as they have often been used as such) because they do not explicitly account for the exposure and vulnerability of human or natural systems.

Part II (Engineering and Public Policy)

While extreme sea level metrics and population inundation exposure estimates are appropriate for risk communication efforts, they are not readily applicable for designing flood protection strategies because they do not consider adjustments needed to account for uncertain sea level change. In Part II (Chapter 4), I present a new decision-making framework to help planners and engineers calculate the optimal height of a flood protection strategy needed to ensure that a given level of financial risk is maintained under uncertain local sea level change (e.g., annual average loss from flooding below $100 million). The framework considers decision-maker preferences such as planning horizons, protection strategies (e.g., storm surge barriers, levees, coastal retreat, and structure elevation), and subjective judgement about Antarctic ice sheet stability.

Part III (Political Science and Public Policy)

Major U.S. coastal cities like Boston, Charleston, New York, Norfolk, Miami, and Houston are currently working with the U.S. Army Corps of Engineers to investigate the use of storm surge barriers, levees, and other coastal flood protection megaprojects to limit damages from coastal storms and sea-level rise. Determining the feasibility of such public works projects is largely dominated by technocratic and engineering-driven frameworks (for example, benefit-cost analysis). However, experience with public works and natural hazard preparedness projects suggests that political and social dimensions of projects have been crucial in their conception, design, and implementation. Part III presents two chapters devoted to better understanding the social and political factors that enable or hinder the implementation of storm surge barriers, levees, and other coastal flood protection megaprojects. In the first of these two chapters (Chapter 5), I review the natural hazard preparedness, infrastructure, public policy literatures to highlight the critical role that social conflict and politics is likely to play in the conception, design, and implementation of climate adaptation works. In the final chapter (Chapter 6), I use original archive research on two storm surge barriers planned for Rhode Island in the mid 20th century in order to better understand the specific political mechanisms that explain why current coastal flood protection megaprojects do or do not progress beyond initial planning stages and break ground.

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Chapter 2

Projecting extreme sea levels under the Paris Agreement

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Abstract

Sea-level rise (SLR) is magnifying the frequency and severity of extreme sea levels (ESLs), which can cause coastal flooding. The rate and amount of global mean sea-level (GMSL) rise is a function of the trajectory of global mean surface temperature (GMST). Therefore, temperature stabilization targets (e.g., 1.5 °C and 2.0 °C of warming above pre-industrial levels, as from the Paris Agreement) have important implications for coastal flood risk. Here, we assess, at a global network of tide gauges, the differences in the expected frequencies of ESLs between scenarios that stabilize GMST warming at 1.5 °C, 2.0 °C, and 2.5 °C above pre-industrial levels. We employ probabilistic, localized SLR projections and long-term hourly tide gauge records to estimate the expected frequencies of historical and future ESLs for the

21st and 22nd centuries. By 2100, under 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilization, respectively, median GMSL is projected to rise 48 cm (90% credible interval of 28–82 cm), 56 cm (28–96 cm), and 58 cm (37–93 cm). As an independent comparison, a semi-empirical sea level model calibrated to temperature and GMSL over the past two millennia estimates median GMSL rise within 7–8 cm of these projections. By 2150, relative to the 2.0 °C scenario and based on median sea level projections, GMST stabilization of 1.5 °C spares the inundation of lands currently home to about 5 million people, including 60,000 individuals currently residing in Small Island Developing States. We quantify projected changes to the expected frequency of historical 10-, 100-, and 500-year ESL events using frequency amplification factors that incorporate uncertainty in both local SLR and historical return periods of ESLs. By 2150, relative to a 2.0 °C scenario, the reduction in the frequency amplification of the frequency of the 100-yr ESL event arising from a 1.5 °C GMST stabilization is greatest in the eastern United States, with ESL event frequency amplification being reduced by about half at most tide gauges. In general, smaller reductions are projected for Small Island Developing States.

2.1 Introduction

Extreme sea levels (ESLs) are defined as the combined height of the astronomical tide and storm surge (i.e., the storm tide) and mean sea level. ESLs can cause coastal floods that threaten life and property when flood defenses are over-topped. Rising mean sea levels are already magnifying the frequency and severity of ESLs that lead to coastal floods (Buchanan et al, 2017; Sweet and Park, 2014), and by the end of the century, coastal flooding may be among the costliest impacts of climate change in some regions (Hsiang et al, 2017; Diaz, 2016; Hinkel et al, 2014). Sea-level rise (SLR) is expected to permanently inundate low-lying geographic areas (Marzeion and Levermann, 2014; Strauss et al, 2015), but these locations will first experience decreases in the return periods of ESL events and associated coastal floods (e.g., Hunter, 2012; Sweet and Park, 2014).

The rate of global mean sea-level (GMSL) rise depends on the trajectory of global mean surface temperature (GMST; Rahmstorf, 2007; Kopp et al, 2016a; Vermeer and Rahmstorf, 2009), with the long-term committed amount of GMSL largely determined by the stabilized level of GMST (Levermann et al, 2013). Thus, the management of GMST has important implications for regulating future GMSL (Schaeffer et al, 2012), and consequently the frequency and severity of ESLs and coastal floods. However, GMST stabilization does not imply stabilization of all climate variables. Under stabilized GMST, GMSL is expected to continue to rise for centuries, due to the long residence time of anthropogenic CO_2, the thermal inertia of the ocean, and the slow response of large ice sheets to forcing (Clark et al, 2016; Levermann et al, 2013; Held et al, 2010). For instance, Schaeffer et al (2012) found that a 2.0 °C GMST stabilization would lead to a GMSL rise (relative to 2000) of 0.8 m by 2100 and $>$ 2.5 m by 2300, but if the GMST increase were held below 1.5 °C, GMSL rise at the end of the 23rd century would be limited to $\sim$1.5 m. These findings suggest that selection of climate policy goals could have critical long-term consequences for the impacts of future SLR and coastal floods (Clark et al, 2016).

The Paris Agreement seeks to stabilize GMST by limiting warming to "well below 2.0 °C above pre-industrial levels" and to further pursue efforts to "limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015a). However, a recent literature review under the United Nations Framework Convention on Climate Change (UNFCCC) found the notion that "up to 2.0 °C of warming is considered safe, is inadequate" and that "limiting global warming to below 1.5 °C would come with several advantages" (UNFCCC, 2015b). The advantages and disadvantages of each GMST target as they relate to coastal floods and ESLs have not been quantified. This is critical, as $>$ 625 million people currently live in coastal zones with $<$ 10 m of elevation, and population growth is expected in these areas (Neumann et al, 2015). Examining the short- and long-term ESL implications of 1.5 °C and 2.0 °C GMST stabilization scenarios, as others have recently done for other climate impacts (e.g. Schleussner et al, 2016a,b; Mitchell et al, 2017; Mohammed et al, 2017), may better inform the policy debate regarding the selection of GMST goals.

In this study, we employ probabilistic, localized SLR projections to assess differences in the frequency of ESLs across 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilization scenarios at a global network of 194 tide gauges (Section 2.2.1). We use long-term hourly tide gauge records and extreme value theory to estimate present and future return periods of ESL events (Section 2.2.4). We extend our analysis through the 22nd century to account for continuing SLR in order to inform multi-century planning and infrastructure investments. Lastly, we assess differences in the exposure of current populations to future SLR under 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilizations (Section 2.3.2). Unlike deterministic or median estimates, the use of probabilistic projections allows for the characterization of uncertainty, which is important for risk management.

Various approaches have been used to project GMSL under GMST targets. For instance, Jevrejeva et al (2016) estimate future local SLR under a GMST increase of 2 °C using a Representative Concentration Pathways (RCP) 8.5 GMST trajectory that passes through 2 °C of warming by mid-century, but this approach likely underestimates SLR relative to a scenario that achieves 2 °C GMST stabilization by 2100 as it neglects the time-lagged, integrated response of the ocean and cryosphere to warming (Clark et al, 2016). More generally, studies that condition future ESL or flood projections on the RCPs may be insufficient for assessing the costs and benefits of climate policy scenarios, such as GMST stabilization targets (e.g., *Section 13.7.2.2* of Church et al, 2013; Buchanan et al, 2017; Hunter, 2012; Tebaldi et al, 2012). The RCPs are designed to be representative of a range of emissions scenarios that result in prescribed anthropogenic radiative forcings by 2100 relative to pre-industrial conditions (e.g., 8.5 Wm^{-2} for RCP8.5). They are not representative of a specific emissions trajectory, climate policy (e.g., GMST target), or socioeconomic and technological change (Moss et al, 2010; van Vuuren et al, 2011). Recently, Jackson et al (2018) produced probabilistic, localized SLR projections under 1.5 °C and 2.0 °C GMST targets, but did not assess ESLs or consider sea-level change after 2100, the latter being necessary for evaluating the effects of GMST stabilization.

Semi-empirical sea level (SESL) models (Rahmstorf et al, 2012) can estimate future GMSL rise under various GMST scenarios (e.g., Schaeffer et al, 2012; Bittermann et al, 2017). Unlike their process-based counterparts (e.g., Kopp et al, 2014), SESL models do not explicitly model individual physical components of sea-level change. They are calibrated over a historical period using the observed statistical relationship between GMSL and a climate parameter (such as GMST). Assuming these relationships hold in the future, SESL models project the rate of GMSL change conditional upon a GMST pathway (e.g., Rahmstorf, 2007;

Vermeer and Rahmstorf, 2009; Kopp et al, 2016a). However, SESL models do not produce estimates of local SLR, which are necessary for local risk assessment and adaptation planning because local SLR can substantially differ from the global mean (Milne et al, 2009).

2.2 Methods

We project probabilistic global and local sea level conditional on GMST stabilization at 1.5 °C, 2.0 °C, and 2.5 °C using the component-based, local sea level projection framework from Kopp et al (2014, henceforth K14). We compare the GMSL projections from the K14 framework to those from the semi-empirical sea level (SESL) model of Kopp et al (2016a) and Bittermann et al (2017). While SESL models cannot produce local projections of SLR, they can serve as a reference point for evaluating the consistency of process-based projections with historical temperature-GMSL relationships. The flow and sources of information used to construct the local SLR and GMSL projections using the K14 method is depicted in Fig. 2.4A, while the flow of information used to generate the SESL projections is provided in Fig. 2.4B. Local SLR projections from the K14 approach are combined with historical distributions of ESL events to estimate future return periods of historical ESL events (Fig. 2.4A), similar to the approaches by Buchanan et al (2017, 2016) and Wahl et al (2017).

2.2.1 Component-based model approach: Global and local sea-level rise projections

Sea-level change does not occur uniformly. Dynamic ocean processes (Levermann et al, 2005), changes to temperature and salinity (i.e., steric processes), and changes in the Earth's rotation and gravitational field associated with water-mass redistribution (e.g., land-ice melt; Mitrovica et al, 2011), as well as glacial isostatic adjustment (GIA; Farrell and Clark, 1976) and other drivers of vertical land motion cause local relative sea levels to differ from the global mean. We model local relative sea level using the K14 framework, but make modifications to accommodate the stratification of Atmosphere-Ocean General Circulation Models (AOGCMs) and RCPs into groups that meet GMST stabilization targets (see Section 2.2.2). AOGCM output from the Coupled Model Intercomparison Project (CMIP) Phase 5 archive

(Taylor et al, 2012) forced with the RCPs (to 2100) and their extensions (to 2300) are used directly for global mean thermal expansion (TE) and local ocean dynamics, and as a driver of a surface mass balance (SMB) model of glaciers and ice caps (GIC; Marzeion et al, 2012). Antarctic Ice Sheet (AIS) and the Greenland Ice Sheet (GIS) contributions are estimated using a combination of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) projections of ice sheet dynamics and SMB (Table 13.5 in Church et al, 2013) and expert elicitation of total ice sheet mass loss from Bamber and Aspinall (2013). As in AR5, ice sheet SMB contributions are represented as being dependent on the forcing scenario, while ice sheet dynamics are not. A spatiotemporal Gaussian process regression model is used with tide gauge data to estimate the long-term contribution from non-climatic factors such as tectonics, GIA, delta processes (e.g., sediment compaction), and human-induced subsidence. Changes in the rate of human-induced subsidence are not considered. Global mean land water storage effects are modeled using relationships between population and groundwater removal and impoundment (Kopp et al, 2014). To generate probability distributions of global and local mean sea level for each GMST scenario at tide gauges (Table S-1 in published appendix, online), we use 10,000 Latin hypercube samples of probability distributions of individual sea level component contributions.

2.2.2 Approximating Global Temperature Stabilization with RCPs

The RCP-driven experiments in the CMIP5 archive are not designed to inform the assessment of climate impacts from incremental temperature changes. As such, we construct alternative ensembles for 1.5 °C, 2.0 °C, and 2.5 °C scenarios using CMIP5 output filtered according to each AOGCM's 2100 GMST. Specifically, we create ensembles for 1.5 °C, 2.0 °C, and 2.5 °C scenarios with AOGCMs that have a 21st century GMST increase (19-yr running average) of 1.5 °C, 2.0 °C, and 2.5 °C (± 0.25 °C). For consistency with the K14 framework, which models 19-yr running averages of SLR relative to 2000, GMST is anomalized to 1991–2009 and then shifted upward by 0.72 °C to account for warming since 1875–1900 (Hansen et al, 2010; GISSTEMP Team, 2017). Selection of the AOGCMs for each scenario ensemble are made irrespective of the AOGCM's RCP forcing. For model outputs that end in 2100, we extrapolate 19-yr running average GMST to 2100 based on the 2070–2090 trend. While we chose 2100 as the determining year for which AOGCMs are selected for each ensemble, it should be noted that Article 2 of the UNFCCC (UNFCCC, 1992) does not require that GMST stabilization be achieved within a particular time frame. The Paris Agreement likewise does not specify a timeframe for GMST stabilization, though its goal of bringing net greenhouse gas (GHG) emissions to zero in the second half of the 21st century implies a similar time frame for stabilization. We make the assumption that AOGCM outputs that end at 2100 either stay within the range of the target ± 0.25 °C or fall below by any amount (i.e., undershoot). For AOGCMs that have GMST output available after 2100, only those that undershoot the target are retained. However, we make an exception to this rule for the 2.5 °C scenario ensemble in order to include AOGCMs for generating post-2100 projections. For RCP4.5 and RCP6, GMST stabilization should not occur before 2150, when greenhouse gas concentrations stabilize (Meinshausen et al, 2011b) and so SLR projections after 2100 may not be representative of conditions under true GMST stabilization. The GMST trajectories and GMSL contributions from TE and glacial ice from selected CMIP5 models that are binned into 1.5 °C, 2.0 °C, and 2.5 °C GMST categories are shown in Figs. 2.1 and 2.5, respectively. Table 2.3 lists the AOGCMs employed in each GMST scenario ensemble and the sea-level components used. Given the paucity of CMIP5 output after 2100, the range of TE and GIC contributions to SLR in the 22nd century is likely underestimated relative to the 21st century. Total ice sheet contributions from AR5 are calculated for each GMST scenario by randomly sampling AIS and GIS ice sheet distribution for each RCP (Table 13.5 in Church et al, 2013) in proportion to the representation of each RCP in the groups of CMIP5 models selected for each GMST scenario.[1]

2.2.3 Global mean sea-level rise projections from a semi-empirical sea level model

We generate estimates for GMSL for 2000–2200 using the SESL model from Kopp et al (2016a) and Bittermann et al (2017) driven with both GMST trajectories from CMIP5 models (Fig. 2.1) and GMST trajectories from the reduced-complexity climate model MAGICC6

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[1] For example, the 1.5 °C GMST employs 12 CMIP5 models from RCP2.6 and 2 from RCP4.5, so 86% of the samples are drawn from the RCP2.6 distribution and 14% are drawn from the RCP4.5 distribution (Table 2.3).

(Meinshausen et al, 2011a, as employed in Rasmussen et al, 2016) for 2100 GMST targets of 1.5 °C, 2.0 °C, and 2.5 °C (± 0.25 °C) (Fig. 2.6). The MAGICC6 GMST trajectories are selected from all RCP-grouped projections using the same criteria as in Section 2.2.2. The SESL model is calibrated to the Common Era temperature reconstruction from Mann et al (2009) and the sea level reconstruction of Kopp et al (2016a). The historical statistical relationship between temperature and the rate of sea-level change is assumed to be constant; not included are nonlinear physical processes or critical threshold events that could substantially contribute to SLR, such as ice sheet collapse (Kopp et al, 2016b; Levermann et al, 2013). Threshold behavior is partially incorporated in the K14 framework through expert assessments of future ice sheet melt contributions (Bamber and Aspinall, 2013), which may be one reason why the K14 framework produces higher estimates in the upper tail of the SLR probability distribution.

2.2.4 Estimating the frequency of historical and future extreme sea level events

The heights of historical ESL events that result from tropical and extra-tropical cyclones, extreme astronomical tides, and other processes are recorded in sub-daily tide gauge observations. Extreme value theory can be used with these tide gauge measurements to estimate the historical return levels of ESL events, including events that occur less often, on average, than the length of the observational record. For example, one could use extreme value theory to estimate the height of the present-day 500-yr (or 0.2% average annual probability per year, on average) ESL event from a record that is $<$ 500 years in length. Assuming no non-linear relationships between SLR and ESL events and no change in the frequency and intensity of processes that cause ESLs (e.g., tropical and extra-tropical cyclones), the estimated return levels of historical ESL events can be combined with local SLR projections to estimate the return levels of future ESL events.

Estimation of historical return levels of extreme sea levels

Here, we use extreme value theory with daily maximum sea levels at tide gauges archived by the University of Hawaii Sea Level Center (*see Supplementary data*; Caldwell et al, 2015) to estimate historical return levels of ESL events. Specifically, we follow Tebaldi et al (2012) and Buchanan et al (2016, 2017) and employ a generalized Pareto distribution (GPD) and a peaks-over-threshold approach (Coles, 2001b,a). The GPD describes the probability of a given ESL height conditional on an exceedance of the GPD threshold. We use the 99th percentile of daily maximum sea levels as the GPD threshold, which is generally both above the highest seasonal tide and balances the bias-variance trade-off in the GPD parameter estimation (Tebaldi et al, 2012). The number of annual exceedances of the GPD threshold is assumed to be Poisson distributed with mean λ. Tide gauge observations are detrended and referenced to Mean Higher High Water (MHHW)[2] and the GPD parameters are estimated using the method of maximum likelihood (*see Supplementary data*). Uncertainty in the GPD parameters is calculated from their estimated covariance matrix and is sampled using Latin hypercube sampling of 1000 normally distributed GPD parameter pairs. For a given tide gauge, the annual expected number of exceedances of ESL height z is given by $N(z)$:

$$N(z) = \begin{cases} \lambda \left(1 + \frac{\xi(z-\mu)}{\sigma}\right)^{-\frac{1}{\xi}} & \text{for } \xi \neq 0 \\ \lambda \, \exp(-\frac{z-\mu}{\sigma}) & \text{for } \xi = 0 \end{cases} \tag{2.1}$$

where the shape parameter (ξ) governs the curvature and upward statistical limit of the ESL event return curve, the scale parameter (σ) characterizes the variability in the exceedances caused by the combination of tides and storm surges, and the location parameter (μ) is the threshold water-level above which return levels are estimated with the GPD, here the 99th percentile of daily maximum sea levels. Meteorological and hydrodynamic differences between sites give rise to differences in the shape parameter (ξ). ESL frequency distributions with $\xi > 0$ are "heavy tailed", due to a higher frequency of events with extreme high water (e.g., tropical and extra-tropical cyclones). Distributions with $\xi < 0$ are "thin tailed" and have a statistical upper bound on extreme high water levels. Events that occur between λ and 182.6/year (i.e., exceeding MHHW half of the days per year) are modeled with a Gumbel distribution, as they are outside of the support of the GPD. Note that ESL events

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[2] Here defined as the average level of high tide over the last 19-years in each tide gauge record, which is different from the current U.S. National Tidal Datum Epoch of 1983–2001.

at tide gauges are not referred to as floods as the occurrence of an actual flood depends on the level of coastal flood protection, terrain, infrastructure, and other local factors.

Extreme sea level event frequency amplification factors

The frequency amplification factor (AF) quantifies the increase in the expected frequency of historical ESL events (e.g., the 100-yr ESL event) due to SLR (Buchanan et al, 2017; Hunter, 2012; Church et al, 2013). Due to variation in the local storm climate and hydrodynamics, the height of ESL event return levels are unique to each location (SI Fig. 2.7). The calculation of the expected AF includes both the uncertainty in the estimates of the return periods of historical ESL events and uncertainty in SLR projections. Following Buchanan et al (2017), we define the expected ESL event frequency amplification factor AF(z) for ESL events with height z as the ratio of the expected number of ESL events after including uncertain SLR to the historical expected number of ESL events:

$$\mathrm{AF}(z) = \frac{\mathrm{E}[N(z-\delta)]}{N(z)} \tag{2.2}$$

where $N(z-\delta)$ is the annual expected number of exceedances of ESL height z after including SLR (δ), E[$\cdot$] is the expectation operator applied to the full probability distribution of SLR projections, and $N(z)$ is the historical annual expected number of exceedances of ESL height z.

Assessment of population exposure

Following the methods used in Kopp et al (2017), we assess the current population living on land exposed to future permanent inundation from GMSL under each GMST stabilization scenario. We emphasize that this is not a literal measure of future population exposure—which will depend upon population growth, the dynamic response of the population to rising sea levels, and coastal protective measures taken—but is instead intended to index the relevance of SLR to current economic development and cultural heritage under different GMST stabilizations. We use a 1-arcsec SRTM 3.0 digital elevation model from NASA (NASA JPL, 2013) referenced to local MHHW levels for the year 2000 and this study's local

SLR projection grids. Projected inundation areas are intersected with LandScan 2010 global population data on a 1 km × 1 km global grid (Bright et al, 2011) and national boundary data (Hijmans et al, 2012). For each GMST target, the current population on land at risk is assessed at the 5th, 50th, and 95th percentile local SLR projection. Further details are provided in the Supplementary Information of Kopp et al (2017).

2.3 Results

2.3.1 Global mean sea-level rise

The GMSL projections for each GMST target from the K14 and SESL method are shown in Fig. 2.1 and are tabulated along with the component contributions in Table 2.1. For the K14 method, differences in median GMSL between 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilization targets do not appear until after 2050, when the 1.5 °C scenario begins to separate from the 2.0 °C and 2.5 °C trajectories (Table 2.1). The median GMST trajectories diverge earlier, around 2030 (Fig. 2.6). This is consistent with the early to mid-century divergence in the radiative forcing pathways and this study's allocation of RCPs in the 1.5 °C (primarily RCP2.6), 2.0 °C (primarily RCP4.5), and 2.5 °C (primarily RCP4.5 and RCP6) scenarios (Table 2.3). Median projections for 2100 GMSL under a 1.5 °C scenario are 48 cm, with a *very likely* range (90% probability) of 28–82 cm. An additional 8–10 cm of median GMSL rise is found for the 2.0 °C and 2.5 °C GMST scenarios, 56 cm (*very likely* 28–96 cm) and 58 cm (*very likely* 37–93 cm), respectively. Prior to mid-century, TE and GIC contributions account for more than half of GMSL projection uncertainty, but by 2100, ice sheet contributions dominate (SI Fig. 2.8). Other studies found similar GMSL results. Using the same framework, Kopp et al (2014) estimated median 2100 GMSL projections under RCP2.6 and RCP4.5 of 50 cm (*very likely* 29–82 cm) and 59 cm (*very likely* 36–93 cm), respectively. Jackson et al (2018) also employs the CMIP5 ensemble to estimate probabilistic local SLR projections for GMST stabilizations, but do not consider non-linear ice dynamics (e.g., Bamber and Aspinall, 2013). Their median projections for 1.5 °C (44 cm; *very likely* 20–67 cm) and 2.0 °C (50 cm; *very likely* 24–74 cm) GMST stabilizations are within 4–6 cm of this study. Using a method that scales SLR component contributions as a function of GMST and ocean heat uptake (Perrette et al, 2013), Schleussner et al (2016a) estimated a median 2100 GMSL for 1.5 °C and 2.0 °C scenarios that is 6–7 cm lower than this study's K14 framework projections. (Table 2.1).

Despite being warmer by a half-degree, the 2.5 °C GMSL projections largely overlap the 2.0 °C scenario (Fig. 2.1). Variation in the transient climate response and ocean heat uptake efficiency across CMIP5 models leads to weak correlation between TE and GMST ($r^2 = 0.10$; Fig. 2.9; Kuhlbrodt and Gregory, 2012; Raper et al, 2002). As such, cooler models may produce more TE than warmer models, and vice versa. Ice sheet contributions are also similar between 2.0 °C and 2.5 °C scenarios (Table 2.1). To test the sensitivity of model-RCP filtering to the choice of GMST stabilization, we additionally calculate GMSL under a 1.75 °C and 2.25 °C GMST scenario. The median 2100 GMSL under the 1.75 °C scenario is 3 cm greater than the 1.5 °C scenario, and the 2.25 °C scenario is 1 cm less than the 2.0 °C scenario (Table 2.4), suggesting that GMST scenarios that are primarily represented by only one RCP (i.e., the 1.5 °C scenario) may be more sensitive to model filtering.

Agreement between central estimates from process-based and semi-empirical projections implies consistency with the observed statistical relationship between GMST and the rate of SLR used to calibrate the SESL model. Across scenarios, median 2100 GMSL projections from the SESL model driven with CMIP5 GMST trajectories are 7–8 cm lower than those from the K14 framework (Fig. 2.1 and Table 2.1), but more disagreement exists between the processed-based and SESL projections when driven with the MAGICC GMST trajectories shown in SI Fig. 2.6 (median projection differences of 4–11 cm; Table 2.1). These differences are smaller in magnitude relative to the differences in the median RCP2.6 and RCP4.5 projections from Kopp et al (2014) and the SESL projections from Kopp et al (2016a) (8–12 cm). After 2100, the differences between projections from the K14 framework and the SESL model become larger. Across scenarios, median 2200 GMSL projections from the K14 framework are higher by 32 cm (1.5 °C), 39 cm (2.0 °C) and 17 cm (2.5 °C) than those from the SESL model driven with CMIP5 GMST trajectories (Fig. 2.1 and Table 2.1). These differences are largely attributed to the treatment of ice sheets in each approach. The K14 framework accounts for non-linearities in crossing threshold ice sheet behavior by drawing from AR5 and Bamber and Aspinall (2013), but the SESL does not because these events are absent from the calibration period.

2.3.2 Population inundation

Under the median projected GMSL for a 2.0 °C GMST stabilization, lands currently home to about 60 million people are projected to be permanently submerged by 2150, including lands currently home to half a million inhabitants of United Nations defined Small Island Developing States (SIDS). Aggregation of all SIDS can mask important risks. For instance, local SLR projections for 2150 under a 2.0 °C GMST stabilization place lands currently home to almost a quarter of the current population of the Marshall Islands at risk of being permanently submerged. In comparison to these totals, under the median projection for the 1.5 °C stabilization scenario, lands currently home to about 5 million people, including 60,000 in SIDS, avoid inundation (Table 2.2), but little difference is found for the Marshall Islands.

2.3.3 Amplification of extreme sea level events

We assess the effects of different GMST stabilizations on the frequency of ESL events by highlighting three cities: 1) New York, New York, USA, 2) Kushimoto, Wakayama, Japan, 3) Cuxhaven, Lower Saxony, Germany (Fig. 2.2). Estimates of the historical 10-, 100-, and 500-yr ESL event (expected frequency of 0.1/year, 0.01/year, and 0.002/year, respectively) and the future ESL frequency amplification factor (AF) for all sites are provided in SI Tables S-4 to S-6. Under a 2.0 °C GMST stabilization, the 2100 median local SLR for New York City is 69 cm (*likely* 44–98 cm). In Fig. 2.2, median local SLR under the 2.0 °C scenario (SL_{50}) shifts the expected historic ESL event return curve to the right [i.e., $N(z)$, the heavy grey curve, becomes $N+SL_{50}$ 2.0 °C, the dashed green curve] and increases the expected annual number of historical 10-yr ESL events from 0.1/year to ~10/year. However, when both the uncertainty in the GPD fit and the SLR projections are considered in the calculation of the projected future ESL event return curve (i.e., N_e 2.0 °C; the heavy green curve), the expected frequency of the current 10-yr ESL event increases from 0.1/year to 36/year (i.e., $>$ 2/month, on average). Discontinuities in the N_e curves can arise at the transition between modeling flood events with two different distributions. Specifically, expected ESL frequencies between the historical frequency of the GPD threshold exceedance (i.e., λ) and 182.6 events per year are modeled with a Gumbel distribution and expected ESL frequencies greater than λ are modeled with a GPD (Section 2.2.4). Discontinuities can also occur at higher levels of ESL height depending on the shape of the SLR uncertainty distribution. Note that because the uncertainty in local SLR varies by location, the distance between the $N+SL_{50}$ and N_e curves also differs by location. GHG mitigation that stabilizes GMST at 1.5 °C reduces projected median local SLR at New York City to 55 cm (*likely* 35–78 cm), and reduces the expected number of current 10-year ESL events by half (15/year). By 2150, the reduction in projected 10-yr ESL events from the 2.0 °C to the 1.5 °C scenario is still ~50% (103/year reduced to 59/year; (Table S-4 in published appendix, online).

Sea-level rise will amplify the frequency of all ESL events, but depending on the shape of the GPD, the frequency of some ESL events may amplify more than others (Buchanan et al, 2017). For example, by 2100 under a 2.0 °C and 1.5 °C GMST stabilization, respectively, median local SLR for Kushimoto, Japan is projected to be 79 cm (*likely* 58–103 cm) and 70 cm (*likely* 52–92 cm), increasing the respective number of historical 10-yr ESL events from 0.1/year, on average, to 146/year (AF of 1462) and 128/year (AF of 1277), on average. However, for the same amount of local SLR, the historical number of expected 500-yr ESL events for Kushimoto increases from .002/year to 83/year (2.0 °C; AF of 41479) and 57/year (1.5 °C; AF of 28645). When the shape of the return curve is log-linear [as occurs when the shape parameter (ξ) is zero], ESL events amplify equally across return periods. For example, by 2100, under a 1.5 °C, 2.0 °C, and 2.5 °C GMST stabilization, respectively, Cuxhaven, Germany is projected to have median local SLR of 43 cm (*likely* 26–65 cm), 53 cm (*likely* 29–82 cm) and 51 cm (*likely* 34–71 cm). The historical 500-yr ESL event is projected to become as or more frequent than the historical 100-yr ESL event for all scenarios: 0.01/year (1.5 °C; AF of 5.7), 0.03/year (2.0 °C; AF of 14.1), and 0.01/year (2.5 °C; AF of 6.5). Because the shape factor of the Cuxhaven GPD is close to zero, the historical 10-yr ESL event also is projected to amplify similarly to the 500-yr ESL event: 0.6/year (1.5 °C; AF of 5.6), 1.0/year (2.0 °C; AF of 13.5), and 0.7/year (2.5 °C; AF of 6.5). For some sites, including Cuxhaven, the AF for the 2.0 °C scenario may be greater than the AF for the 2.5

°C scenario. This can be partly attributed to higher SLR projections in the upper tail of the 2.0 °C probability distribution influencing the AF calculation.

We assess regional differences in 100-yr ESL event frequency amplification between 2.0 °C and 1.5 °C GMST stabilization by binning ratios of 2.0 °C/1.5 °C expected AFs for 2100 and 2150 (Fig. 2.3). Bins on the right side of each graph become filled when there are decreases in the frequency of ESL events at regional groups of tide gauges from 1.5 °C over 2.0 °C GMST stabilization, while bins on the left side of each graph become filled when there are either no changes or increases in ESL event frequency at stations from 1.5 °C GMST over 2.0 °C GMST stabilization. In general, decreases in the frequency of ESL events from a 1.5 °C GMST stabilization grow as GMSL trajectories between scenarios separate from one another (Table 2.1). By 2100 and 2150, substantial decreases in the frequency of ESL events from 1.5 °C GMST stabilization are expected in the East and Gulf Coasts of the United States, where ESL event amplification between GMST scenarios is reduced by roughly half. By 2150, smaller contributions from either local ocean dynamics or GICs in the 2.0 °C scenario attenuate SLR in parts of Europe, leading to lower median local SLR than from 1.5 °C GMST stabilization. Less local SLR in the 2.0 °C scenario causes ESL event frequencies to decrease, relative to the 1.5 °C scenario. We find small decreases or no change in ESL event frequency from achieving a 1.5 °C GMST stabilization over a 2.0 °C GMST stabilization at most tide gauges located in SIDS, as local SLR projections in these areas are similar between GMST scenarios (Fig. 2.3).

2.4 Discussion and Conclusions

The Paris Agreement seeks to stabilize GMST by limiting warming to “well below 2.0 °C above pre-industrial levels”, but a recent literature review under the UNFCCC found the notion that “up to 2.0 °C of warming is considered safe, is inadequate” and that “limiting global warming to below 1.5 °C would come with several advantages” (UNFCCC, 2015b). However, the location-specific increases in the frequency of ESLs illustrate the divergence between local and global perspectives on the question of what climate changes are ‘dangerous’. The selection of a GMST target has important implications for long-term GMSL rise, ESLs, and consequently, coastal flooding. Assessing the distribution of impacts of incremental levels of warming on ESLs is of relevance to $>$ 625 million people who currently reside in low-lying coastal areas (Neumann et al, 2015) and are vulnerable to current and future ESL events. For countries without the economic and physical capacity to construct flood protection and flood-resilient infrastructure—including some recognized by the United Nations as Small Island Developing States—local SLR that results in permanent inundation and unmanageable flooding may threaten their existence (Wong et al, 2014; Diaz, 2016). The only feasible option for maintaining habitability for these locations may be the management of GMST through international climate accords, like the Paris Agreement, that govern the long-term committed rise in GMSL.

Only considering changes to the mean local sea level, we find that, under median projections, lands currently home to 5 million people will be spared from being permanently submerged by local mean sea levels by 2150 under a 1.5 °C GMST stabilization compared to local mean sea levels under the 2.0 °C case. This includes lands in SIDS currently home to 60,000 people (Table 2.2). The effects of GMST stabilization on ESLs varies greatly by region and by historical return period (e.g., the 10-yr versus the 100-yr ESL event, ect.). Globally, for the historical 100-yr ESL event, we find that by 2100, the Eastern and Gulf coasts of the U.S. and Europe could experience substantial benefits from a 1.5 °C GMST stabilization relative to a 2.0 °C GMST stabilization, with ESL frequency amplification being reduced by about half. However, while fractional reductions may appear substantial in some cases, small absolute differences may warrant similar coastal flood risk management responses. For instance, for New York City, we estimate the expected number of historical 100-yr ESL events per year between a 2.0 °C to a 1.5 °C GMST stabilization is only 2 and 1 times per year, respectively (Fig. 2.2).

While these data could be used in support of local probabilistic risk management strategies that intend to reduce current and future exposure and vulnerability to extreme flood events, some caveats should be highlighted. First, while our projections carry probabilities, these are not uniquely identifiable probabilities; ice sheet contributions in particular are deeply uncertain, so unique probability distributions for their future values do not exist (e.g., Kopp et al, 2017). Moreover, our projections assume linear accelerations of ice-sheet contributions. Detailed physical models (e.g., Deconto and Pollard, 2016) suggest that these approximations may fail over the course of the next three centuries. Rates of ice-sheet contributions may stabilize, or they may cross critical thresholds leading to non-linear accelerations. While the results of Deconto and Pollard (2016) suggest a critical threshold above 2 °C leading to considerably larger Antarctic contributions than at lower temperatures, estimates of the existence, location, and consequences of such thresholds are deeply uncertain. Second, we assume that the frequency of storm arrivals and their intensity will remain constant—and thus the Poisson and GPD parameters (Section 2.2.4). Changes to storm frequency and severity could significantly influence future ESL events (e.g., Reed et al, 2015; Emanuel, 2013; Knutson et al, 2010). Modifications could be made to include changes in these parameters with time (Ceres et al, 2017). Third, these are projections of extreme high water at specific tide gauges and are not regional flood projections. Future flood projections are dependent on the dynamics of flood propagation, wave action, and future measures taken to reduce flood risk.

The selection of the level at which to stabilize the GMST in the coming years will determine the committed amounts of future GMSL (Clark et al, 2016; Levermann et al, 2013). Our projected coastal ESL impacts through the end of the 22nd century should be placed in the context of longer timeframes. Stabilization of GMST does not imply stabilization of GMSL. Regardless of the mitigation scenario chosen, GMSL rise due to TE is expected to continue for centuries to millennia. Additionally, some studies suggest that sustained GMST warming above given thresholds, potentially those as low as 1 °C, could lead to a near-complete loss of the GIS over a millennium or more (Robinson et al, 2012). Coincident with continued GMSL rise will be further increases in the frequency of historical ESL events and an increasing number of currently inhabited lands that will be permanently submerged. A comprehensive approach to managing coastal flood risks would take into account changes on these very long time frames.

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Figures and Tables

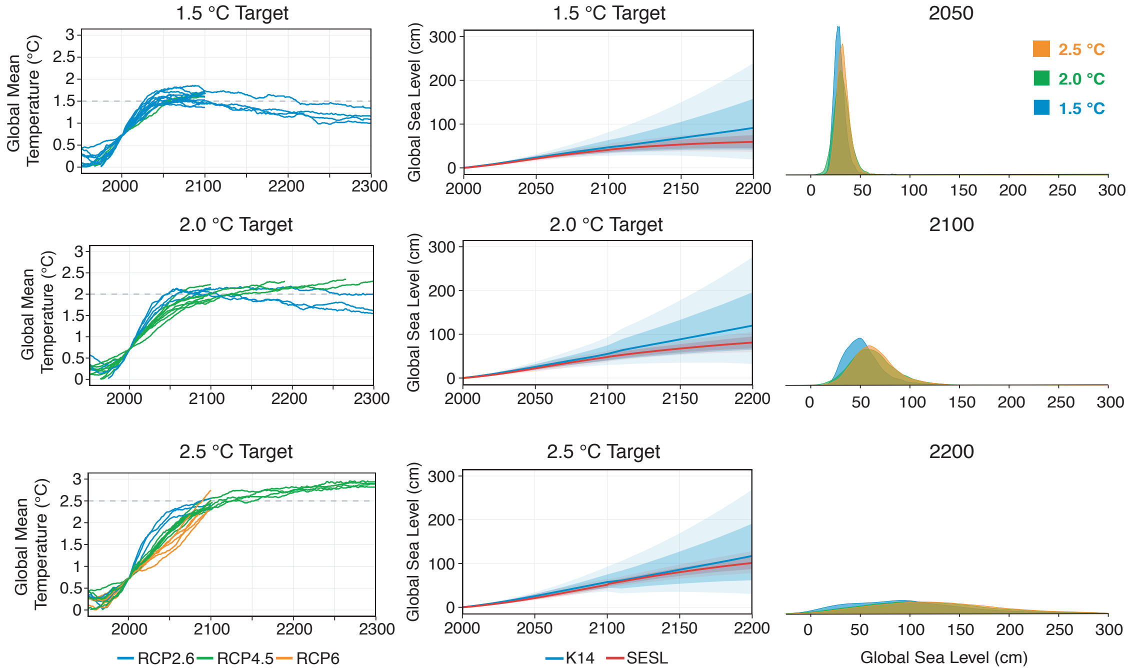


Figure 2.1: **Left Column:** Global mean surface temperature (GMST) trajectories from CMIP5 models (1950–2300) that have a 19-year running average 2100 GMST of 1.5 °C, 2.0 °C, and 2.5 °C ± 0.25°C (relative to 1875–1900; blue = RCP2.6, green = RCP4.5, orange = RCP6). GMST is anomalized to 1991–2009 and shifted up by 0.72°C to account for warming since 1875–1900 (Hansen et al, 2010; GISSTEMP Team, 2017). Table 2.3 lists the CMIP5 models used for each GMST target. **Middle Column:** Global mean sea-level rise (cm; relative to 2000) from the methodology of Kopp et al (2014) (K14; blue), using CMIP5 temperature trajectories from Left Column, and a semi-empirical global sea-level (SESL) model from Kopp et al (2016a) (red). Temperature trajectories that drive the SESL model are shown in the Left Column. The thick line is the 50th percentile, heavy shading is the 17/83rd percentile, and light shading is the 5/95th percentile. **Right Column:** Probability distributions of projected 2050, 2100, and 2200 global mean sea-level rise for GMST stabilization targets using the Kopp et al (2014) framework (blue = 1.5 °C, green = 2.0 °C, orange = 2.5 °C).

Table 2.1: Global mean sea-level projections. All values are cm above 2000 CE baseline. AIS = Antarctic Ice Sheet, GIS = Greenland Ice Sheet; TE = Thermal Expansion; GIC = Glaciers and Ice Caps; LWS = Land-Water Storage. AIS and GIS ice sheet distributions for each Representative Concentration Pathway (RCP) from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (Church et al, 2013) are randomly sampled in proportion to the RCP representation in the CMIP5 model filtering (Table 2.3). K16: Semi-empirical sea level (SESL) model from Kopp et al (2016a) driven with GMST trajectories from MAGICC (see SI Fig. 2.6) and CMIP5 GMST trajectories (see Fig. 2.1); J18: Jackson et al (2018); S16: Schleussner et al (2016a)

	1.5 °C			2.0 °C			2.5 °C		
cm	50	17–83	5–95	50	17–83	5–95	50	17–83	5–95
2100—Components									
AIS	6	-4–17	-8–35	6	-5–17	-8–34	6	-5–16	-8–34
GIS	7	4–12	3–19	8	4–14	2–22	8	4–15	2–22
TE	19	14–23	10–27	25	15–34	7–42	26	20–31	16–35
GIC	11	8–13	6–15	11	7–16	2–21	13	11–15	9–17
LWS	5	3–7	2–8	5	3–7	2–8	5	3–7	2–8
Total	48	35–64	28–82	56	39–76	28–96	58	45–75	37–93
Projections by year									
2050	24	20–28	18–32	25	20–32	15–37	26	22–30	19–34
2070	34	27–41	24–50	38	28–48	21–58	38	32–47	27–55
2100	48	35–64	28–82	56	39–76	28–96	58	45–75	37–93
2150	69	42–107	28–151	88	50–133	25–181	86	54–126	35–171
2200	93	43–161	20–241	120	57–197	20–281	118	62–189	31–268
Other projections for 2100									
K16[1]	38	33–43	30–47	45	39–52	35–58	54	47–62	42–68
K16[2]	41	36–48	32–53	48	41–56	36–62	51	45–59	41–65
J18	44	30–58	20–67	50	35–64	24–74	–	–	–
S16	41	29–53	–	50	36–65	–	–	–	–
Other projections for 2200									
K16[1]	58	45–72	36–81	79	65–93	56–104	100	85–115	75–127
K16[2]	59	45–75	37–88	81	68–95	59–105	101	87–116	78–128

[1] SESL model driven with MAGICC6 GMST trajectories shown in SI Fig. 2.6

[2] SESL model driven with CMIP5 GMST trajectories shown in Fig. 2.1

Table 2.2: The current population (in millions) living on lands exposed to future permanent inundation from median (5–95th percentile) local sea-level rise (SLR) projections. Population estimates are from 2010. The top five countries with the most exposure in 2150 are included in the table as well as United Nations defined Small Island Developing States (SIDS).

Human population exposure under 2100 local SLR projections (millions)

Region	Total Pop.	1.5 °C	2.0 °C	2.5 °C
World	6,836.42	46.12 (31.92–69.23)	48.76 (32.01–79.65)	50.35 (33.33–77.38)
China	1,330.20	11.70 (5.89–20.37)	12.75 (6.00–22.05)	13.26 (6.18–22.91)
Vietnam	89.55	6.57 (4.56–9.91)	6.96 (4.58–10.65)	7.16 (4.66–11.05)
Japan	126.66	4.44 (3.84–5.56)	4.62 (3.88–5.85)	4.69 (3.89–6.11)
Netherlands	16.78	4.71 (4.20–5.57)	4.86 (4.16–5.87)	4.85 (4.36–5.63)
Bangladesh	156.13	2.83 (1.98–4.33)	3.03 (2.05–4.77)	3.09 (2.13–4.92)
SIDS	62.08	0.40 (0.30–0.56)	0.42 (0.30–0.64)	0.43 (0.32–0.63)

Human population exposure under 2150 local SLR projections (millions)

Region	Total Pop.	1.5 °C	2.0 °C	2.5 °C
World	6,836.42	56.05 (32.54–112.97)	61.84 (32.89–138.63)	62.27 (34.08–126.95)
China	1,330.20	14.46 (5.73–31.00)	16.92 (5.86–37.08)	16.58 (5.75–36.48)
Vietnam	89.55	7.60 (4.46–15.19)	8.47 (4.51–17.13)	8.33 (4.54–16.58)
Japan	126.66	4.92 (3.87–7.69)	5.40 (3.94–8.72)	5.35 (3.89–8.61)
Netherlands	16.78	5.06 (4.12–6.49)	5.18 (4.22–6.45)	5.28 (4.38–6.48)
Bangladesh	156.13	4.48 (2.58–9.78)	5.10 (2.67–11.95)	5.01 (2.82–11.15)
SIDS	62.08	0.46 (0.29–0.91)	0.52 (0.29–1.14)	0.52 (0.31–1.01)

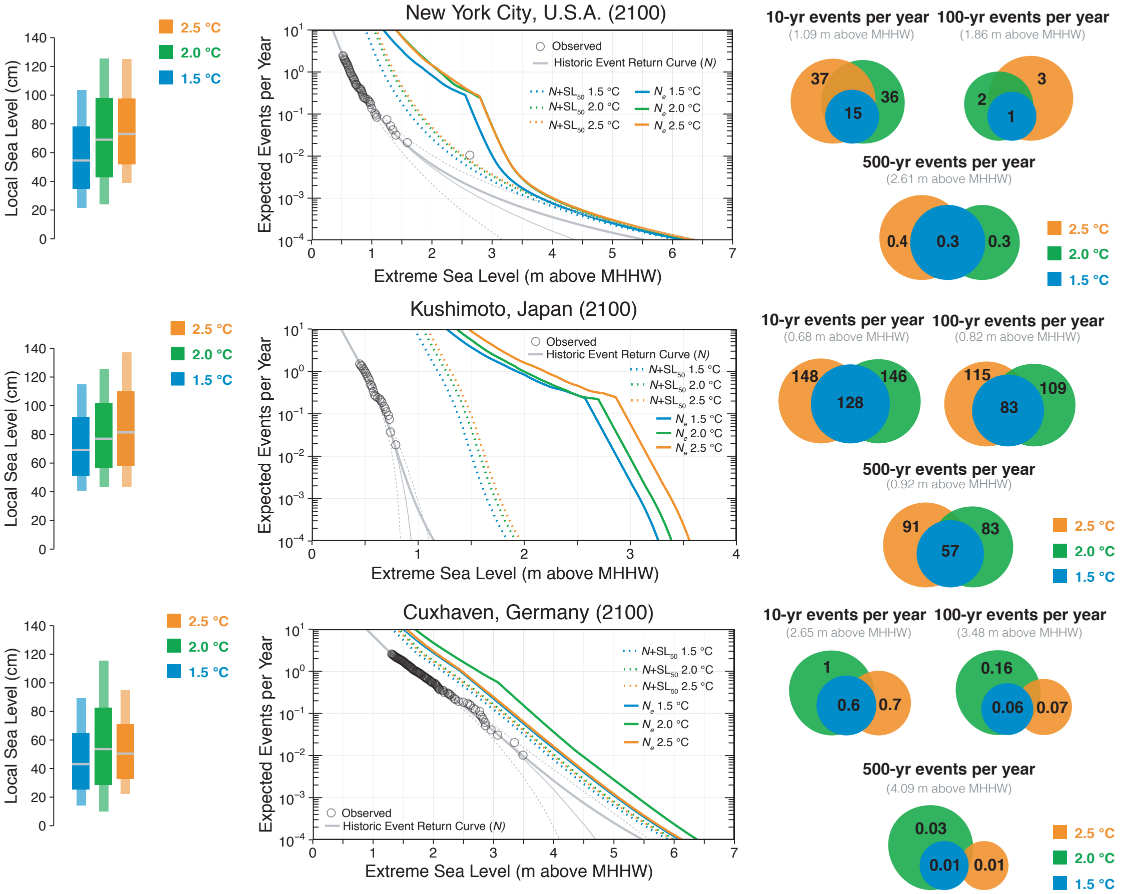


Figure 2.2: **Top Left:** 2100 local sea-level rise (SLR) (cm; relative to 2000) for New York City, U.S.A., under 1.5 °C (blue), 2.0 °C (green), and 2.5 °C (orange) global mean surface temperature (GMST) stabilizations. Grey bars are median, heavy colors are 17/83 percentile and light shading is 5/95 percentile. **Top Middle:** Extreme sea level (ESL) event return curves for New York City indicating the relationship between the expected number of ESL events per year and ESL height [m above mean higher high water (MHHW)] for: 1) historical conditions (grey curves) and 2) year 2100 under both different GMST stabilizations (blue = 1.5 °C, green = 2.0 °C, orange = 2.5°C) and consideration of local SLR uncertainty [dotted curves consider median SLR only (i.e., a fixed offset from N, $N + \mathrm{SL}_{50}$); solid curves (N_e) incorporate local SLR projection uncertainty by integrating across both the entire SLR probability distribution and GPD parameter uncertainty; blue, green, and orange colors are the 1.5 °C, 2.0 °C, 2.5 °C scenarios, respectively]. The thick grey curve is the expected historical ESL height return curve (N) that incorporates the uncertainty in the GPD parameter fit, open grey circles are observed ESL events from the tide gauge record, and thin grey lines are the historical ESL height return curves for the 17/50/83 percentiles of the GPD parameter uncertainty range (dotted/solid/dotted lines, respectively). The shape of the N_e curve varies by location in part because both local SLR uncertainty and the shape of the historical return curve vary by location. **Top Right:** The expected number of ESL events per year by historical return period for New York City for 2100 under a 1.5 °C (blue), 2.0 °C (green), and 2.5 °C (orange) GMST stabilization. **Second Row:** As for Top Row, but for Kushimoto, Japan. **Third Row:** As for Top Row, but for Cuxhaven, Germany.

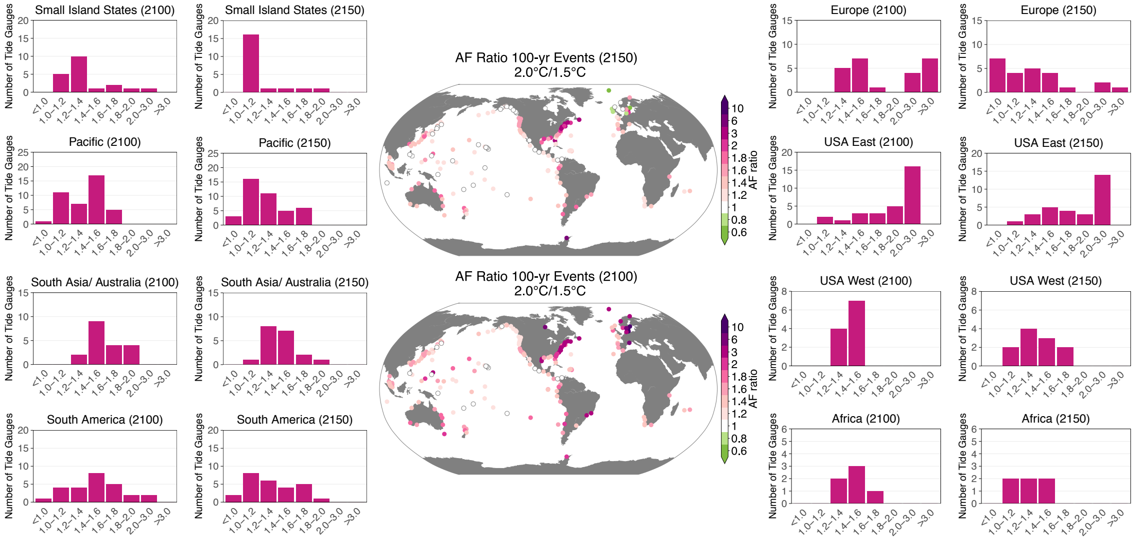


Figure 2.3: **Maps:** The ratio of expected extreme sea level (ESL) event amplification factors (AFs) for historical 100-yr ESL events between a 1.5 °C and 2.0 °C global mean surface temperature (GMST) stabilization target for the years 2150 (top) and 2100 (bottom). Larger 2.0 °C/1.5 °C AF ratios indicate where the historical 100-yr ESL event occurs less often under 1.5 °C GMST stabilization than 2.0 °C GMST stabilization. **Histograms:** Regionally binned ratios of 2.0 °C/1.5 °C expected AFs for the historical 100-yr ESL event for 2100 and 2150. "Small Island States" are United Nations defined Small Island Developing States. The list of tide gauges included in each region are given in Table S-1 in published appendix, online.

2.5 Appendix: Preparation of tide gauge data for extreme value analysis

Tide gauge observations are prepared as the basis for extreme value analysis following the methods of Tebaldi et al (2012). First, daily maximum tide gauge values are calculated from the "Research Quality" hourly observations from the University of Hawaii Sea Level Center (retrieved from: https://uhslc.soest.hawaii.edu/, June 2017; Caldwell et al, 2015). We only use tide gauges with record lengths $\geq$ 30 years and $\geq$ 80 percent data completion within each record therein. A list of tide gauges and the portion of their records used in this study is provided in Table S-1 in published appendix (online).

The long-term trend in sea-level change over the tide gauge record is removed to isolate the impact on sea levels from day-to-day weather, astronomical tides and seasonal cycles. Specifically, monthly mean sea levels over the tide gauge record are used to linearly de-trend the daily maximum observations. The de-trended daily maximum observations are then registered to the mean higher high water (MHHW) height at each tide gauge. At each tide gauge, the MHHW height is estimated using the average of the daily maximum tide gauge observations over the most recent 19-year period in the tide gauge record. While the MHHW calculation approach differs from the current U.S. standard (which is defined over the National Tidal Datum Epoch of 1983–2001), it is done after de-trending of the daily time series and should therefore be close to stationary.

Finally, at each tide gauge the daily maximum observations above the 99th percentile are de-clustered to separate multiple observations made during the same extreme sea level event and so that each observation used to estimate the extreme value distribution is statistically independent of one another. The 99th percentile is used as it is generally above the highest seasonal tide and it balances the bias-variance trade-off in the GPD parameter estimation. If too low of a GPD threshold is chosen, more observations than those exclusively in the tail of the GPD distribution might end up being included in the parameter calculation, causing bias. If too high of a GPD threshold is chosen, then too few observations may be incorporated in the estimation of distribution parameters leading to greater variance, relative to a case that uses more observations.

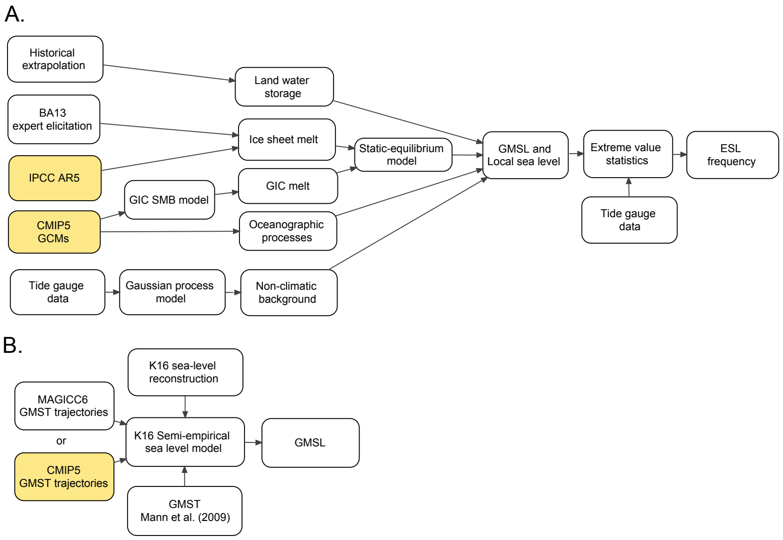


Figure 2.4: **Top:** Logical flow of sources of information used in local sea-level projections and extreme sea level (ESL) event return curves. GCMs are global climate models; GIC is glaciers and ice caps; SMB is surface mass balance; GMST is global mean surface temperature; GMSL is global mean sea level; BA13 is Bamber and Aspinall, 2013; K16 is Kopp et al, 2016a. Orange shades indicate where RCP and model grouping occurs (see Table 2.3). **Bottom:** Logical flow of sources of information used to construct semi-empirical GMSL projections. Note that either the MAGICC6 or CMIP5 GMST trajectories can be used to drive the semi-empirical sea level model.

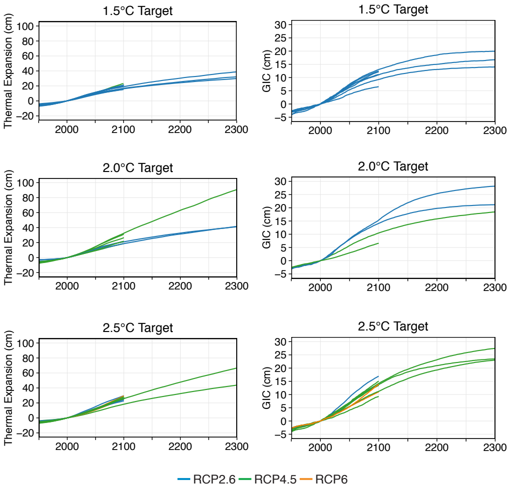


Figure 2.5: **Left Column:** Thermal expansion contribution to global mean sea-level (GMSL) rise (cm; relative to 2000) from CMIP5 models that have been smoothed and corrected for model drift for global mean surface temperature stabilization targets of 1.5 °C, 2.0 °C, and 2.5 °C (blue = RCP2.6, green = RCP4.5, orange = RCP6). **Right Column:** As for Left Column, but for glaciers and ice cap (GIC) contributions to GMSL rise (cm; relative to 2000) using the model from Marzeion et al (2012). Table 2.3 lists the models used for each temperature target.

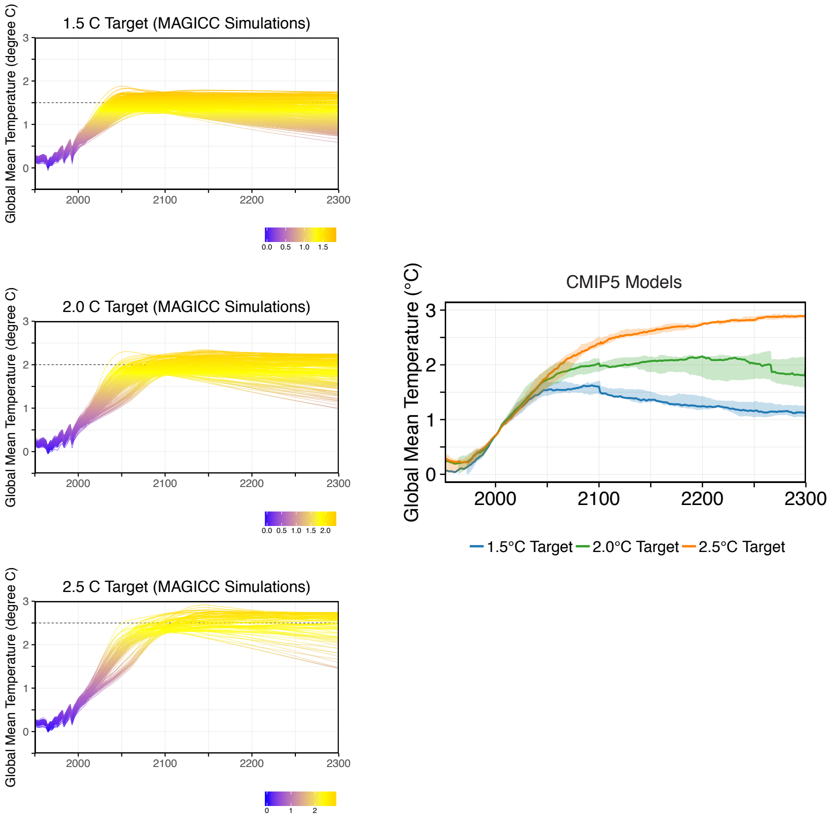
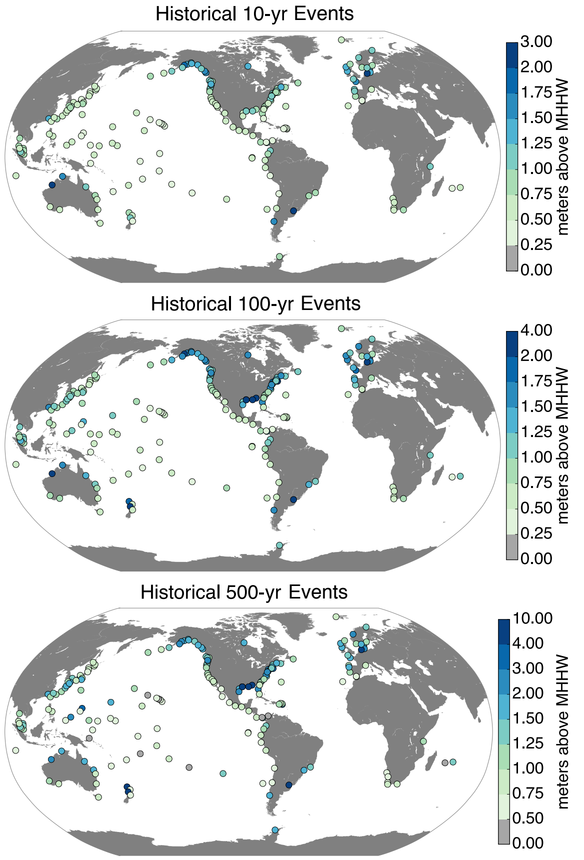


Figure 2.6: **Left:** Global mean temperature trajectories from MAGICC6 that have a 2100 GMST of 1.5 °C, 2.0 °C, and 2.5 °C ± 0.25°C (relative to 1875–1900). Temperatures are relative to 1875–1900. **Right:** Global mean surface temperature (GMST) trajectories from CMIP5 models (1950–2300) that have a 2100 GMST of 1.5 °C, 2.0 °C, and 2.5 °C ± 0.25°C (relative to 1875–1900). GMST is anomalized to 1991–2009 and shifted up by 0.72°C to account for warming since 1875–1900 (Hansen et al, 2010; GISSTEMP Team, 2017). Solid line is the 50th percentile and shading is the 17th/83rd range.



Historical 10-yr Events

Historical 100-yr Events

Historical 500-yr Events

Figure 2.7: Historical extreme sea level height [meters above mean higher high water (MHHW)] for return periods of 10-, 100-, and 500-years.

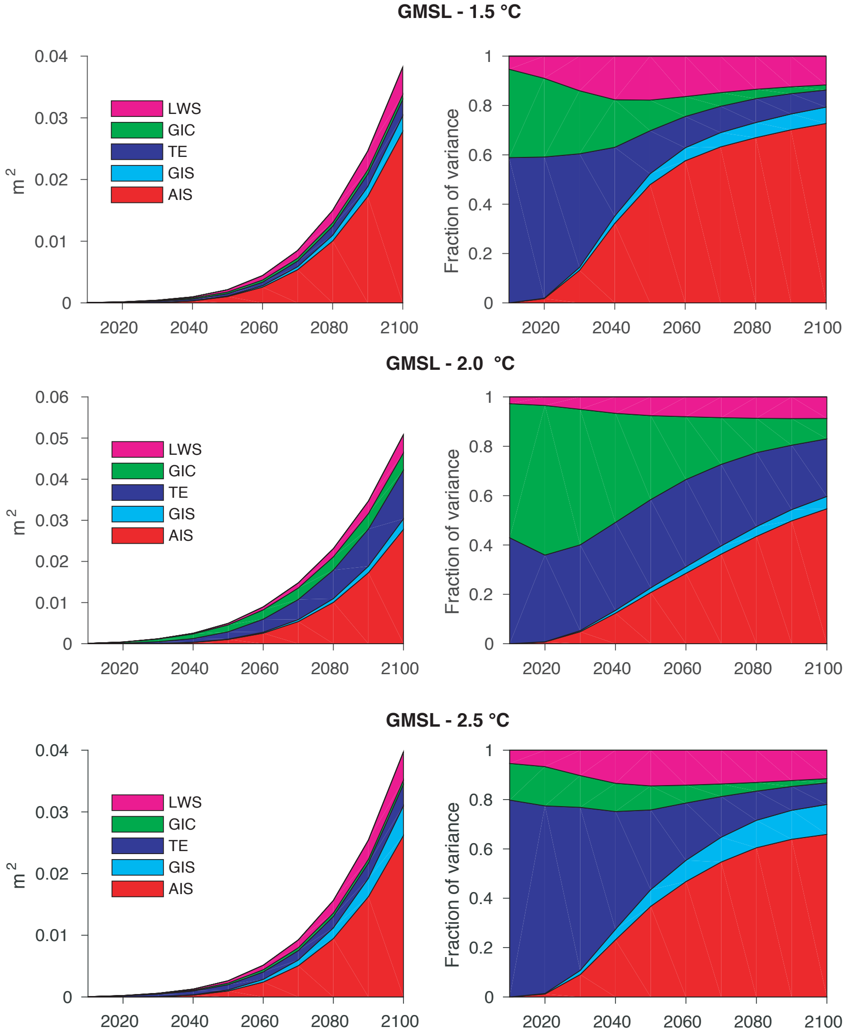


Figure 2.8: Global mean sea level (GMSL) sources of variance in raw and fractional terms in 1.5 °C, 2.0 °C, and 2.5 °C global mean surface temperature stabilization scenarios. AIS: Antarctic ice sheet, GIS: Greenland ice sheet, TE: thermal expansion, GIC: glaciers and ice caps, LWS: land water storage

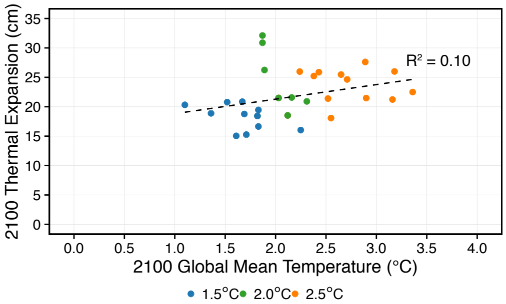


Figure 2.9: Relationship between 2100 global mean thermal expansion contribution to sea-level rise (i.e., 'zostoga') (cm) and the 19-yr running average of global mean surface temperature (GMST) for 2100 from CMIP5 model output (°C, relative to 1875–1900) under 1.5 °C (blue), 2.0 °C (green), and 2.5 °C (orange) GMST stabilization scenarios. Black dotted line is the linear fit across all temperature scenarios and all models.

Table 2.3: Inventory of CMIP5 models and their RCPs used for 1.5 °C, 2.0 °C, and 2.5 °C global mean surface temperature (GMST) stabilization targets. Information is given for the 19-yr running average 2100 GMST (°C; relative to 1875–1900), the lengths of the GMST projections, and the models used for generating contributions to global and local sea-level change from oceanographic processes and glaciers and ice caps (GIC; from Marzeion et al (2012)). 'Ocean Dynamics' is the local dynamic sea surface height anomaly (i.e., CMIP5 model output variable 'zos'; used only for local sea level projections) and 'Thermal Expansion' refers to the contribution to the change in the global mean sea level due to thermal expansion (i.e., CMIP5 model output variables 'zostoga' and 'zosga'). For the global average sea level projections, only the 'Thermal Expansion' component is considered, while local sea level projections use both the 'Ocean Dynamics' and 'Thermal Expansion' components.

1.5 °C

Model	RCP	2100 GMST (°C)	GMST	Ocean Dynamics	Thermal Expansion	GIC
bcc-csm1-1	RCP 2.6	1.51	23	23	23	23
BNU-ESM	RCP 2.6	1.62	21			
CCSM4	RCP 2.6	1.45	23	23	21	21
FIO-ESM	RCP 4.5	1.7	21	21		
GFDL-ESM2G	RCP 4.5	1.61	21	21		
HadGEM2-AO	RCP 2.6	1.74	21			
IPSL-CM5A-LR	RCP 2.6	1.74	23	23	23	23
IPSL-CM5A-MR	RCP 2.6	1.6	21	21	21	
MIROC5	RCP 2.6	1.62	21			21
MPI-ESM-LR	RCP 2.6	1.44	23	23	23	23
MPI-ESM-MR	RCP 2.6	1.36	21	21	21	
MRI-CGCM3	RCP 2.6	1.72	21	21	21	21
NorESM1-M	RCP 2.6	1.52	21	21	21	21
NorESM1-ME	RCP 2.6	1.67	21	21	21	

2.0 °C

Model	RCP	2100 GMST (°C)	GMST	Ocean Dynamics	Thermal Expansion	GIC
bcc-csm1-1-m	RCP 4.5	2.13	21	21	21	
CanESM2	RCP 2.6	2.17	23	23	23	23
CESM1-BGC	RCP 4.5	2.24	21	21		
CESM1-CAM5	RCP 2.6	2.13	23			
CSIRO-MK3-6-0	RCP 2.6	2.04	21		21	
FGOALS-G2	RCP 4.5	2.01	23			
GFDL-ESM2M	RCP 4.5	1.84	22	21	21	
GISS-E2-H-CC	RCP 4.5	2.03	21			
GISS-E2-R	RCP 4.5	1.88	23	23	23	23
GISS-E2-R-CC	RCP 4.5	1.87	21	21	21	
HadGEM2-ES	RCP 2.6	1.97	23	23	23	23
inmcm4	RCP 4.5	2.04	21	21	21	21

2.5 °C

Model	RCP	2100 GMST (°C)	GMST	Ocean Dynamics	Thermal Expansion	GIC
CCSM4	RCP 4.5	2.31	23	23	21	21
CNRM-CM5	RCP 4.5	2.56	23	23	23	23
FIO-ESM	RCP 6.0	2.34	21	21		
GFDL-CM3	RCP 2.6	2.57	21	21	21	21
GFDL-ESM2G	RCP 6.0	2.35	21	21	21	
GFDL-ESM2M	RCP 6.0	2.53	21	21	21	
GISS-E2-R	RCP 6.0	2.52	21	21	21	21
IPSL-CM5B-LR	RCP 4.5	2.37	21	21		
MIROC-ESM	RCP 2.6	2.32	21	21	21	21
MIROC-ESM-CHEM	RCP 2.6	2.42	21	21	21	
MIROC5	RCP 4.5	2.38	21		21	21
MPI-ESM-LR	RCP 4.5	2.38	23	23	23	23
MPI-ESM-MR	RCP 4.5	2.39	21	21	21	
MRI-CGCM3	RCP 4.5	2.51	21	21		21
NorESM1-M	RCP 6.0	2.74	21	21	21	23
NorESM1-M	RCP 4.5	2.33	23	23	21	
NorESM1-ME	RCP 4.5	2.44	21	21	21	

21 = to 2100, 22 = to 2200, 23 = to 2300

Table 2.4: Global mean sea level projections from a 1.75 °C and a 2.25 °C GMST scenario. All values are cm above 2000 CE baseline. AIS = Antarctic Ice Sheet, GIS = Greenland Ice Sheet; TE = Thermal Expansion; GIC = Glaciers and Ice Caps; LWS = Land-Water Storage.

	1.75°C			2.25°C		
cm	50	17–83	5–95	50	17–83	5–95
2100—Components						
AIS	6	-4–17	-7–34	6	-4–17	-8–33
GIS	7	4–13	3–20	8	4–14	2–22
Ocean	20	11–30	4–37	23	20–27	17–30
GIC	12	8–15	6–17	12	9–16	5–20
LWS	5	3–7	2–8	5	3–7	2–8
Total	51	36–70	26–88	55	42–72	34–89
Projections by year						
2050	25	20–30	17–34	25	21–30	18–34
2070	36	27–45	22–54	37	30–45	26–54
2100	51	36–70	26–88	55	42–72	34–89
2150	73	45–112	30–157	82	53–120	38–163
2200	99	48–167	22–248	111	58–180	30–260

Chapter 3

Climate scientists may misrepresent future flood risks using popular extreme sea level metrics

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Abstract

Estimating changes in the frequency or height of extreme sea levels (ESLs; e.g., the 100-yr event) is a popular approach used by climate and sea level scientists to communicate future coastal flood risk to policy makers and the public under various climate change scenarios. However, physical ESL metrics and associated thresholds only account for water levels (i.e., the hazard). They do not consider societal outcomes (e.g., loss of life, property damage). As a result, policy makers may inadvertently disseminate misleading estimates of future coastal flood risk under different climate scenarios. This has critical implications for risk communication and adaptation decision-making. Here, we illustrate how some measures of societal

exposure can lead to sizable differences in estimates of future coastal flood risk, relative to when only considering physical impacts using 1) projected ESLs under +2 °C and +5 °C temperature stabilization scenarios and 2) the current population exposure of 414 cities around the world. For some locations with a modest projected increase in the height of an ESL event, the corresponding change in local population exposure is substantial. This suggests that physical ESL metrics may be poor surrogates for capturing some societal impacts. While population exposure is just one measure, communicating a variety of human system, natural resource, and ecosystem-based outcomes may provide a more complete snapshot of either exposure or coastal flood risk under a wide array of climate scenarios.

3.1 Introduction

Extreme sea levels (ESLs) are the occurrence or the level of a short-lived (hours to days), exceptionally high local sea-surface height, usually as a result of coastal storms, waves, or astronomical tides (Gregory et al, 2019). When ESLs overtop natural (e.g., dunes, cliffs) or engineered (e.g., seawalls, bulkheads, levees) protection, potentially deadly and costly floods can occur in areas unprepared to deal with the hazard. Observational studies have shown that ESLs are occurring at tide gauges with increasing frequency, largely as a result of rising mean sea level (MSL) due to global warming and other non-climatic local factors (e.g., ground subsidence; Sweet and Park, 2014; Dahl et al, 2017; Menéndez and Woodworth, 2010). State-of-the-art global flood exposure assessments that consider future projections of sea level change, inundation from ESLs, and current distributions of populations and property have estimated that hundreds of millions of people and trillions of U.S dollars in property value are susceptible (Neumann et al, 2015; Kirezci et al, 2020; Hanson et al, 2011; Kulp and Strauss, 2019; McGranahan et al, 2007; Jongman et al, 2012; Lichter et al, 2011). Global flood risk assessments (risk as defined by Weyer, In press) that consider the interaction of hazard, exposure, and vulnerability have found that ESLs are projected to cost trillions of U.S. dollars per year by 2100 (Diaz, 2016; Hinkel et al, 2014; Jevrejeva et al, 2018). While these studies are essential for broadly communicating climate risks, they generally only consider a few sea level scenarios, which is insufficient to account for the true state of uncertainty in future sea level change (Kopp et al, 2019b). On the other hand, ESL frequency amplification factors (AFs) developed by climate and sea level scientists are relatively simple calculations that can be run on a desktop computer to quickly estimate changes in still water level hazards at a tide gauge under a wide array of future sea level projections.

ESL frequency AFs (also called "factors of increase" or "multiplication factors") indicate the change in the expected frequency of a given ESL event (e.g., the 1-in-100-yr ESL event; Hunter, 2012; Buchanan et al, 2017; Rasmussen et al, 2018; Frederikse et al, 2020; Vitousek et al, 2017; Taherkhani et al, 2020; Church et al, 2013; Howard and Palmer, 2020). For example, a 0.5 m increase in MSL at a tide gauge in San Juan, Puerto Rico is expected to increase the frequency of the historical 100-yr ESL event from 0.01 events yr^{-1} to $\sim$30 events yr^{-1}, on average (i.e., an AF of 3000; Rasmussen et al, 2018). Similarly, ESL return level AFs denote the relative change in the height of the ESL associated with a given return period. Both ESL frequency and return level AFs have often been used by climate scientists to communicate "flood risk" to policy makers and the public under a wide array of future sea level scenarios (Vitousek et al, 2017; Taherkhani et al, 2020; Buchanan et al, 2017; Kriebel et al, 2015; Frederikse et al, 2020; Garner et al, 2017; Howard and Palmer, 2020), including multiple plausible contributions from "deeply uncertain"[1] sea level components, such as the Antarctic Ice Sheet (Rasmussen et al, 2020; Frederikse et al, 2020).

While ESL frequency AFs purport to communicate "flood risk" , they only consider still water height at a tide gauge (i.e., the hazard), such as the height of the 100-yr ESL event. They do not consider the corresponding level of exposure (e.g., population or damage to property and natural resources), nor do they consider vulnerability. This is important because ESL AFs have appeared in prominent climate assessment reports such as the Intergovernmental Panel on Climate Change (IPCC)(Oppenheimer et al, in press; Wong et al, 2014; Church et al, 2013), the U.S. National Climate Assessment (Sweet et al, 2017), and others (Kopp et al, 2019a). Without a proper distinction, climate scientists and policy mak-

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[1] Deep uncertainty (also synonymous with Knightian uncertainty and Ellsbergian 'ambiguity') describes situations where there is either ignorance or disagreement by experts or decision makers over 1) conceptual models used to describe key system processes and 2) probability distribution functions used to characterize uncertainty related to key variables and parameters (Weyer, In press)

ers could disseminate misleading projections of coastal flood risk. For example, investigators that have focused on the frequency of exceedances of physical thresholds (e.g., the height of the 50-yr ESL event) have claimed that 0.5 m of MSL rise could lead to a doubling of "flood" events within decades for certain regions (Vitousek et al, 2017) or exponential increases in the frequency of "floods" (quotes imply authors mean ESLs; Taherkhani et al, 2020). While these claims may be true of the hazard (i.e., ESLs), they may not apply to the corresponding societal outcome (e.g., "a doubling of population exposure" or an "exponential increase in the rate of population exposure"). Some locations may be protected to a level above the height of the ESL event in question (i.e., no flood occurs), or there may exist little to no societal exposure at or below the ESL height (i.e., a flood occurs, but there is no societal impact). In the San Juan example, while the historical 100-yr ESL event is projected to occur $\sim$3000 times as often under a 0.5 m increase in MSL, there are currently $<$ 1,000 people living below the elevation of the 100-ESL event ($<$ 0.1% of the total city population; Fig. 3.1). Hauer et al (2020) also recently noted differences between projections of physical ESL metrics and those that are based on population exposure in the U.S.

The problems associated with metrics omitting exposure and vulnerability extend beyond risk communication. Climate and sea level scientists have also developed frameworks intended to optimize the design of coastal risk reduction strategies that only consider the return periods of still water heights. For example, ESL hazard "allowances" have been developed to assist flood managers seeking to maintain a given level of flood protection under uncertain sea level change (Howard and Palmer, 2020; Hunter, 2012; Hunter et al, 2013; Buchanan et al, 2016; Slangen et al, 2017). A hazard allowance is a deliberately-selected vertical buffer intended to ensure that the expected number of ESL events is kept constant as sea levels change (e.g., the height of a levee that protects against the 100-yr ESL event). These events are usually measured at tide gauges, which may differ from the return period of floods at other inland locations (Moore and Obradovich, 2020). Without inundation modeling, ESL hazard allowances calculated at tide gauges may lead to sub-optimal flood protection designs (e.g., Rasmussen et al, 2020).

In this study, we use a simple inundation model with a new global elevation dataset (Kulp and Strauss, 2018, 2019) to highlight the limitations and consequences of using ESL metrics that only consider the physical heights of water levels, specifically ESL AFs (frequency and return level) and ESL hazard allowances. We connect ESLs measured at a global network of tide gauges to present-day population exposure for 414 coastal cities around the world. We project future changes in both the frequency and return levels of historical ESLs and the exposure of current populations under two climate change scenarios (Sec. 3.3.1). We note that these are not estimates of future population exposure because we do not make future projections of population change. Additionally, we use a simple, static inundation approach that has not been globally validated. These projections are merely intended to highlight the limitations of physical ESL metrics when quantifying coastal flood risk. Sophisticated flood risk analyses are needed to better understand current and future risk levels. We then show how ESL hazard allowances may under-predict the necessary vertical buffer needed to maintain a hypothetical exposure-based protection level (Sec. 3.3.2). While population exposure is used as the risk measure in this study, it is just one component of coastal flood risk, broadly speaking. A diversity of possible metrics exist. We illustrate how using other risk measures could capture other relevant components of the same "coastal risk story" (Sec. 3.3.3). This includes impacts to vulnerable demographics, property damage, critical infrastructure, loss of natural resources, and harm to ecosystem services (e.g., wetland loss). Future studies could use our framework to further explore these metrics using other datasets.

3.2 Framework

An overview of the sources of information used to generate population inundation estimates are given in Fig. 3.5. Additional details and limitations to our approach are given in the supporting information (Secs. 3.5.1 to 3.2.4). First, we estimate the present-day probability of ESLs of various heights at a global network of tide gauges using extreme value theory and a long-term record of hourly sea level observations (Sec. 3.5.1). Second, we project changes in both the frequency and height of ESLs using local probabilistic projections of relative sea level change (RSLC)[2] that incorporate ice sheet mass loss estimates from structured expert judgment (Sec. 3.2.1). Third, we produce 1-dimensional, city-specific functions of population

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[2] Relative sea level change is defined as the change in local mean sea level relative to the sea floor or the underwater surface of the solid Earth (Gregory et al, 2019).

versus ground elevation to estimate the current population exposure to ESLs (Sec. 3.2.2). Fourth, by combining the population exposure damage functions with the future estimates of ESLs, we compute the change in the number of people exposed to various ESLs for each city using population exposure AFs (Sec. 3.2.3). Finally, we use ESL allowances to calculate the vertical buffer needed to maintain the current expected annual population exposure (Sec. 3.2.4).

3.2.1 Relative sea level change projections

Probabilistic, time-varying, local RSLC projections for each tide gauge are taken from the component-based study of Kopp et al (2014), except that ice sheet contributions are from the structured expert judgement (SEJ) study of Bamber et al (2019). Projections of RSLC after mid-century are highly dependent on ice sheet melt because of their potential for substantial contributions to global mean sea-level rise (Oppenheimer et al, in press; Kopp et al, 2019b). However, incomplete understanding of the physical processes that govern ice sheet melt inhibits realistic representations in process-based models. In such cases of incomplete scientific understanding, SEJ using calibrated expert responses is one approach for estimating such uncertain quantities (as employed here). Each RSLC probability distribution is conditional on a scenario in which global mean surface air temperature (GSAT) stabilizes in 2100 at either +2 °C (consistent with the Paris Agreement; UNFCCC, 2015) or +5 °C (consistent with unchecked emissions growth; GSAT relative to 1850–1900; Hausfather and Peters, 2020). Samples from each RSLC probability distribution are used to shift the ESL return curves in the direction of the RSLC. Figs. 3.2A and 3.2D show the future (2070) ESL return curves for tide gauges located at San Juan (Puerto Rico) and Sewell's Point (Norfolk, USA). The "kinks" in the return curves appear as a result of the highest samples in the RSLC probability distribution causing the expected ESL frequency calculation to saturate and then subsequently increase the expected number of ESL events. Both the positioning and the presence of the kinks are sensitive to the choice of where the upper-tail of the RSLC distribution is truncated (Rasmussen et al, 2020). More details and limitations are provided in the supporting information (Sec. 4.7.1).

3.2.2 Exposure analysis

We map flood extents for each city using the "bathtub" model, a static inundation approach that only considers the vertical elevation of two surfaces, 1) the terrain and 2) a given ESL return level (e.g., 100-yr event) measured at the nearest tide gauge within a 100-km radius of each city center. The return level of interest is spatially extrapolated over the terrain. Static inundation approaches have many limitations (Sec. 3.5.2), including overestimating observed flood extents relative to hydrodynamic models (Breilh et al, 2013; Gallien, 2016; Ramirez et al, 2016; Seenath et al, 2016; Bates et al, 2005; Vousdoukas et al, 2016). However, hydrodynamic modeling is computationally expensive, and producing state-of-the-art projections of population exposure is not the goal of this study. Land elevation data are from CoastalDEM, a modified version of NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) that uses a neural network trained using lidar-derived elevation data in the U.S.[3] to reduce SRTM errors (Kulp and Strauss, 2018, 2019; Farr et al, 2007). The SRTM is a near-global DEM commonly used for flood exposure modeling but is known to have large vertical bias (an estimated 3.7 m in coastal areas in the U.S.; Kulp and Strauss, 2018). This is important because coastal flood risk analysis is largely performed within this elevation range and these biases are roughly the same magnitude as projections of future local RSLC over this century (generally < 2 m relative to 2000; Oppenheimer et al, in press). Connected components analysis excludes low-elevation inland areas that are not linked to the ocean. More details and limitations are provided in both the supporting information (Sec. 3.5.2) and in Kulp and Strauss (2018, 2019).

The vertical population profile of a city can determine the population exposure to a given ESL event. We produce 1-dimensional (vertical) population profiles for 414 global cities using CoastalDEM and population density data from the WorldPop 2010 high resolution (3 arc second) gridded global population data set (Tatem, 2017). We note that this differs from Kulp and Strauss (2019), which uses LandScan population density. In order to simplify our analysis and also isolate the impact of RSLC on population exposure, we assume that population remains fixed in time. Thus, our results are not literal projections of

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[3] NOAA Digital Coast Coastal Lidar, http://coast.noaa.gov/digitalcoast/data/coastallidar

future population exposure—which will depend upon population growth (Hauer et al, 2016; Jongman et al, 2012) and the dynamic response of the population to RSLC (Merkens et al, 2016; Hauer, 2017)—but are instead intended to highlight the impact of ESL events relative to changes in their frequency. Population exposure profiles for San Juan (Puerto Rico) and Norfolk (USA) are given in Figs. 3.2B,E. Exposure profiles for all cities are included in the supporting data.

Most populations living in low-lying areas around the world (e.g., deltaic regions) are very likely protected by flood defenses such as levees, seawalls, and deliberately raised structures (e.g., buildings on stilts; Scussolini et al, 2016). Following previous flood exposure studies (Neumann et al, 2015; Hanson et al, 2011; Kulp and Strauss, 2019; McGranahan et al, 2007; Jongman et al, 2012; Lichter et al, 2011), our exposure estimates do not account for these defenses because they can be overtopped; only the population in the floodplain is considered. However, protection is assumed to only change the flood hazard and enters our integrated calculations of population exposure that consider all ESL return levels (Sec. 3.2.4). To our knowledge, verified, location-specific levels of protection are not available at the global scale[4]. To account for flood defenses that provide a margin of safety, we make multiple arbitrary assumptions regarding the current level of protection for all cities. Specifically, we produce results assuming spatially uniform "no protection" and protection up to the height of the 1- and 10-yr ESL event. These assumptions may greatly differ from reality and could lead to gross over-estimates for cities with existing flood protection that afford a high margin of safety from rare storms, such as London, New Orleans, Tokyo, Shanghai, and most major cities in the Netherlands (Nicholls et al, 2008; Hallegatte et al, 2013; Xian et al, 2018; Scussolini et al, 2016). Despite this, we still include protection assumptions for all cities to 1) limit the inclusion of the lowest elevations which are most prone to vertical errors in the DEM (Sec. 3.5.2) and 2) to highlight the importance of the flood protection assumption and the need for accurate estimates thereof (e.g., Scussolini et al, 2016).

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[4] However, Hallegatte et al (2013) and Scussolini et al (2016) give upper and lower estimates of flood protection for over 100 major cities around the world based on surveyed responses from local experts. But these responses have not been verified, and local protection can vary within a city.

3.2.3 Estimating physical and population exposure amplification factors

Following Buchanan et al (2017), the ESL frequency AF for an event of height z^* under uncertain RSLC is $\mathbb{E}[N(z^* - \delta)/N(z^*)]$, where $N(z^* - \delta)$ is the expected number of exceedances of height z^* after considering RSLC δ (Sec. 3.5.1). The ESL return level AF is given by $1 + \mathbb{E}[\delta]/z^*$. Here, we extend the ESL return level AF to changes in population exposure. We define the population exposure AF for an event of height z^* under uncertain RSLC as $\mathbb{E}[D(z^* + \delta)/D(z^*)]$, where $D(\cdot)$ is a 1-dimensional vertical population profile of a city (Sec. 3.2.2). Note that since $D(\cdot)$ is solely a function of z, the frequency amplification of population exposure events is equivalent to the ESL frequency AFs for the same city. Probability distributions of ESL AFs (frequency and return level) and population exposure AFs are produced for each tide gauge using the RSLC samples for each climate scenario (Sec. 3.2.1). Results are then taken from these distributions (Sec. 4.4).

3.2.4 Estimating population exposure allowances

While population exposure AFs are well suited to identify and communicate future societal impacts at local scales, ESL allowances are instead intended to optimize the design height of flood protection when desiring to maintain a specific margin of safety under uncertain sea level change (as opposed to using a benefit-cost approach). Expressed mathematically, if $f(z^*)$ is the current annual exceedance probability (AEP) with return level z^* (e.g., the 100-yr event), then the ESL hazard allowance $A(z^*)$ that maintains the current AEP under uncertain sea level change Δ is given by:

$$f(z^*) = \int_{\Delta} f(z^* - \Delta + A(z^*))P(\Delta)\,\mathrm{d}\Delta, \tag{3.1}$$

where $f(z^* - \Delta)$ is the AEP of z^* after including sea level change Δ whose uncertainty is given by the PDF, $P(\Delta)$. If Δ is known, then $A = \Delta$. Rasmussen et al (2020) extended ESL hazard allowances to facilitate optimizing the height of a flood mitigation strategy (e.g., elevation of structures, levee height, necessary coastal retreat) needed to maintain a given region's historical annual average loss (i.e., a "damage" allowance). Damage allowances conceptually illustrate the consequences of including aspects of exposure and vulnerability when designing adaptive solutions. In lieu of damages, here we consider the expected annual number of people affected by floods (EAF) to illustrate the limitations of hazard allowances. An overview of both sea level allowances and the EAF is given in the SI (Sec. 3.5.3).

To offset additional population exposure due to RSLC, we create a "protected" population exposure function using an idealized representation of how a flood reduction strategy could impact the relationship between ESLs and populations affected by floods. Specifically, we assume that the city population elevates by an amount A. This corresponds to a horizontal shift of the unprotected populated exposure function $D(z)$ (Sec. 3.2.2). This strategy is purely hypothetical and is only intended to illustrate differences between allowance frameworks that both do and do not consider societal exposure. In order to maintain the historical EAF under uncertain RSLC, the current EAF must equal the projected EAF that includes both an arbitrary sea level change (δ) and the adjustment A to offset the change in EAF resulting from RSLC. This can be mathematically represented by:

$$\int_{A_{min}}^{\infty} \int_{\delta} D(z-A) f(z-\delta) P(\delta)\,\mathrm{d}\delta\,\mathrm{d}z = \int_{A_{min}}^{\infty} D(z) f(z)\,\mathrm{d}z, \tag{3.2}$$

where $D(z-A)$ is a protected populated exposure function that elevates all populations within the damage function by the height A such that the current EAFF is maintained under RSLC and A_{min} is the height of the assumed current protection level (either no protection, the height of the 1-ESL event or the 10-yr ESL event; Sec. 3.2.2).

3.3 Results

3.3.1 Extreme sea level metrics may poorly predict population exposure

We highlight two cities to illustrate how a policy maker could both over- and under-estimate coastal flood exposure using a physical ESL metric. In San Juan (Puerto Rico), by 2070 the expected frequency of the historical 100-yr ESL event increases from 0.01/yr to a noteworthy 30/yr (+2 °C) and 102/yr (+5 °C), on average (Tables 3.1,3.2; Fig. 3.2A). However, $<$ 1,000 people ($<$ 0.1% of the total population) are currently exposed to the historical 100-yr ESL event (Figs. 3.1C and 3.2B,C). While sea-level rise is expected to increase the height of the 100-yr ESL event from 0.7 m above MHHW to 1.2 m (+2 °C) and 1.4 m (+5 °C), the corresponding population exposure is still $< 0.1\%$ of the total population (Tables 3.1,3.2; Figs. 3.2B,C). This is due to a low gradient in the population profile over the range of increase in the return level, partially as a result of a steep shoreline around much of San Juan (Figs. 3.1A and 3.2B). On the other hand, Norfolk (USA) has both a much steeper population profile than San Juan over the range of increase in the expected 100-yr return level (Fig. 3.2E) and a greater fraction of its total current population is exposed to the 100-yr ESL event (2.3%; Tables 3.1,3.2). By 2070, the expected 100-yr ESL return level increases from 1.5 m above MHHW to 2.1 m (+2 °C) and 2.4 m (+5 °C). This increases the expected population exposure to the 100-yr ESL from ∼16,000 to 64,000 (+2 °C) and 104,000 (+5 °C; Tables 3.1,3.2; Figs. 3.2E,F). Results for an additional 17 other cities and their uncertainties are given in Tables 3.1,3.2.

Relationships between physical and societal metrics vary by city in part due to differences in RSLC and the shape of both the ESL return curves and population profiles (Fig. 3.6). Globally, population exposure AFs vary from < 1 to > 10 (Fig. 3.3A). We sort global cities by geographic region in order to look for more localized patterns (Fig. 3.3B; the region/city mapping is given in the supporting data files). Across most regions examined, ESL return level AFs generally underestimate risks related to population exposure. Notable exceptions are the western coasts of North America and South America. Within these regions, there is a greater fraction of cities with a stronger correlation between ESL return level AFs and population exposure AFs. This suggests that population profiles are more linear over the range of increases in the height of the 100-yr ESL, perhaps due to a smaller variance in ESLs as a result of 1) a narrower continental shelf that leads to a smaller tidal range (Pugh and Woodworth, 2014) and 2) fewer tropical cyclones (Knapp et al, 2010). Plots for 2100 and for the +5 °C scenario are given in the supporting information and results for all cities are tabulated in the supporting data files.

The 100-yr ESL is just one of many possible hazards. Integrated metrics, like the EAF (Section 3.2.4), considers the probability and consequence of all ESLs. The San Juan and Norfolk EAF for the historical (1991–2009) and future scenarios is denoted as filled colored circles on the x-axis in Figs. 3.2C,F. For both cities, the historical EAF is small, $< 1{,}000$

(assumes protection from the 10-yr ESL), but differences emerge under RSLC. By 2070, the EAF for Norfolk increases to ~16,000 (+2 °C) and 45,000 (+5 °C), while the EAF for San Juan remains $< 1{,}000$ for both scenarios. However, flood protection assumptions can greatly change the EAF and the EAF AF. For instance, assuming that Norfolk has no flood protection, the EAF AF for 2070 is 3.4, but if assuming protection from the 10-yr event, it increase to 13.7 (Table 3.9). The current and future EAF at cities around the globe under different protection assumptions are tabulated in the supporting data files.

3.3.2 Extreme sea level allowances versus population exposure allowances

The map in Fig. 3.4 shows the expected population exposure allowance needed to maintain the historical EAF for each city under projected 2070 RSLC (+2 °C). The population exposure allowance assumes all cities are currently protected against the 10-yr ESL (i.e., $A_{min} = z_{10}$, where z_{10} is the local return level of the 10-yr event) and that the historical EAF is maintained by elevating all populations within each city by the same amount A (Sec. 3.2.4). Globally, the exposure allowance ranges from < 0 m (i.e., where expected RSLC is negative) to > 2 m. For some regions, the 100-yr ESL allowance is quite similar to the population exposure allowance (Western North America, Europe, and Eastern South America), but for others, the relationship between the two is less strong (e.g., Eastern North America). The 100-yr ESL allowance sometimes both over- and under-predicts the allowance needed to maintain the current EAF. For most cities, the population exposure allowance for 2070 is larger than the expected RSLC (Tables 3.3 and 3.4; Fig. 3.7).

3.3.3 The choice of the metric may impact estimates of flood risk

Many consequences can result from the same hazard, and most risk metrics only consider one consequence. For example, using a population exposure risk metric in New York City would not account for two major airports that are currently exposed to the 100-yr ESL event (LaGuardia and John F. Kennedy International; Fig. 3.10B). Furthermore, risks estimated using population exposure may vary when considering specific population subgroups. For example, low household income residents of New York City ($<$\$50,000 yr^{-1}) are projected to have expected exposure increases ~4-6% greater than when considering all household incomes (2100; Table 3.5; Fig. 3.9). While these differences are small, those that emerge when considering property damage are much larger. In New York City, the current expected damage from a 100-yr ESL event is roughly $4 billion. By 2100, this number is expected to grow by roughly 3 and 4 fold under a +2 °C and +5 °C GSAT stabilization scenario, respectively (assumes constant 2017 US$; Table 3.6).

3.4 Discussion and Conclusion

Physical ESL metrics do not consider the harms of a particular ESL event to human systems, natural resources, and to ecosystem services. By not distinguishing between hazard, exposure, and vulnerability, policy makers using these metrics could misrepresent projected changes in coastal flood risk. Despite this, physical ESL metrics continue to be used in assessment reports and the scientific literature as proxies for estimating coastal flood risk under different climate change scenarios (Vitousek et al, 2017; Taherkhani et al, 2020; Buchanan et al, 2017; Kriebel et al, 2015; Frederikse et al, 2020; Garner et al, 2017; Oppenheimer et al, in press; Wong et al, 2014; Church et al, 2013; Sweet et al, 2017; Kopp et al, 2019a; Howard and Palmer, 2020). This misuse of terminology could lead to inaccuracies in risk communication and poor planning. Our analysis specifically calls out ESL AFs (frequency and return level) and ESL hazard allowances. First, ESL return level AFs may both over- and under-estimate flood exposure as shown by the city-level examples of San Juan and Norfolk, as well as within and across regions (Sec. 3.3.1). Both the current population exposure and the gradient of the population profile play a crucial role in determining the amplification of population exposure. Second, we show that sub-optimal flood protection design could occur if ESL allowances do not consider a specific consequence (e.g., population exposure; Sec. 3.3.2). However, within some regions, the population exposure allowance does not appreciably differ from the ESL hazard allowance (Fig. 3.4). Third, we illustrate how coastal flood exposure and risk assessments can be strongly dependent on the chosen exposure and risk metric by considering household income, the siting of critical infrastructure, and property damage (Sec. 3.3.3).

All risk metrics have limitations in what they are able to communicate. Choosing what consequences to include in an exposure or risk assessment is subjective and depends on the preferences and goals of flood managers. There is no “best” metric. Many measures of risk are possible and all tell a part of the same “risk story”. However, metric choice is critical for determining what kinds of information can come from an exposure or risk assessment, including that which can inform decision-making (Kunreuther and Slovic, 1996; Slovic et al, 1982; Slovic, 1987). Such limitations point to the importance of choosing a broad and balanced set of metrics. While hazard metrics are essentially value-free, different stakeholders may have different opinions about what exposure or risk metric is most relevant. These factors may include practicality (i.e., ease of calculation) and suitability (i.e., informing specific risk management decisions) (NRC, 1996). In this paper we use current population exposure as an example of a viable metric for estimating societal exposure to coastal floods, but have noted that others are possible.

We acknowledge a number of caveats. First—and most importantly—we emphasize that this study does not make literal estimates of future population exposure to ESLs. Results presented in this paper are intended to highlight the implications of the ongoing misuse of hazard-based metrics to communicate coastal flood exposure and risk. Model performance has not been extensively validated and is challenged by a lack of observed flood extents. Second, almost all coastal cities have developed over time with some margin of safety against ESLs, but including these defenses and any spatial variation within cities is challenging without obtaining detailed and accurate data. In the absence of this information, we make multiple assumptions regarding uniform protection for each city. The protection assumptions do not impact AFs above the height of the protection level, but can significantly impact integrated metrics that consider all ESLs and impacts, such as the EAF (Table 3.9). We encourage future efforts to compile accurate information on urban flood protection levels around the world. Third, exposure analyses are most sensitive to spatially-autocorrelated vertical errors in the DEM at local scales and when assessing population vulnerability at low elevations (e.g., < 0.5 m; Kulp and Strauss, 2019). The higher the elevation that population exposure is being assessed at (e.g., longer return periods, such as the 100-yr event), the less of an impact these errors will have on exposure (Kulp and Strauss, 2019). To assess the impact of elevation errors on population exposure AFs, we use the example of the 100-year ESL event in New York City (Fig. 3.10A). Considering lidar topography as ground truth, we find that the EAF AFs are generally insensitive to errors in CoastalDEM; small differences only appear by 2100 for the +5 °C scenario (2.3 vs 2.6; Table 3.8). This is despite CoastalDEM underestimating population exposure relative to lidar (connected components analysis not performed for this test; Tables 3.7,3.8).

In conclusion, we suggest that policy makers and climate risk communication efforts should avoid using physical ESL metrics as proxies for coastal flood risk. This includes avoiding language that conflates physical metrics with societal impacts (e.g., calling all ESLs "floods"). Not doing so may miss important societal aspects that are overlooked when only viewing through a physical science lens. Additionally, to better illustrate sea-level rise and coastal flood impacts, broadly speaking, multiple risk or exposure metrics should be presented when possible.

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Figures and Tables

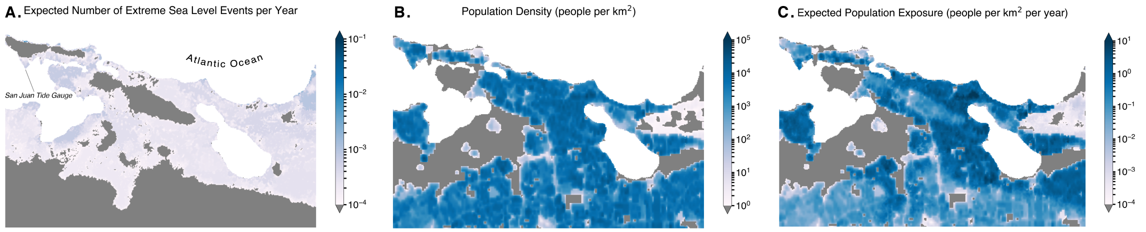

Figure 3.1: **A.** A map of San Juan (Puerto Rico) showing the expected number of extreme sea level (ESL) events per year as estimated using 1) ESL return levels from the San Juan tide gauge (indicated), 2) ground elevation from CoastalDEM, and 3) the "bathtub" flood inundation method (Sec. 3.5.2). **B.** Map showing population density (people per km^2) from the 2010 WorldPop global gridded population database (Tatem, 2017). **C.** Map showing the annual expected population exposure (people per km^2 per year)

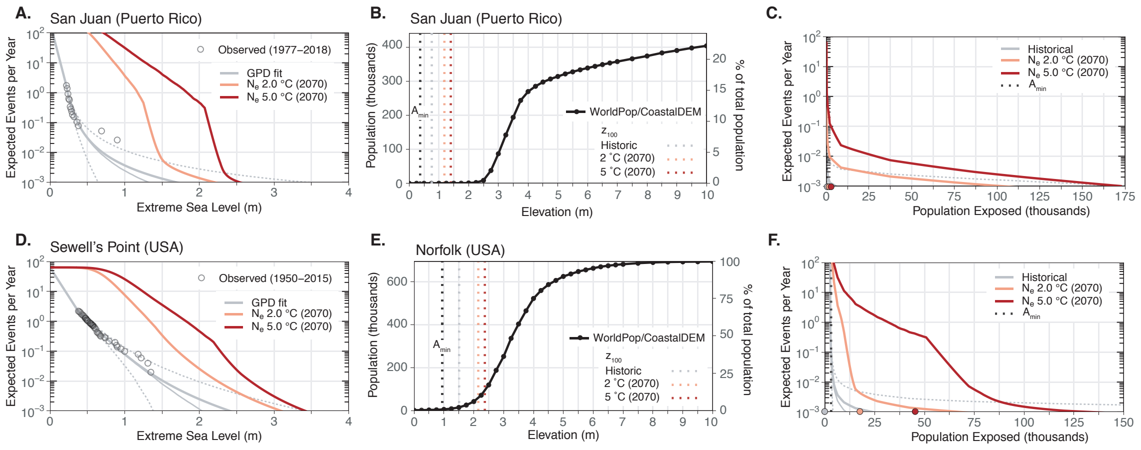

Figure 3.2: **A.** Expected number of extreme sea level (ESL) events per year as a function of ESL height (meters above local mean higher high water; MHHW) calculated by fitting a generalized Pareto distribution (GPD) to tide gauge observations (open grey circles) at San Juan (Puerto Rico) for 1991–2009 mean sea level (MSL; thick grey line), projected relative sea-level rise (RSLR) in 2070 under a scenario in which global mean surface air temperature (GSAT) is stabilized in 2100 at +2 °C (orange line) and +5 °C (red line; GSAT relative to 1850–1900). Thin grey lines are the historical ESL return curves for the 5/50/95 percentiles of the GPD parameter uncertainty range (dotted/solid/dotted lines, respectively). **B.** A population exposure function that estimates the total population (left y-axis) and percent of total population (right y-axis) currently as risk of inundation as a function of ESL height (meters above MHHW) for San Juan (total population: 1.82 million). Filled black circles are population data from the 2010 WorldPop global gridded population database (Tatem, 2017) applied to the elevation surfaces of CoastalDEM (Kulp and Strauss, 2018). Linear interpolation is used to produce a continuous curve between the WorldPop data (black line). City boundaries are those as defined by Kelso and Patterson (2012) and may differ from actual political boundaries. Populations are assumed to remain constant in time. Denoted is the current level of protection (A_{min}), assumed to be the 10-yr ESL event, the height of the historical 100-yr ESL event (grey), and the expected heights of the 100-yr ESL event under a +2 °C (orange) and +5 °C (red) climate scenario. **C.** As for top left, but for the population exposed per event under 1991–2009 MSL (grey lines) and RSLR in 2070 under +2 °C (orange line) and +5 °C 2100 GSAT stabilization scenarios (red line). The projected future inundated population estimates assume that San Juan's population remains constant in time. Denoted are the assumptions of arbitrarily assuming that populations are protected below the height of the 10-yr ESL event. The expected annual population exposure (assuming protection from a 10-yr ESL event) is denoted with a filled colored circle on the x-axis for the historical period (grey) and for the +2 °C (orange) and +5 °C (red) scenarios. **Second Row:** As for Top Row, but for Norfolk (USA; total population: 695,000) using the expected number of ESL events from a tide gauge located at Sewell's Point (USA).

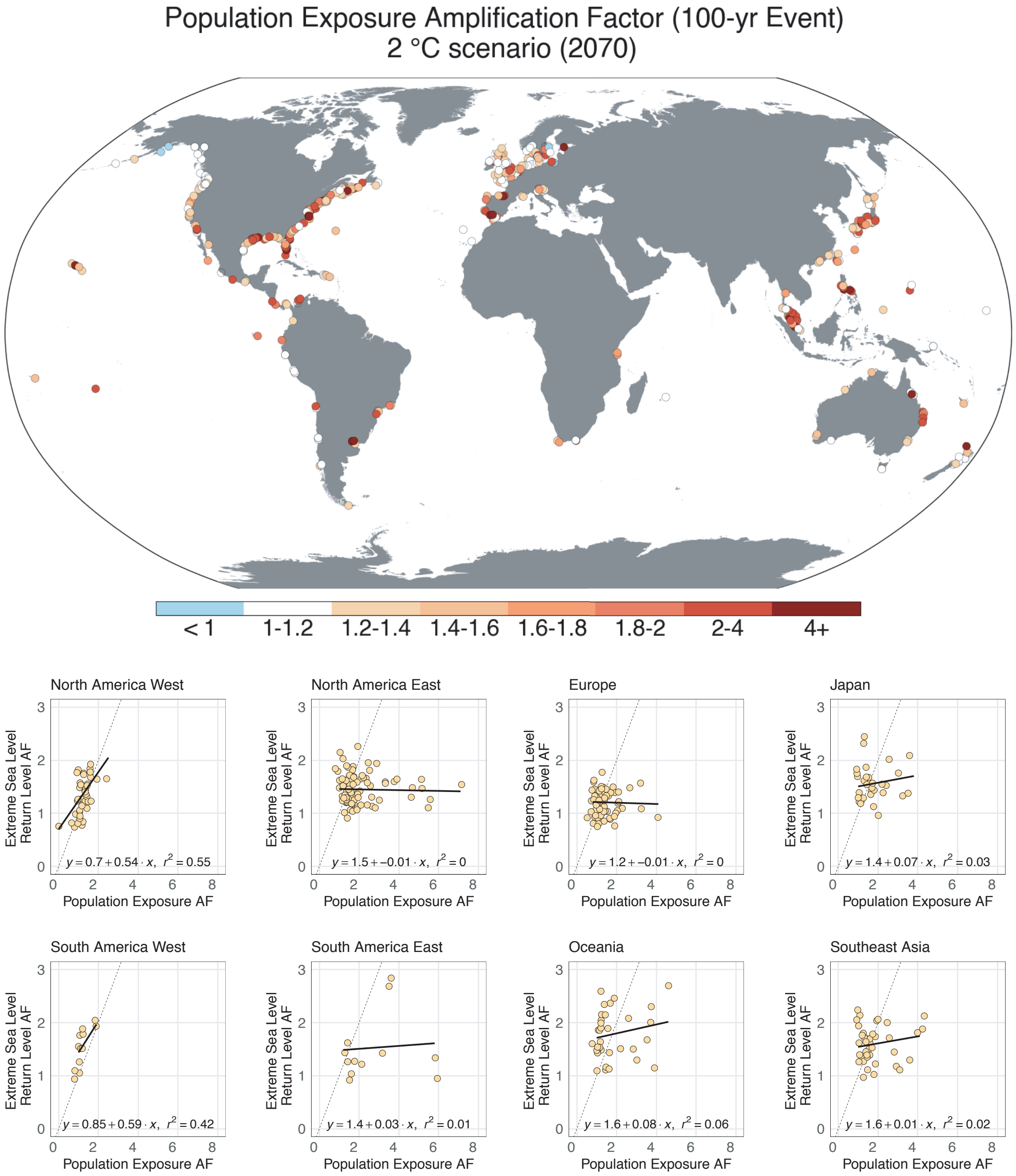

Figure 3.3: **Map:** Population exposure AFs for cities for 2070 under a climate scenario where the global mean surface air temperature is stabilized in 2100 at +2 °C (relative to 1850–1900). Populations are assumed to remain constant in time. **Regional scatter plots:** Extreme sea level (ESL) return level AFs plotted against population exposure AFs for the 100-yr ESL event for 2070 for the same climate scenario as the map. A list of the cities in each defined region is given in the supporting data files. Note that some cities may not appear in the scatter plots if 1) current and future population inundation is zero, 2) the current inundation is zero but future inundation is non-zero (i.e., a population exposure AF of infinity), or 3) the population exposure AF is more than two times the standard deviation of all other cities within each region. Cities are not shown in the scatter plots if the population exposure AF is greater than two standard deviations from the mean of each region.

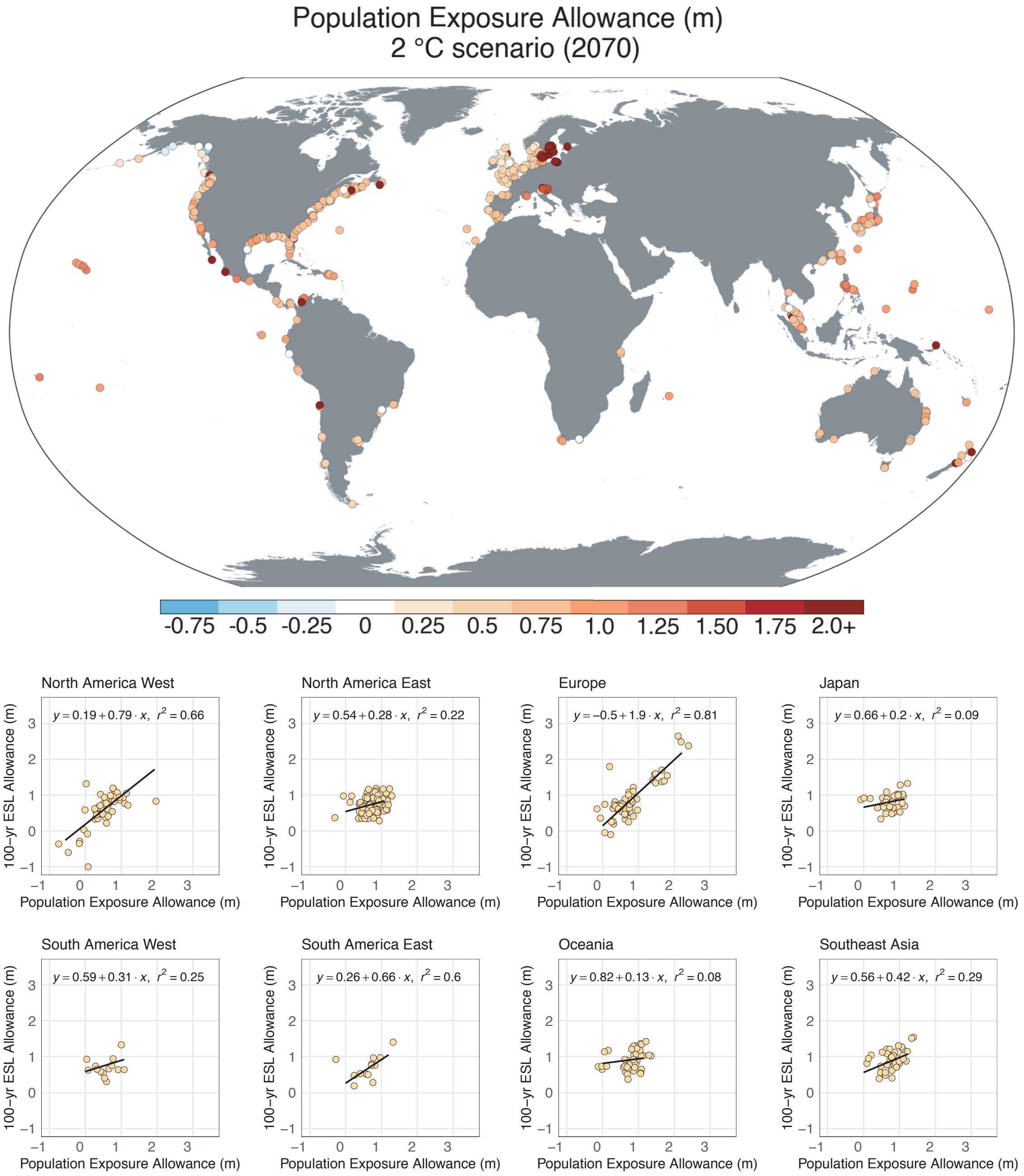

Figure 3.4: **Map:** Population exposure allowances (also the design height of a flood protection strategy) for cities for 2070 under a climate scenario where the global mean surface air temperature is stabilized in 2100 at +2 °C (relative to 1850–1900). The population exposure allowance (also the design height of a flood protection strategy) maintains the historical annual expected population inundation exposure from extreme sea levels (ESLs) and assumes population distributions remain constant in time and that cities are protected from the current 10-yr extreme sea-level (ESL) event (1991–2009). Careful consideration should be given for cities in the Baltic and North Sea region. Difference of sign in modeled changes in ocean dynamics can lead to anomalously large allowances in comparison to relative sea level change (Fig. 3.7). **Regional scatter plots:** ESL allowances for the 100-yr ESL event plotted against population exposure allowances for 2070 for the same climate scenario as the map. A list of the cities in each defined region is given in the supporting data files. Cities are not shown in the scatter plots if the population exposure allowance is greater than two standard deviations from the mean of each region.

Table 3.1: Table listing both physical and societal extreme sea level (ESL) metrics for select major coastal cities. Given are the heights of the historical 100-yr ESL return period (meters relative to mean higher high water; expected/5th/95th percentile), the percent of the total population exposed to the expected 100-yr ESL event, 2070 probabilistic relative sea-level change (RSLC) (meters, relative to 1991–2009) from a climate scenario in which global mean surface air temperature (GSAT) is stabilized in 2100 at +2 °C (relative to 1850–1900; Bamber et al, 2019), ESL return period amplification factors (AFs) for the 100-yr ESL event, ESL return level AFs for the 100-yr ESL event, the population exposure AF, the estimated total population exposed to the future 100-yr ESL event (thousands), and the percent increase in the latter, relative the historical population exposure. The expected value and the 5/95 percentile of the estimate are given for each. The 5/95 percentile for the current ESL return period considers the uncertainty in the generalized Pareto distribution (GPD) parameters, while the 5/95 percentile for RSLC and AFs reflect the uncertainty from both contributions to local RSLC and from the GPD. The * denotes instances of when the height of the current 100-yr ESL event occurs more often than the present-day frequency of exceeding MHHW (given for each tide gauge in the supporting information). The mapping of tide gauges to cities is given in the supporting information.

100-yr ESL event			2070 (2.0 °C)					
	Historical		Physical metrics			Societal metrics		
City (Total population in thousands)	100-yr ESL (m)	% Pop exposed	RSLC (m)	ESL frequency AF	ESL level AF	Pop exposure AF	Pop exposed (thousands)	% increase
Buenos Aires, Argentina (11,980)	2.6 (2.1-3.3)	7.5%	0.4 (0.2-0.7)	3 (2-7)	1.2 (1.1-1.3)	1.5 (1.2-1.7)	1,321 (1,111-1,520)	3.5% (1.8-5.2%)
Copenhagen, Denmark (1,337)	1.1 (1.0-1.1)	1.5%	0.2 (-0.8-1.1)	991 (0-9677)	1.2 (0.3-2.1)	1.3 (0.0-3.2)	26 (0-63)	0.4% (-1.5-3.2%)
Dar es Salaam, Tanzania (2,322)	0.7 (0.6-0.7)	1.0%	0.5 (0.2-0.8)	2441 (254-6678)	1.7 (1.3-2.2)	1.7 (1.1-2.6)	39 (25-59)	0.7% (0.1-1.6%)
Hamburg, Germany (1,854)	4.0 (3.6-4.4)	14.9%	0.4 (0.1-0.7)	4 (2-9)	1.1 (1.0-1.2)	1.1 (1.0-1.2)	301 (285-320)	1.3% (0.4-2.3%)
Hong Kong, China (22,232)	1.8 (1.2-2.5)	32.9%	0.4 (0.1-0.8)	5 (1-12)	1.2 (1.1-1.4)	1.2 (1.1-1.4)	8,988 (7,788-10,111)	7.5% (2.1-12.6%)
Honolulu, HI, USA (466)	0.4 (0.3-0.4)	0.5%	0.5 (0.2-0.9)	12385 (942-14455)	2.4 (1.6-3.4)	4.6 (2.1-8.5)	11 (5-20)	1.8% (0.6-3.7%)
London, England (9,878)	0.9 (0.7-1.1)	1.8%	0.4 (0.2-0.7)	61 (4-188)	1.4 (1.2-1.7)	2.1 (1.4-2.9)	368 (252-515)	1.9% (0.8-3.4%)
Manila, Philippines (5,782)	0.8 (0.7-0.9)	36.5%	0.9 (0.6-1.2)	15443 (3322-*)	2.1 (1.8-2.5)	1.1 (1.1-1.2)	2,336 (2,249-2,440)	3.9% (2.4-5.7%)
New Orleans, LA, USA (711)	2.3 (1.2-4.1)	77.7%	1.0 (0.7-1.3)	4 (2-7)	1.4 (1.3-1.6)	1.2 (1.1-1.2)	643 (623-663)	12.7% (9.9-15.5%)
New York, NY, USA (12,520)	1.9 (1.5-2.3)	3.7%	0.6 (0.3-0.9)	11 (2-29)	1.3 (1.1-1.5)	1.4 (1.2-1.7)	654 (543-799)	1.5% (0.6-2.7%)
Norfolk, VA, USA (695)	1.5 (1.1-2.0)	2.3%	0.6 (0.4-1.0)	32 (4-81)	1.4 (1.3-1.6)	4.1 (2.2-7.3)	64 (35-114)	6.9% (2.8-14.2%)
Phuket, Thailand (159)	0.9 (0.8-1.0)	9.0%	0.5 (0.2-0.8)	1723 (37-7875)	1.5 (1.2-1.9)	1.2 (1.1-1.4)	17 (16-20)	1.9% (0.9-3.5%)
Rio de Janeiro, Brazil (9,110)	0.9 (0.8-1.1)	0.3%	0.5 (0.2-0.8)	992 (8-5242)	1.5 (1.2-1.9)	1.8 (1.3-2.5)	59 (43-80)	0.3% (0.1-0.5%)
San Diego, CA, USA (2,323)	0.7 (0.7-0.7)	0.2%	0.5 (0.2-0.8)	4726 (298-15431)	1.7 (1.4-2.2)	3.0 (1.6-5.7)	13 (7-25)	0.4% (0.1-0.9%)
San Juan, Puerto Rico (1,821)	0.7 (0.5-1.1)	0.0%	0.5 (0.2-0.8)	2918 (4-*)	1.7 (1.3-2.1)	1.4 (1.1-1.9)	0 (0-0)	0.0% (0.0-0.0%)
Shenzhen, China (12,518)	1.8 (1.2-2.6)	17.5%	0.4 (0.1-0.8)	5 (1-12)	1.2 (1.1-1.4)	1.2 (1.1-1.3)	2,651 (2,327-2,938)	3.6% (1.1-5.9%)
Sydney, Australia (3,483)	0.7 (0.7-0.7)	0.2%	0.4 (0.2-0.8)	3213 (60-16480)	1.6 (1.3-2.1)	1.2 (1.1-1.3)	9 (9-11)	0.0% (0.0-0.1%)
Tokyo, Japan (25,339)	1.5 (1.0-2.1)	5.5%	0.4 (0.1-0.7)	8 (1-18)	1.2 (1.1-1.5)	1.9 (1.1-3.0)	2,656 (1,610-4,278)	4.9% (0.8-11.3%)
Vancouver, Canada (1,810)	1.3 (1.1-1.6)	11.8%	0.2 (0.0-0.5)	28 (1-94)	1.2 (1.0-1.4)	1.0 (1.0-1.0)	218 (214-223)	0.2% (0.0-0.5%)

Table 3.2: As for Table 3.1, but for a climate scenario in which global mean surface air temperature (GSAT) is stabilized in 2100 at +5 °C (relative to 1850–1900; Bamber et al, 2019).

100-yr ESL event			2070 (5.0 °C)					
	Historical		Physical metrics			Societal metrics		
City (Total population in thousands)	100-yr ESL (m)	% Pop exposed	RSLC (m)	ESL frequency AF	ESL level AF	Pop exposure AF	Pop exposed (thousands)	% increase
Buenos Aires, Argentina (11,980)	2.6 (2.1-3.3)	7.5%	0.6 (0.3-1.1)	8 (2-20)	1.2 (1.1-1.4)	1.6 (1.4-1.9)	1,449 (1,241-1,682)	4.6% (2.9-6.6%)
Copenhagen, Denmark (1,337)	1.1 (1.0-1.1)	1.5%	0.5 (0.1-1.0)	841 (10-5575)	1.5 (1.1-1.9)	1.6 (1.1-2.5)	31 (21-51)	0.9% (0.1-2.3%)
Dar es Salaam, Tanzania (2,322)	0.7 (0.6-0.7)	1.0%	0.7 (0.3-1.2)	4720 (620-6678)	2.1 (1.5-2.9)	2.3 (1.1-3.1)	52 (26-70)	1.3% (0.1-2.0%)
Hamburg, Germany (1,854)	4.0 (3.6-4.3)	14.9%	0.6 (0.3-1.1)	9 (2-22)	1.2 (1.1-1.3)	1.1 (1.1-1.2)	314 (293-338)	2.0% (0.9-3.3%)
Hong Kong, China (22,232)	1.8 (1.2-2.6)	32.9%	0.6 (0.2-1.2)	120 (2-155)	1.4 (1.1-1.7)	1.3 (1.2-1.5)	9,636 (8,437-10,847)	10.4% (5.0-15.9%)
Honolulu, HI, USA (466)	0.4 (0.3-0.4)	0.5%	0.8 (0.4-1.3)	14017 (14455-14455)	3.1 (2.0-4.7)	8.1 (3.2-18.4)	19 (7-43)	3.5% (1.1-8.6%)
London, England (9,878)	0.9 (0.7-1.1)	1.8%	0.6 (0.3-1.0)	223 (12-1242)	1.6 (1.3-2.1)	2.6 (1.8-4.1)	468 (310-728)	2.9% (1.3-5.6%)
Manila, Philippines (5,782)	0.8 (0.7-0.9)	36.5%	1.1 (0.7-1.6)	17547 (8662-*)	2.4 (1.9-3.0)	1.1 (1.1-1.2)	2,402 (2,276-2,597)	5.0% (2.8-8.4%)
New Orleans, LA, USA (711)	2.3 (1.2-4.2)	77.7%	1.2 (0.8-1.7)	94 (3-27)	1.5 (1.4-1.7)	1.2 (1.1-1.2)	655 (634-677)	14.4% (11.5-17.6%)
New York, NY, USA (12,520)	1.9 (1.5-2.3)	3.7%	0.8 (0.4-1.3)	228 (3-296)	1.4 (1.2-1.7)	1.6 (1.2-2.1)	738 (578-957)	2.2% (0.9-3.9%)
Norfolk, VA, USA (695)	1.5 (1.1-1.9)	2.3%	0.9 (0.5-1.4)	343 (7-1660)	1.6 (1.3-1.9)	6.6 (2.7-13.9)	104 (42-219)	12.6% (3.9-29.2%)
Phuket, Thailand (159)	0.9 (0.8-1.0)	9.0%	0.7 (0.3-1.2)	6012 (208-*)	1.7 (1.3-2.3)	1.4 (1.1-1.8)	19 (16-26)	3.2% (1.3-7.1%)
Rio de Janeiro, Brazil (9,110)	0.9 (0.8-1.1)	0.3%	0.7 (0.3-1.2)	3951 (30-14619)	1.7 (1.4-2.3)	2.2 (1.5-3.5)	71 (49-110)	0.4% (0.2-0.9%)
San Diego, CA, USA (2,323)	0.7 (0.7-0.7)	0.2%	0.7 (0.3-1.2)	9611 (798-15431)	2.0 (1.5-2.8)	4.5 (2.0-8.6)	20 (9-38)	0.7% (0.2-1.4%)
San Juan, Puerto Rico (1,821)	0.7 (0.5-1.1)	0.0%	0.7 (0.3-1.2)	10225 (10-*)	2.0 (1.5-2.7)	3.3 (1.2-5.4)	0 (0-1)	0.0% (0.0-0.0%)
Shenzhen, China (12,518)	1.8 (1.2-2.7)	17.4%	0.6 (0.2-1.2)	120 (2-155)	1.4 (1.1-1.7)	1.3 (1.1-1.4)	2,813 (2,496-3,131)	5.0% (2.5-7.6%)
Sydney, Australia (3,483)	0.7 (0.7-0.7)	0.2%	0.7 (0.3-1.1)	8942 (374-16480)	2.0 (1.5-2.7)	1.4 (1.1-2.6)	11 (9-21)	0.1% (0.0-0.4%)
Tokyo, Japan (25,339)	1.5 (1.0-2.2)	5.5%	0.6 (0.2-1.2)	455 (2-914)	1.4 (1.1-1.8)	2.6 (1.4-4.3)	3,635 (1,880-5,935)	8.9% (1.9-17.9%)
Vancouver, Canada (1,810)	1.3 (1.1-1.6)	11.8%	0.4 (0.1-0.9)	436 (2-1065)	1.3 (1.0-1.6)	1.0 (1.0-1.1)	221 (215-229)	0.4% (0.1-0.8%)

Table 3.3: Table listing both physical and societal extreme sea level (ESL) metrics for select major coastal cities. Given are the heights of the current 100-yr ESL return period [meters relative to mean higher high water (MHHW); expected/5th/95th percentile], the percent of the total population exposed to the expected 100-yr ESL events, the expected annual number of people affected by floods (EAF; thousands of people), 2070 probabilistic relative sea-level change (RSLC) (meters, relative to 1991–2009) from a climate scenario in which global mean surface air temperature (GSAT) is stabilized in 2100 at +2 °C (relative to 1850–1900; Bamber et al, 2019), the ESL allowance that maintains the frequency of the historical 100-yr event (meters above MHHW), the projected EAF (thousands), the percent increase in the EAF, and the population exposure allowance (meters above MHHW).

Allowances				2070 (2.0 °C)				
	Historical			Physical metrics		Societal metrics		
City (Total population in thousands)	100-yr ESL (m)	% Pop exposed	EAF (thousands)	RSLC (m)	100-yr ESL allowance	EAF (thousands)	% increase	Pop exposure allowance
Buenos Aires, Argentina (11,980)	2.6 (2.1-3.3)	7.5%	23	0.4 (0.2-0.7)	0.5	85	269.4%	0.5
Copenhagen, Denmark (1,337)	1.1 (1.0-1.1)	1.5%	2	0.2 (-0.8-1.1)	2.4	89	5481.4%	2.2
Dar es Salaam, Tanzania (2,322)	0.7 (0.6-0.7)	1.0%	1	0.5 (0.2-0.8)	1.0	46	3058.5%	0.8
Hamburg, Germany (1,854)	4.0 (3.6-4.4)	14.9%	24	0.4 (0.1-0.7)	0.5	73	207.1%	0.5
Hong Kong, China (22,232)	1.8 (1.2-2.5)	32.9%	524	0.4 (0.1-0.8)	0.5	5,611	970.8%	0.6
Honolulu, HI, USA (466)	0.4 (0.3-0.4)	0.5%	0	0.5 (0.2-0.9)	1.2	22	14353.0%	1.1
London, England (9,878)	0.9 (0.7-1.1)	1.8%	11	0.4 (0.2-0.7)	0.6	174	1504.1%	0.5
Manila, Philippines (5,782)	0.8 (0.7-0.9)	36.5%	156	0.9 (0.6-1.2)	1.3	2,350	1408.9%	1.2
New Orleans, LA, USA (711)	2.3 (1.2-4.1)	77.7%	36	1.0 (0.7-1.3)	1.0	475	1231.2%	1.1
New York, NY, USA (12,520)	1.9 (1.5-2.3)	3.7%	34	0.6 (0.3-0.9)	0.6	391	1056.1%	0.7
Norfolk, VA, USA (695)	1.5 (1.1-2.0)	2.3%	1	0.6 (0.4-1.0)	0.7	16	1271.2%	0.7
Phuket, Thailand (159)	0.9 (0.8-1.0)	9.0%	1	0.5 (0.2-0.8)	0.9	17	1541.3%	0.8
Rio de Janeiro, Brazil (9,110)	0.9 (0.8-1.1)	0.3%	3	0.5 (0.2-0.8)	0.8	50	1803.1%	0.8
San Diego, CA, USA (2,323)	0.7 (0.7-0.7)	0.2%	0	0.5 (0.2-0.8)	1.0	18	5635.2%	0.9
San Juan, Puerto Rico (1,821)	0.7 (0.5-1.1)	0.0%	0	0.5 (0.2-0.8)	0.7	0	232.5%	0.8
Shenzhen, China (12,518)	1.8 (1.2-2.6)	17.5%	160	0.4 (0.1-0.8)	0.5	1,730	980.7%	0.6
Sydney, Australia (3,483)	0.7 (0.7-0.7)	0.2%	1	0.4 (0.2-0.8)	0.9	9	1395.9%	0.8
Tokyo, Japan (25,339)	1.5 (1.0-2.1)	5.5%	98	0.4 (0.1-0.7)	0.5	1,104	1025.8%	0.6
Vancouver, Canada (1,810)	1.3 (1.1-1.6)	11.8%	18	0.2 (0.0-0.5)	0.4	177	866.2%	0.4

Table 3.4: As for Table 3.3, but for a climate scenario in which global mean surface air temperature (GSAT) is stabilized in 2100 at +5 °C (relative to 1850–1900; Bamber et al, 2019).

Allowances				2070 (5.0 °C)				
	Historical			Physical metrics		Societal metrics		
City (Total population in thousands)	100-yr ESL (m)	% Pop exposed	EAF (thousands)	RSLC (m)	100-yr ESL allowance	EAF (thousands)	% increase	Pop exposure allowance
Buenos Aires, Argentina (11,980)	2.6 (2.1-3.3)	7.5%	23	0.6 (0.3-1.1)	0.7	213	830.6%	0.8
Copenhagen, Denmark (1,337)	1.1 (1.0-1.1)	1.5%	2	0.5 (0.1-1.0)	1.1	32	1896.1%	0.9
Dar es Salaam, Tanzania (2,322)	0.7 (0.6-0.7)	1.0%	1	0.7 (0.3-1.2)	1.7	68	4493.5%	1.5
Hamburg, Germany (1,854)	4.0 (3.6-4.3)	14.9%	24	0.6 (0.3-1.1)	0.7	119	397.9%	0.7
Hong Kong, China (22,232)	1.8 (1.2-2.6)	32.9%	525	0.6 (0.2-1.2)	0.9	7,855	1396.5%	1.1
Honolulu, HI, USA (466)	0.4 (0.3-0.4)	0.5%	0	0.8 (0.4-1.3)	2.0	71	46941.1%	2.0
London, England (9,878)	0.9 (0.7-1.1)	1.8%	11	0.6 (0.3-1.0)	1.0	324	2888.1%	1.0
Manila, Philippines (5,782)	0.8 (0.7-0.9)	36.5%	156	1.1 (0.7-1.6)	2.0	2,563	1545.9%	1.9
New Orleans, LA, USA (711)	2.3 (1.2-4.2)	77.7%	36	1.2 (0.8-1.7)	1.3	559	1470.4%	1.7
New York, NY, USA (12,520)	1.9 (1.5-2.3)	3.7%	34	0.8 (0.4-1.3)	1.0	547	1517.9%	1.2
Norfolk, VA, USA (695)	1.5 (1.1-1.9)	2.3%	1	0.9 (0.5-1.4)	1.2	45	3745.6%	1.3
Phuket, Thailand (159)	0.9 (0.8-1.0)	9.0%	1	0.7 (0.3-1.2)	1.6	24	2152.5%	1.5
Rio de Janeiro, Brazil (9,110)	0.9 (0.8-1.1)	0.3%	3	0.7 (0.3-1.2)	1.4	83	3053.1%	1.4
San Diego, CA, USA (2,323)	0.7 (0.7-0.7)	0.2%	0	0.7 (0.3-1.2)	1.8	38	12326.7%	1.6
San Juan, Puerto Rico (1,821)	0.7 (0.5-1.1)	0.0%	0	0.7 (0.3-1.2)	1.5	1	995.1%	1.5
Shenzhen, China (12,518)	1.8 (1.2-2.7)	17.4%	160	0.6 (0.2-1.2)	0.9	2,336	1363.1%	1.1
Sydney, Australia (3,483)	0.7 (0.7-0.7)	0.2%	1	0.7 (0.3-1.1)	1.5	20	2995.9%	1.4
Tokyo, Japan (25,339)	1.5 (1.0-2.2)	5.5%	98	0.6 (0.2-1.2)	1.0	2,846	2809.1%	1.2
Vancouver, Canada (1,810)	1.3 (1.1-1.6)	11.8%	18	0.4 (0.1-0.9)	1.0	221	1107.6%	0.9

3.5 Appendix: Methods

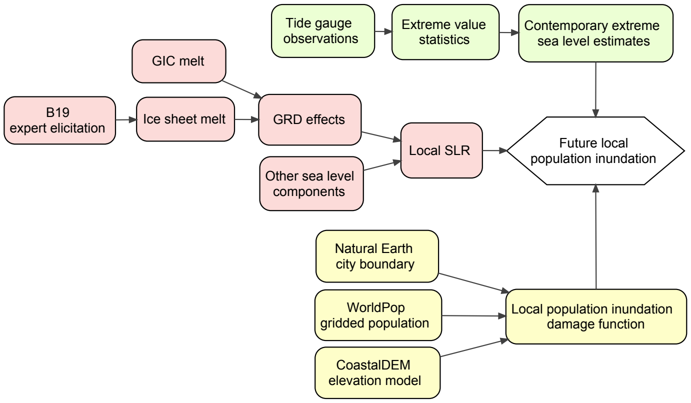

Figure 3.5: Flow of information used in this study to produce projected local population inundation estimates (white hexagon). Green rectangles are for extreme sea level estimation. Red rectangles are for sea-level rise projections. Yellow rectangles are for local population inundation estimates. B19 is Bamber et al (2019); SLR is sea-level rise; GIC are glaciers and ice caps; GRD are gravitational, rotational, and deformational effects; "Other sea level components" includes land water storage, oceanographic processes, and non-climatic background changes, such as glacial-isostatic adjustment.

3.5.1 Estimating extreme sea levels

We use long-term records of hourly or sub-hourly sea level observations from quality controlled tide gauges from the University of Hawaii Sea Level Center[5] and also supplement with other tide gauges from the GESLA2 data set (Woodworth et al, 2016). We limit our use of tide gauge records to only those that have record lengths > 30 consecutive years in which each year has > 80 percent of observations available. In total, we use 360 unique tide gauges, with median and average record lengths of 48 and $\sim$54 years, respectively (a list of the tide gauges used is given in the supporting information). For each day in the tide gauge record with $>$12 hours of data, we estimate the daily maximum sea level. We note that this temporal resolution only facilitates the estimation of still-water heights and is

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[5] retrieved from: https://uhslc.soest.hawaii.edu, January 2020; (Caldwell et al, 2015)

likely not sufficient to capture wave setup and swash contributions, which can be significant (Melet et al, 2018; Arns et al, 2017). To isolate the variation in extreme sea levels (ESLs), we remove the effect of mean sea level (MSL) change by subtracting the annual MSL from each daily maximum value (i.e., values are de-trended). The de-trended daily maximum tide values are then referenced to local mean higher high water (MHHW; relative to the de-trended mean sea level), defined as the average highest high tide at the tide gauge over a given period (here, either 1993–2012 or the last available 19-year period in the record). Daily maximum sea levels that are 1) above the 99th percentile and 2) within 3 days of each other are de-clustered to meet the statistical independence assumption of the extreme value approach (below).

We estimate the present-day probability of ESLs by applying extreme value theory to long-term hourly tide gauge records. Extreme value theory is a statistical extrapolation method that fits an extreme value distribution to empirical data in order to estimate the likelihood of events too rare to appear in an observational record (e.g., determining the height of 100-yr ESL event from a 30-yr record of tide gauge data). Following previous studies (Tebaldi et al, 2012; Buchanan et al, 2017; Rasmussen et al, 2018; Frederikse et al, 2020; Wahl et al, 2017), we estimate the annual expected number of ESL events of various heights at each tide gauge using a generalized Pareto distribution (GPD; Coles, 2001b,a). The GPD is a peaks over threshold modeling approach that describes the probability of a given ESL height conditional on the exceedance of a threshold (assumed to be Poisson distributed with mean λ). Various extreme value distributions and approaches to implement them have been proposed (Coles, 2001a), but in the case of ESL estimation there currently is not an agreed upon "best approach". Depending on the specific project goals, a particular extreme value modeling strategy may be preferred over another. For example, if the tide gauge record is short, a peaks over threshold approach that uses sub-annual extremes may be preferred over an approach that only uses annual maximums (Lang et al, 1999; Cunnane, 1973). The GPD has the advantage over other generalized extreme value models in that 1) unlike the annual maximum flood value modeling approach, it can accommodate sub-annual observations (i.e., retain more information), 2) unlike the more restrictive Gumbel distribution (Buchanan et al, 2017), it includes a parameter that allows for the flexibility for the distribution to take on different shapes (shape parameter, ξ, and its value depends on the characteristics of the underlying data), and 3) it can be combined with a Poisson rate parameter (λ) to translate ESL exceedance probabilities into expected numbers of annual ESL exceedances. The latter may be more intuitive and thus better for communicating the frequency of ESL events. Increases or decreases in storminess could change λ, but is not considered in this study. For a given tide gauge, the annual expected number of exceedances of height z is given by $N(z)$:

$$N(z) = \begin{cases} \lambda \left(1 + \frac{\xi(z-\mu)}{\sigma}\right)^{-\frac{1}{\xi}} & \text{for } \xi \neq 0 \\ \lambda \, \exp(-\frac{z-\mu}{\sigma}) & \text{for } \xi = 0 \end{cases} \tag{3.3}$$

where the shape parameter (ξ) governs the curvature and upward statistical limit of $N(z)$, the scale parameter (σ) characterizes the variability in the exceedances, and the location parameter (μ) is the threshold water-level above which return levels are estimated with the GPD—here the 99th percentile of daily maximum sea levels. Observed GPD threshold exceedances and the fitted GPD $N(z)$ for tide gauges located at San Juan (Puerto Rico) and Sewell's Point (Norfolk, USA) are given in Figs. 3.2A,D. The GPD parameters for all tide gauges are given in the supporting data files.

Selecting the threshold μ is critical element of the peaks over threshold approach. If the threshold is too low, it could bias the estimates because the included values may not be extreme enough. On the other hand, if the threshold is too high, the variance might be too large because too few points are being included in the analysis (Lang et al, 1999). Here, the 99th percentile is used because it generally is above the highest seasonal tide, balances the bias-variance trade-off in the GPD parameter estimation (Tebaldi et al, 2012) and has been found to perform well at global scales (Wahl et al, 2017). The location parameter μ shifts as MSL changes. The storm climates and hydrodynamic characteristics of each site result in differences in the shape parameter (ξ) across sites. ESL frequency distributions with $\xi > 0$ are "heavy tailed", due to a larger variation in extremes (e.g., existence of tropical and extra-tropical cyclones). Distributions with $\xi < 0$ are "thin tailed" and have a statistical upper bound on ESLs. The GPD parameters are estimated using maximum likelihood, and their uncertainty is calculated from their estimated covariance matrix and is sampled using a Latin hypercube sampling of 1000 normally distributed GPD parameter pairs. Note that the fit of the GPD and the uncertainty bounds may not always well capture the observed exceedances (e.g., San Juan; Fig 3.2A). While we extrapolate estimates for ESL events up to the frequency of the 1000-yr event, we caution in using any estimate of ESL that exceeds four times the length of the observation record (Pugh and Woodworth, 2014). Events that occur with a frequency greater than λ (i.e., the expected number of exceedances of the GPD threshold per year) are outside of the support of the GPD and are modeled with a Gumbel distribution. Other probability mixture model approaches have been proposed that combine a GPD with another distribution (e.g., a Normal distribution; Ghanbari et al, 2019). We do not consider future changes in storm frequency (Walsh et al, 2016), intensity (Sobel et al, 2016), or track (Garner et al, 2017), which could all modify the GPD parameters. We also do not consider changes in the tide-surge interaction (Schindelegger et al, 2018; Arns et al, 2017) or changes in geomorphology, which can impact storm surge (Familkhalili and Talke, 2016; Talke et al, 2014).

Relative sea level change projections

The other RSLC component contributions are from ocean thermal expansion, glaciers and ice caps, and land-water storage. General circulation model (GCM) output is used to generate the steric and glacial ice melt sea level components for each global mean surface air temperature (GSAT) stabilization scenario. The +2 °C scenario used the GCM outputs specified for the same GSAT scenario in Rasmussen et al (2018) and the +5 °C scenario used GCM outputs from the representative concentration pathway (RCP) 8.5 from Kopp et al (2014). Also accounted for are regional effects such as ocean dynamics (from GCM output), gravitational and rotational effects of ice mass redistribution, glacial isostatic adjustment, and other local vertical land motion factors (e.g., sediment compaction and ground water withdrawal). Probability distributions of local RSLC are produced using 10,000 Latin hypercube samples of each individual sea level component contribution. The probability distributions are truncated at the 99.9th percentile to remove samples that are deemed to be physically implausible (Oppenheimer et al, in press). As noted by Rasmussen et al (2020), both ESL frequencies and allowances are sensitive to truncation selection. More details and limitations to the RSLC projections are provided elsewhere (Kopp et al, 2014; Bamber et al, 2019; Rasmussen et al, 2020).

3.5.2 Exposure analysis

A vertical adjustment was made to the ESLs to reference the same local mean higher high water (MHHW) datum as CoastalDEM. ESLs use tide gauge data for estimating MHHW, while CoastalDEM uses an estimation technique from National Oceanic and Atmospheric Administration's (NOAA) VDatum tool (version 3.7; Parker et al, 2003). This leads to differences in estimates of MHHW for some locations. To convert both data sets to a common vertical reference, an adjustment is made to the tide gauge ESLs to account for differences between the tide gauge estimates and the CoastalDEM ground elevations (adjustments are provided in the supporting data files).

We take a static inundation modeling approach by spatially extrapolating return periods of ESLs, measured at tide gauges, onto the surrounding topography. We map one tide gauge to each city. For cities where there is more than one tide gauge within a 100-km radius (e.g., Willet's Point and the Battery in NYC, Fig. 3.10A), the tide gauge with the longest record is used (the tide gauges assigned to each city are listed in the supporting data files). While the height of a given ESL return period may vary within a city, in part due to complicated bathymetry and coastlines, Kulp and Strauss (2017) has shown that ESL population exposure results for the U.S. are generally insensitive to tide gauge assignment within a 100-km radius. In any case, static inundation approaches do not account for complex local geomorphology, local ocean dynamics, and frictional losses as water moves over different land surfaces (e.g., wetlands, beaches, urban areas). More complex hydrodynamic inundation approaches that model the flow of the ocean onto a variety of land surfaces could be used to more accurately estimate local floods for cities across the globe. However, such an approach is out of the scope of this study as our intention is to merely highlight the limitations of physical ESL metrics. Furthermore, we note that hydrodynamic inundation modeling may not necessarily outperform simpler approaches, especially in active tropical cyclone regions (Hunter et al, 2017; Muis et al, 2016, 2017; Wahl et al, 2017), in part due to poor representation of tide-surge interactions (Arns et al, 2020) and short simulation periods that are less likely to produce rare, extreme events found in multi-decadal tide gauge records. For some locations, the height of the 100-yr ESL event can be under-predicted by up to 3 meters compared to tide gauge-derived estimates (supporting information of Muis et al, 2017).

The WorldPop population data are resampled to align with CoastalDEM raster (for more details, see Kulp and Strauss, 2019), integrated over select elevations (-2 to 13 m above MHHW, either 0.25 or 0.5 m increments), and then tabulated according to the satellite-derived urban footprint for each city from Natural Earth (which may differ from the actual administrative boundary; Kelso and Patterson, 2012). Coastal cities are only included in the analysis if there are populations with in the defined boundary at any elevation < 13 m above local MHHW. Linear interpolation is used between each select elevation to produce a continuous 1-dimensional population exposure profile $D(z)$, where z is the ESL height. We note that z could be a vector to account for spatial differences in ESL height for the same return period within a city and also spatial variation in flood protection.

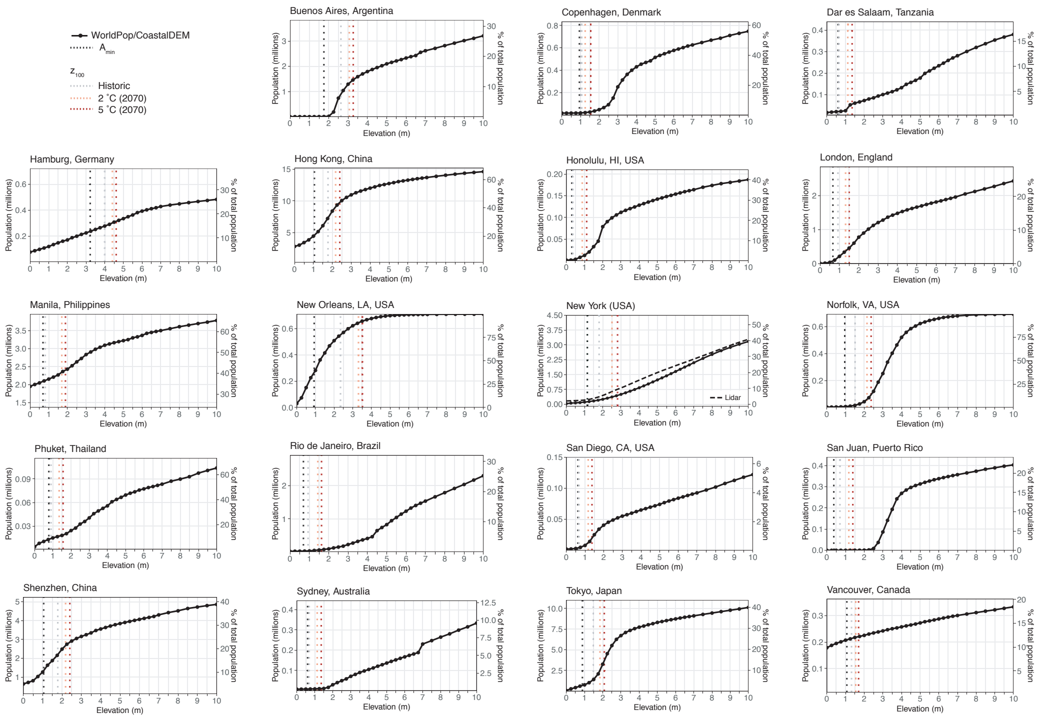


Figure 3.6: Population exposure functions that estimate the total population currently as risk of inundation as a function of ESL height (meters above MHHW) for cities given in Tables 3.1-3.4. Filled black circles are population data from the 2010 WorldPop global population database (Tatem, 2017) applied to the elevation surfaces of CoastalDEM (Kulp and Strauss, 2018, 2019). Linear interpolation is used to produce a continuous curve between the WorldPop data (black line). City boundaries are those as defined by Kelso and Patterson (2012) and may differ from actual political boundaries. Populations are assumed to remain constant in time. Denoted is the current level of protection (A_{min}), assumed to be the 10-yr ESL event, the height of the historical 100-yr ESL event (grey), and the expected heights of the 100-yr ESL event under a +2 °C (orange) and +5 °C (red) climate scenario. Also shown for New York City is a population profile generated using a 0.3-m horizontal resolution light detection and ranging (LiDAR)-derived digital elevation model for the City of New York (https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc).

3.5.3 Estimating hazard allowances and annual population exposure

While ESL and population exposure AFs are well suited to identify and communicate local coastal flood risks, allowances are perhaps more useful for informing the design of coastal flood defense efforts (e.g., determining optimal levee heights or how high to raise a residence to maintain a given margin of safety; Rasmussen et al, 2020). Following Buchanan et al (2016), we calculate the ESL hazard allowance A that maintains a given annual exceedance probability (AEP) under uncertain RSLC δ, whose uncertainty is given by the PDF, $P(\delta)$,

$$f(z^*) = \int_\delta f(z^* - \delta + A(z^*))P(\delta)\,\mathrm{d}\delta, \tag{3.4}$$

where $f(z^*)$ is the current AEP of a given ESL event with height z^* (e.g., the 100-yr event). For a given AEP, the hazard allowance can be interpreted as the horizontal distance between the expected historical and future ESL return curve (Fig. 3.2A). If δ is known, then $A = \delta$, but if δ is unknown, $A > \delta$ for mathematical reasons given previously (Hunter, 2012; Buchanan et al, 2016; Buchanan et al, 2017). Rasmussen et al (2020) extend the ESL hazard allowance concept to account for the societal impacts of ESL events by employing a simple, time-invariant damage function $D(z)$ that describes the relationship between ESLs and a societal impact (e.g., property damage or population exposure). The damage allowance is the design height of a flood mitigation strategy (e.g., elevation of structures, levee height, necessary coastal retreat) needed to maintain a given integrated exposure metric under RSLC (e.g., current expected annual property damage).

Here we consider the damage (population exposure) allowance needed to maintain the current expected annual population exposure (EAE). The projected EAE under RSLC is given by:

$$EAE = \int_{A_{min}}^{\infty} \int_\delta D(z) f(z - \delta) P(\delta)\,\mathrm{d}\delta\,\mathrm{d}z \tag{3.5}$$

where $f(z - \delta)$ is the PDF of ESLs after considering RSLC δ, $P(\delta)$ is the PDF of RSLC δ, $D(z)$ is the populated exposure function (Sec. 3.2.2), and A_{min} is the height of the assumed current protection level (either no protection, the height of the local 1-yr or 10-yr ESL event; Sec. 3.2.2).

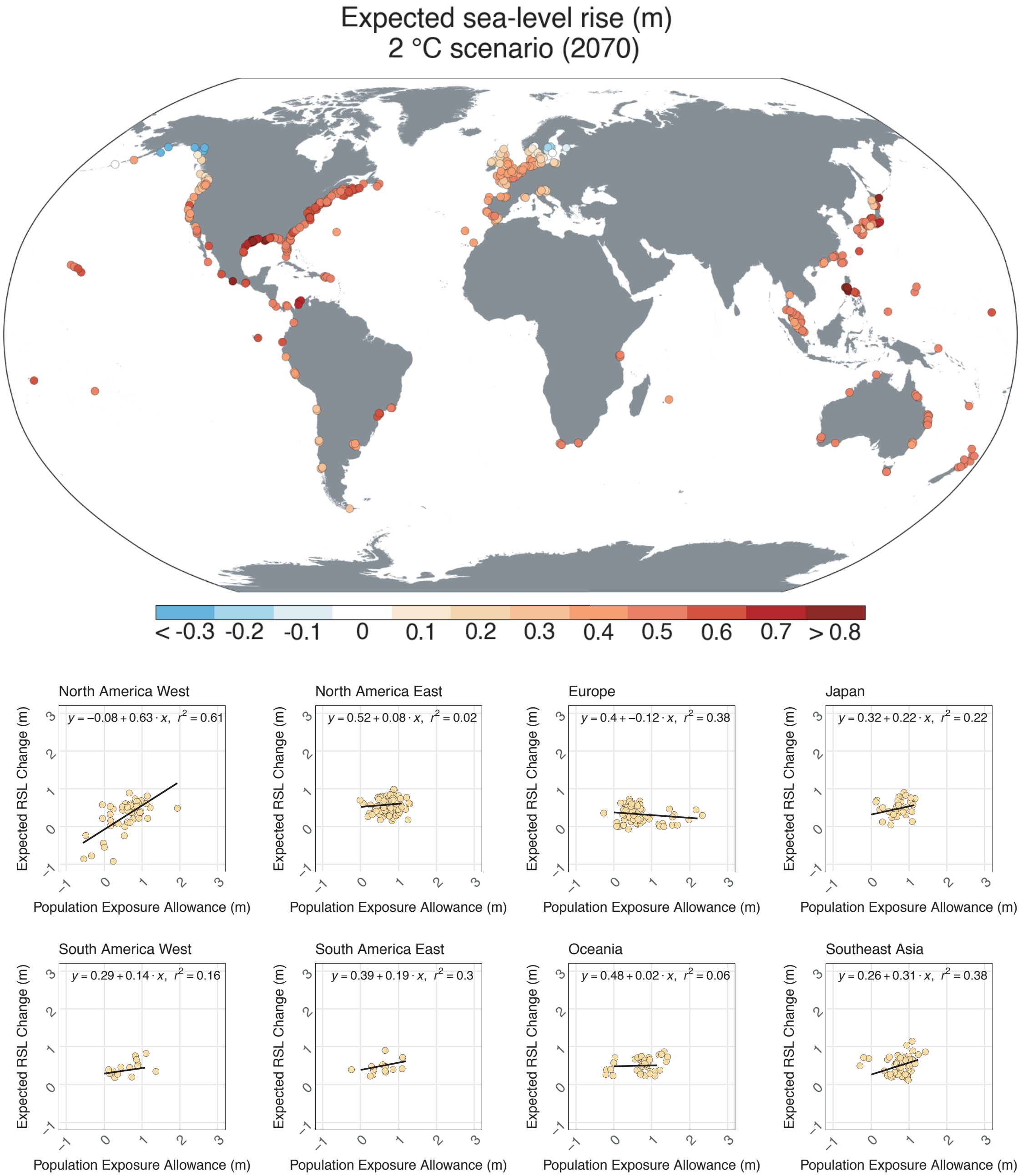
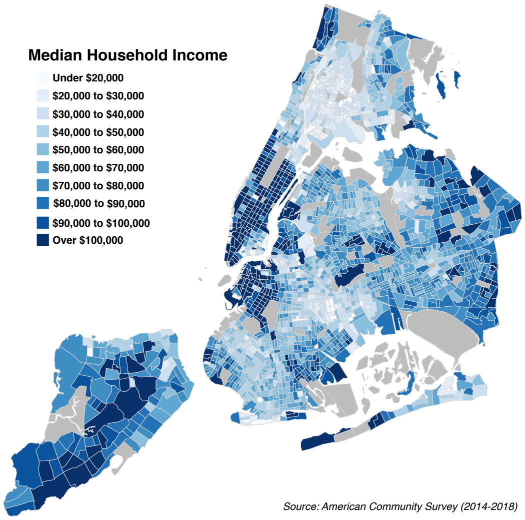


Figure 3.7: **Map:** Expected relative sea level (RSL) change (meters, relative to 1991–2009) for 2070 under a climate scenario where the global mean surface air temperature is stabilized in 2100 at +2 °C (relative to 1850–1900). **Regional scatter plots:** Expected RSL change plotted against population exposure allowances for 2070 that integrate over the entire RSL change probability distribution for the same climate scenario as the map. A list of the cities in each defined region is given in the supporting data files.

Table 3.5: Population exposure amplification factors for New York City by household income for 2070 and 2100 under climate scenarios in which global mean surface air temperature is stabilized in 2100 at +2 °C and +5 °C (relative to 1850–1900; Bamber et al, 2019). The expected value and the 5/95 percentile (in parentheses) of the estimate are given for each and reflects the uncertainty in both relative sea level change and the generalized Pareto distribution parameters. Also given are the total populations for each income group and the percent of the group population currently exposed to the 100-yr ESL event. Median household income is given by New York City census tract from the American Community Survey (2014-2018).

New York City			Population Exposure AF			
	Population		2070		2100	
Household income	Total (millions)	% Exposed (Current 100-yr ESL)	2.0 °C	5.0 °C	2.0 °C	5.0 °C
All incomes	8.05	2.8%	1.5 (1.2-1.9)	1.8 (1.3-2.4)	1.8 (1.3-2.6)	2.6 (1.6-4.4)
$<\$50,000\ \text{yr}^{-1}$	3.54	2.6%	1.5 (1.2-1.9)	1.8 (1.3-2.4)	1.9 (1.3-2.7)	2.7 (1.6-4.7)
$\$50,000\text{-}\$100,000\ \text{yr}^{-1}$	2.06	2.9%	1.5 (1.2-1.9)	1.8 (1.3-2.4)	1.8 (1.3-2.6)	2.6 (1.6-4.4)
$>\$100,000\ \text{yr}^{-1}$	2.32	3.0%	1.5 (1.2-1.9)	1.8 (1.3-2.4)	1.8 (1.3-2.6)	2.5 (1.6-4.2)



Source: American Community Survey (2014-2018)

Figure 3.8: Median Household income by New York City census tract from the American Community Survey (2014-2018).

Table 3.6: Property damage amplification factors for New York City for 2070 and 2100 under climate scenarios in which global mean surface air temperature is stabilized in 2100 at +2 °C and +5 °C (relative to 1850–1900; Bamber et al, 2019). The expected value and the 5/95 percentile (in parentheses) of the estimate are given for each and reflects the uncertainty in both relative sea level change and the generalized Pareto distribution (GPD) parameters. Also given is the current expected damage from the 100-yr ESL event with the 5/95 percentile estimates in parentheses (samples uncertainty in the GPD parameters only). Monetary amounts assume constant 2017 US$. The methods for calculating the damage function are given in Rasmussen et al (2020).

New York City		Property Damage AF			
		2070		2100	
	Current 100-yr ESL	2.0 °C	5.0 °C	2.0 °C	5.0 °C
Property Damage	$4 billion ($2-$7 billion)	2.0 (1.4-2.9)	2.6 (1.6-3.9)	2.7 (1.5-4.3)	4.2 (2.0-7.8)

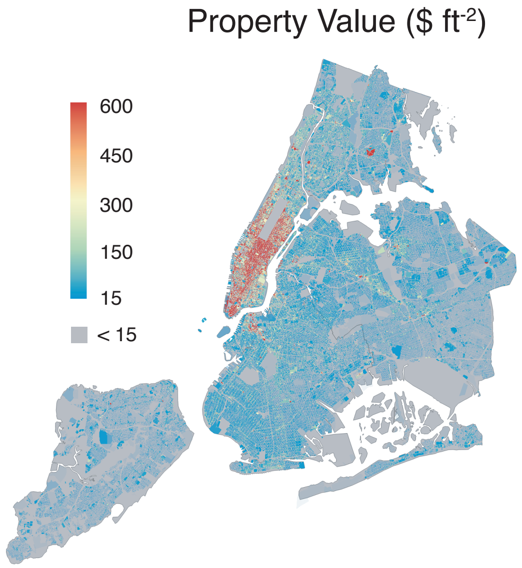


Figure 3.9: The estimated density of property for New York City (excludes land value) given as the tax assessed building value per square foot of building lot area (2017 US$ ft^{-2}). Data are from the NYC Department of City Planning (NYC Planning, 2018).

Table 3.7: Estimated total population exposure and amplification factors for the 100-yr extreme sea level (ESL) event for New York City using 1) a 0.3-m horizontal resolution light detection and ranging (LiDAR)-derived digital elevation model for the City of New York (https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc) and 2) CoastalDEM. Future projections assume a climate scenarios in which global mean surface air temperature is stabilized in 2100 at +2 °C (relative to 1850–1900; Bamber et al, 2019).

2.0 °C	2010	2070		2100	
	Population (thousands)	Population (thousands)	Pop Exposure AF	Population (thousands)	Pop Exposure AF
Lidar	399 (293-564)	607 (488-745)	1.5 (1.2-1.9)	708 (518-938)	1.8 (1.3-2.4)
CoastalDEM	229 (168-324)	351 (280-440)	1.5 (1.2-1.9)	421 (297-596)	1.8 (1.3-2.6)

Table 3.8: As for Table 3.7, but for a climate scenarios in which global mean surface air temperature is stabilized in 2100 at +5 °C (relative to 1850–1900; Bamber et al, 2019).

5.0 °C	2010	2070		2100	
	Population (thousands)	Population (thousands)	Pop Exposure AF	Population (thousands)	Pop Exposure AF
Lidar	399 (293-564)	687 (529-880)	1.7 (1.3-2.2)	917 (617-1,398)	2.3 (1.5-3.5)
CoastalDEM	229 (168-324)	405 (303-548)	1.8 (1.3-2.4)	589 (355-1,010)	2.6 (1.6-4.4)

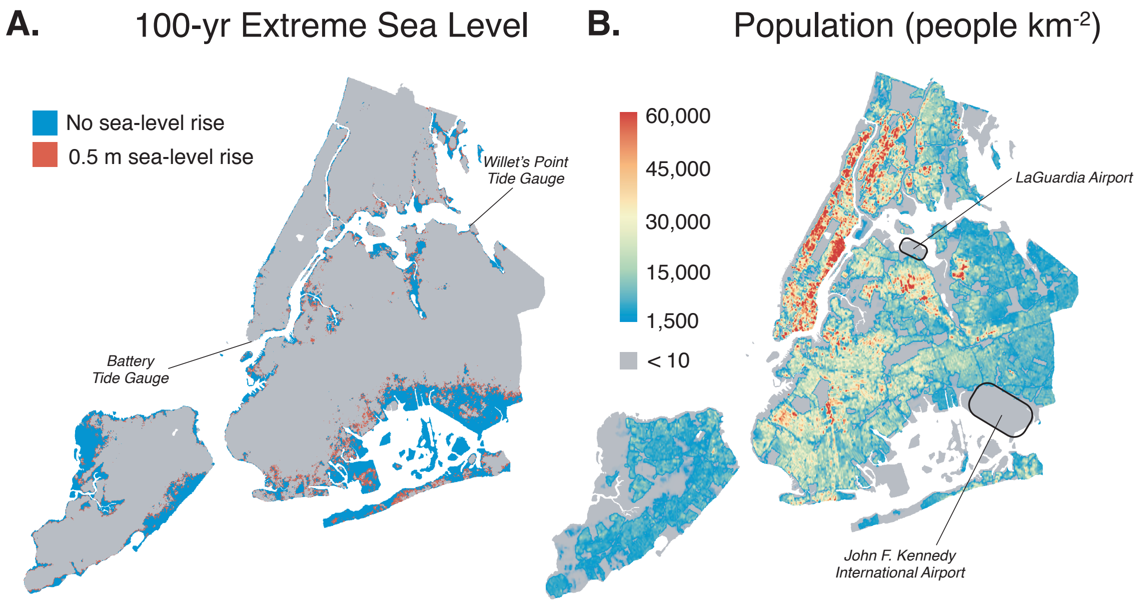


Figure 3.10: **A.** The estimated spatial flood extent for New York City as a result of the 100-yr extreme sea level (ESL) event under 1991–2009 mean sea level (blue) and with 0.5 m of sea-level rise (red; extent above 1991–2009 levels). The "bathtub" approach (Sec. 3.2.2) is used to model flood inundation using the height of the current and projected future 100-yr ESL event at a tide gauge located at the Battery. Topography data are CoastalDEM (Kulp and Strauss, 2018). **B.** The estimated population density (people km^{-2}) for New York City from the 2010 WorldPop global population database (Tatem, 2017). Highlighted are the locations of John F. Kennedy International and LaGuardia Airports, critical infrastructure at risk that is not represented using population data.

Table 3.9: Expected annual population exposure (EAE; millions) under different assumptions of existing coastal flood protection (no protection and protection against the 1-yr and 10-yr events) and amplification factors (AFs) for the EAE for 2050, 2070, and 2100 under the same coastal flood protection assumptions and under a climate scenario in which global mean surface air temperature is stabilized in 2100 at +2 °C (relative to 1850–1900; Bamber et al, 2019).

					2.0 °C								
		2010 EAE (millions)			2050 EAE AF			2070 EAE AF			2100 EAE AF		
City	Population (millions)	None	1-yr	10-yr	None	1-yr	10-yr	None	1-yr	10-yr	None	1-yr	10-yr
Shenzhen, China	12.52	1.07	0.70	0.70	1.3	2.0	2.0	1.6	2.5	2.5	2.3	3.5	3.5
Vancouver, Canada	1.81	0.20	0.13	0.13	1.0	1.6	1.6	1.0	1.7	1.7	1.1	1.8	1.8
New York, USA	12.52	0.22	0.15	0.15	1.4	2.1	2.1	1.8	2.6	2.6	2.8	4.1	4.1
London, UK	9.88	0.04	0.03	0.03	3.0	3.6	3.6	5.0	5.9	5.9	9.9	11.7	11.6
Buenos Aires, Argentina	11.98	0.03	0.03	0.03	2.0	2.1	2.1	3.4	3.5	3.5	11.7	12.1	12.2
San Diego, USA	2.32	<0.01	<0.01	<0.01	2.4	4.3	4.3	5.2	9.1	9.1	12.5	21.8	21.8
Rio de Janeiro, Brazil	9.11	0.03	0.02	0.02	1.3	2.2	2.2	2.0	3.3	3.3	4.1	6.7	6.7
Hong Kong, China	22.23	3.99	2.53	2.53	1.2	1.9	1.9	1.4	2.2	2.2	2.1	3.3	3.3
Manila, Philippines	5.78	2.06	1.24	1.24	1.1	1.8	1.8	1.1	1.9	1.9	1.3	2.2	2.2
Copenhagen, Denmark	1.34	0.02	0.01	0.01	2.3	3.8	3.8	4.9	7.8	7.8	15.1	24.4	24.4
Dar es Salaam, Tanzania	2.32	0.02	0.01	0.01	1.2	2.3	2.3	2.2	3.9	3.9	3.3	5.9	5.9
Sydney, Australia	3.48	0.01	<0.01	<0.01	1.1	1.8	1.8	1.2	2.0	2.0	3.2	5.2	5.2
Phuket, Thailand	0.16	0.01	0.01	0.01	2.0	2.3	2.3	2.3	3.4	2.3	3.4	3.4	3.4
Tokyo, Japan	25.34	0.55	0.38	0.38	1.4	2.1	2.1	2.0	2.9	2.9	5.9	8.7	8.7
New Orleans, USA	0.71	0.17	0.13	0.13	2.2	3.0	3.0	2.8	3.7	3.7	3.6	4.7	4.7
Norfolk, USA	0.69	<0.01	<0.01	<0.01	2.0	2.7	6.9	3.4	4.7	13.7	13.9	19.0	55.5
San Juan, Puerto Rico	1.82	<0.01	<0.01	<0.01	2.5	2.6	2.7	3.0	3.1	3.3	16.6	17.3	18.3

Chapter 4

A flood damage allowance framework for coastal protection with deep uncertainty in sea-level rise

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Abstract

Deep uncertainty describes situations when there is either ignorance or disagreement over 1) models used to describe key system processes and 2) probability distributions used to characterize the uncertainty of key variables and parameters. Future projections of Antarctic ice sheet (AIS) mass loss remain characterized by deep uncertainty. This complicates decisions on long-lived coastal protection projects when determining what margin of safety to implement. If the chosen margin of safety does not properly account for uncertainties in sea-level rise (SLR), the effectiveness of flood protection could decrease over time, potentially putting lives and properties at a greater risk. To address this issue, we develop a flood damage allowance framework for calculating the height of a flood protection strategy needed to ensure that a given level of financial risk is maintained. The damage allowance frame-

work considers decision maker preferences such as planning horizons, protection strategies, and subjective views of AIS stability. We use Manhattan—with the population and built environment fixed in time—to illustrate how our framework could be used to calculate a range of damage allowances based on multiple plausible scenarios of AIS melt. Under high greenhouse gas emissions, we find that results are sensitive to the selection of the upper limit of AIS contributions to SLR. Design metrics that specify financial risk targets, such as expected flood damage, allow for the calculation of avoided flood damages (i.e., benefits) that can be combined with estimates of construction cost and then integrated into existing financial decision-making approaches (e.g., benefit-cost analysis).

4.1 Introduction

Rising sea levels increase the expected frequency of extreme sea level (ESL) events of a given height (Buchanan et al, 2017; Vitousek et al, 2017; Wahl et al, 2017; Vousdoukas et al, 2018). For example, a 0.5 m increase in mean sea level at the Battery in lower Manhattan (New York City, USA) would increase the expected frequency of the local 100-yr ESL event from once every 100 years to about once every 20 years (Rasmussen et al, 2018). This poses a challenge to designers of coastal flood protection tactics that seek to maintain a given margin of safety over time (e.g., protection against the 100-yr flood). Without accounting for sea-level rise (SLR) in the design of coastal flood protection the originally selected margin of safety could decrease, potentially leading to increased flood damages and greater numbers of people at risk. To deal with this issue, ESL hazard 'allowances' have been developed (Hunter, 2012; Slangen et al, 2017; Buchanan et al, 2016). A hazard allowance is the vertical distance an asset needs to be raised in order to ensure that the expected number of ESL events is kept constant under SLR.

We note two limitations of hazard allowances. First, hazard allowances only consider the heights of physical water levels and not their damages. If risk is characterized by the probability of a hazard and its consequence (Kaplan and Garrick, 1981), then the assessment of the benefits of coastal risk reduction measures requires consideration of both the probability of an ESL event and subsequent damages. An allowance that maintains financial risk over time (e.g., the annual average loss [AAL] due to flooding) rather than a physical hazard (e.g., ESLs) directly quantifies reductions in damage and could better inform financial decision-making (e.g., benefit-cost analysis; BCA). Second, future projections of global mean sea level (GMSL) are characterized by 'deep uncertainty' (Lempert et al, 2003). Deep uncertainty (also synonymous with Knightian uncertainty and Ellsbergian 'ambiguity') describes situations where there is either ignorance or disagreement by experts or decision makers over 1) conceptual models used to describe key system processes and 2) probability distribution functions (PDFs) used to characterize uncertainty related to key variables and parameters (Weyer, In press). Incomplete understanding of the physical processes that govern the behavior the Antarctic ice sheet (AIS) inhibits the characterization of a single, unambiguous PDF of future GMSL under a given emissions scenario (Bakker et al, 2017; Kopp et al, 2017; Cozannet et al, 2017; Kopp et al, 2019). Considerably different probabilistic projections can result from differing physical modeling approaches. Therefore, coastal decision-making approaches should accommodate multiple plausible PDFs of AIS melt (e.g., Slangen et al, 2017; Wong and Keller, 2017; Kopp et al, 2019). In this study, we address these two limitations by linking ESLs to financial loss using a simple, time-invariant damage function that is modified based on the flood protection tactic used and also employ future probabilistic projections of local SLR that accommodate multiple subjective beliefs regarding future AIS behavior.

Flood mitigation tactics can produce significant benefits to society by reducing damage to buildings and infrastructure and can potentially save lives (Lincke and Hinkel, 2018; Scussolini et al, 2017; Aerts et al, 2014). Without additional investments in adaptation measures, by the end of the century direct damages from coastal floods on the global scale could exceed one trillion U.S. dollars per year (Hinkel et al, 2014; Diaz, 2016; Jevrejeva et al, 2018), with most losses occurring in highly exposed coastal cities (Hanson et al, 2011; Hallegatte et al, 2013). In response, many of these urban areas are exploring or implementing flood protection tactics (e.g., Pirazzoli and Umgiesser, 2006; Merrell et al, 2011; UK Environment Agency, 2012; SIRR, 2013). These tactics can be categorized as accommodation, defense, advance, and retreat (Oppenheimer et al, in press). Accommodation reduces damage when inundation occurs (e.g., elevating structures or other flood-proofing measures), while defense seeks to prevent inundation using structural measures such as levees and storm surge barriers. Advance creates new lands by building into the sea and retreat permanently moves assets and populations away from the coastline. The height of a protection tactic (i.e., the design height) is a key variable as it is generally consistent with the reduction in the AAL due to flooding; the greater the height, the larger the reduction (all else being equal). A poorly selected design height could lead to greater residual risks in terms of public safety and damage, or overprotection and unnecessary spending.

Formal decision-making approaches can aid in the appraisal of flood protection tactics, including design height calculations. For example, BCA is commonly used by government agencies to economically optimize design heights by balancing incremental reductions in risk with incremental investments in greater margins of safety (e.g., van Dantzig, 1956; Fankhauser, 1995; Ramm et al, 2017; Kanyama et al, 2019). Different decision approaches have different variables that can be prescribed by users (e.g., construction cost, discount rates). For BCA, the margin of safety is not a parameter that can be specified (e.g., protection against the 100-yr ESL event), but rather a variable to be solved for (e.g., by maximizing expected net present value). This approach may be insufficient if a specific margin of safety is desired. On the other hand, hazard allowance frameworks specify a margin of safety (Buchanan et al, 2016), but design heights are calculated without regard to cost.

To fill the space between these two existing decision approaches, we develop a flood 'damage allowance' framework that facilitates estimation of the design heights of flood protection tactics aimed at maintaining a user-defined level of risk (i.e. AAL) under multiple assumptions of future AIS mass loss (i.e., the damage allowance). We consider four protection options: elevation, coastal retreat, a levee, and a storm-surge barrier. Advance is not included due to complexities associated with projecting property growth in new lands. If avoided damages from each protection option are considered benefits, they could be combined with the costs of implementing each approach (not quantified in this study) and then input into a BCA or cost-effectiveness framework (e.g., Aerts et al, 2014; Scussolini et al, 2017). We use Manhattan (New York City) to illustrate framework application but note that in this study we focus on the development of the flood damage allowance framework and give less attention to developing rigorous estimates of current and future flood damages. Users can employ the damage allowance framework with their preferred flood modeling approach or damage functions.

4.2 Framework

The flow and sources of information used in our framework are shown in Fig. 4.7. Additional details and limitations to our approach are given in the Supporting Information (SI). First, we estimate the present-day probability of ESLs of various heights by applying extreme value theory to a long-term record of sea-level observations (Fig. 4.1A; Sec. 4.7.1). Second, increases in ESL frequency are accounted for using probabilistic, local SLR projections (Sec. 4.7.1) that have been adjusted by 1) subjectively weighting the likelihood of rapid AIS mass loss mechanisms and 2) specifying an upper limit to 2100 AIS contributions to GMSL (Sec. 4.2.2). Third, we develop a simple, aggregate flood damage function using 1) a "bathtub" approach to model the spatial variation in floods (Sec. 4.7.2), 2) building stock data, and 3) observed relationships between flood depth and building type (Fig. 4.1B; Sec. 4.7.2). The damage function assumes a "frozen city", in that the population and assets remain in place over time (except when modeling retreat). Fourth, a flood protection tactic is chosen that modifies the shape of the damage function (e.g., levee; Fig. 4.1B). Fifth, the location's AAL due to flooding is projected into the future using the damage function and the PDF of ESLs under SLR (Fig. 4.1C). Finally, the design height of a given flood mitigation tactic is calculated such that the future AAL due to flooding under uncertain SLR equals a user-specified level of acceptable financial risk (e.g., the current AAL).

4.2.1 A generalizable damage stabilizing model

If $f(z^*)$ is the current annual exceedance probability (AEP) of a given ESL event with surge height z^* (e.g., the 100-yr event), then the instantaneous hazard allowance $A(z^*)$ that maintains the AEP under uncertain sea level change Δ can be expressed as:

$$f(z^*) = \int_{\Delta} f(z^* - \Delta + A(z^*))P(\Delta)\,\mathrm{d}\Delta, \tag{4.1}$$

where $f(z^* - \Delta)$ is the AEP of z^* after including sea level change Δ whose uncertainty is given by the PDF, $P(\Delta)$. For a given AEP, the hazard allowance can be interpreted as the horizontal distance between the expected historical and future ESL return curve (Fig. 4.1). If Δ is known, then $A = \Delta$, but if SLR projection uncertainty is considered, the hazard allowance will always be greater than the expected SLR due to an approximately log-linear relationship between the AEP of ESLs and water height (Buchanan et al, 2016).

We extend the hazard allowance concept to damage events by employing a simple, time-invariant damage function that describes the relationship between ESLs and direct physical damages. The damage allowance is the design height of a flood mitigation tactic needed to maintain the current frequency of damage events under uncertain SLR (i.e., the AAL due to flooding, calculated by integrating under the damage return curve). To offset additional damages due to SLR, we create a "protected" damage function using idealized representations of how the flood damage reduction tactics of elevation (Sec. 4.2.1), a levee or storm surge barrier (Sec. 4.2.1), and coastal retreat (Sec. 4.2.1) could impact the relationship between ESLs and damage in the "unprotected" damage function. In order to stabilize the AAL resulting from uncertain SLR, the current AAL must equal the projected AAL that includes both an arbitrary sea level change (Δ) plus an adjustment to offset the increase in damages resulting from SLR. This "conservation of damage" can be mathematically represented by:

$$\int_{A_{min}}^{\infty} \int_{\Delta} D^*(z) f(z-\Delta) P(\Delta)\, \mathrm{d}\Delta\, \mathrm{d}z = \int_{A_{min}}^{\infty} D(z) f(z)\, \mathrm{d}z, \tag{4.2}$$

where z is the ESL height, $D^*(z)$ is a protected damage function that includes adjustments to mitigate additional flood damage resulting from SLR depending on the adaptation tactic used (elevation, levee, storm surge barrier, or coastal retreat; Secs. 4.2.1 to 4.2.1), $D(z)$ is the unprotected damage function (Sec. 4.7.2), and A_{min} is the current protection height. While all allowances traditionally aim to maintain the current level of risk (i.e., the historical AAL), we note that this could be replaced by any user-specified level of risk. In the SI, we show how Eq. 4.2 can return Eq. 4.1 (Sec. 4.7.3).

Damage reduction tactic: elevation

Accommodation tactics, such as elevating buildings on columns, reduces the vulnerability to populations and the built environment. Elevation allows for floods to occur below the design height without incurring significant damage to the structure. We model an elevation tactic that raises all structures by the vertical height A at or below the land elevation A (Fig. 4.2A). Our approach is also consistent with wet-proofing basements and building new floors on top of the existing structure. To estimate the height A that structures need to be elevated to maintain the current AAL under uncertain SLR, $D^*(z)$ is substituted in Eqn. 4.2 with the following:

$$D_e^*(z, A) = \underbrace{\phi(z - A) \int_{e_{min}}^{A} p(e)\, \mathrm{d}e}_{\text{Damage to elevated structures}} + \underbrace{\int_{A}^{z} p(e) \cdot \phi(z - e)\, \mathrm{d}e,}_{\text{Damage to non-elevated structures}} \tag{4.3}$$

where z is the ESL height, A is the damage allowance (above the current protection level, A_{min}), $p(e)$ is the amount of property at elevation e and $\phi(z - e)$ is an inundation depth-damage function for NYC that relates the flood height $(z - e)$ to damage as a fraction of the total property value (see Sec. 4.7.2). Equation 4.3 is plotted in Fig. 4.2B assuming $A = 1.75$ m. Note that no flood damage occurs to structures when $z < A$, but when $z \geq A$, $D_e^*(z, A)$ begins to converge to the unprotected damage function $D(z)$. A method for elevating all structures within a damage function is also provided (Sec. 4.7.3).

Damage reduction tactics: levee and storm surge barrier

Flood defenses physically block the inland advance of ESLs and include both hard (e.g., levees and storm surge barriers) and soft (e.g., beach-dune systems) approaches. Levees are stationary embankments strategically used to prevent areas from flooding. While they may not require private actors to undertake action (e.g., purchasing insurance, elevation or retreat), levees have the disadvantage of maximal loss occurrence by either being overtopped (e.g., by experiencing EWLs outside of the designed margin of safety) or by suffering structural failure (breaching). We model the probability of levee failure (p_f) conditional on the ESL z (i.e., the structural load), the targeted design height A, the failure rate for the water load at the design height (tol_A; assumed to be 0.10, which is the minimum threshold for the probability of a loading breach for Dutch flood defenses (TAW, 1998)), and the height of the freeboard F_b (i.e., arbitrary additional protection above A): $p_f = P(fail \,|\, z, A, tol_A, F_b)$. According to Wolff (2008), for a well-designed levee, the probability of failure below the design height should be "unlikely" and then increase rapidly until it reaches unity at the targeted design height plus the specified freeboard. We model p_f using an exponential relationship that is a function of z, $p_f = a \cdot \exp(b \cdot z)$, where $b = \ln(1/tol_A)/F_b$ and $a = \exp(-b \cdot A + \ln(tol_A))$ (Fig. 4.13). For levees, D^* is substituted in Eq. 4.2 with:

$$D_l^*(z) = p_f(z, A)D(z). \tag{4.4}$$

In other words, total damage scales with the probability of levee failure until overtopping occurs (Figs. 4.2B and 4.13). The base of the levee is assumed to rest on top of the existing flood protection (A_{min}; Fig. 4.2).

Storm surge barriers are gates placed within bodies of water (usually tidally influenced rivers or estuaries) that remain open to allow for tidal flushing and maritime navigation, but close during forecasted ESLs (e.g., coastal storms). Storm surge barriers are often placed within levee systems (Mooyaart and Jonkman, 2017). We model storm surge barriers similarly to levees, but include a parameter that governs gate closure. Due to increased chances of mechanical failure, environmental impacts, and shipping disruption, the frequency of storm surge barrier gate closure is often restricted (Sustainable Solutions Lab, 2018a). This prevents storm surge barriers from protecting against more frequent events that can cause minor flooding, such as extreme tides (Sweet et al, 2016). Some of the largest storm surge barriers are designed to close approximately once every 10 years, such as the Maeslant Barrier (Netherlands), while smaller to medium sized barriers, such as the Thames Barrier (United Kingdom), have historically been designed to close no more than two to three times per year (Sustainable Solutions Lab, 2018a). Fig. 4.1A shows the modified damage function for a surge barrier that closes when $z \geq 1.0$ m. For storm surge barriers, D^* is substituted in Eq. 4.2 with:

$$D_b^*(z) = H_b[z]D(z), \tag{4.5}$$

where H_b is,

$$H_b[z] = \begin{cases} p_f(z, A), & z \geq z_{close}, \\ 1, & z < z_{close}. \end{cases} \tag{4.6}$$

Damage reduction tactic: coastal retreat

Coastal retreat can be described as the reduction in exposure to ESLs through the removal of building stock and populations below a specified elevation A in order to reduce expected flood damages. Such action could occur through voluntary migration, forced displacement, or planned relocation. Retreat is the only tactic that completely eliminates residual risks if there is perfect retreat compliance (i.e. 100% of population moves). Mathematically, coastal retreat modifies the unprotected damage function $D(z)$ by subtracting out damages below A that would have occurred had they not retreated (Fig. 4.2B). This implies that building stock below A is removed from the damage function. This also means that building stock and populations on the risk map below A are also removed. We do not allow for populations to move to higher elevations within the study area; they are assumed to move to a different region. The protected damage function is,

$$D_r^*(z) = D(z)H_r[z], \tag{4.7}$$

where H_r is,

$$H_r[z] = \begin{cases} 1 - \alpha, & z < A, \\ 1 - \alpha \dfrac{D(A)}{D(z)}, & z > A, \end{cases} \tag{4.8}$$

and α is the fraction of assets and populations below A that have retreated (i.e., the retreat compliance; $\alpha \in [0, 1]$). Perfect compliance should not be expected, especially if retreat is voluntary. Some risk targets may not be achievable using coastal retreat if compliance is not high enough. As retreat compliance decreases, $D_r^*(z)$ approaches the unprotected damage function (Fig. 4.14).

4.2.2 Uncertainty in Antarctic ice sheet collapse

Beyond mid-century, the dynamic response of the AIS to warming is a key uncertainty in protecting future sea levels. Several different plausible estimates of continental-scale AIS melt exist (e.g., Golledge et al, 2019; Edwards et al, 2019; Deconto and Pollard, 2016; Ritz et al, 2015; Levermann et al, 2014; Bamber and Aspinall, 2013; Little et al, 2013b,a), but there is currently not an agreed upon full range of outcomes and likelihoods necessary for risk assessment using a single SLR PDF. Recent modeling of ice sheet behavior, discussed in detail in Oppenheimer et al (in press) and Kopp et al (2019), demonstrates divergent PDFs and likelihoods of a partial collapse of the AIS from different modeling approaches . An implication of this ambiguity is that the PDF of SLR in the second half of the century remains strongly dependent upon subjective assessment of potential AIS contributions. Employing multiple PDFs based on such assumptions is one method to characterize this deep uncertainty (e.g., Sriver et al, 2018; Kopp et al, 2017; Rohmer et al, 2019; Slangen et al, 2017; Wong and Keller, 2017; Wong et al, 2017).

Imprecise probability methods can be used in cases where multiple PDFs cannot be reduced to a single distribution. For example, a probability box (or 'p-box') can be used to express SLR incertitude by constraining plausible cumulative probability distribution functions (CDFs) of SLR within a defined space (Baudrit et al, 2007; Cozannet et al, 2017). If it is assumed that the upper (i.e., right edge) and lower (i.e., left edge) limits of the p-box contain the unknown distribution, then the true probability of exceeding a given amount of SLR lies within the bounds of the CDFs. A p-box is shown in Fig. 4.5A for 2100 local SLR at the Battery tide gauge in lower Manhattan. Here, we limit the upper p-box boundary with local probabilistic SLR projections from Kopp et al (2017), which employ the fast ice loss AIS projections from Deconto and Pollard (2016), and the lower p-box boundary with SLR projections from Kopp et al (2014), which include more sluggish AIS mass loss based on a combination of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment

Report and expert elicitation of total ice sheet mass loss from Bamber and Aspinall (2013). These SLR projections were chosen for illustrative purposes only. For instance, a more credible approach could be to employ the more recent projections from Bamber et al (2019) that include new expert elicitation of AIS behavior. End-of-century SLR projections from Bamber et al (2019) under RCP8.5 largely fall in between those from Kopp et al (2014, 2017), but have a higher probability of SLR $\geq$ 3 m (Fig. 4.21).

Subjective beliefs regarding future AIS behavior are used to generate an "effective" SLR distribution within the p-box (Sec. 4.7.1). The "effective" distribution is generated by 1) selecting an upper limit to 2100 AIS contributions (AIS$_{max}$) and 2) averaging the upper and lower bounds of the p-box using a weight that reflects the subjective likelihood of AIS collapse initiation before 2100 ($\beta_c \in [0, 1]$). Larger values of β_c imply a higher likelihood of AIS collapse initiation before 2100, while lower values of β_c imply a lower likelihood. We consider AIS$_{max}$ scenarios of 1.75, 1.5, 1.0, 0.5, and 0.25 m (relative to 2000). More details regarding the SLR projections and the p-box construction are given in the SI (Secs. 4.7.1 and 4.7.1, respectively). Similar approaches that weight worst-case outcomes for SLR and other climate variables have been used for decision-making under deep uncertainty (Buchanan et al, 2016; McInerney et al, 2012).

4.2.3 Damage allowance framework decision sequence

The flow of the damage allowance framework is presented in Fig. 4.3A. First, an acceptable AAL risk target is selected. This could be the current AAL to maintain the current level of flood risk (i.e., the traditional allowance definition), or any value greater than zero. Second, both the timeframe and the approach for meeting the risk target are chosen. We only consider the instantaneous allowance (i.e., risk is kept below the target through the duration of the project and is met in the final year); however, this could alternatively be a period of years over which the mean AAL equals the risk target (earlier years are below the risk target and later years are above it; i.e., the average annual design life allowance, Sec. 4.7.3). Third, a flood damage mitigation tactic is selected. While combined protection tactics are possible (e.g., retreat and a levee; Sec. 4.7.3), in this paper we illustrate damage allowances using only a single option. Finally, two parameters that govern AIS contributions to SLR are subjectively chosen: AIS$_{max}$ and β_c (Sec 4.2.2).

4.3 Illustration of damage allowance framework: Manhattan, New York City

We use Manhattan to illustrate our damage allowance framework. Manhattan is an island, surrounded by the Hudson, East, and Harlem Rivers, and is the economic and administrative center of New York City (NYC; Fig. 4.4A). NYC ranks among the top urban areas in the world in terms of current assets and population exposed to coastal floods (Hallegatte et al, 2013; Hanson et al, 2011). In Manhattan alone, more than $50 billion[1] of property lies within the 100-yr flood plain (Figs. 4.4B,C; NYC Comptroller, 2014). The AAL due to flooding in Manhattan is expected to increase with SLR (Orton et al, 2019; Gornitz et al, 2019). Using our flood damage model, we estimate that the current AAL could increase by more than a factor of 10 by 2070, from $0.1 billion/yr to ∼$1.6 billion/yr (Fig. 4.1C). As such, NYC is exploring multiple public flood protection strategies (USACE, 2016, 2019; SIRR, 2013; NYC, 2019b,a). A direct comparison of the current AAL with other studies is difficult due to differences in geographic scope and flood protection assumptions. Nonetheless, Aerts et al (2014) and Houser et al (2015) found an AAL of $0.18 and $0.53 billion/yr for all of NYC, respectively, and Hallegatte et al (2013) found an AAL of $0.79 billion/yr for the entire NYC-Newark, New Jersey region. We note that due to the simplifications made in estimating flood risk (Secs. 4.7.2-4.7.2), the options presented in this study are not intended to be specific recommendations for Manhattan. We also do not fully address the feasibility of implementation (e.g., financial or technical). For example, it may be impractical to elevate high-rise structures[2] or flood-proof all exposed buildings. In the case of coastal retreat, we assume that populations associated with removed property move to either a different borough of New York City or elsewhere. More detailed assessments could be used to further

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[1] All monetary values in this paper are given in 2017 U.S. dollars (US$)

[2] However, roughly 88% of all buildings in Manhattan sited at $\leq$ 8 m in elevation (relative to MHHW) have less than six floors above ground level (NYC Planning, 2018). These buildings tend to be older and their relation to the total fraction of damage is unclear.

investigate the feasibility of preferred courses of action. Manhattan is used because there is 1) a tide gauge with a long record from which to construct an ESL distribution[3], 2) a fairly uniform tidal range around Manhattan (Orton et al, 2019), 3) freely available building stock data (NYC Planning, 2018), and 4) a relatively uniform level of existing "flood protection", a 1.0 m bulkhead (relative to MHHW[4]; Colle et al, 2008).

We consider changes to the flood damage function and return curve if Manhattan implemented a levee, storm surge barrier, elevation or coastal retreat (Fig. 4.2B and C, respectively). For illustrative purposes, the 1.0 m bulkhead around Manhattan is not considered here. A hypothetical 1.75 m levee would prevent all flood damage events $<$ \$2 billion and would decrease the current AAL from \$1.6 billion/yr to \$1.2 billion/yr (assuming no bulkhead). The effect of a 1.75 m storm surge barrier is similar to the levee, but reduces the current AAL slightly less because ESLs $<$ 1 m are allowed to occur when barrier gates are open (decreases current AAL from \$1.6 billion/yr to \$1.3 billion/yr). Raising all existing structures with first-floor elevations of 1.75 m or less to 1.75 m reduces the AAL similar to that of the levee and surge barrier, from \$1.6 billion/yr to \$1.0 billion/yr. While, over-topping does not occur with the elevation tactic, we note that the failure of elevated structures is possible, but not considered in this study. Of all options explored, coastal retreat reduces the current AAL the most. If all existing structures with first-floor elevations of 1.75 m or less retreat, the AAL is reduced from \$1.6 billion/yr to \$0.3 billion/yr. Coastal retreat not only eliminates damage to building stock $\leq$ 1.75 m, it also eliminates the possibility of damage to these structures for ESLs $>$1.75 m because they are removed from the damage function. For both the levee and storm surge barrier, we note that levee and barrier failure is not depicted in Fig. 4.2B or Fig. 4.2C, but is considered in the damage allowance calculation (Sec. 4.2.1).

An application of the damage allowance framework for Manhattan is shown in Fig. 4.3B. In this example, a government planner chooses to maintain Manhattan's current AAL due to flooding through 2100 using a storm surge barrier placed across the tidal straight between

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[3] https://tidesandcurrents.noaa.gov/stationhome.html?id=8518750

[4] This is approximately the height with which water begins to flow over the bulkhead at the Battery in lower Manhattan (retrieved from https://water.weather.gov/ahps; July, 2019). This is also a simplification, as the bulkhead height varies around the island of Manhattan (1.25 to 1.75 m above MSL or 0.5 to 1 m above MHHW; Colle et al, 2008).

Staten Island and Brooklyn (Fig. 4.4A). We assume that the surge barrier would be similar in design to that of the Maeslant Barrier (Netherlands), designed to close no more than once every 10 years on average under current mean sea levels. This corresponds to an ESL closure threshold (z_{close}) of roughly 1.0 m above MHHW, as estimated from Fig. 4.1A. We assume the barrier has a 10% probability of failure at the design height, 0.5 m of freeboard, and that the 2100 AIS mass loss contributions to GMSL is $\leq$ 1.0 m (relative to 2000) and collapse initiation of the AIS is "less likely" ($\beta_c = 0.25$). According to the framework, the storm surge barrier should be built to a height of 3.3 m above MHHW. This increases by 0.5 m if the AIS collapse odds are instead believed to be "most likely" ($\beta_c = 1.0$).

4.4 Results

4.4.1 Characterizing deep uncertainty: sea-level rise and extreme sea level return periods

In Fig. 4.5, we illustrate deep uncertainty associated with 2100 local SLR and ESLs in Manhattan under multiple values of AIS$_{max}$ for both RCP8.5 and RCP2.6 (high and low climate forcing scenarios, respectively). Deep uncertainty is explored within each p-box under multiple assumptions regarding the likelihood and speed of collapse of the AIS ($\beta_c \in$ [0,1]). Under RCP8.5 and AIS$_{max}$ = 1.75 m, the probability of local SLR $\geq$ 1.5 m is 6% under the least likely AIS collapse assumption ($\beta_c = 0$), but is 65% under the most likely AIS collapse assumption ($\beta_c = 1$; Fig. 4.5A). The spread between these probabilities reflects the level of deep uncertainty. The sensitivity of SLR in 2100 to β_c decreases as AIS$_{max}$ decreases. For instance, in the case of AIS$_{max}$ = 1.0 m, the probability of SLR $\geq$ 1.5 m is 6% (β_c = 0) and 51% ($\beta_c = 1$), while in the case of AIS$_{max}$ = 0.5 m, the probability of SLR $\geq$ 1.5 m is 5% ($\beta_c = 0$) and 24% ($\beta_c = 1$; Figs. 4.5B and C, respectively). Deep uncertainty for the AIS is larger under RCP8.5 than RCP2.6. Under RCP2.6, assumptions regarding future AIS behavior do not significantly impact projections. For instance, for AIS$_{max}$ = 1.75 m, the probability of SLR $\geq$ 1.0 m is 7% under $\beta_c = 0$, but is 14% under $\beta_c = 1$ (Fig. 4.5D). For AIS$_{max}$ = 0.5 m, these probabilities reduce slightly to 5% and 13%, respectively (Fig.

4.5F). Additional p-boxes are given in the SI for 2050 and 2070 and AIS$_{max}$ = 1.5 and 0.25 m (Figs. 4.16 to 4.20).

Deep uncertainty associated with the AIS is also reflected in the projected increase in the expected number of ESL events in 2100. For instance, under RCP8.5 and AIS$_{max}$ = 1.75 m, the number of present-day 100-yr ESL events in Manhattan is expected to increase from 0.01/yr, on average, to between roughly 6/yr ($\beta_c = 0$) and 100/yr ($\beta_c = 1$), on average (Fig. 4.5A). Reducing AIS$_{max}$ decreases the spread of the ESL return curves under different values of β_c. For instance, under RCP8.5 (AIS$_{max}$ = 0.5 m), the expected number of historical 100-yr ESL events is roughly 4/yr ($\beta_c = 0$) and 20/yr ($\beta_c = 1$), on average (Fig. 4.5C). Under RCP2.6, both the absolute expected number of ESL events and the spread of the ESL return curves decreases. For instance, assuming AIS$_{max}$ = 1.75 m, the projected number of present-day 100-yr ESL events is roughly between 0.2/yr ($\beta_c = 0$) and 1/yr ($\beta_c = 1$), on average (Fig. 4.5D), but for AIS$_{max}$ = 1.0 m the projected number of 100-yr ESL events is approximately between 0.2/yr ($\beta_c = 0$) and 0.7/yr ($\beta_c = 1$), on average (Fig. 4.5E). For AIS$_{max}$ = 0.5 m, there is little to no difference in the expected number of 100-yr flood events based on the perceived likelihood of AIS collapse; the number of expected 100-yr flood events for both $\beta_c = 0$ and $\beta_c = 1$ is roughly 0.2/yr, on average (Fig. 4.5F). Additional ESL return curves are given in the SI (Figs. 4.16 to 4.20).

4.4.2 Flood damage allowances: surge barrier and coastal retreat

Hazard allowances only consider the physical heights of water and do not assure that the number of damage events will simultaneously be held constant over time. ESL return curves for Manhattan are shown in Fig. 4.1A for both $\Delta = 0.5$ m and the entire PDF of projected 2070 SLR ($P(\Delta)_{2070}$). Here, the hazard allowance A is 0.5 m for $\Delta = 0.5$ m, but $A = 0.86$ m when considering $P(\Delta)_{2070}$. However, depending on local flood protection, an ESL event may or may not lead to damage. For example, a 1.0 m bulkhead around Manhattan prevents ESLs ≤ 1 m from causing damages $< \sim\$0.5$ billion (Fig. 4.1B). Adding a levee on top of the 1.0 m bulkhead reduces losses for some ESL heights (Fig. 4.1B). Under 2070 SLR, this levee needs to be built to 1.70 m above the bulkhead to maintain the current AAL (i.e., the damage allowance; Fig. 4.1C), nearly two times greater than the hazard allowance (0.86 m) and more than twice as large as the expected 2070 SLR (0.80 m; Table 4.2).

Damage allowances for a levee and coastal retreat that maintain the current AAL for Manhattan under different assumptions of AIS behavior are given in Fig. 4.6 (RCP8.5 and RCP2.6). We assume 0.5 m of freeboard for the levee and a 10% failure rate (see Sec. 4.2.1). Both damage allowances are relative to a 1 m bulkhead above MHHW ($A_{min} = 1$ m). As sea levels rise, the damage allowances increase. The allowances for the levee increase faster than coastal retreat because as the levee height increases, more property becomes subjected to potential over-topping or breaching. This added risk must be compensated by an increase in levee height. The damage allowances for the levee and coastal retreat also increase at faster rate compared to local SLR (Tables 4.2-4.4). For instance, the mean SLR for 2050, 2070, and 2100 is 0.4 m, 0.8 m, and 1.8 m, respectively, while the corresponding levee damage allowances are 0.9 m, 1.6 m, and 3.4 m, respectively (RCP8.5; AIS$_{max}$ = 1.75 m and $\beta_c = 0$). For both RCPs, the assumptions regarding AIS behavior make little or no difference in the levee damage allowances before mid-century. However, after mid-century under RCP8.5, levee damage allowances may differ by up to 1.4 m, depending on AIS$_{max}$ and β_c. Under RCP2.6, differences only occur after 2080 for $\beta_c > 0.75$ and are ≤ 0.6 m (Fig. 4.6A and Table 4.3). The sensitivity of allowances based on assumptions of AIS behavior is consistent with previous findings (Slangen et al, 2017). Results for a storm surge barrier and elevation are given in the SI (Figs. 4.22 and 4.23; Tables 4.5 and 4.6).

4.4.3 Result sensitivity to extreme sea-level rise samples

Both ESL frequencies and damage allowances are sensitive to the selection of AIS$_{max}$, which effectively limits the upper tail of the SLR PDF. The smaller the value of AIS$_{max}$, the more low probability, extreme SLR samples excluded. This is important because extreme SLR samples can strongly influence results. For example, in the case of ESL frequency, the highest samples in the SLR PDF can cause the ESL event frequency to saturate at 182.6/yr (e.g., the $\beta_c = 0$ return curve in Fig. 4.5A and the $\beta_c = 1$ return curve in Fig. 4.5D). This saturation subsequently increases the expected number of ESL events and visually appears as "kinks" in the return curves. Both the positioning and the presence of the kinks are sensitive to the choice of AIS$_{max}$. The kinks disappear for AIS$_{max} \leq 1.0$ m (Fig. 4.5B,C,E, and F). Extreme SLR samples can also increase damage allowances beyond that which might result when considering only the 95th percentile of SLR. To illustrate, we calculate damage allowances that only consider the 5/95th percentiles 2100 SLR projections, rather than the entire SLR PDF (shown in the margins of each panel in Fig. 4.6). For AIS$_{max}$ = 1.75 m and $\beta_c = 0$ (RCP8.5), the damage allowances that consider only the 95th percentile SLR are lower than those that consider the entire SLR PDF. If the SLR PDF in consideration is long tailed, then illustrating allowance uncertainty based on the 5/95th SLR percentiles may be more practical for some design applications. On the other hand, not fully considering the upper tail could under-represent risk. Users of existing ESL and allowance frameworks should take note of the sensitivity to the truncation of the SLR PDF (e.g., Buchanan et al, 2016; Buchanan et al, 2017; Rasmussen et al, 2018).

4.5 Discussion

While simple models like flood damage allowances may make too many approximations for readily implementable final project designs, they are well-suited for early planning phases when the focus is on exploring coastal protection strategies worth examining in greater detail with more complex models. Rather than being viewed as substitutes, reduced-form models can complement their more complex peers. For example, while more complex integrated assessment frameworks may better simulate reality, they demand high computational costs which places limits on the number of flood protection strategies that can be investigated simultaneously (e.g., Fischbach et al, 2017). Simple models may be more useful in cases where the appraisal of several project designs is needed, such as robust strategy identification (e.g., Lempert et al, 2003; Sriver et al, 2018). Additionally, exploring interactions between multiple variables with complex models can make it challenging to understand how different flood protection tactics and SLR assumptions impact benefits from proposed solutions.

Despite the mentioned advantages, there are multiple caveats associated with flood damage allowances. First, the effectiveness of flood protection is dependent on both the changing hazard (SLR, ground subsidence rates, coastal storm frequency and severity) and changes in the consequence (e.g., what is behind the levee and how vulnerable is it to flood damage). In this study, SLR is the only variable that evolves over time. Design heights needed to meet risk tolerance targets could be higher or lower depending on these and other variables. For instance, it has been observed that well-designed flood protection strategies can lead to increased development in protected areas due to a greater sense of perceived safety (the "levee effect"; White, 1945; Di Baldassarre et al, 2018). This can increase residual flood risk over time. Additionally, from an aesthetic perspective, elevation, levee and surge barrier construction, and retreating from the floodplain could all impact building amenity value. These impacts could be important, but are not considered. Second, allowances assume risk tolerance remains constant over the lifetime of the investment, during which one may wish to increase the margin of safety. Third, levees and storm surge barriers can produce storm surge funneling effects that further elevate the water surface. This, as well as the added impact of waves, are not considered and could increase the damage allowance. Fourth, damages and loss of lands from permanent inundation or coastal erosion are not accounted for. This could have a significant impact on the effectiveness of a specific flood protection tactic. In the case of a storm surge barrier, after sea level has risen above the gate closure threshold, the barrier may need to remain closed to be effective. Finally, if the damage allowances are used to produce benefits for a BCA or cost-effectiveness framework, limitations associated with those methods also apply (e.g., Arrow et al, 1996). This includes potentially giving less weight to lower income groups. Calculations that are instead based on human population exposure could give more consideration to these demographics.

So-called flexible/adaptive decision strategies can address challenges associated with deep uncertainty. Flexible/adaptive decision approaches commit to short-term actions in response to new information (e.g., Haasnoot et al, 2013; Wise et al, 2014; Walker et al, 2013). They have the advantage of being less dependent on accurate projections of the future (e.g., flexible levee design allowing for heightening over time as risk tolerances change or as new information is learned about hard-to-predict variables). Despite this key advantage, there are multiple political reasons why a multiple priors approach (like flood damage allowances) might be pursued over a flexible/adaptive framework.

Efforts to use flexible/adaptive approaches could be complicated by existing laws and government agency protocols that promote BCA and cost-effectiveness analysis. For example, the U.S. Army Corps of Engineers, the principal agency tasked with designing and implementing coastal flood risk management projects in the U.S., uses future projections of SLR in their BCA to assess and select coastal protection strategies that best "contribute to national economic development consistent with protecting the Nation's environment" (U.S. Water Resources Council, 1983; Public Law, 1936; USACE, 2019). Second, financing for disaster preparedness projects is usually only available following major disasters (NRC, 2014), in part due to motivations of elected officials (Healy and Malhotra, 2009). Current flood protection revenue streams are inadequate for supporting either new construction or regular upgrades that may occur with a flexible/adaptive approach (Knopman et al, 2017; Sustainable Solutions Lab, 2018b). This financing arrangement may reinforce the use of prediction-first approaches that force a decision to be made now with no planned opportunity to revisit the course of action in the future. Third, flexible/adaptive approaches may be more expensive compared to designing once (Fankhauser et al, 1999; Haasnoot et al, 2019), and they may involve more political overhead to change existing governance structures away from appraisals based on BCA (e.g., Ramm et al, 2017; Kanyama et al, 2019). This could delay making a decision regarding what flood protection tactic to pursue during which additional flood damages may occur. Development times for building flood protection are already long. For example, experience with storm surge barriers has shown that it can take decades to design and build a multi-billion dollar project (Morang, 2016; Sustainable Solutions Lab, 2018a).

4.6 Conclusions

A number of formal decision-making frameworks exist for designing strategies that mitigate flood damages (Walker et al, 2013). These are generally driven by economic objectives, such as choosing courses of action where monetized discounted benefits exceed discounted costs (i.e., BCA). We introduce flood damage allowances as a new strategy for determining the design heights of coastal protection tactics in this class of financial decision-making frameworks. They follow a 'decision-centered' approach (e.g., Ranger et al, 2013) because their outcomes are dependent on more than just SLR projections alone. Decision makers specify a tolerable level of risk (represented by a focal AAL), a protection tactic (elevation, levee, storm surge barrier, and coastal retreat), and assumptions regarding future AIS behavior (maximum AIS melt contribution and AIS stability). The latter is significant because decision-making approaches that employ future projections of SLR may be appropriate when uncertainty can confidently be represented with a single PDF (e.g., near mid-century, when AIS melt uncertainty is well defined), but is insufficient when uncertainty is deep (e.g., late century AIS melt; Hall, 2007). While there is value in information to reduce deep uncertainty (e.g., constraining projections of AIS melt contributions; Dutton et al, 2015), until understanding improves regarding these aspects, approaches to flood protection design that rely on future distributions of relevant variables may require a multi-prior approach to more accurately depict current states of knowledge. This includes accounting for uncertainties in future changes in coastal storm frequency and severity.

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Figures and Tables

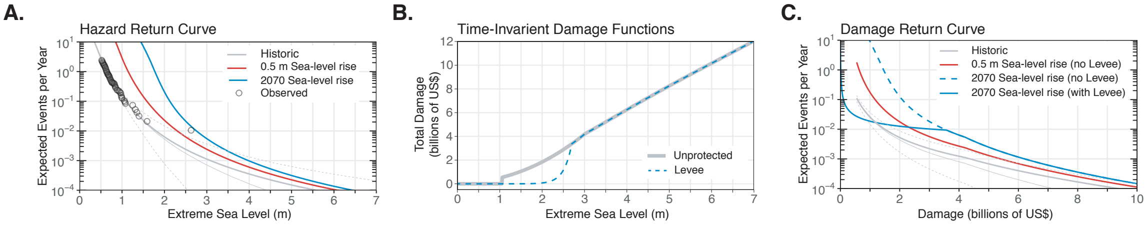


Figure 4.1: **A.** Expected number of extreme sea level (ESL) events per year as a function of ESL height (meters above mean higher high water) at the Battery (Manhattan, New York City) for historical mean sea level (grey lines), 0.5 m of sea-level rise (SLR; red line), and projected SLR in 2070 (blue line). Thin grey lines are the historical ESL height return curves for the 5/50/95 percentiles of the generalized Pareto distribution parameter uncertainty range (dotted/solid/dotted lines, respectively). Tide gauge observations (1920–2014) are plotted as open black circles. **B.** Direct physical flood damage in Manhattan (billions of 2017 US$) as a function of ESL height (meters above mean higher high water) as estimated by a time-invariant flood damage function (Sec. 4.7.2) that assumes a 1.0 m high bulkhead around Manhattan (grey curve) and a time-invariant flood damage function that assumes a 1.7 m high levee on top of the bulkhead protecting Manhattan that includes the probability of structural failure below the top of the levee (dashed blue curve; Sec. 4.2.1). **C.** As for A, but for the expected number of flood damage events per year (billions of 2017 US$) for historical mean sea level (grey lines), 0.5 m of SLR and no added protection (red line), projected SLR in 2070 with no added protection (dash blue line), and projected SLR in 2070 with a 1.7 m levee that maintains the historical annual average loss due to flooding (solid blue line). The projected damages assume that Manhattan's distribution of buildings, people, and infrastructure remains constant in time.

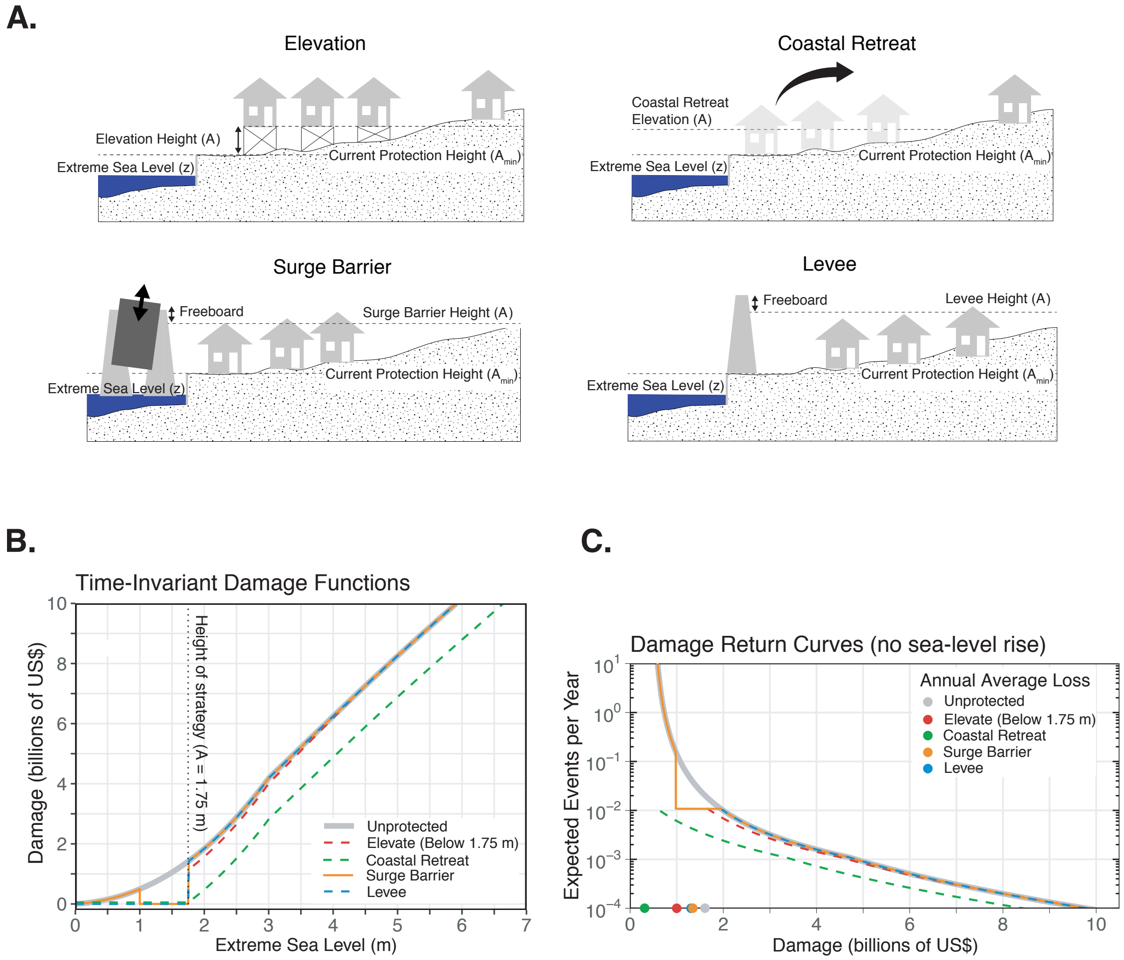
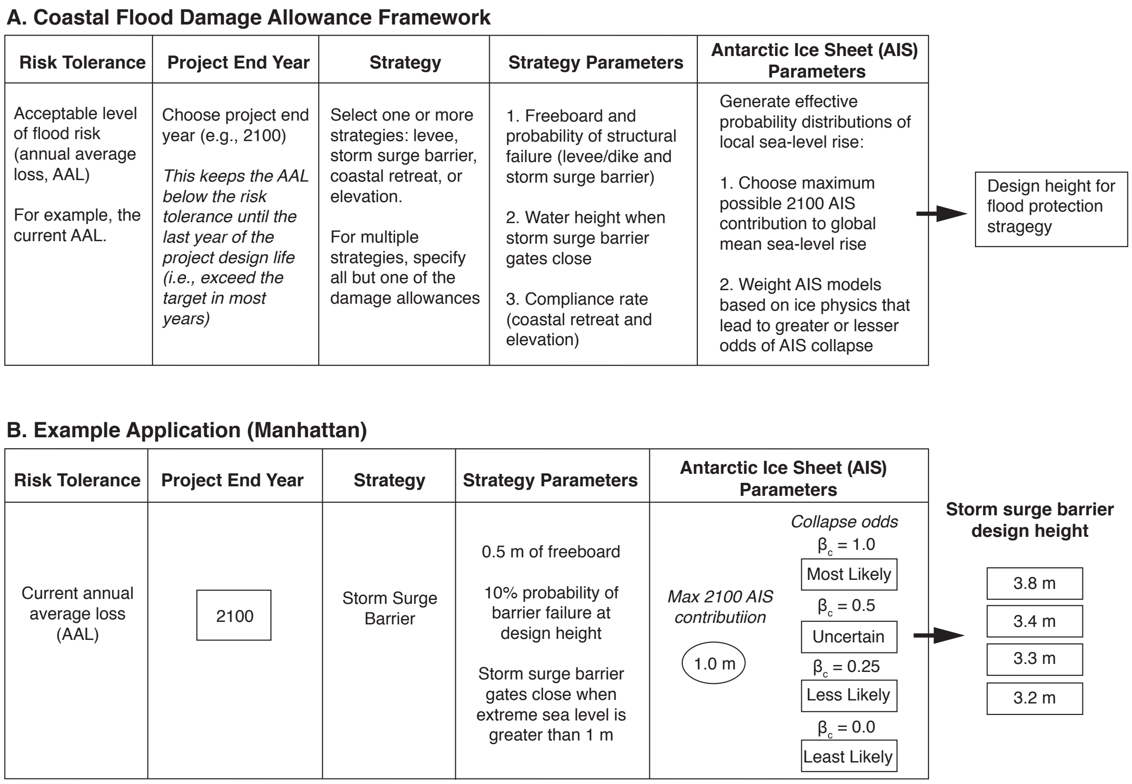


Figure 4.2: **A.** Schematics illustrating each flood protection tactic for an arbitrary protection height (A). **B.** Time-invariant damage functions for Manhattan that relate extreme sea level (ESL; meters) to total direct damage due to flooding (billions of US$; Sec. 4.7.2). The thick grey line is the unprotected damage function that assumes no existing bulkhead around Manhattan ($A_{min} = 0$); the dashed red line is the damage function after elevating all structures 1.75 m below 1.75 m in elevation; the dashed green line is the damage function for coastal retreat of all structures below 1.75 m of elevation; the solid orange line is the damage function for a storm surge barrier with a protection height of 1.75 m with gates that close when the ESL is $>$ 1.0 m and has zero probability of structural failure and no freeboard; the dashed blue line is the damage function for a levee with a protection height of 1.75 m that has zero probability of structural failure and no freeboard. **C.** Damage event return curves under no sea-level rise showing the expected number of flood damage events per year (billions of 2017 US$) with no protection tactic (thick grey curve) and under the flood protection tactics of elevation (dashed red curve), coastal retreat (dashed green curve), a storm surge barrier (solid orange curve), and a levee (dashed blue curve). All cases assume that Manhattan's distribution of buildings, people, and infrastructure remains constant in time. For illustrative purposes, all cases assume no bulkhead around Manhattan ($A_{min} = 0$) and the storm surge barrier and levee tactics assume no possibility of structural failure and no freeboard. The discontinuity for the storm surge barrier (solid orange curve) occurs due to protection being limited to a range of ESLs (here 1.0 m to 1.75 m). The annual average loss under each protection tactic is plotted on the x-axis with a filled circle.



A. Coastal Flood Damage Allowance Framework

Risk Tolerance	Project End Year	Strategy	Strategy Parameters	Antarctic Ice Sheet (AIS) Parameters
Acceptable level of flood risk (annual average loss, AAL) For example, the current AAL.	Choose project end year (e.g., 2100) *This keeps the AAL below the risk tolerance until the last year of the project design life (i.e., exceed the target in most years)*	Select one or more strategies: levee, storm surge barrier, coastal retreat, or elevation. For multiple strategies, specify all but one of the damage allowances	1. Freeboard and probability of structural failure (levee/dike and storm surge barrier) 2. Water height when storm surge barrier gates close 3. Compliance rate (coastal retreat and elevation)	Generate effective probability distributions of local sea-level rise: 1. Choose maximum possible 2100 AIS contribution to global mean sea-level rise 2. Weight AIS models based on ice physics that lead to greater or lesser odds of AIS collapse

→ Design height for flood protection stragegy

B. Example Application (Manhattan)

Risk Tolerance	Project End Year	Strategy	Strategy Parameters	Antarctic Ice Sheet (AIS) Parameters		Storm surge barrier design height
Current annual average loss (AAL)	2100	Storm Surge Barrier	0.5 m of freeboard 10% probability of barrier failure at design height Storm surge barrier gates close when extreme sea level is greater than 1 m	*Max 2100 AIS contributiion* 1.0 m	*Collapse odds*	
					$\beta_c = 1.0$ Most Likely	3.8 m
					$\beta_c = 0.5$ Uncertain	3.4 m
					$\beta_c = 0.25$ Less Likely	3.3 m
					$\beta_c = 0.0$ Least Likely	3.2 m

Figure 4.3: **A.** Flowchart illustrating how to apply the coastal flood damage allowance framework **B.** An example application for Manhattan seeking to maintain the current annual average loss from flood damages using a storm surge barrier.

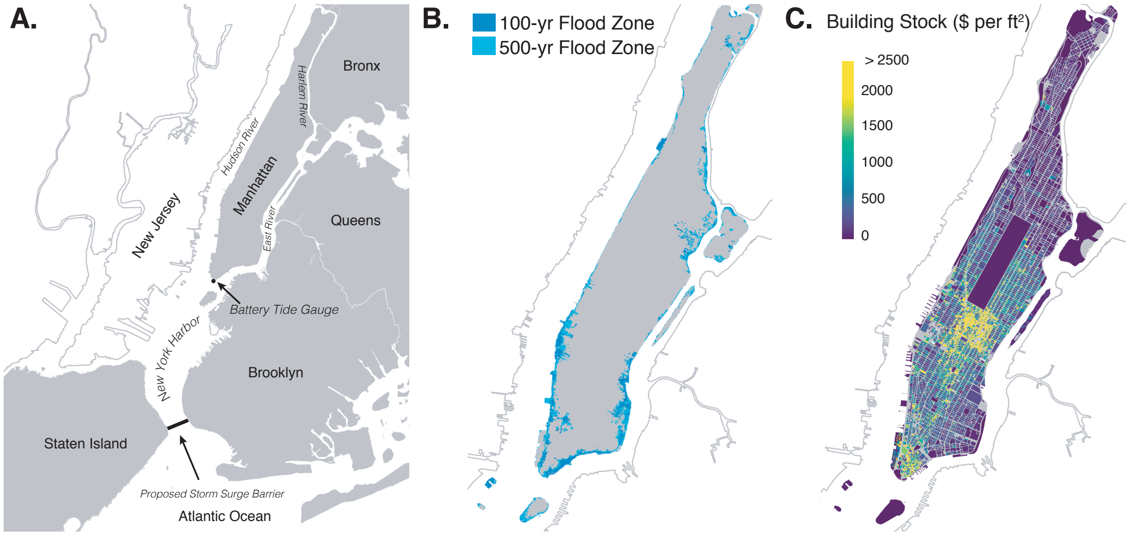


Figure 4.4: **A.** A map showing Manhattan and the surrounding boroughs, the location of the Battery tide gauge in lower Manhattan, and the location of a proposed storm surge barrier at the entrance to New York Harbor. **B.** Estimated 100- (blue) and 500-yr (cyan) flood zones in Manhattan generated using the "bathtub" approach that estimates spatial flood extents using 1) extreme sea level return periods from the Battery tide gauge and 2) a 0.3 m horizontal resolution light detection and ranging (LiDAR)-derived digital elevation model for the City of New York (https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc) **C.** The spatial distribution of tax assessed building stock value in Manhattan (excludes land value). Building stock value is given as tax assessed building value per square foot of building lot area (2017 US$ per ft^2). Data are from the NYC Department of City Planning (NYC Planning, 2018).

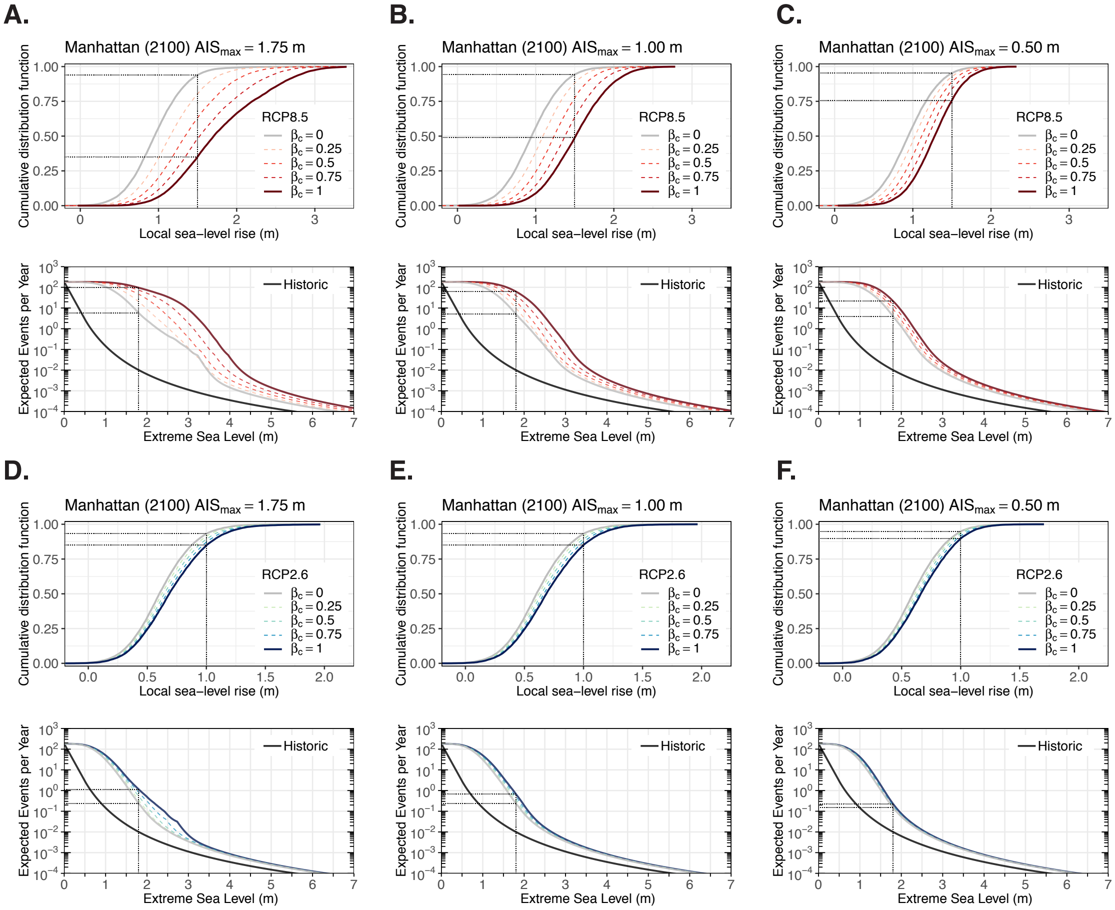


Figure 4.5: **A.** Top Row: probability boxes ('p-boxes'; solid lines) for 2100 local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions (CDFs) of local SLR (dashed lines) are generated within each p-box by averaging the p-box edges using weights ($\beta_c \in [0,1]$) that reflect a user's belief of Antarctic ice sheet (AIS) collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 AIS melt (AIS$_{max}$, relative to 2000; here, 1.75 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m or 1.0 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom Row: extreme sea level (ESL) return curves for Manhattan showing the relationship between the expected number of ESLs per year and ESL height (meters above mean higher high water) for: 1) historical sea levels (black curve) and 2) year 2100 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for AIS$_{max}$ = 1.0 m. **C.** As for A, but for AIS$_{max}$ = 0.5 m. **D.** As for A, but for RCP2.6. **E.** As for A, but for RCP2.6 and AIS$_{max}$ = 1.0 m. **F.** As for A, but for RCP2.6 and AIS$_{max}$ = 0.5 m.

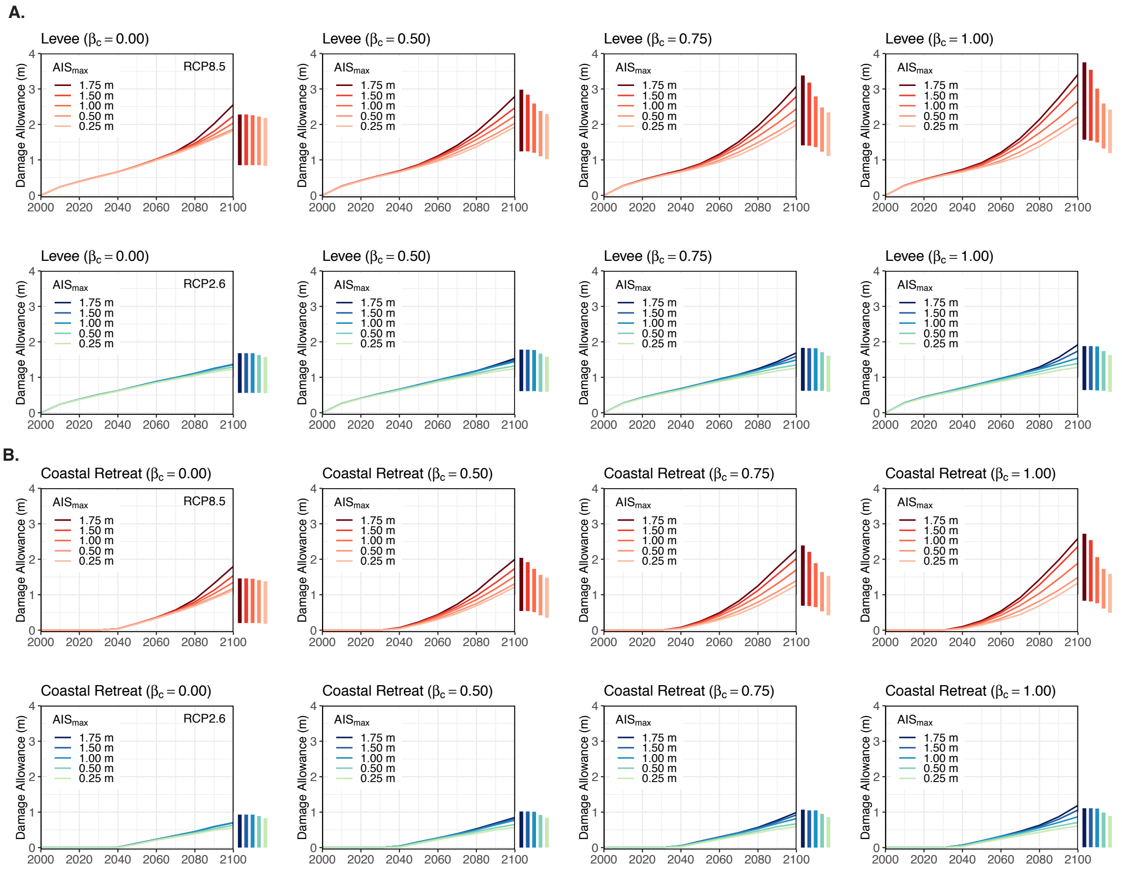


Figure 4.6: **A.** Top Row: Levee damage allowances (meters above the current protection height) over time (2000–2100) for protecting Manhattan under different maximum 2100 Antarctic ice sheet (AIS) contribution thresholds (AIS_{max}, relative to 2000), different subjectively perceived likelihoods of AIS collapse (β_c; 0 being 'most unlikely' and 1 being 'most likely'), and for the representative concentration pathway (RCP) 8.5 climate forcing scenario. The colored bars in the margins of each plot show the 2100 damage allowances using only the 5/95th percentile local sea-level rise projections. The levee allowances include 0.5 m of freeboard and have a 10% probability of failure at the design height. Bottom Row: As for Top Row, but for RCP2.6. **B.** As for A, but for coastal retreat (assuming perfect retreat compliance).

4.7 Appendix: Methods

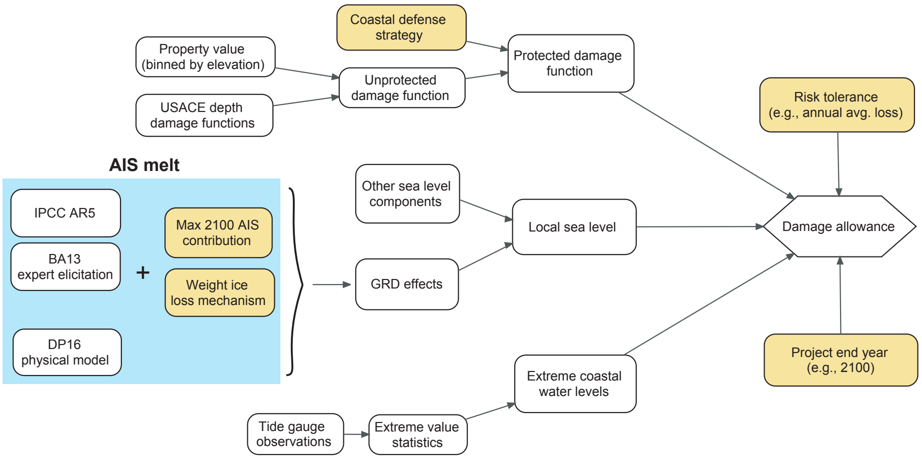


Figure 4.7: Logical flow of sources of information used in damage allowance calculation. Yellow shading indicates points where decision maker input is required (Fig. 4.3). AIS is Antarctic Ice Sheet; USACE is U.S. Army Corps of Engineers; BA13 is Bamber and Aspinall (2013); DP16 is Deconto and Pollard (2016); GRD are gravitational, rotational, and deformational effects; "Other sea level components" includes land water storage, Greenland ice sheet melt, glacier ice melt, ocean dynamics, and non-climatic background changes, such as human-induced subsidence.

4.7.1 Modeling the frequency of extreme sea levels

We model the spatial extent of ESLs throughout Manhattan using the "bathtub" approach. This approach employs a 0.3 m (1 ft) horizontal resolution light detection and ranging (LiDAR)-derived digital elevation model (DEM[5]; Fig. 4.8) and empirical estimates of the likelihood of ESLs at a single, long-standing tide gauge (1920–2014), located at the Battery in lower Manhattan. We calculate daily maximum sea levels from quality-controlled tide gauge records from the University of Hawaii Sea Level Center[6]. These tide gauge observations are de-trended to remove the effect of SLR and then referenced to a common datum, mean higher high water (MHHW)[7]. The water levels at the Battery tide gauge are spatially extrapolated throughout Manhattan while considering 1) the topography of the study region and 2) an assumed 1-m high bulkhead (above MHHW) around the entire borough that serves as an

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[5] https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc

[6] retrieved from: https://uhslc.soest.hawaii.edu, June 2017; Caldwell et al (2015)

[7] Here defined as the average level of high tide over the last 19-years in the tide gauge record, which is different from the current U.S. National Tidal Datum Epoch of 1983–2001.

estimate of the current level of coastal flood protection (Colle et al, 2008). We acknowledge that the bathtub approach is likely to be a poor estimator of the spatial ESL variation in this study region. The frequency of extreme water levels is known to differ throughout the New York-New Jersey Harbor Estuary due to hydrological factors such as varying coastal bathymetry and shoreline topography. A three-dimensional hydrodynamic model may more accurately represent these local characteristics (e.g., Aerts et al, 2014; Patrick et al, 2019). In any case, we note that the our estimated 100-yr flood extents (Fig. 4.4) are comparable to the preliminary flood insurance rate maps for New York City presented in Patrick et al (2019).

We estimate the return periods of ESLs of various heights at the Battery tide gauge using extreme value theory, a statistical extrapolation method that fits an extreme value distribution to empirical data to estimate the likelihood of events too rare to appear in an observational record (e.g., determining the height of the 100-yr ESL from a 30-yr tide gauge record). Various extreme value distributions and approaches to implement them have been proposed (e.g., Coles, 2001b), but in the case of ESL estimation there currently is not an agreed upon “best approach”. Depending on the specific project goals, a particular extreme value modeling strategy may be preferred over another (e.g., the length of observation record; Wahl et al, 2017).

Following previous studies (Tebaldi et al, 2012; Buchanan et al, 2016; Rasmussen et al, 2018), we estimate the annual probability of ESLs $f(z)$ at the Battery tide gauge using a generalized Pareto distribution (GPD; Coles, 2001b,a). The GPD has the advantage over other generalized extreme value models in that 1) it can accommodate sub-annual observations, 2) its third parameter (i.e., shape) allows for added flexibility to take on different shapes in log-linear space depending on the characteristics of the underlying data, and 3) it can be combined with a Poisson rate parameter (λ) to translate ESL exceedance probabilities into the expected number of annual ESL exceedances. The latter may be more intuitive and thus better for communicating the physical impacts of ESLs. The GPD is given by:

$$f_{(\xi,\mu,\sigma)}(z) = \frac{1}{\sigma}\left(1 + \frac{\xi(z-\mu)}{\sigma}\right)^{\left(-\frac{1}{\xi}-1\right)}, \tag{4.9}$$

for $z \geqslant \mu$ when $\xi \geqslant 0$, and $\mu \leqslant z \leqslant \mu - \sigma/\xi$ when $\xi < 0$.

The GPD parameters are the following: the shape parameter (ξ) governs the curvature and upward statistical limit of the ESL probability distribution function (PDF) and embodies the local coastal storm climate, the scale parameter (σ) characterizes the annual variability in the maxima of tides and storm surges, and the location parameter (μ) is the threshold water-level above which return levels are estimated with the GPD—here the 99th percentile of daily maximum sea levels, which is generally above the highest seasonal tide, balances the bias-variance trade-off in the GPD parameter estimation (Tebaldi et al, 2012) and has been found to perform well at global scales (Wahl et al, 2017). Daily maximum sea levels above the 99th percentile are de-clustered to meet the statistical independence assumption of the GPD. The GPD parameters are estimated using the method of maximum likelihood. Uncertainty in the GPD parameters is calculated from their estimated covariance matrix and is sampled using Latin hypercube sampling of 1000 normally distributed GPD parameter pairs. The GPD parameters used are given in Table 4.1. The historical flood return curve at the Battery tide gauge is presented in Fig. 4.1A. While we estimate flood heights up to the frequency of 1 in 10,000, we caution in using any extrapolations exceeding four times the length of the record (Pugh and Woodworth, 2014). Increases in SLR are accounted for linearly, as the nonlinear effect of SLR on ESL height has been determined to be very small for the Battery (Lin et al, 2012).

Site	Lat	Lon	Uhawaii ID	Start	End	λ	μ (m)	ξ	σ
Battery	40.7	-74.15	745a	1920	2014	2.63	0.51	0.19 (0.05, 0.33)	0.13 (0.10, 0.15)

Table 4.1: Generalized Pareto distribution (GPD) and Poisson rate parameters estimated for the Battery tide gauge in Manhattan (New York City; Sec. 4.7.1). The Poisson rate parameter (λ) is the average rate of GPD threshold exceedances per year as estimated from the historical record. The GPD threshold (μ) is given as meters above mean higher high water (MHHW). Both the shape (ξ) and scale (σ) parameters are estimated using the method of maximum likelihood and are given as 50th (5th/95th) percentiles from the Latin hypercube sampling.

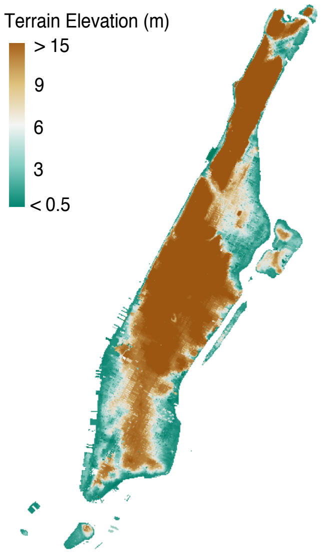

Figure 4.8: Terrain elevation map for Manhattan (meters above the North American Vertical Datum of 1988) using a 0.3 m horizontal resolution light detection and ranging (LiDAR)-derived digital elevation model (DEM) from the City of New York (https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc)

Sea-level rise projections

Probabilistic, time-varying, local relative sea level (RSL) projections for Manhattan (modeled at the Battery tide gauge[8]) are taken from the component-based studies of Kopp et al (2014) and Kopp et al (2017). Both frameworks are identical except in how they model Antarctic ice sheet (AIS) contributions. Kopp et al (2014) combines the Intergovernmental Panel on Climate Change's Fifth Assessment Report likely range projections of ice sheet dynamics and surface mass balance (table 13.5 in Church et al, 2013) and tail shape information from the expert elicitation of total ice sheet mass loss from Bamber and Aspinall (2013), while Kopp et al (2017) implement a limited ensemble of physical AIS simulations from Deconto and Pollard (2016). Deconto and Pollard (2016) includes two glaciological processes previously not accounted for in other continental scale models that can rapidly increase ice-sheet mass loss (marine ice-sheet hydrofracturing and marine ice-cliff instability; Pollard et al, 2015). The simulations from Deconto and Pollard (2016) do not sample the full

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[8] https://tidesandcurrents.noaa.gov/stationhome.html?id=8518750

model parameter space, as such they do not provide a probabilistic assessment of future AIS behavior (Kopp et al, 2017; Edwards et al, 2019). Nonetheless, they previously have been implemented in probabilistic projection frameworks (Le Bars et al, 2017; Bakker et al, 2017). Probability distributions of local RSL are produced using 10,000 Latin hypercube samples of individual sea level component contributions. Each probability distribution is conditional on either the high greenhouse gas (GHG) emission scenario of representative concentration pathway (RCP) 8.5 or the strong GHG reduction scenario of RCP2.6 (Van Vuuren et al, 2011). The general circulation model output used to generate the steric and glacial ice melt sea level components for each RCP scenario are given in Table S2 in the Supporting Information of Kopp et al (2014).

Probability box construction

Our approach to constructing a probability box ('p-box') is presented in Section 4.2.2, but is expanded with more details here. In order to keep the p-box boundaries from overlapping, we arbitrarily truncate the maximum AIS contribution from Kopp et al (2014) at 1.75 m (relative to 2000), the highest predicted AIS contributions from Deconto and Pollard (2016). This limits the maximum 2100 GMSL projection below 3.5 m (relative to 2000). We note that this truncation is arbitrary and is used only for the purpose of illustrating the p-box approach to dealing with deep uncertainty. The truncation of the AIS contribution about the 1.75 m limit could impact results in a significant way, but is not investigated here. There currently is no consensus upper limit for 2100 GMSL or AIS contributions. The 5/95th percentile ranges of GMSL from Kopp et al (2014) and Kopp et al (2017) roughly bound either the 17/83 or 5/95 end-of-century ranges from current published RCP8.5 GMSL projections surveyed in Horton et al (2018), but not those for RCP2.6.

Flood allowances and ESL return curves that consider the full probability distribution of sea level projections have been shown to be sensitive to upper-bound estimates of AIS ice mass loss in the second half of the 21st century (Buchanan et al, 2016; Slangen et al, 2017; Rasmussen et al, 2018). As such, we use a parameter that sets the truncation of the upper tail of the 2100 AIS contribution distribution (AIS$_{max}$). Specifically, we use AIS$_{max}$ values of 0.25, 0.5, and 1.0 m, which are in-line with the range of published end-of-century AIS melt estimates (e.g., Table 2 in Cozannet et al, 2017), as well as limits of 1.5 m and 1.75 m, which are upper-end estimates from Deconto and Pollard (2016). An additional parameter weighs contributions from the projections that bound the p-box ($\beta_c \in [0, 1]$). When there is greater confidence of AIS collapse (i.e., larger values of β_c), more weight is given to the Kopp et al (2017) projections, which include faster ice mass loss and greater AIS contributions to GMSL in the second half of the 21st century (via marine ice-sheet hydrofracturing and ice-cliff collapse; Pollard et al, 2015), relative to Kopp et al (2014). Note that a value of zero for β_c does not imply a scenario in which there is zero probability of AIS collapse initiation, nor does a value of one for β_c imply certainty in AIS collapse initiation. β_c simply corresponds to the relative likelihoods of AIS collapse initiation before 2100. The effective probability distribution $\tilde{P}$ at time t is given by:

$$\tilde{P}(\beta_c, \text{AIS}_{max}, t) = \beta_c P_{high}(\text{AIS}_{max}, t) + (1 - \beta_c) P_{low}(\text{AIS}_{max}, t), \tag{4.10}$$

where $P_{low}(\Delta, t)$ and $P_{high}(\Delta, t)$ are the minimum and maximum projections at each point in the CDFs from Kopp et al (2014) and Kopp et al (2017). All the SLR projection scenarios used in this study are highlighted in Table 4.2.

4.7.2 Extreme sea level damage model

We model the annual average loss (AAL) due to extreme sea level (ESL) damage as the average loss (insured and uninsured) of all modeled ESL damage events $D(z)$, weighted by the annual probability of occurrence $f(z)$. This can mathematically be written as,

$$\mathbb{E}[D(z)] = \int_z D(z) f(z)\,\mathrm{d}z. \tag{4.11}$$

While this is a one-dimensional model (vertical direction only), we note that spatial variation in coastal protection and ESL event frequency could be accommodated using a three-dimensional damage model where the ESL parameter (z) is a vector that also varies spatially. For example, this could be done using a three-dimensional hydrodynamic model (e.g., Aerts et al, 2014; Patrick et al, 2019). Other limitations to our flood damage modeling approach that could impact results are noted throughout the methodological overview given below.

Following the methodology from Diaz (2016), we construct a one-dimensional (z-direction), aggregate ESL damage function for Manhattan by integrating damages from the lowest unprotected elevation e_{min} to an ESL height z using:

$$\mathrm{D(z)} = \int_{e_{min}}^{z} p(e) \cdot \phi(z-e)\mathrm{d}e \tag{4.12}$$

where $p(e)$ is the total tax assessed value of all buildings at the estimated first floor elevation e from the NYC Department of City Planning (Fig. 4.9; NYC Planning, 2018)[9], z is the ESL height, and $\phi(z-e)$ is an aggregate inundation depth-damage function for Manhattan that relates the flood height $(z-e)$ to damage as a fraction of the total tax assessed building value (see Sec. 4.7.2). The first floor structure elevation was estimated in 0.1 m increments starting from 0 m above the North American Vertical Datum of 1988 (NAVD88) using a 0.3 m horizontal resolution LiDAR-derived digital elevation model (DEM) from the City of New York[10]. Other covariates that may cause damage, such as wind gusts, waves, and precipitation, are not included. Also, not included in our damage accounting is the loss of

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[9] Note that the NYC Department of City Planning makes available both tax assessed building value and combined tax assessed building and property value. We assume that floods only damage structures and not the land itself.

[10] https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc

human life, damage to infrastructure (both above and below ground), the value lost from permanently inundated lands, and indirect damage effects such as business interruption. In order to simplify our analysis and to isolate the impact of sea-level rise on changing risk, we assume that the population and distribution of property within Manhattan remains fixed in time. We acknowledge that this assumption may not be realistic. For instance, the NYC Department of City Planning has projected a 3.9% increase in the population of Manhattan over 2020–2050 (NYMTC, 2015). Population projections for Manhattan after mid-century are not available, but other flood damage mitigation studies have argued that the population and building stock of NYC will become relatively stable after mid century (Aerts et al, 2014).

Figure 4.1B shows the damage function. The damage function is multiplied by the ESL probability distribution (Sec. 4.7.1) to give a probability distribution of flood damages (Fig. 4.1C). We estimate that the current AAL for Manhattan is \$0.10 billion/yr. Comparison with other studies is difficult due to differences in geographic scope and building stock. Nonetheless, Aerts et al (2014) and Houser et al (2015) found an AAL of \$0.18 and \$0.53 billion/yr for all of NYC, respectively, and Hallegatte et al (2013) found an AAL of \$0.79 billion/yr for the entire NYC-Newark, New Jersey region (all values given in 2017 US\$).

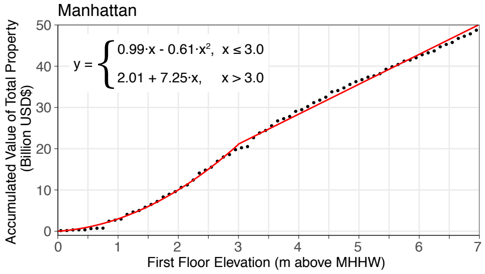

Figure 4.9: Accumulated tax-assessed value of Manhattan property (building only, land excluded; billion USD\$) by first floor building elevation [meters above mean higher high water (MHHW); black circles] and piece-wise fit using a quadratic function below 3 m and linear function above 3 m (red line). Property data is from the New York City Department of City Planning (NYC Planning, 2018).

Depth-damage functions

Depth-damage functions describe relationships between flood-depth and levels of structure damage. They are often constructed from post-disaster assessments of actual damage to various classes of structures (e.g., one-story residential homes with basements, schools, shopping centers). Depth-damage functions are a commonly used approach for modeling flood damage given flood depth (e.g., FEMA, 2018). Depth-damage functions are simplistic representations of the relationship between floods and structure damage in part because they only consider one characteristic of floods—depth. They do not consider other potentially important flood characteristics that may cause more damage, such as flood velocity, wave height, and flood duration (Merz et al, 2010).

In this study, we employ structure-specific depth-damage functions constructed from expert elicitation (USACE, 2015). While Manhattan is comprised of several thousand varieties of structures, each potentially having a unique relationship between inundation depth and damage, we simplify by assuming only three distinct classes of buildings in the study region of Manhattan (New York City). New York City property tax assessments indicate that Manhattan is comprised of roughly 95 percent residential and 5 percent commercial (NYC Department of Finance, 2018). Accordingly, we reduce the complexity of building type to three inundation depth-damage functions that represent these classes of buildings, high-rises with basements (95 percent of Manhattan) and two-story residences with basements (5 percent of Manhattan). We note that this simplification could have a significant impact on aggregate flood damage estimates for Manhattan.

The depth-damage function for an urban high-rise ($\phi_{hrise}(z-e)$) is shown in SI Fig. 4.11, and the least-squares fit is given by:

$$\phi_{hrise}(z-e) = \begin{cases} 0.142 + 0.0541 \cdot (z-e) - 0.00368 \cdot (z-e)^2 - 0.00133 \cdot (z-e)^3, & \text{if } z > e \\ 0, & \text{otherwise} \end{cases}$$

where z is the height of the extreme water level, e is the first-floor elevation of the structure, and $z-e$ is the flood height. The depth-damage function for a two-story residential structure with a basement ($\phi_{res}(z-e)$) is shown in SI Fig. 4.10, and the least-squares fit is given by,

$$\phi_{res}(z-e) = \begin{cases} 0.18 + 0.178 \cdot (z-e) + 0.0233 \cdot (z-e)^2 - 0.00778 \cdot (z-e)^3, & \text{if } z > e \\ 0, & \text{otherwise} \end{cases}$$

An aggregate depth-damage function for Manhattan is constructed using the weighted average of the equations for each building class,

$$\phi(z-e) = 0.95 \cdot \phi_{hrise}(z-e)) + 0.05 \cdot \phi_{res}(z-e).$$

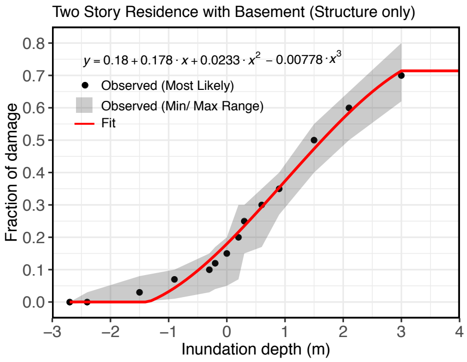

Figure 4.10: Observed depth-damage relationship for two story residences with basements (structure only) from USACE (2015). The contents of the structure are not included. A 3rd-order polynomial is fit through the observed (most likely) values (red line).

Two Story Residence with Basement (Structure only)

Depth (ft)	Depth (m)	Min	Most Likely	Max
-9.0	-2.7	0.000	0.000	0.000
-8.0	-2.4	0.000	0.000	0.030
-5.0	-1.5	0.000	0.030	0.080
-3.0	-0.9	0.010	0.070	0.100
-1.0	-0.3	0.030	0.100	0.150
-0.5	-0.2	0.040	0.120	0.170
0.0	0.0	0.050	0.150	0.200
0.5	0.2	0.070	0.200	0.300
1.0	0.3	0.150	0.250	0.300
2.0	0.6	0.170	0.300	0.350
3.0	0.9	0.270	0.350	0.400
5.0	1.5	0.400	0.500	0.550
7.0	2.1	0.500	0.600	0.650
10.0	3.0	0.620	0.700	0.800

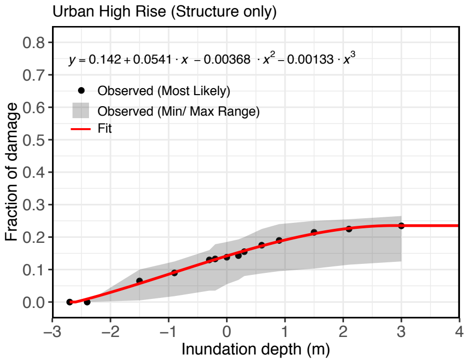

Figure 4.11: Observed depth-damage relationship for an urban high-rise (structure only) from USACE (2015). A 3rd-order polynomial is fit through the observed (most likely) values (red line).

Urban High Rise (Structure only)

Depth (ft)	Depth (m)	Min	Most Likely	Max
-9.0	-2.7	0.000	0.000	0.000
-8.0	-2.4	0.000	0.000	0.000
-5.0	-1.5	0.005	0.065	0.100
-3.0	-0.9	0.018	0.090	0.125
-1.0	-0.3	0.035	0.130	0.160
-0.5	-0.2	0.035	0.133	0.178
0.0	0.0	0.055	0.138	0.185
0.5	0.2	0.068	0.143	0.193
1.0	0.3	0.080	0.155	0.200
2.0	0.6	0.088	0.175	0.225
3.0	0.9	0.095	0.190	0.240
5.0	1.5	0.103	0.215	0.250
7.0	2.1	0.115	0.225	0.255
10.0	3.0	0.125	0.235	0.265

4.7.3 Allowances

Returning hazard allowances from the damage allowance framework

We show how Eq. 4.2 can return the traditional hazard allowance (Eq. 4.1). If $D^{*}(z)$ is given by $D(z-A)$, then Eq. 4.2 becomes,

$$\int_{z}\int_{\Delta} D(z-A)f(z-\Delta)P(\Delta)\,\mathrm{d}\Delta\,\mathrm{d}z = \int_{z} D(z)f(z)\,\mathrm{d}z, \tag{4.13}$$

While Eq. 4.13 is appropriate for estimating the adjustment to maintain the overall risk, adjustments can be calculated for specific AEPs. If z^{*} is the surge height of the current AEP event then,

$$\int_{z^{*}}^{\infty}\int_{\Delta} D(z-A)f(z-\Delta)P(\Delta)\,\mathrm{d}\Delta\,\mathrm{d}z = \int_{z^{*}}^{\infty} D(z)f(z)\,\mathrm{d}z, \tag{4.14}$$

integrating over z gives,

$$\int_{\Delta} D(z^{*}-A)\mathrm{F}(z^{*}-\Delta)P(\Delta)\,\mathrm{d}\Delta \;= D(z^{*})\mathrm{F}(z^{*}), \tag{4.15}$$

where F is the cumulative distribution function, which is related to the expected number of exceedances in a given year N by $N = -\log(\mathrm{F})$ (Hunter, 2012; Pugh, 1996),

$$\int_{\Delta} D(z^{*}-A)N(z^{*}-\Delta)P(\Delta)\,\mathrm{d}\Delta \;= D(z^{*})N(z^{*}). \tag{4.16}$$

where $N(z^{*})$ is the number of expected flood events per year of height z^{*} without SLR. Integrating over $P(\Delta)$, the SLR PDF, gives

$$D(z^{*}-A)N_{e}(z^{*}-\Delta) = D(z^{*})N(z^{*}), \tag{4.17}$$

where $N_e(z^*)$ is the number of expected flood events per year of height z^* after considering the SLR PDF. The traditional allowances for physical flood heights (e.g., Buchanan et al, 2016; Hunter, 2012) can be returned if $D(z)$ is the function,

$$D[z] = \begin{cases} 0, & z < z^*, \\ 1, & z \geq z^*. \end{cases} \tag{4.18}$$

Substituting Eq. 4.18 in Eq. 4.14 gives,

$$\int_{z^*+A}^{\infty} \int_{\Delta} f(z - \Delta) P(\Delta) \, \mathrm{d}\Delta \, \mathrm{d}z = \int_{z^*}^{\infty} f(z) \, \mathrm{d}z, \tag{4.19}$$

and then integrating over all possible surges z gives,

$$\int_{\Delta} N(z^* - \Delta + A) P(\Delta) \, \mathrm{d}\Delta = N(z^*), \tag{4.20}$$

where $N(z^*)$ is the average number of flood exceedance events of height z^* per year. After integrating over the SLR probability distribution the equality becomes,

$$N_e(z^* + A) = N(z^*), \tag{4.21}$$

where $N_e(z)$ returns the average number of flood exceedance events of height z per year after including uncertain SLR. The allowance height A must be solved for numerically.

Elevation of all structures by same height

While not used for Manhattan due to the impracticality of elevating high-rises, we present an method for elevation all structures within the damage function (Fig. 4.12). If A is the vertical height that all structures would need to be elevated in order to maintain the current AAL under uncertain sea-level rise and if α is the fraction of assets [0,1] that have elevated by A (i.e., the elevation compliance), then the protected damage function is:

$$D^*(z, A) = \underbrace{\alpha D(z - A)}_{\text{Damage to elevated structures}} + \underbrace{(1 - \alpha) D(A).}_{\text{Damage to non-elevated structures}} \tag{4.22}$$

The elevation of all structures is mathematically represented as a horizontal shift of the "unprotected" damage function by A to represent the uniform elevation of all assets by A.

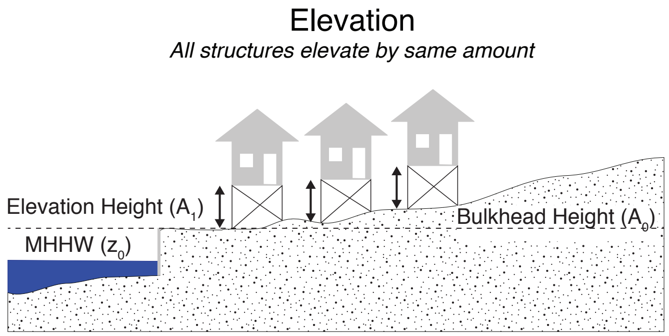

Figure 4.12: Schematic illustrating an elevation flood defense strategy (all structures) for an arbitrary design height (A_1).

Hazard allowances: instantaneous vs. average annual design life

Two types of hazard allowances have been proposed in the literature: 1) instantaneous and 2) average annual design life. Instantaneous hazard allowances are designed for maintaining a target level of risk in the final year of a project design life (traditionally the expected number of ESL exceedances). In the preceding years, the average level of risk protection would be above the target. On the other hand, the average annual design life hazard allowance (not explored in this study), maintains the average risk over the lifetime of a project by providing greater protection than prescribed during the early years of the design life and less protection than prescribed at the end of the design life (Buchanan et al, 2016).

Combined flood protection strategy approach

A multi-strategy approach to flood defenses may provide an added level of safety through redundancy. For example, if a single levee fails, the area behind the levee is impacted. A second line of defense could compensate for failures of the first. If multiple strategies are employed, users could either assign a fraction of the total risk target to mitigate for each strategy or specify a damage allowance for all but one mitigation strategy and then solve for the unknown damage allowance. For example, if a user desires to maintain the current

AAL using both coastal retreat and a levee, they may choose to retreat coastal assets below a pre-determined elevation A_1 that is also the base of the levee (e.g., $A_1 = 1.0$ m) and then solve for the height of the levee A_2 (Fig. 4.15A). This can mathematically be described by:

$$\underbrace{\int_{z_{min}}^{A_1} \int_{\Delta} D_r^*(z) f(z-\Delta) P(\Delta)\, \mathrm{d}\Delta\, \mathrm{d}z}_{\text{Damages below retreat elevation}} + \underbrace{\int_{A_1}^{\infty} \int_{\Delta} D_l^*(z) f(z-\Delta) P(\Delta)\, \mathrm{d}\Delta\, \mathrm{d}z}_{\text{Damages from levee failure and overtopping}} = \underbrace{\int_{z_{min}}^{\infty} D(z) f(z)\, \mathrm{d}z.}_{\text{Current AAL}} \tag{4.23}$$

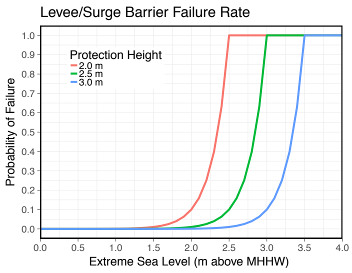

Figure 4.13: Fragility curves showing the relationship between structural loading on a levee or storm surge barrier from extreme sea levels (meters above mean higher high water [MHHW]) and the conditional probability of structural failure of the levee or storm surge barrier for protection design heights of 2.0 m (red), 2.5 m (green), 3.0 m (blue), all with 0.5 m of freeboard above the design height. For all, the structural failure rate for extreme sea levels at the design height is 0.10.

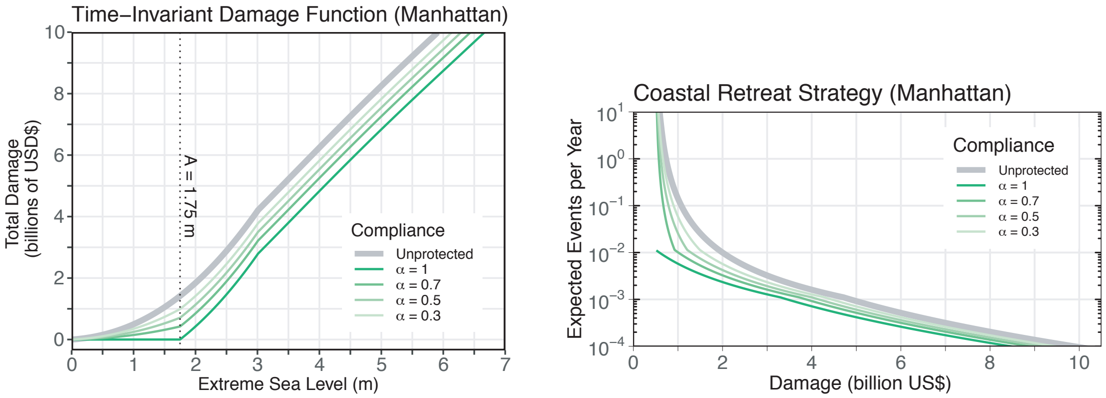

Figure 4.14: **(Left)** Expected number of damage events per year for Manhattan assuming no change in protection strategy (grey line) and using an elevation strategy (1.75 m) with various levels of compliance (α; red lines) **(Right)** As for Left, but for a coastal retreat strategy (1.75 m; green lines)

Flood damage allowances: multi-strategy approach

We present an example of how a multi-strategy approach could be designed using both coastal retreat and a levee for Manhattan (Fig. 4.15A). For both 2070 and 2100, the flood damage risk (AAL) is mapped out for varying elevations below which coastal retreat occurs (A_1) and for the height of a levee (A_2, levee height is relative to A_1) assuming $\text{AIS}_{max} = 1.50$ m and $\beta_c = 0.0$ (Fig. 4.15B). A user could select a preferred AAL and subsequently set the coastal retreat and levee heights. For example, to maintain the current AAL of $0.1 billion/yr in 2100 with coastal retreat below 2 m of elevation, a levee of roughly 0.75 m would need to be constructed. Additional heat maps could be used to depict alternative assumptions of future AIS behavior.

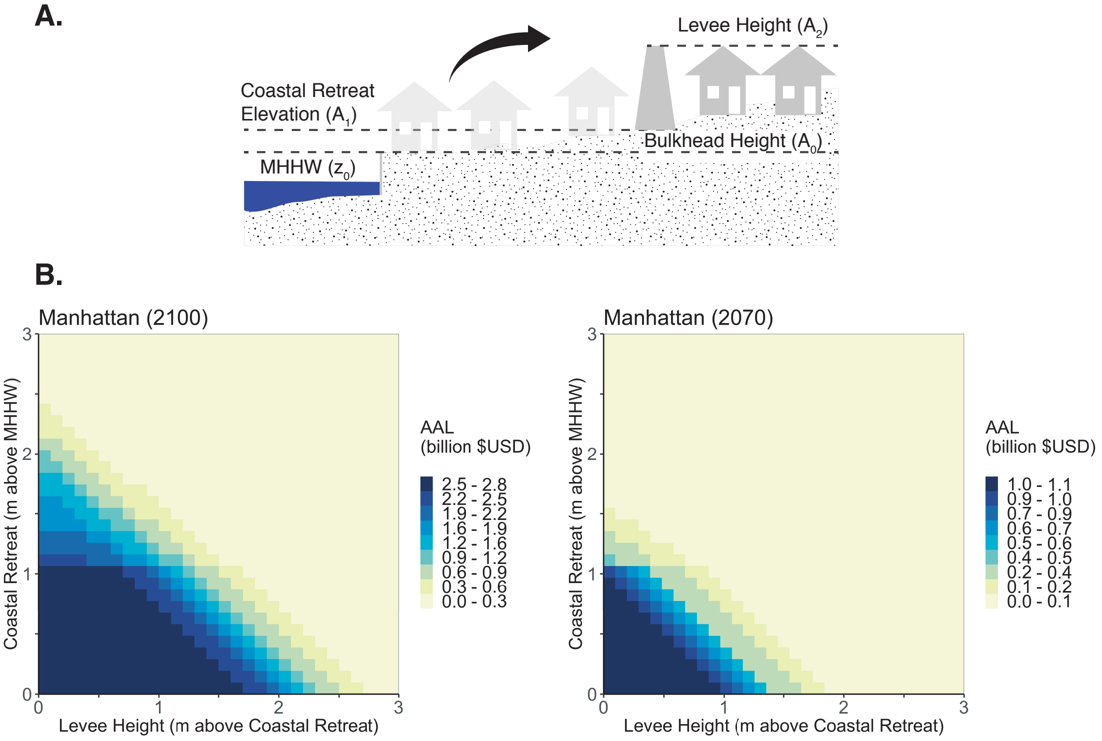

Figure 4.15: **A.** Schematic depicting the combined implementation of coastal retreat and a levee. **B.** Heat maps of annual average loss due to flood damages for 2100 (Left) and 2070 (Right) using the flood protection strategies of coastal retreat (y-axis) and a levee (x-axis) with design heights between 0 and 3 m for each strategy. An additional 0.5 m of freeboard for the levee is not included in the depicted design heights along the x-axis. The levee has a 10% probability of structural failure at the design height.

4.8 Appendix: Supplemental Results, Figures and Tables

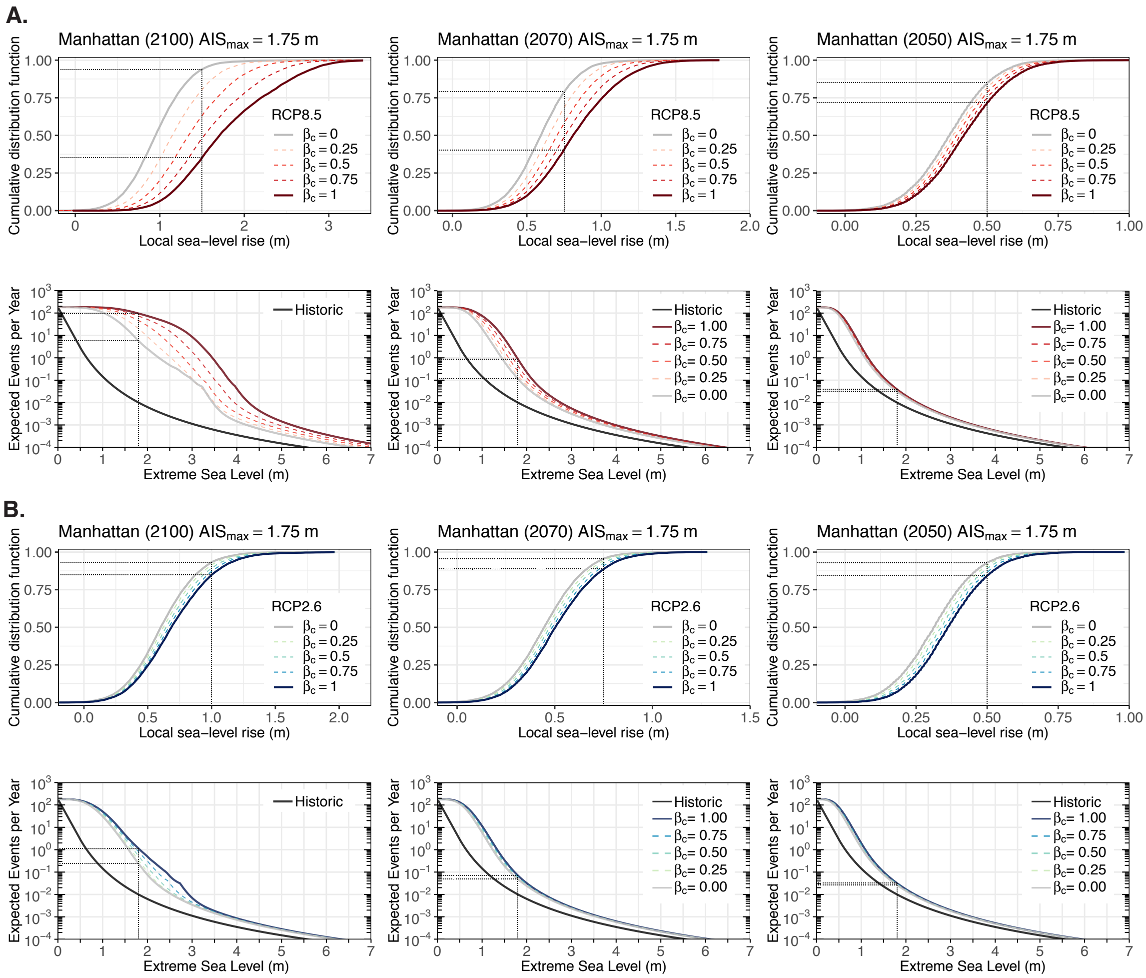

Figure 4.16: **A.** Top: Probability boxes ('p-boxes'; solid lines) for 2100 (left), 2070 (center), and 2050 (right) local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions of local SLR (dashed lines) are generated within each p-box by averaging the edges using weights ($\beta_c \in$ [0,1]) that reflect a user's belief of AIS collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 Antarctic Ice Sheet (AIS) melt (AIS$_{max}$, relative to 2000; here, 1.75 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m, 1.0 m, or 0.5 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom: extreme sea level (ESL) event return curves for Manhattan showing the relationship between the expected number of ESL events per year and ESL height (meters above mean higher high water) for: 1) historical sea levels (black curve) and 2) the year 2100, 2070, and 2050 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for RCP2.6.

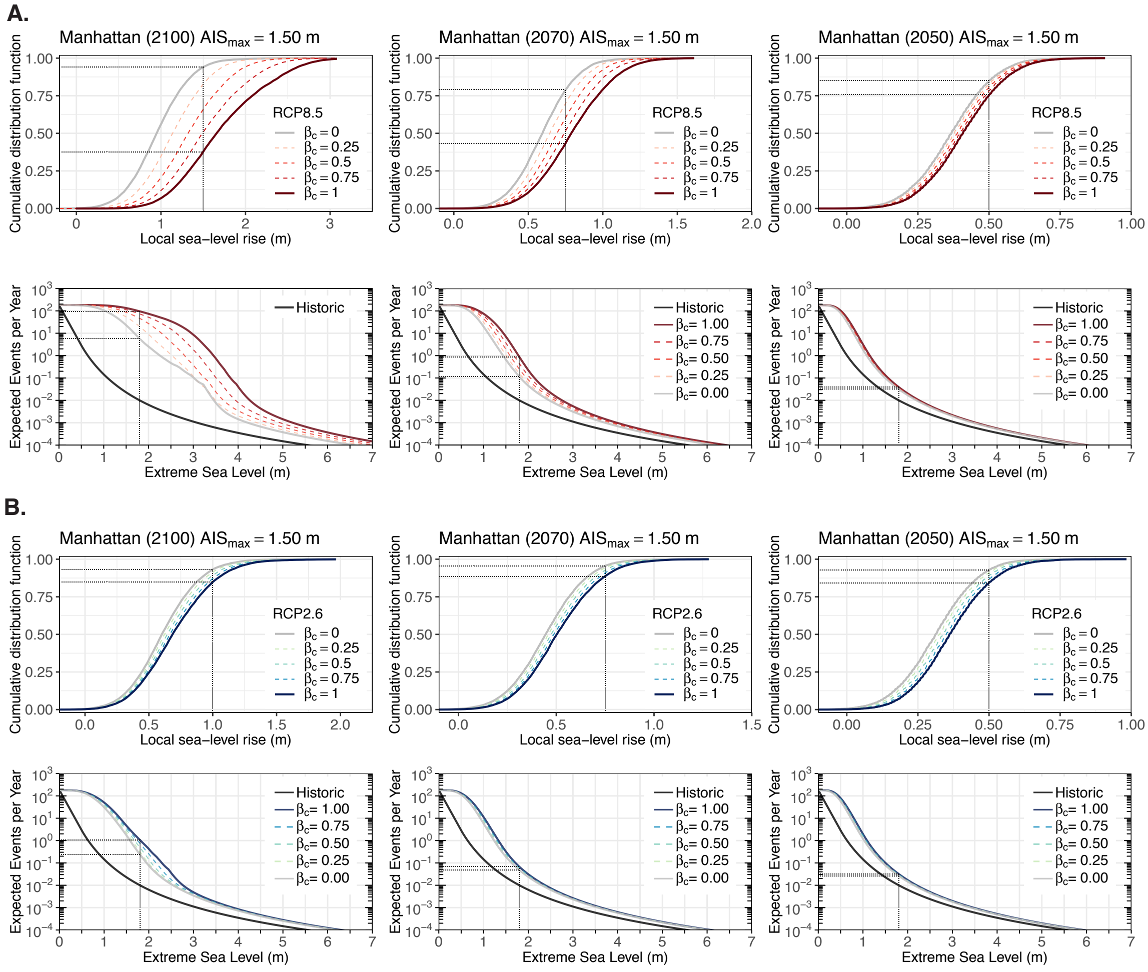

Figure 4.17: **A.** Top: Probability boxes ('p-boxes'; solid lines) for 2100 (left), 2070 (center), and 2050 (right) local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions of local SLR (dashed lines) are generated within each p-box by averaging the edges using weights ($\beta_c \in [0,1]$) that reflect a user's belief of AIS collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 Antarctic Ice Sheet (AIS) melt (AIS$_{max}$, relative to 2000; here, 1.5 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m, 1.0 m, 0.75 m, or 0.5 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom: extreme sea level (ESL) event return curves for Manhattan showing the relationship between the expected number of ESL events per year and ESL height (meters above mean higher high water) for: 1) historical sea levels (black curve) and 2) the year 2100, 2070, and 2050 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for RCP2.6.

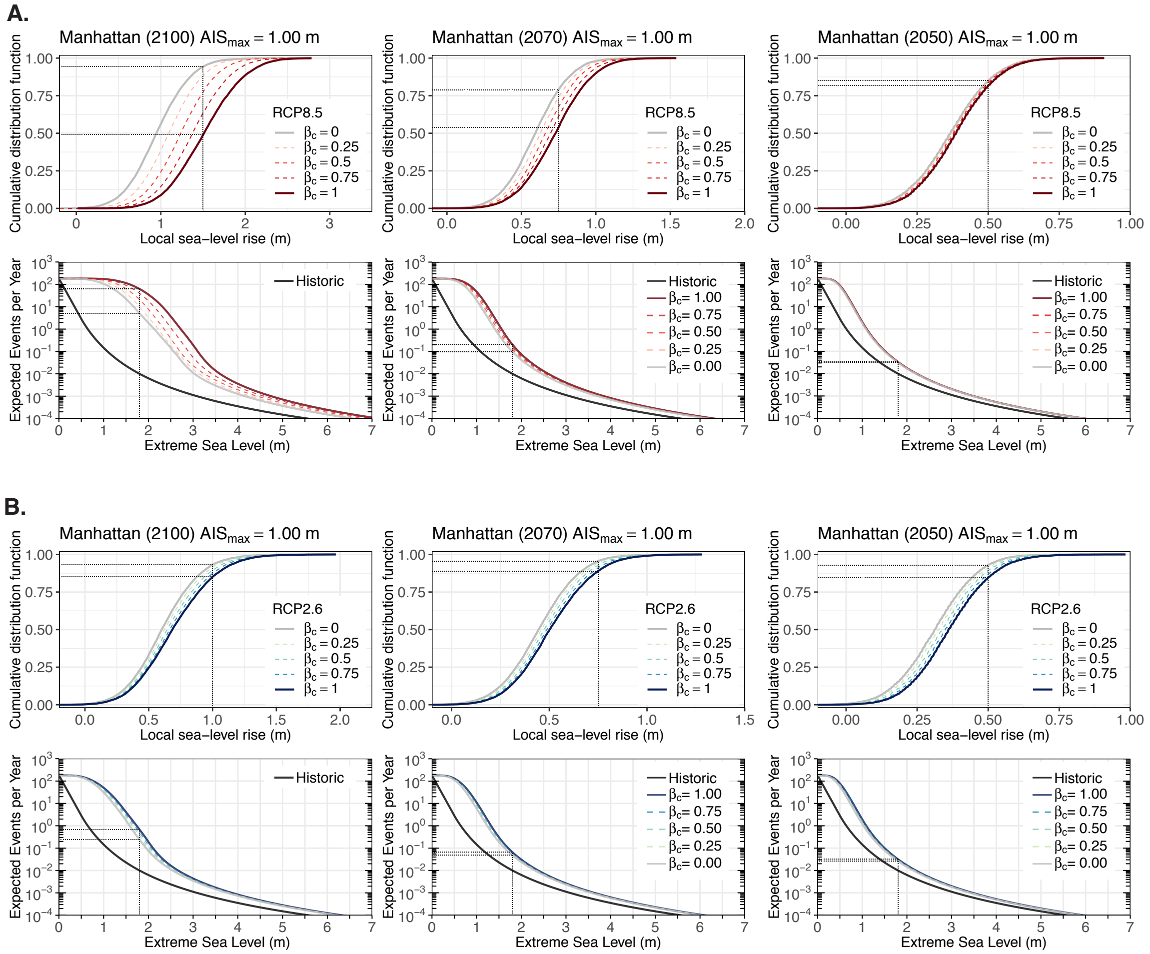

Figure 4.18: **A.** Top: Probability boxes ('p-boxes'; solid lines) for 2100 (left), 2070 (center), and 2050 (right) local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions of local SLR (dashed lines) are generated within each p-box by averaging the edges using weights ($\beta_c \in$ [0,1]) that reflect a user's belief of AIS collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 Antarctic Ice Sheet (AIS) melt (AIS_{max}, relative to 2000; here, 1.0 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m, 1.0 m, 0.75 m, or 0.5 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom: extreme sea level (ESL) event return curves for Manhattan showing the relationship between the expected number of ESL events per year and ESL height (meters above mean higher high water) for: 1) historical sea levels (black curve) and 2) the year 2100, 2070, and 2050 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for RCP2.6.

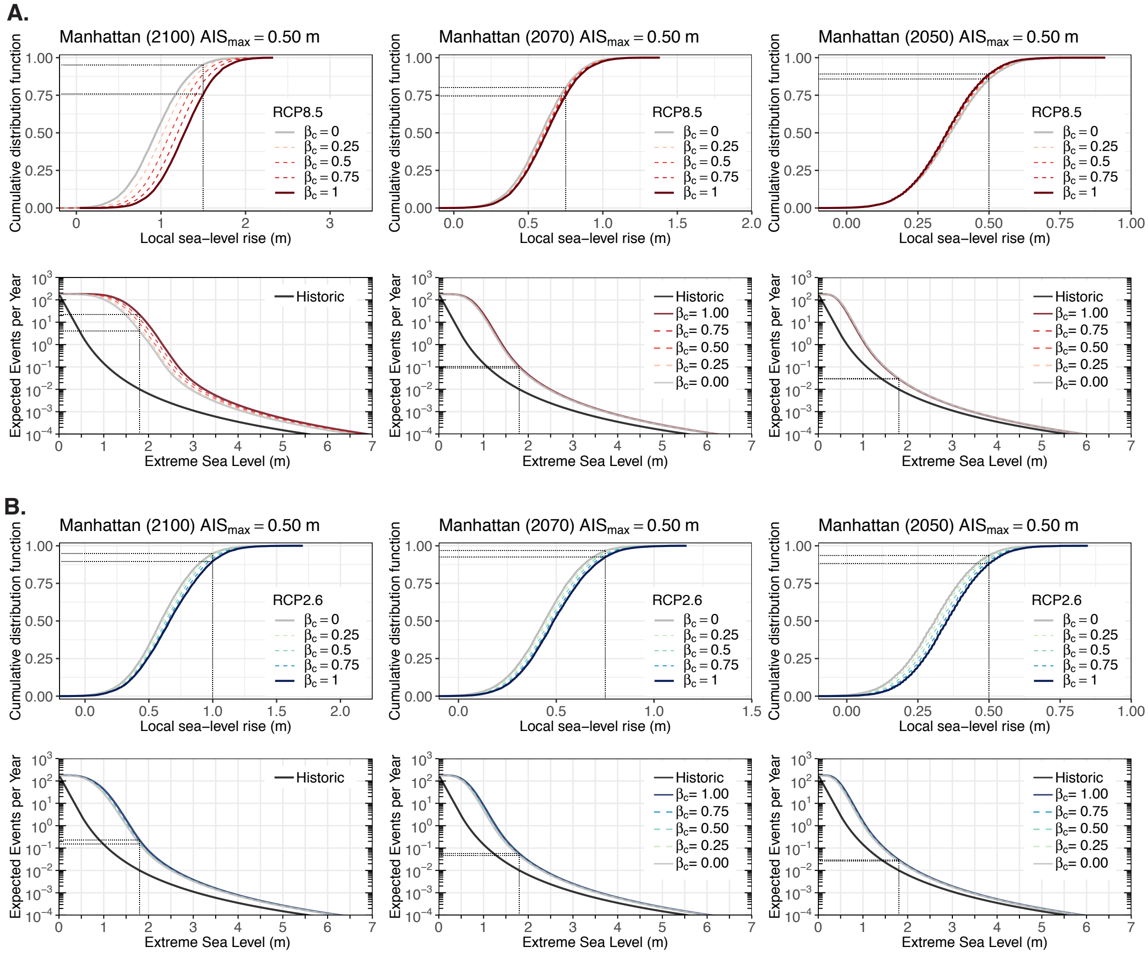

Figure 4.19: **A.** Top: Probability boxes ('p-boxes'; solid lines) for 2100 (left), 2070 (center), and 2050 (right) local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions of local SLR (dashed lines) are generated within each p-box by averaging the edges using weights ($\beta_c \in [0,1]$) that reflect a user's belief of AIS collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 Antarctic Ice Sheet (AIS) melt (AIS$_{max}$, relative to 2000; here, 0.5 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m, 1.0 m, 0.75 m, or 0.5 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom: extreme sea level (ESL) event return curves for Manhattan showing the relationship between the expected number of ESL events per year and ESL height (meters above mean higher high water) for: 1) historical sea levels (black curve) and 2) the year 2100, 2070, and 2050 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for RCP2.6.

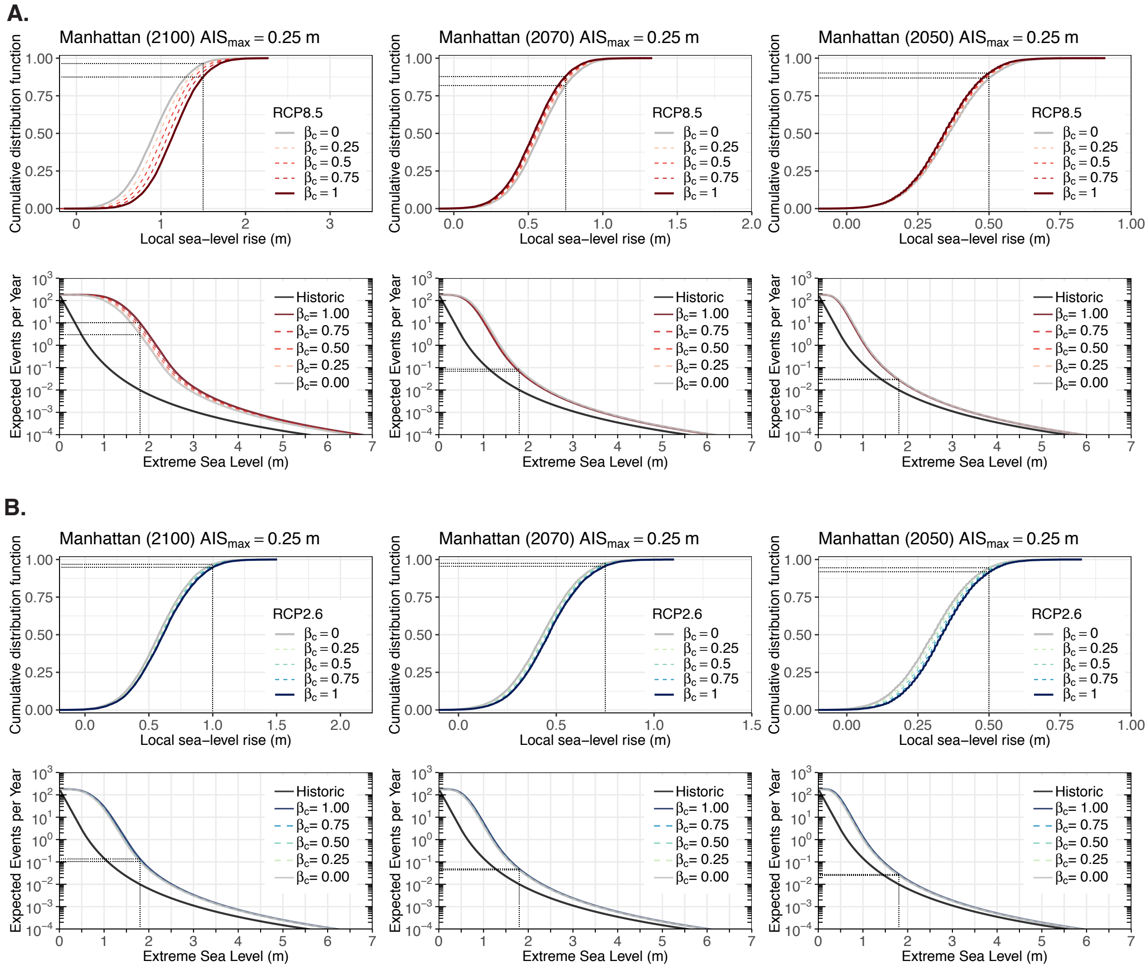

Figure 4.20: **A.** Top: Probability boxes ('p-boxes'; solid lines) for 2100 (left), 2070 (center), and 2050 (right) local sea-level rise (SLR) in Manhattan (located at the Battery tide gauge) under the representative concentration pathway (RCP) 8.5 climate forcing scenario. Effective cumulative distribution functions of local SLR (dashed lines) are generated within each p-box by averaging the edges using weights ($\beta_c \in [0,1]$) that reflect a user's belief of AIS collapse initiation within the 21st century (higher values reflect higher likelihood of collapse) and by constraining the maximum possible 2100 Antarctic Ice Sheet (AIS) melt (AIS$_{max}$, relative to 2000; here, 0.25 m; Sec. 4.2.2). The black dotted lines highlight the probability of exceeding 1.5 m, 1.0 m, 0.75 m, or 0.5 m of local SLR (1−CDF) under different assumptions of AIS collapse initiation (i.e., values of β_c). Bottom: extreme sea level (ESL) event return curves for Manhattan showing the relationship between the expected number of ESL events per year and ESL height (meters above mean higher high water [MHHW]) for: 1) historical sea levels (black curve) and 2) the year 2100, 2070, and 2050 (RCP8.5) for different values of β_c. All curves incorporate generalized Pareto distribution (GPD) parameter uncertainty (Sec. 4.7.1) and the future return curves additionally incorporate local SLR projection uncertainty by integrating across the entire local SLR probability distribution. The black dotted lines highlight the annual expected number of historically experienced 100-yr ESL events under different values of β_c. **B.** As for A, but for RCP2.6.

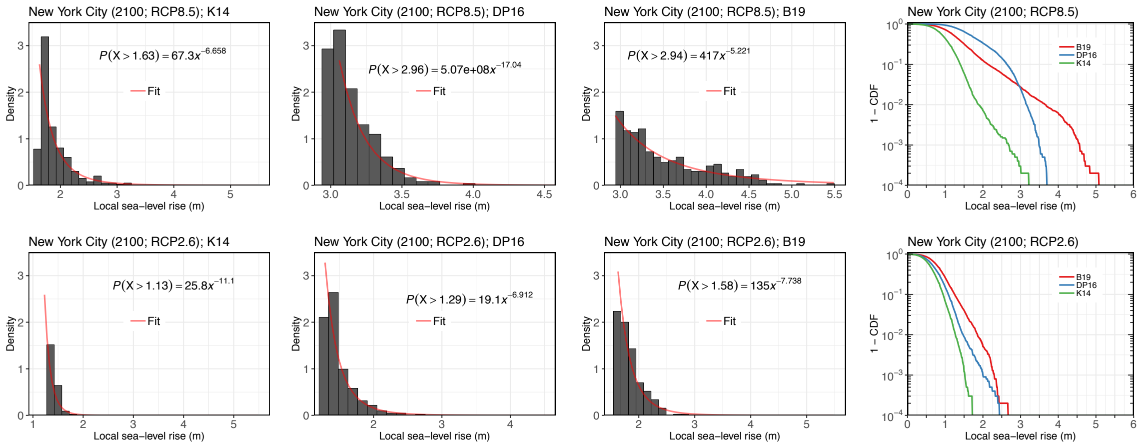

Figure 4.21: **Top Row:** Density plot of local sea-level rise (SLR) samples (meters relative to 2000) above the 97th percentile for 2100 for New York City (RCP8.5) and a power function fit (red line). The smaller the absolute value of the exponent of the power function fit, the longer the tail of the SLR distribution. The SLR samples in each plot are from the probabilistic projections of Kopp et al (2014)(K14), Deconto and Pollard (2016)(DP16), and Bamber et al (2019)(B19). Far right plot is a survival function for 2100 local SLR (meters) for New York City from Bamber et al (2019)(B19; red), Deconto and Pollard (2016)(DP16; blue), and Kopp et al (2014)(K14; green). **Bottom Row:** As for Top Row, but for RCP2.6.

Table 4.2: Future local sea-level rise (SLR) projections (meters; relative to 2000) at a tide gauge located at the Battery in lower Manhattan (New York City) for 2100, 2070, and 2050 under representative concentration pathway (RCP) 8.5 and RCP2.6 and for different assumptions regarding future Antarctic ice sheet (AIS) behavior (e.g, likelihood of AIS collapse [β_c] and maximum 2100 AIS contribution [AIS_{max}]). Values given are: expected (5th percentile–95th percentile).

Local Sea-Level Rise (m; relative to 2000)

RCP8.5				AIS_{max}			RCP2.6				AIS_{max}		
	β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m		β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m
2100							2100						
	1	1.8 (1.0–2.9)	1.7 (0.9–2.7)	1.5 (0.9–2.2)	1.3 (0.8–1.8)	1.2 (0.7–1.7)		1	0.7 (0.3–1.2)	0.7 (0.3–1.2)	0.7 (0.3–1.2)	0.7 (0.3–1.1)	0.6 (0.2–1.0)
	0.75	1.6 (0.8–2.5)	1.5 (0.8–2.3)	1.4 (0.8–2.0)	1.2 (0.7–1.7)	1.1 (0.6–1.6)		0.75	0.7 (0.3–1.2)	0.7 (0.3–1.2)	0.7 (0.3–1.2)	0.7 (0.3–1.1)	0.6 (0.2–1.0)
	0.5	1.4 (0.7–2.2)	1.3 (0.7–2.0)	1.2 (0.7–1.8)	1.1 (0.6–1.6)	1.0 (0.6–1.6)		0.5	0.7 (0.2–1.1)	0.7 (0.2–1.1)	0.7 (0.2–1.1)	0.6 (0.2–1.0)	0.6 (0.2–1.0)
	0.25	1.2 (0.6–1.8)	1.2 (0.6–1.8)	1.1 (0.6–1.7)	1.0 (0.5–1.6)	1.0 (0.5–1.5)		0.25	0.6 (0.2–1.1)	0.6 (0.2–1.1)	0.6 (0.2–1.1)	0.6 (0.2–1.0)	0.6 (0.2–1.0)
	0	1.0 (0.4–1.5)	1.0 (0.4–1.5)	1.0 (0.4–1.5)	0.9 (0.4–1.5)	0.9 (0.4–1.5)		0	0.6 (0.2–1.1)	0.6 (0.2–1.1)	0.6 (0.2–1.1)	0.6 (0.2–1.0)	0.6 (0.2–1.0)
2070							2070						
	1	0.8 (0.4–1.3)	0.8 (0.4–1.2)	0.7 (0.4–1.1)	0.6 (0.3–0.9)	0.5 (0.2–0.8)		1	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.7)
	0.75	0.8 (0.4–1.2)	0.8 (0.4–1.1)	0.7 (0.4–1.0)	0.6 (0.3–0.9)	0.6 (0.3–0.8)		0.75	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.7)
	0.5	0.7 (0.4–1.1)	0.7 (0.4–1.1)	0.7 (0.3–1.0)	0.6 (0.3–0.9)	0.6 (0.3–0.9)		0.5	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.7)
	0.25	0.7 (0.3–1.0)	0.7 (0.3–1.0)	0.6 (0.3–0.9)	0.6 (0.3–0.9)	0.6 (0.3–0.9)		0.25	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.8)	0.5 (0.2–0.7)	0.4 (0.2–0.7)
	0	0.6 (0.3–0.9)	0.6 (0.3–0.9)	0.6 (0.3–0.9)	0.6 (0.3–0.9)	0.6 (0.3–0.9)		0	0.5 (0.2–0.7)	0.5 (0.2–0.7)	0.5 (0.2–0.7)	0.4 (0.2–0.7)	0.4 (0.2–0.7)
2050							2050						
	1	0.4 (0.2–0.7)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.3 (0.2–0.6)	0.3 (0.1–0.5)		1	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.3 (0.1–0.5)
	0.75	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.3 (0.1–0.6)		0.75	0.4 (0.1–0.6)	0.4 (0.1–0.6)	0.3 (0.1–0.6)	0.3 (0.1–0.6)	0.3 (0.1–0.5)
	0.5	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.3 (0.1–0.6)		0.5	0.3 (0.1–0.6)	0.3 (0.1–0.6)	0.3 (0.1–0.6)	0.3 (0.1–0.5)	0.3 (0.1–0.5)
	0.25	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)		0.25	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)
	0	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.2–0.6)	0.4 (0.1–0.6)		0	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)	0.3 (0.1–0.5)

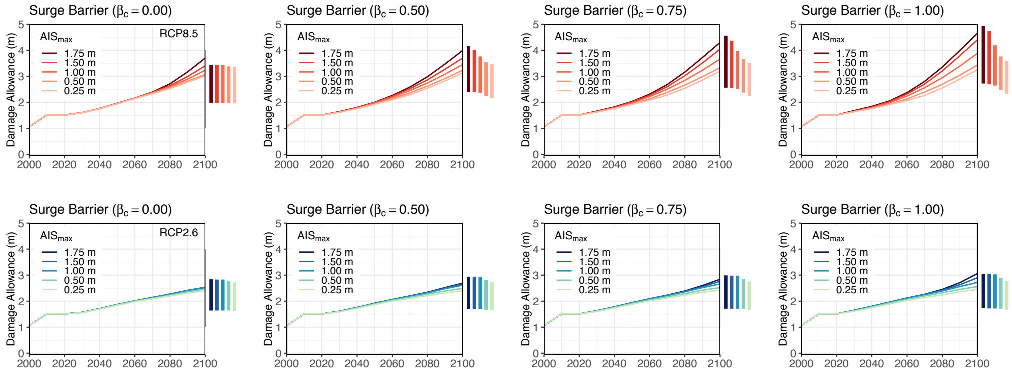

Figure 4.22: **Top Row:** Instantaneous flood damage allowances (meters above mean higher high water [MHHW]) over time (2000–2100) for a storm surge barrier protecting Manhattan under different maximum 2100 Antarctic Ice Sheet (AIS) contribution thresholds (AIS_{max}, relative to 2000), different subjectively perceived likelihoods of AIS collapse (β_c; 0 being 'most unlikely' and 1 being 'most likely'), and for the representative concentration pathway (RCP) 8.5 climate forcing scenario. The colored bars in the margins of each plot show the 2100 damage allowances using only the 5/95th percentile local sea-level rise projections. The storm surge barrier allowances include 0.5 m of freeboard, have a 10% probability of failure at the design height, and the barrier gates close when water levels are > 1.0 m above MHHW. **Bottom Row:** As for Top Row, but for RCP2.6.

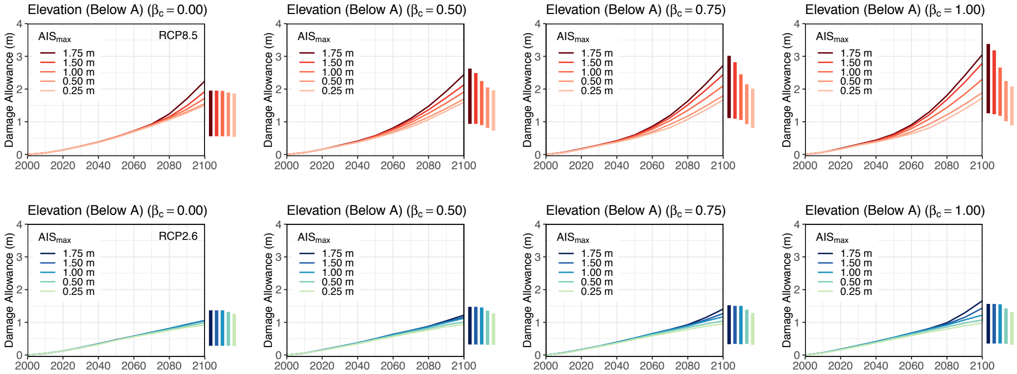

Figure 4.23: **Top Row:** Instantaneous flood damage allowances (meters above mean higher high water [MHHW]) over time (2000–2100) for an elevation strategy below the damage allowance A for Manhattan under different maximum 2100 Antarctic Ice Sheet (AIS) contribution thresholds (AIS_{max}, relative to 2000), different subjectively perceived likelihoods of AIS collapse (β_c; 0 being 'most unlikely' and 1 being 'most likely'), and for the representative concentration pathway (RCP) 8.5 climate forcing scenario. The colored bars in the margins of each plot show the 2100 damage allowances using only the 5/95th percentile local sea-level rise projections. The damage allowances assume perfect compliance (i.e., all structures below A elevate). **Bottom Row:** As for Top Row, but for RCP2.6.

Table 4.3: Levee damage allowances (meters above the current protection height) for 2100, 2070, and 2050 under representative concentration pathway (RCP) 8.5 and RCP2.6 and for different assumptions regarding future Antarctic ice sheet (AIS) behavior (e.g, likelihood of AIS collapse [β_c] and maximum 2100 AIS contribution [AIS_{max}]). Levee damage allowances include 0.5 m of freeboard and have a 10% probability of failure at the design height.

Levee Damage Allowances (m)

RCP8.5		AIS_{max}					RCP2.6		AIS_{max}				
	β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m		β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m
2100							2100						
	1.0	3.4	3.1	2.6	2.2	2.0		1.0	1.9	1.7	1.5	1.4	1.3
	0.75	3.1	2.8	2.4	2.1	2.0		0.75	1.7	1.6	1.5	1.4	1.3
	0.50	2.8	2.5	2.2	2.0	1.9		0.50	1.5	1.5	1.4	1.3	1.2
	0.25	2.6	2.2	2.1	1.9	1.9		0.25	1.4	1.4	1.4	1.3	1.2
	0.0	2.6	2.2	2.0	1.9	1.8		0.0	1.4	1.4	1.4	1.3	1.2
2070							2070						
	1.0	1.6	1.5	1.4	1.2	1.1		1.0	1.1	1.1	1.1	1.1	1.0
	0.75	1.5	1.4	1.3	1.2	1.1		0.75	1.1	1.1	1.1	1.0	1.0
	0.50	1.4	1.4	1.3	1.2	1.1		0.50	1.1	1.1	1.0	1.0	1.0
	0.25	1.3	1.3	1.2	1.2	1.2		0.25	1.0	1.0	1.0	1.0	1.0
	0.0	1.2	1.2	1.2	1.2	1.2		0.0	1.0	1.0	1.0	1.0	0.9
2050							2050						
	1.0	0.9	0.9	0.8	0.8	0.8		1.0	0.8	0.8	0.8	0.8	0.8
	0.75	0.9	0.9	0.8	0.8	0.8		0.75	0.8	0.8	0.8	0.8	0.8
	0.50	0.9	0.9	0.8	0.8	0.8		0.50	0.8	0.8	0.8	0.8	0.8
	0.25	0.8	0.8	0.8	0.8	0.8		0.25	0.8	0.8	0.8	0.8	0.7
	0.0	0.8	0.8	0.8	0.8	0.8		0.0	0.8	0.8	0.8	0.7	0.7

Table 4.4: Coastal retreat damage allowances (meters above the current protection height) for 2100, 2070, and 2050 under representative concentration pathway (RCP) 8.5 and RCP2.6 and for different assumptions regarding future Antarctic ice sheet (AIS) behavior (e.g, likelihood of AIS collapse [β_c] and maximum 2100 AIS contribution [AIS$_{max}$]). Assumes perfect compliance of coastal retreat (i.e., $\alpha = 1$; Sec. 4.2.1).

Coastal Retreat Damage Allowances (m)

RCP8.5		AIS$_{max}$					RCP2.6		AIS$_{max}$				
	β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m		β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m
2100							2100						
	1.0	2.6	2.4	1.9	1.5	1.3		1.0	1.2	1.1	0.9	0.7	0.6
	0.75	2.3	2.0	1.7	1.4	1.3		0.75	1.0	0.9	0.8	0.7	0.6
	0.50	2.0	1.7	1.5	1.3	1.2		0.50	0.8	0.8	0.8	0.7	0.6
	0.25	1.8	1.5	1.4	1.2	1.2		0.25	0.8	0.8	0.7	0.6	0.6
	0.0	1.8	1.5	1.4	1.2	1.1		0.0	0.7	0.7	0.7	0.6	0.6
2070							2070						
	1.0	0.9	0.8	0.7	0.6	0.4		1.0	0.5	0.4	0.4	0.4	0.3
	0.75	0.8	0.7	0.7	0.5	0.5		0.75	0.4	0.4	0.4	0.4	0.3
	0.50	0.7	0.7	0.6	0.5	0.5		0.50	0.4	0.4	0.4	0.3	0.3
	0.25	0.6	0.6	0.6	0.5	0.5		0.25	0.4	0.4	0.4	0.3	0.3
	0.0	0.6	0.6	0.5	0.5	0.5		0.0	0.3	0.3	0.3	0.3	0.3
2050							2050						
	1.0	0.3	0.2	0.2	0.2	0.1		1.0	0.2	0.2	0.2	0.2	0.1
	0.75	0.2	0.2	0.2	0.2	0.2		0.75	0.2	0.2	0.2	0.1	0.1
	0.50	0.2	0.2	0.2	0.2	0.2		0.50	0.2	0.2	0.2	0.1	0.1
	0.25	0.2	0.2	0.2	0.2	0.2		0.25	0.1	0.1	0.1	0.1	0.1
	0.0	0.2	0.2	0.2	0.2	0.2		0.0	0.1	0.1	0.1	0.1	0.1

Table 4.5: Damage allowances (meters) for a storm surge barrier for 2100, 2070, and 2050 under representative concentration pathway (RCP) 8.5 and RCP2.6 and for different assumptions regarding future Antarctic ice sheet (AIS) behavior (e.g, likelihood of AIS collapse [β_c] and maximum 2100 AIS contribution [AIS_{max}]). The allowances are relative to mean higher high water (MHHW). The storm surge barrier allowances include 0.5 m of freeboard, have a 10% probability of failure at the design height, and the barrier gates close when water levels are > 1.0 m above MHHW (approximately once every 10 years based on observations from the recent past; Fig. 4.1A).

Storm Surge Barrier Damage Allowances (m)

RCP8.5		AIS_{max}					RCP2.6		AIS_{max}				
	β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m		β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m
2100							2100						
	1.0	4.6	4.3	3.8	3.4	3.2		1.0	3.0	2.8	2.7	2.5	2.4
	0.75	4.2	4.0	3.6	3.3	3.1		0.75	2.8	2.7	2.6	2.5	2.4
	0.50	3.9	3.6	3.4	3.2	3.1		0.50	2.6	2.6	2.6	2.4	2.3
	0.25	3.7	3.4	3.3	3.1	3.0		0.25	2.5	2.5	2.5	2.4	2.3
	0.0	3.6	3.3	3.2	3.0	2.9		0.0	2.5	2.5	2.5	2.4	2.3
2070							2070						
	1.0	2.7	2.6	2.5	2.3	2.2		1.0	2.2	2.2	2.2	2.1	2.1
	0.75	2.6	2.5	2.4	2.3	2.2		0.75	2.2	2.2	2.2	2.1	2.1
	0.50	2.5	2.5	2.4	2.3	2.2		0.50	2.1	2.1	2.1	2.1	2.1
	0.25	2.4	2.4	2.3	2.3	2.2		0.25	2.1	2.1	2.1	2.1	2.0
	0.0	2.3	2.3	2.3	2.3	2.3		0.0	2.1	2.1	2.1	2.1	2.0
2050							2050						
	1.0	2.0	2.0	1.9	1.9	1.8		1.0	1.9	1.9	1.9	1.9	1.8
	0.75	2.0	1.9	1.9	1.9	1.9		0.75	1.9	1.9	1.9	1.8	1.8
	0.50	1.9	1.9	1.9	1.9	1.9		0.50	1.9	1.8	1.8	1.8	1.8
	0.25	1.9	1.9	1.9	1.9	1.9		0.25	1.8	1.8	1.8	1.8	1.8
	0.0	1.9	1.9	1.9	1.9	1.9		0.0	1.8	1.8	1.8	1.8	1.8

Table 4.6: Damage allowances (meters) for an elevation strategy in which structures elevate below the allowance height (A; Fig. 4.2A) for 2100, 2070, and 2050 under representative concentration pathway (RCP) 8.5 and RCP2.6 and for different assumptions regarding future Antarctic ice sheet (AIS) behavior (e.g, likelihood of AIS collapse [β_c] and maximum 2100 AIS contribution [AIS$_{max}$]). The allowances are relative to the current protection height around Manhattan (assumed to be a bulkhead 1.0 m above mean higher high water [MHHW]). The elevation strategy assumes perfect compliance (i.e., all structures elevate).

Elevation (below A) Damage Allowances (m)

RCP8.5		AIS$_{max}$					RCP2.6		AIS$_{max}$				
	β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m		β_c	1.75 m	1.5 m	1.0 m	0.5 m	0.25 m
2100							2100						
	1.0	3.1	2.8	2.3	1.9	1.7		1.0	1.7	1.4	1.2	1.1	1.0
	0.75	2.7	2.4	2.1	1.8	1.7		0.75	1.4	1.3	1.2	1.0	1.0
	0.50	2.4	2.1	1.9	1.7	1.6		0.50	1.2	1.2	1.1	1.0	0.9
	0.25	2.3	1.9	1.8	1.6	1.6		0.25	1.1	1.1	1.1	1.0	0.9
	0.0	2.2	1.9	1.7	1.6	1.5		0.0	1.1	1.1	1.1	1.0	0.9
2070							2070						
	1.0	1.3	1.2	1.1	0.9	0.8		1.0	0.8	0.8	0.8	0.8	0.7
	0.75	1.2	1.1	1.0	0.9	0.8		0.75	0.8	0.8	0.8	0.7	0.7
	0.50	1.1	1.0	1.0	0.9	0.8		0.50	0.8	0.7	0.7	0.7	0.7
	0.25	1.0	1.0	0.9	0.9	0.9		0.25	0.7	0.7	0.7	0.7	0.7
	0.0	0.9	0.9	0.9	0.9	0.9		0.0	0.7	0.7	0.7	0.7	0.7
2050							2050						
	1.0	0.6	0.6	0.6	0.5	0.5		1.0	0.5	0.5	0.5	0.5	0.5
	0.75	0.6	0.6	0.6	0.5	0.5		0.75	0.5	0.5	0.5	0.5	0.5
	0.50	0.6	0.6	0.5	0.5	0.5		0.50	0.5	0.5	0.5	0.5	0.5
	0.25	0.6	0.5	0.5	0.5	0.5		0.25	0.5	0.5	0.5	0.5	0.5
	0.0	0.5	0.5	0.5	0.5	0.5		0.0	0.5	0.5	0.5	0.5	0.4

Chapter 5

The political complexity of coastal flood risk reduction: lessons for climate adaptation public works in the U.S.

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Abstract

Coastal climate adaptation public works, such as storm surge barriers and levees, are central elements of several current proposals to limit damages from coastal storms and sea-level rise in the U.S. Academic analysis of these public works projects is dominated by technocratic and engineering-driven frameworks. However, social conflict, laws, political incentives, governance structures, and other political factors have played pivotal roles in determining the fate of government-led coastal flood risk reduction efforts. Here, we review the ways in which politics has enabled or hindered the conception, design, and implementation of coastal

risk reduction projects in the U.S. We draw from the literature in natural hazards, infrastructure, political science, and climate adaptation and give supporting examples. Overall, we find that 1) multiple floods are often needed to elicit earnest planning; 2) strong and continuous leadership from elected officials is necessary to advance projects; 3) stakeholder participation during the design stage has improved outcomes; 4) legal challenges to procedural and substantive shortcomings under environmental protection statutes present an enduring obstacle to implementing megastructure proposals.

5.1 Introduction

Climate adaptation public works (hereafter, adaptation works) are engineered, structural infrastructure projects, initiated, designed, and implemented by governments, with the intention of reducing the economic and social burden of climate change. For example, rising sea levels (Sweet et al, 2017), expanding coastal development (Crossett et al, 2013; Neumann et al, 2015; Titus et al, 2009), and recent hurricane disasters have encouraged several U.S. cities to investigate strategies for managing coastal floods, including adaptation works such as levees, storm surge barriers and other megastructures (Table 5.1; City and of San Francisco, 2016; City of New York, 2013; Sustainable Solutions Lab, 2018a; USACE, 2016, 2018a,b, 2019, 2020,?). These risk reduction strategies have proven to be technically and economically viable options for densely populated areas to manage sea-level rise and coastal flooding (e.g., the Fox Point Hurricane Barrier in Providence, Rhode Island; Fig. 6.1; Aerts et al, 2014; Hill et al, 2012; Jonkman et al, 2013; Kirshen et al, 2020; Merrell et al, 2011; Mooyaart and Jonkman, 2017; Morang, 2016; NRC, 2014). Densely populated regions often lack the space to take advantage of nature-based approaches (e.g., beach widening and wetland restoration) and other coastal adaptation options (e.g., managed retreat, informed land-use planning, building codes, and insurance) can conflict with local development goals. While there are several plans for storm surge barriers, sea walls, and levees in the U.S. (Table 5.1), few have broken ground, even when technoeconomic analyses by entities such as the U.S. Army Corps of Engineers (USACE) indicate that they are technically feasible and economically beneficial. A better understanding of the political and social factors that determine whether coastal risk reduction efforts succeed or fail could allow future adaptation works to be designed and executed in a more efficacious and less costly manner.

Existing research on why plans for adaptation works ultimately do or do not break ground focuses on identifying complex processes and interactions and classifying them into various adaptation barriers or enablers (Oppenheimer et al, in press). Moser and Ekstrom (2010) define adaptation barriers as "...impediments that can stop, delay, or divert the adaptation process" (Biesbroek et al, 2014; Eisenack et al, 2014; Klein et al, 2014). These barriers have been identified at stages of the adaptation process related to project conception, design, and implementation (Fig. 6.2; Moser and Ekstrom, 2010). Among these hinderances are political factors such as those that discourage support from elected officials (Healy and Malhotra, 2009; Jacobs, 2016), environmental laws (Bligh, 2006; Buzbee, 2014; Kagan, 1991; Kysar and McGarity, 2006), governance structures (Lubell, 2017), and social conflict resulting from interactions between diverse groups, organizations, and communities with heterogenous values, beliefs, interests, and influence (Adger et al, 2009; Dolšak and Prakash, 2018; Eakin et al, 2017; Eriksen et al, 2015; Leiserowitz, 2006; Sovacool and Linnér, 2016). In addition to barriers that can hinder adaptation works, enablers have been put forward as a way to overcome some of these challenges (Dutra et al, 2015; Dyckman et al, 2014). Examples include stakeholder participation and improving coordination between government agencies (Rabe, 1995).

While assessments that identify conceptual barriers and enablers are important, remaining key challenge include 1) determining which barriers are likely to manifest and under what contexts and 2) ascertaining which enablers would effectively address them. Specificity matters, because the scope and scale of an adaptation works project is likely to 1) influence which barriers are encountered in the policy process and 2) determine the ways to overcome them (Moser and Ekstrom, 2010). For example, large infrastructure projects (i.e., "megaprojects") inherently have broad scope and thus impact diverse groups of citizens through, for example, urban land-use changes that threaten the environment (Altshuler and Luberoff, 2003; Buzbee, 2014; Flyvbjerg et al, 2003). While empirically informed literature reviews exist for different adaptation arenas (Biesbroek et al, 2014, 2015; Bisaro and Hinkel, 2016; Hinkel et al, 2018; Measham et al, 2011; Sieber et al, 2018; Wellstead et al, 2014), none are specific to coastal adaptation works in the U.S. This is relevant because federal systems of governing, like the U.S., divide planning authorities in ways different from unitary governments, where planning is the sole responsibility of a central governing body (Austin et al, 2018; Elazar, 1987).

To inform coastal adaptation works in the U.S., we present a non-comprehensive, mini review of the literature on the political and social dimensions of coastal flood risk reduction, with an emphasis on the use of megaprojects. Coastal adaptation strategies—especially storm surge barriers, levees, and other engineered coastal defenses—are largely extensions of existing practices to manage flooding outside of a climate change context (Field et al, 2012; Sovacool and Linnér, 2016; Thomalla et al, 2006; NRC, 2014). Thus, several decades of empirical research can provide insights. We give examples—primarily from the literature in natural hazards, infrastructure, political science, and climate adaptation—of where politics plays a role in the conception (Section 5.2), design (Section 5.3), and implementation (Section 5.4) stages of coastal risk reduction project. These stages are chosen for organizational purposes only. They are loosely based off those used by Moser and Ekstrom (2010) to delineate adaptation implementation and those devised by Kingdon (2011) to describe the policy process. In reality, the stages of a coastal risk reduction project may not occur in this order or be as clearly defined. Throughout, we give examples of current and past projects to better explain how these factors manifest in the real world. While we focus on the U.S., our findings are relevant to adaptation works in other democracies in which the responsibility for managing natural hazards is split between a central governing body and constituent units (e.g., states/providences or municipalities). We conclude (Section 5.5) by highlighting four lessons from historical experience with coastal risk reduction with respect to factors that will enable or impede future adaptation works. Focusing on these factors will improve coastal risk reduction efforts so that they are less likely to result in delays, deadlocks, and failures that can waste valuable time and planning resources.

5.2 The decision to pursue adaptation works

All coastal risk reduction projects begin when the decision to initially explore options appears on a government agenda (a range of problems to which government officials are paying serious attention to at a given time). There are many possible ways in which a coastal risk reduction project can appear on an agenda. For example, the state or local government simply requires action, the federal government offers financial incentives, an extreme weather event highlights a need for adaption works, or groups and/or prominent leaders advocate for action. On the other hand, political incentives have discouraged coastal risk reduction from landing on an agenda or advancing to subsequent stages of planning.

5.2.1 How adaptation works can arrive on the government agenda

In the U.S., the federal government does not have the authority to coerce states and local communities to meet coastal flood safety standards (NRC, 2014); this is in contrast to other environmental domains with federal standards, such as water and ambient air quality (Downing and Kimball, 1982). However, Congress has created various federal programs to incentivize local preparedness by 1) making grants available to states and local communities to finance projects they would otherwise not be able to afford through local tax revenues and debt issuances alone and 2) reducing premiums for government-sponsored insurance programs if communities undertake risk-reduction measures (for example, through the National Flood Insurance Program's Community Ratings System) (Carter and Normand, 2019). Federal grants are available either following a natural disaster [e.g., Federal Emergency Management Agency's (FEMA) Hazard Mitigation Program and the Department of Housing and Urban Development's (HUD) Community Development Block Grant (CDBG) Program] or ex ante [e.g., FEMA's Mitigation Assistance Program and its Building Resilient Infrastructure and Communities (BRIC) Program—formerly the Pre-Disaster Mitigation Program]. In both cases, recipients are required to have a standing FEMA-approved hazard mitigation plan in order to be eligible. While meager annual budgets (appropriations $<$ \$250 million/yr) restrict FEMA support for infrastructure-based coastal risk reduction (Carter and Normand, 2019), some grants through HUD are larger. For example, HUD awarded New York City over $300 million through the Rebuild by Design competition to assist with funding the $1.45 billion East Side Coastal Resiliency Project (City of New York, 2020a). But overall, federal funding is 1) often tied to specific disasters, making it inaccessible to communities not impacted, 2) is contingent on annual congressional appropriations, leading to fluctuations in the levels of support. Additionally, annual USACE appropriations are minuscule compared to that needed to fund coastal risk reduction megastructures. For these projects, substantial federal assistance is needed from either Energy and Water Development appropriations acts or emergency supplementation appropriation following disasters (Carter, 2018; Knopman et al, 2017; Kousky and Shabman, 2017; Scodari, 2014; Sustainable Solutions Lab, 2018b; NRC, 2014). Comprehensive reviews of coastal risk reduction financing are provided elsewhere (Bisaro and Hinkel, 2018; Sustainable Solutions Lab, 2018b; Woodruff et al, 2020).

5.2.2 Flood disasters highlight the need for coastal risk reduction

A perennial challenge for natural hazard preparedness has been mobilizing support for action. Historically, local governments have tended to view extreme weather events (e.g., floods, hurricanes, tornados) and other rare hazards (e.g., earthquakes, wildfires, pandemics) as minor problems that take a backseat to more frequent and visible issues like unemployment, crime, housing, and education (Birkland, 1996; Burby, 2006; Godschalk et al, 2003; May, 1985; Rossi et al, 1981, 1982), despite acknowledgement of risks (White et al, 2001). For example, acknowledging the risk of a major hurricane hitting New Orleans (Kates et al, 2006) and New York City (Aerts and Botzen, 2011; Rosenzweig et al, 2011). However, evidence has shown the salience—or level of perceived importance—of preparedness rises through the occurrence of a disaster and by those who advocate for action (Birkland, 1996). As the salience of risks increase, so does the likelihood of efforts to address them. Indeed, more frequent coastal floods and other extreme weather events often attributed to climate change are increasing support for risk reduction efforts from the public (Cain et al, 2020; Demski et al, 2017; MacInnis and Krosnick, 2020) and elected officials (Yusuf et al, 2014).

In one model of the policy process, floods, hurricanes, and other extreme weather events have been viewed as “focusing events”, whereby they refocus the attention of elected officials and publics on an existing problem (Birkland, 1996; Kingdon, 2011; Zahariadis, 2003). During a focusing event, a "policy window" of opportunity opens for a short period, and advocates emerge (Olson, 1971), racing to push their preferred solutions through before the window closes (Birkland, 1996; Christoplos, 2006; Kingdon, 2011). If no viable solutions reach government officials while the window is opened, changes are unlikely (Kingdon, 2011). Cumulative learning helps reinforce lessons (Sadowski and Sutter, 2008). Sometimes, multiple disasters are needed to increase issue salience enough to push a solution through (Birkland, 1996; Kingdon, 2011). For example, despite destructive hurricanes in 1938 and 1944, New England did not begin to address coastal flooding with public works until Hurricane Carol in 1954. This was in part due to exogenous economic and geopolitical events crowding out government-led risk reduction efforts, such as the Great Depression and World War II (Morang, 2016; Chambers II, 1980). In another example, the USACE proposed levees and berms for the South Shore of Staten Island following damaging winter storms in December 1992 and March 1993. However, the project ultimately required the advent of Hurricane Sandy in order to stimulate congressional authorization and appropriation, 20 years after the flood issue initially became apparent (USACE, 2016).

5.2.3 Groups and individuals advocate for coastal risk reduction

Advocacy coalitions are groups whose goal is to increase the perceived importance of a particular policy issue and to encourage the adoption of strategies in order to meet their policy objectives (Sabatier, 1988). Advocacy coalitions for natural hazard risk management have been slow to emerge in part due to the technical nature of the hazards themselves, which has limited their study largely to scientific communities in government and academia (Birkland, 1997; May, 1991b). For instance, few public interest groups focused specifically on hurricanes exist in the U.S. (Birkland, 1997). Such "policies without publics" (May, 1991a) constrain the response following future extreme weather events, or lead to inefficient policies (Birkland, 1997). In the absence of sufficient citizen attention, the federal government has formed and supported groups that promote natural hazard preparedness in the public's interest (e.g., the U.S. National Earthquake Hazards Reduction Program[1]; Birkland, 1997).

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[1] `https://www.nehrp.gov/`

However, creating federal advocacy groups has proven to be challenging; an attempt to create government-sponsored technical group for hurricanes was made but ultimately failed due to a lack of congressional support (the National Hurricane Research Initiative; Board, 2007). On the other hand, subnational advocacy groups have emerged for coastal adaptation, such as the Southeast Florida Regional Climate Change Compact (SFRCCC, 2012).

In additional to organized groups, the emergence of high-profile individuals as "policy entrepreneurs" have raised the salience of an issue in order to sustain interest. Policy entrepreneurs who are government executives have pushed their own agendas to address issues that they believe to be important (Kingdon, 2011; Moser et al, 2019; Renner and Meijerink, 2018; Smith et al, 2009). For example, in the wake of Hurricane Sandy, New York City Mayor Michael Bloomberg championed climate adaptation efforts, such as the Special Initiative on Rebuilding and Resiliency and the creation of the Mayor's Office of Resiliency and Recovery[2]. However, subsequent leadership must continue to value adaptation in order to sustain implementation, which has sometimes taken decades (Section 5.4). Policy entrepreneurs that advocate for adaptation works may leave office and then new leaders might scrap the plans of the previous leadership because the projects do not align with their goals (Kingdon, 2011). For example, President Trump repealed an Obama-era Executive Order amendment requiring consideration of sea-level rise in federal infrastructure decisions (Friedman, 2017). While focusing events, advocacy coalitions, and policy entrepreneurs have all helped to place adaptation works on policy agendas, countervailing political incentives have discouraged their prioritization by governments.

5.2.4 Political incentives can hinder coastal risk reduction efforts

Political incentives can discourage elected officials from reducing exposure to coastal hazards and also from promoting protective measures. For instance, the short time scales of election cycles can encourage politicians to focus on contemporary societal welfare at the expense of the future (Jacobs, 2016). If the primary goal of an elected official is to get re-elected (Mayhew, 1974), then it is rational for them to address problems with benefits that are visible to their constituents during their time in office. This includes favoring dis-

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[2] `https://www1.nyc.gov/site/sirr/report/report.page`

aster relief over preparedness (Gasper and Reeves, 2011; Healy and Malhotra, 2009; Posner, 2006). Disaster relief can be distributed in the weeks to months following a disaster, while adaptation projects can take years to plan and implement and may only positively impact a small fraction of the voting population. An electorate may only come to appreciate the preparedness measures after they successfully mitigate a disaster, which could be years—if ever—long after the incumbent vacates office. For example, the villagers of Fudai, Japan, praised a tsunami protection structure following the Tōhoku Earthquake in 2011 after previously labeling it a boondoggle and ridiculing the mayor who championed its construction (Mail, 2011). Ultimately, without the willpower from elected officials to pay upfront political costs in order for publics to receive net returns in the future, the status quo is likely to endure.

The U.S. faces a preparedness dilemma that can inhibit adaptation works: while the federal government seeks to protect citizens from natural disasters, it has limited control over efforts to do so. Both the vulnerability to and consequences of a coastal hazard are largely shaped by state and local land use and building codes (Simmons et al, 2018; NRC, 2014). For instance, local jurisdictions may be incentivized by the potential benefits from economic growth to develop lands exposed to hazards (e.g., coastlines Burby, 2001; Knowles and Kunreuther, 2014; Peterson, 1981; Stone, 1989). At the same time, local jurisdictions bear reduced responsibility for protecting vulnerable and exposed developments, in part due to the expectation of ex post federal aid (e.g., disaster relief); the latter takes pressure off local officials to set aside surplus revenue for unexpected events (Rossi et al, 1982). In essence, the rewards of high-risk development accrue to property developers and local and state governments in the form of employment, contracts, profits, and tax revenue, while the federal government is largely responsible for disaster aid. This misalignment of risk, reward, and responsibility between federal and local governments can suppress local interest in pursuing adaptation and remains an enduring challenge (Burby, 2006; NRC, 2014). In the U.S., some efforts have been made to discourage development on coastal lands (e.g., the Coastal Barrier Resources Act and the Coastal Zone Management Act), but new construction continues in these areas (Central and Zillow, 2018; Lazarus et al, 2018; NRC, 2014).

5.3 Designing coastal risk reduction strategies

Once governments have decided to reduce flood risks (Section 5.2), they must determine how to do so. Multiple solutions are often technically feasible, including strategies that reduce the hazard (building surge barriers, levees, and other structural defense measures) and strategies that reduce the consequences of the hazard (elevating structures above extreme water levels, moving populations and the built environment away from the coastline, building codes) (Oppenheimer et al, in press). Either a single strategy (e.g., levee system) or combination of strategies could be employed (e.g., levee system and building codes). We conceptualize selecting a proposal as two steps: 1) producing alternative strategies and 2) choosing among them. These are not merely technical decisions made behind closed doors. Modern approaches to planning seek to create an open, transparent forum for government agencies, elected officials, and the public to deliberate over the best course of action (Davidoff, 1965; Pateman, 1970; UNFCCC, 1992). A number of political and social factors are involved, including government agency biases, political power, laws, tension between public participation and technical expertise, and government subsidy schemes.

5.3.1 Political and social factors in creating alternative strategies

Alternatives are the range of potential risk reduction options (sometimes a sequence of options over time) that satisfy a given policy objective (e.g., protection from a 100-year flood). For some projects, proposing alternatives is required by law. The National Environmental Policy Act (NEPA) mandates that government agencies consider more than one solution if a proposed project poses significant harm to the quality of the natural environment (Luther, 2008). Creating a viable risk reduction strategy is not simply a matter of scientific expertise and skillful engineering. Technical experts are able to answer the question of what can be built, but not the normative question of what should be built. Proposed solutions are influenced by their designers' values and beliefs regarding what constitutes "good" options (Gregory and Keeney, 1994; Sovacool and Linnér, 2016) and it is generally impossible to accommodate the diversity of preferences held by stakeholders (Few et al, 2007; Gregory and Keeney, 1994). While project designers forecast net positive social welfare gains, underneath there are likely “winners” and “losers” (Sovacool and Linnér, 2016). Choices inherently entail difficult tradeoffs between the present and the future, and success in the near-term may be maladaptive in the long-run, and vice-versa (Barnett and O’Neill, 2010).

Participatory and collaborative approaches such as iterative design and planning workshops have helped to mitigate disagreements and produce consensus-supported strategies for flood risk management in East Boston, England, and Austria (Kirshen et al, 2018; Löschner et al, 2016; Pasquier et al, 2020). In the Netherlands, the original Delta Works plan to close off the Eastern Scheldt Estuary with an impermeable dam invoked strong public opposition from yachters, the shellfish industry, and environmental groups (Disco, 2002). In response, engineers and environmental scientists worked together to design an alternative that simultaneously served the interests of safety, the economy, and the local ecology. The result was a storm surge barrier across the Eastern Scheldt with closeable gates wide enough to not significantly impede the natural tidal flow, therefore minimizing the structure’s environmental impact (Bijker, 2002; Disco, 2002). However, public interest in natural hazard mitigation is not always strong (Godschalk et al, 2003), and participatory approaches do not always lead to improved outcomes (Bloomfield et al, 2001; Few et al, 2007; Reed, 2008) or technically feasible designs (Araos, 2020). For example, following Hurricane Sandy, the City of New York and HUD worked together through the Rebuild by Design competition to develop the East Side Coastal Resilience Project, a flood protection system integrated into Manhattan’s East River Park. After years of public participation through an iterative design process, the final consensus design was thrown out by the City’s Department of Design and Construction on the grounds that it was not technically sound from an engineering standpoint. The Department of Parks and Recreation also came to the conclusion that it was not interested in managing a floodable park, as the original design had called for. These conclusions were largely made behind closed doors, upsetting many who had believed their participation would be reflected in the final project design (Araos, 2020). A revised plan was made in place of the original collaborative design. The experience highlights the vulnerability of inclusive, participatory risk reduction efforts to both scientific reevaluation and existing power structures (Flyvbjerg, 1998).

Government agencies tasked with reducing coastal flood risks also have a history of favoring particular approaches, in part due to their statutory missions that lead them to look through different lenses. For example, FEMA's emphasis on individual assistance has focused its disaster mitigation programs largely on private strategies that reduce the consequences of floods, such as property acquisition/buyouts and building-specific measures like flood proofing and structure elevation (CRS, 2009). On the other hand, the USACE has a history of deploying concrete and steel-based projects that impact large regions (Mazmanian and Nienaber, 1979). Many of the USACE's recent coastal risk reduction proposals have continued to favor structural measures over working with nature (Table 5.1), despite an espoused and to some extent, real interest on the part of USACE in the later (USACE, 2015)

5.3.2 Political and social factors in choosing among alternatives

Many of the same political and social factors involved in creating a coastal risk reduction strategy play a role when choosing what solutions to employ. This includes accommodating a diversity of values, beliefs, and desires from all stakeholders, government agency biases towards particular strategies, and political power. Additional factors include debate over how to best appraise alternatives, adverse impacts of strategies after implementation, the influence of laws on choosing alternatives, and the impact of government cost sharing. Environmental impact statements (EISs) as required under NEPA and other State or local impact reports (e.g., California, New York State, and New York City) are typical examples of appraisal documents (Luther, 2008; Talen, 1996). Various decision analysis methods have been developed to help appraise large-scale coastal flood risk reduction strategies with respect to chosen objectives (e.g., benefit-cost analysis, robust decision-making and flexible/adaptive decision-making Chambwera et al, 2014; Haasnoot et al, 2013, 2019; Lempert et al, 2003; Ranger et al, 2013), but the selection of these objectives, in part, depend on policy goals (Kleindorfer et al, 1993). Even if the objective is agreed upon by all stakeholders (e.g., protection from a 100-yr flood), it does not necessarily encourage consensus for choosing a course of action. For example, all of the USACE's proposed alternatives for flood protection in the New York Metropolitan Area provided protection from a 100-yr flood event (USACE, 2019), but proponents of nature-based flood risk reduction (e.g., dunes and beach nourishment, oyster beds, wetland restoration) loudly objected to the use of storm surge barriers (Royte, 2019; Ong, 2018; Roff and Gallay, 2018; Stringer, 2019). Furthermore, they attacked the USACE's benefit-cost analysis approach on the grounds that it under-valued ecosystem services, biodiversity, and cultural heritage (Ong, 2018). Political motivations have also led to strategic manipulation of decision analyses by planners to obtain desired outcomes (Ferejohn, 1974; Flyvbjerg, 1998; Flyvbjerg et al, 2002; Wachs, 1989, 1990; Mazmanian and Nienaber, 1979).

Anticipated regulatory hurdles and funding subsidies have also influenced choices among presented alternatives. For instance, besides being cheaper, small-scale coastal risk reduction projects that can be implemented quickly have been favored over larger, infrastructure-based measures that have historically taken decades to complete, in part due to lengthy government approval (i.e., multiple Acts of Congress), appropriations processes (Carter and Normand, 2019), and long construction times (Mooyaart and Jonkman, 2017). New York City's Special Initiative for Rebuilding and Resiliency and a University of Massachusetts-Boston study both favored smaller-scale projects over large, engineered projects like levees and surge barriers because they have been implemented faster and have co-benefits that address social justice issues (City of New York, 2013; Kirshen et al, 2020). For example, floodable parks that provide historically marginalized groups access to recreation and green space. Simple, small-scale projects are eligible to be undertaken at the discretion of cities and the USACE, without the need for both approval and appropriations from Congress (Carter and Normand, 2019; Normand, 2019). USACE projects like dune building, beach nourishment, and aquatic ecosystem restoration also have local-federal cost sharing schemes that are more favorable to local jurisdictions (Mullin et al, 2018; USACE-IWR, 2003) and are compatible with coastal management strategies that aim to keep future options open (e.g., Haasnoot et al, 2013, 2019). However, numerous small-scale measures taken together may not add up to credible regional protection against rare storms (e.g., a 100-yr flood).

5.4 Implementing coastal risk reduction

The design and selection of any coastal risk reduction project (Section 5.3) is not itself sufficient to assure its implementation. Political scientists and planners have long understood the bottleneck that implementation poses to policy making and planning (Bardach, 1977; Mazmanian and Sabatier, 1983; Palumbo and Calista, 1990; Pressman and Wildavsky, 1984; Sabatier, 1986; Talen, 1996; Younis, 1990). Based on past experiences with public works and coastal risk reduction efforts, implementation is likely to be challenged by environmental protection laws, siting-related opposition, institutional complexity (e.g., permitting), and lack of support from elected officials (Fukuyama, 2017; Howard, 2015).

5.4.1 Environmental protection laws have challenged coastal risk reduction efforts

Experience with public works suggests that laws related to environmental protection provide opportunities to challenge the implementation of coastal adaptation works (Bligh, 2006; Buzbee, 2014; Kagan, 1991; Kysar and McGarity, 2006; Luther, 2006; Murchison, 2007). Prior to the passage of contemporary environmental laws in the U.S., by and large the only legal question that proponents of a flood protection project needed to answer was if it impeded maritime navigation (Scarano, 2013). Today, mandatory consideration of environmental impacts has made infrastructure implementation a more complex legal process (Altshuler and Luberoff, 2003; Mazmanian and Nienaber, 1979; Taylor, 1984). For example, under NEPA, all federally funded projects that pose significant harms to the quality of the natural environment must analyze and publicly disclose a proposal's environmental impacts through an environmental impact statement (EIS) and receive public comment on the proposal and its alternatives. Reviews may also be required at the state and local level (e.g., the California Environmental Quality Act, the California equivalent of NEPA, and New York City's City Environmental Quality Review). While this process is not a direct legal barrier to project implementation per se, the transparency of potential environmental harms it provides can trigger lawsuits from neighborhood groups, environmental organizations, and other special interests if they believe the submitted EIS does not sufficiently account for environmental impacts (Luther, 2008).

There are several instances in which environmental laws have led to delays and project failures. In the midst of an effort to implement flood protection in the greater New Orleans region, the USACE was successfully sued in 1977 (*Save Our Wetlands, Inc. v. U.S. Army Corps of Engineers*, 553 F.2d 100 (5th Cir. 1977)). While the *Save Our Wetlands* lawsuit did not completely block the USACE's flood protection efforts, it did lead to a multi-year delay in implementation and an increase in project costs (Bligh, 2006; Kysar and McGarity, 2006). More recently, neighborhood activists in the Lower East Side of Manhattan unsuccessfully sued the City of New York arguing that the new plan for the East Side Resiliency Project needed to go through an extra round of environmental review (Araos, 2020; Smith, 2020)(*East River Park Action v. City of New York*, docket 151491/2020 (N.Y. Sup. Ct.)). On the other hand, some environmental laws have blocked projects altogether. Under the Clean Water Act, projects cannot be built in coastal waterways unless 1) the sponsoring agency proves they need to be built in the water or 2) the underlying project will not cause "significant degradation" to important aquatic habitats (Copeland, 2016). In New York City, the Sierra Club successfully sued and blocked an effort to issue a landfill permit under the Clean Water Act (*Sierra Club v. U.S. Army Corps of Engineers*, 609 F. Supp. 1052 (S.D.N.Y. 1985)). The permit was needed to break ground on the Westway Project, a proposed Manhattan superhighway (Buzbee, 2014). While there is little doubt that the emergence of the environmental protection movement greatly improved environmental quality, it has led to a number of new laws and lengthy, formalized processes that have the potential to challenge the implementation of adaptation works, much in the same way it has challenged the deployment of public works in general (Fukuyama, 2017; Howard, 2015; Kagan, 1991).

5.4.2 Not in my backyard: siting opposition to coastal risk reduction

Despite the well-intentioned benefits of adaptation works, the siting of some projects is likely to raise public opposition [e.g., not-in-my-backyard (NIMBY) syndrome; McAvoy (1999)]. NIMBY syndrome can present problems for governments trying to construct public works that aim to increase the welfare of its citizens broadly, but also imposes direct net costs on some groups given their geographic proximity. These projects are perceived by local citizens to bring few, if any, direct benefits while imposing large immediate costs via eminent domain, decreases in property value, deterioration of the natural environment, and loss of amenities (Aldrich, 2008; Devine-Wright, 2011; McAdam and Boudet, 2012; McAvoy, 1999; Quah and Tan, 2002; Smith and Klick, 2007). For example, a 1960s USACE proposal for storm surge barriers across three entrances to Narragansett Bay in Rhode Island was met with strong public opposition, including from recreational boaters who argued the massive structure would induce strong currents and subsequently impede maritime navigation (Evening Bulletin, 1964). Ultimately, the State of Rhode Island asked the USACE to shelve the project believing that the public would not support a bond referendum to pay for the substantial local share of the project cost (Journal, 1965). More recently, neighborhood activists in the Lower East Side of Manhattan expressed opposition to the revised East Side Coastal Resilience Project, in part because of necessary lengthy closures of the East River Park (a key neighborhood amenity) and the removal of nearly a thousand trees (Araos, 2020). Overall, opposition to public works projects is expected to increase over time due to less undeveloped land, rising educational levels that lead to greater access to technical information and legal resources, increased environmental awareness, and declining confidence in government (Aldrich, 2008).

Siting issues can also raise environmental justice concerns if projects with negative externalities (e.g., pollution) are planned near communities with less political and economic power (Aldrich, 2008). In the case of flood risk reduction, these justice concerns largely have centered around who is afforded flood protection and who is left out (Adger et al, 2006; Liao et al, 2019). For example, the East Side Coastal Resilience Project was, in part, designed to provide protection to socially vulnerable populations in the Lower East Side of Manhattan (Araos, 2020; City of New York, 2020b; de Sherbinin and Bardy, 2015). However, the revised project plan resulted in dispute between neighborhood activists and those affiliated with low-income public housing (residents and their formal representatives). The former prioritized conservation of the existing park, while the latter supported long-term flood protection (Araos, 2020).

5.4.3 Complex governance structures complicate coordination

The arrangement of government agencies and institutions[3] plays a critical role in the implementation of a coastal risk reduction project. In the U.S., planning authority is divided in a manner that protects the sovereignty of sub-national states (Austin et al, 2018; Elazar, 1987). Fragmented arrangements of government agencies and institutions hinder the implementation of adaptation works by complicating intergovernmental relations and coordination between cities, states, and the federal government (Den Uyl and Russel, 2018; Fukuyama, 2017; Glicksman, 2010; Lubell, 2017; Peterson, 1981). This structure is characterized by fragmented decision-making and a lack of coordination, comprising a "vetocracy" where many diverse interests are involved with strongly held, divergent views (Fukuyama, 2017). Additionally, without reforms and new laws, some long-standing government agencies may not be well equipped to manage coastal flooding and sea-level rise.

In the U.S., there is no federal coordinating body with the sole focus of reducing coastal flood risk (NRC, 2014). Instead, there are at least nine federal agencies with various flood management responsibilities (USACE, 2015). Each federal agency has a different geographic jurisdiction, regulatory authority, and capacity. In addition, state and local level governments overlap with and often duplicate federal authority. For example, in addition to three federal agencies (Environmental Protection Agency, USACE, and the U.S. Fish & Wildlife Service), the San Francisco Bay and its shorelines are also managed by four state agencies (Bay Conservation and Development Commission, Water Quality Control Board, California Coastal Conservancy, and California Dept. of Fish & Wildlife) and over 100 local governments and special districts. This complex arrangement of authority has hampered efforts to use wetland restoration as a local coastal risk reduction strategy (Pinto et al, 2018). In light of this and other struggles, stakeholders surveyed in the San Francisco Bay area almost unanimously favored more central coordination and integrated planning but disagreed on the preferred governance arrangement (Lubell, 2017). A key question is how to achieve cooperation within complex, multi-level systems. Possible approaches include integration and

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[3] Institutions are broadly defined as rules (formal and informal) that structure interactions between groups. They provide important coordination mechanisms and give actors the ability to acquire technical and financial resources that they otherwise would not have access to (Ostrom, 2005).

consolidation of permits (Rabe, 1995), creating new agencies with extensive authority over coastal adaptation issues, and physical climate data centers to minimize duplication in the production of estimates of coastal flood hazards (Lubell, 2017). Task forces have been used to facilitate coordination between federal agencies and local municipalities. For example, following Hurricane Sandy, President Obama formed the Hurricane Sandy Rebuilding Task Force to improve coordination as communities were making decisions about long-term recovery (Hurricane Sandy Rebuilding Task Force, 2013). Although this was not specifically focused on reducing coastal flood risk, its success highlights the potential for similar task forces to help with intergovernmental coordination.

When forced to adapt to a changing climate, some long-standing government agencies may no longer operate effectively. Without fundamental changes and restructuring, these legacy institutions will hinder society's ability to adapt to climate change (Libecap, 2011; Lubell, 2017). For example, in four Southeastern U.S. states, efforts to elevate state highways that become impassible during nuisance or "sunny day" flood events have run into challenges with jurisdictional boundaries (Jones et al, 2019). Flood managers in the Hampton Roads region of southeast Virginia have also cited jurisdictional boundaries as an impediment to regional responses (John and Yusuf, 2019).

5.4.4 Support from elected officials is critical for advancing large projects

Support from congressional delegates is needed to shepherd large USACE projects through Congress. For example, the failed Narragansett Bay storm surge barriers lacked support from both the Governor (Evening Bulletin, 1963) and the Rhode Island congressional delegation (Van Dusen, 1964). On the other hand, the Fox Point Hurricane Barrier received strong, sustained support from both the public and elected officials, including the mayor of Providence, the Governor, and even the President (Providence Journal, 1958, 1959, 1960). More recently, when the USACE's South Shore Staten Island project was in doubt over an issue with encroaching on federal lands, Congressman Max Rose and Senator Chuck Schumer led an effort to pass new legislation that allowed the Corps to access Great Kills Park, part of Gateway National Recreation Area (Michel, 2020). While support from elected officials is necessary, it is not sufficient for large projects to advance. As learned from the Westway experience, legal challenges can trump near unanimous support from elected officials (Buzbee, 2014).

5.5 Lessons learned: Creating a politically favorable environment for coastal adaptation works

Experience with coastal risk reduction indicates that simply looking good on the drawing board is insufficient to cause a project to materialize. The prospects for breaking ground on storm surge barriers, levees, and other coastal adaptation megaproject in the U.S. are not solely a function of technically feasible and economically justifiable plans. In this non-comprehensive review, we draw from the literature on natural hazards, infrastructure, political science, and climate adaptation to show that large coastal risk reduction projects are deeply embedded in politics and social conflict. We give particular attention to the project phases of conception (Section 5.2), design (Section 5.3), and implementation (Section 5.4).

Despite political challenges, several coastal risk reduction megaprojects have been built in the U.S. (Table 5.2; Morang, 2016). Projects completed prior to 1970 benefited from preceding modern environmental laws, and in a recent case, some environmental procedures were overridden as a result of the urgent need to protect New Orleans after Hurricane Katrina (CRS, 2006; Luther, 2006). New coastal adaptation works continue to progress (Table 5.1). For example, the South Shore Staten Island and East Side Coastal Resiliency projects in New York City both await construction after receiving funding and necessary approvals (Cohen, 2019; Smith, 2020).

From our review of social and political coastal risk reduction factors, we highlight four lessons that reflect factors that will enable or impede future adaptation works:

1. *Multiple floods are often needed to incite interest in coastal risk reduction*

   The misalignment of risk, reward, and responsibility between federal and local governments continues to suppress local interest in pursuing coastal risk reduction (Section 5.2.4). Furthermore, public policy problems that have spatial or temporal immediacy continue to be prioritized over those that may be justified from a long-term strategic perspective such as coastal flood protection, but public support for climate adaptation is increasing (Section 5.2.2). Flood disasters provide windows of opportunity for interest in coastal risk reduction to greatly increase. However, these windows are, as of yet, rare and are only open for a short period of time (Section 5.2.2). This highlights the critical importance of taking advantage of these occasions. Particularly, plans are needed in advance so that when a disaster happens, elected officials have specific projects to support, authorize, and fund. Furthermore, past experience suggests that multiple disasters are sometimes needed for coastal risk reduction to receive sufficient attention (Section 5.2.2).

2. *Participatory planning has helped produce consensus-supported strategies*

   Experience suggests that participatory approaches such as iterative design and planning workshops have helped to rectify disagreements between stakeholders and produce consensus-supported strategies (Section 5.3.1). However, outcomes that offer little improvement over the status quo are still possible. First, the outcome of a consensus in collaborative decision-making has been a solution that, while acceptable to all stakeholders, fails to address the issue at hand (Section 5.3.2). Second, public apathy has led to a disproportionate representation by special interests (Section 5.4.2). Third, consensus outcomes are sometimes not technically feasible (Section 5.3.1).

3. *Strong and continuous leadership is necessary to advance big projects*

   USACE megaprojects require multiple acts of Congress to advance from an initial plan to implementation (Section 5.3.2). This process can take several years. Furthermore, Congress must deal with many policy issues that compete for attention (Section 5.2.1). The success of USACE megaprojects critically depends on strong and continued support from mayors, local congressional delegations, governors, and even presidents (Section 5.4.4). However, while it is necessary, support is not always sufficient for projects to advance to implementation. Public opposition and legal challenges have overridden near unanimous support from elected officials (Section 5.4.1).

4. *Environmental laws and public opposition are enduring challenges*

> In the case of large coastal flood protection megaprojects, protecting human safety and the environment are sometimes in direct conflict (Section 5.4.1). Powerful and organized groups (e.g., environmental NGOs) have exerted a significant influence over the implementation of coastal megastructures (Section 5.4.2). This influence is usually not countered by lobbying and litigation from other interests who are in favor of projects. Environmental laws provide opportunities for special interests to legally challenge projects if they believe certain environmental impacts have not been properly accounted for. Lengthy litigation has caused project delays, deadlocks, and even failures (Section 5.4.1).

Breaking ground on a project that is judged by technocratic agencies to be feasible and economically beneficial may not always be desirable. Coastal adaptation works will not solve all problems and they are just one option from a spectrum of possible responses (e.g., protection, accommodation, retreat, advance; Oppenheimer et al, in press). Coastal adaptation works may lead to undesirable outcomes not recognized in their analyses such as being maladaptive (Barnett and O'Neill, 2010), inflexible (Arthur, 1989; Corvellec et al, 2013; Markolf et al, 2018; Payo et al, 2016), environmentally harmful (Orton et al, 2019; Swanson et al, 2012), or have the potential to worsen the circumstances of marginalized groups. For these reasons, knowing why projects fail is also useful for those who wish for a particular project to fail. Rather than thinking of protection strategies that focus on a single, critical threshold (e.g., 100-yr flood), a more diverse suite could be used, such as those that are redundant, "safe-to-fail" (Kim et al, 2017), less reliant on probabilistic estimates of variables (such as heights of extreme water; Kopp et al, 2019; Rasmussen et al, 2020), more affordable, and more modular/flexible. These characteristics are the foundation of "resilience"-based approaches (Linkov et al, 2014; Council, 2012; Park et al, 2013; Woods, 2015).

While our review emphasizes the importance of considering political complexities when pursuing adaptation works, it stops short of detailing specific mechanisms that may be necessary to generate effective policy recommendations. Future research could uncover these. For example, examining historical case studies of controversial public works proposals could further open up the "black box" of politics and allow for identification of causal processes (Biesbroek et al, 2014; Elmore, 1979; Wellstead et al, 2013). Such an approach is also likely to yield practical advice to policy makers on how to intervene, overcome implementation barriers, and obtain favorable outcomes and could also contribute to building political theory. This includes examining how the political forces involved in management of coastal and other environmental risks affect decisions (i.e., political economy). Examples of potential case studies include storm surge barriers and other public works that address societal risks (e.g., renewable energy, drinking water availability, and public transit), earthquake building codes and warning systems, and pandemic planning and response (e.g., COVID-19).

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Figures and Tables

Figure 5.1: The Fox Point Hurricane Barrier following completion in March 1966 (Providence, Rhode Island). Photo taken by the New England Division of the U.S. Army Corps of Engineers (Waltham, Massachusetts).

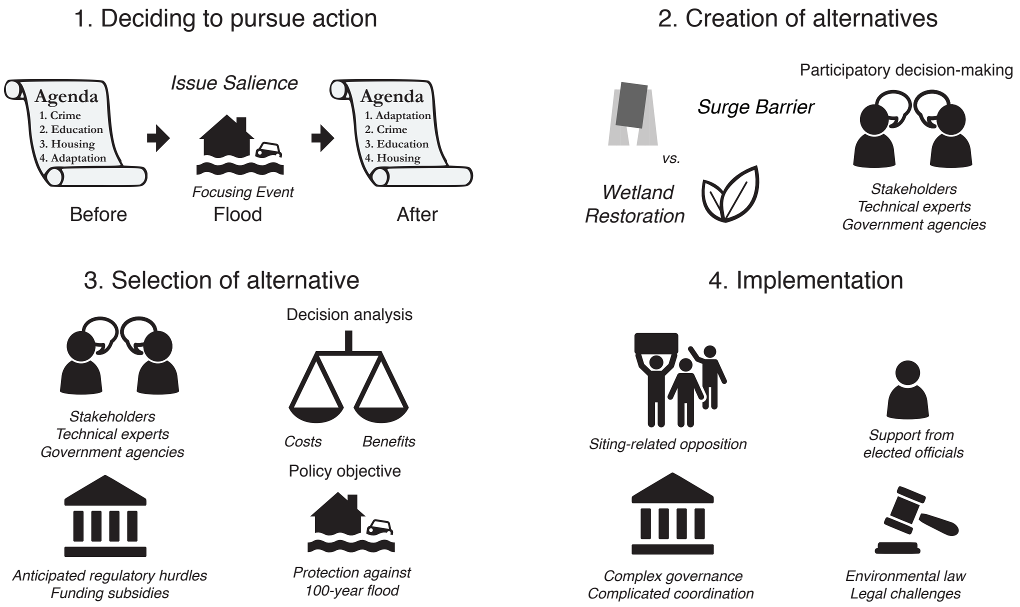

Figure 5.2: The process leading up to breaking ground on an adaptation works project organized into four different steps: 1) deciding to pursue action (Section 5.2), creating alternatives (Section 5.3.1), selecting from alternatives (Section 5.3.2), and implementation (Section 5.4).

Table 5.1: An incomplete list of proposed public works coastal flood protection projects in the U.S. (USACE is the U.S. Army Corps of Engineers; CSRM is Coastal Storm Risk Management; HUD is Department of Housing and Urban Development; NYC is New York City; SSPEED is the Severe Storm Prediction, Education, and Evacuation from Disasters Center)

Project	Location	Strategy	Proposed	Lead Agency	Project Cost	Status (as of 2020)
Boston Harbor Surge Barrier	Boston, MA	Levee/Barrier	2018	UMass-Boston	$6.5 to 11.0 billion	Proposed
East Side Coastal Resiliency Project	New York, NY	Levee/Nonstructural	2014	NYC/HUD	$1.5 billion	Approved by the City
Lower Manhattan Climate Resiliency Project	New York, NY	Coastal Advance/Fill	2019	NYC	$10 billion	Proposed
Embarcadero Seawall	San Francisco, CA	Seawall	2018	City of SF	$5 billion	Proposed
Red Hook Integrated Flood Protection System	New York, NY	TBD	2013	NYC	$0.1 billion	Undergoing a redesign
Coastal Texas Protection and Restoration Project	Coastal Texas	Levee/Barrier/Nonstructural	2015	USACE	$23.1 to 31.8 billion	Proposed
Galveston Bay Park	Galveston, TX	Levee/Barrier/Nonstructural	2020	SSPEED	$2.3 to 2.8 billion	Proposed
South Shore of Staten Island CSRM Project	New York, NY	Levee/Nonstructural	1993	USACE	$0.6 billion	Ready to break ground
Charleston Peninsula: A Coastal Flood Risk Management Project	Charleston, SC	Levee/Seawall	2020	USACE	$1.7 billion	Proposed
City of Norfolk CSRM Project	Norfolk, VA	Levee/Barrier/Nonstructural	2015	USACE	$0.9 to 2.3 billion	Awaiting authorization
Miami-Dade Back Bay CSRM Project	Miami, FL	Levee/Barrier/Nonstructural	2020	USACE	$0.9 to 5.2 billion	Proposed
Collier County CSRM Project	Naples, FL	Levee/Barrier/Nonstructural	2020	USACE	$2.2 billion	Proposed
Fairfield and New Haven Counties, CT CSRM Project	Fairfield/New Haven, CT	Levee/Seawall/Pumps	2019	USACE	$0.05 to 0.3 billion	Proposed
New York – New Jersey Harbor and Tributaries Project	New York, NY	Levee/Barrier/Nonstructural	2019	USACE	$15 to 119 billion	Planning suspended

Table 5.2: An incomplete list of completed public works coastal flood protection projects in the U.S. (USACE is the U.S. Army Corps of Engineers).

Public Works Flood Protection	Location	Completed	Agency	Cost (unadjusted)
Galveston Seawall	Galveston, TX	1904	USACE	$1.5 million
Herbert Hoover Dike	Lake Okeechobee, FL	1938	USACE	Unknown
Pawcatuck Hurricane Protection Barrier	Pawcatuck, CT	1963	USACE	$851,000
New Bedford Hurricane Barrier	New Bedford, MA	1966	USACE	$18.6 million
Fox Point Hurricane Barrier	Providence, RI	1966	USACE	$16.2 million
Stamford Hurricane Protection Barrier	Stamford, CT	1969	USACE	$14.5 million
Charles River Dam	Boston, MA	1978	USACE	$61.3 million
New London Hurricane Protection Barrier	New London, CT	1986	USACE	$12.0 million
Lake Pontchartrain and Vicinity Hurricane Protection (Levee/Dike)	New Orleans, LA	Destroyed during Katrina, 2005	USACE	$760 million
Inner Harbor Navigation Canal Lake Borgne	New Orleans, LA	2013	USACE	$1.1 billion

Chapter 6

Coastal flood protection megaprojects in an era of sea-level rise: politically feasible strategies or Army Corps fantasies?

Abstract

Storm surge barriers, levees, and other coastal flood protection megaprojects are currently being proposed as strategies to protect U.S. cities against coastal storms and rising sea levels. However, social conflict and other political factors add a layer of complexity that casts doubt on their status as practical climate adaptation options. The specific mechanisms for why some projects do not progress beyond initial planning stages has remained unclear. Here we study the outcomes of two Army Corps storm surge barrier proposals to explore the political reasons why some coastal flood protection megastructures break ground in the U.S., while others do not. Using original archive research, we find that acceptable forecasted environmental harms and broad and consistent support from both the public and elected officials are important factors for projects to move beyond the initial planning stages. However, we are pessimistic that storm surge barriers will be politically feasible

climate adaptation options for most U.S. cities as a result of 1) modern environmental laws that elevate oppositional viewpoints, 2) the allure of alternative options that are more aesthetically pleasing and cheaper and faster to implement, and 3) lengthy and complex decision-making procedures that coincide with fading memories of floods.

6.1 Introduction

6.1.1 The puzzle: coastal cities need flood protection, but big projects rarely break ground

The need for coastal flood mitigation in the U.S. is widely apparent given the societal impact of recent costly and deadly hurricanes (2018: Florence and Michael, 2017: Harvey and Irma, 2012: Sandy, 2011: Irene, among others) (USACE, 2015). Further emphasizing the need for risk reduction is 1) increasing coastal development (Crossett et al, 2013; Neumann et al, 2015; Titus et al, 2009), 2) sea-level rise—which decreases the return periods of extreme sea levels that can lead to floods (Buchanan et al, 2017; Rasmussen et al, 2020)—and 3) the fiscally-stressed National Flood Insurance Program (Brown, 2016). State and local governments in the U.S. are currently investigating various strategies to reduce damages caused by coastal floods, including engineered (e.g., levees and storm surge barriers) and natural (e.g. oyster beds and wetland restoration) risk reduction structures, flood accommodation (e.g., elevating the built environment), coastal advance (e.g., building out into the water via land reclamation), and retreating from the coastline. Each strategy comes with different risk reduction costs and benefits (both monetized and non-monetized), including different levels of impact on ecosystems and the natural environment.

Storm surge barriers, levees and other megastructures are specific structural defense strategies that are technically viable options for densely populated areas to manage sea-level rise and coastal flooding (Aerts et al, 2014; Jonkman et al, 2013; Mooyaart and Jonkman, 2017; Morang, 2016; US National Research Council, 2014)(e.g., the Fox Point Hurricane Barrier in Providence, Rhode Island; Fig. 6.1). For example, the Stamford (Connecticut) storm surge barrier has been used hundreds of times for storms and high tides. In 2012, it prevented an estimated $25 million US dollars (USD) in damages to businesses and homes from high waters produced by Hurricane Sandy. Stamford's mayor said, "[the barrier] was extremely effective in protecting areas that would have been flooded completely by this storm. It made all the difference in the world" (Navarro, 2012). Densely populated cities, like Stamford, often lack the space to take advantage of natural defenses (e.g., sand dunes or wetland restoration), and other coastal adaptation options (e.g., managed retreat, informed land-use planning, building codes, and insurance) can conflict with goals for local development.

The Civil Works program of the U.S. Army Corps of Engineers, the principal federal agency responsible for studying and designing coastal flood protection infrastructure (hereafter, the Corps)(USACE, 1998), is currently proposing storm surge barriers and levees for several U.S. cities (USACE, 2016a, 2018a,b, 2019b, 2020c,a,b). Non-Corps entities have proposed similar projects (City and County of San Francisco, 2016; City of New York, 2013, 2020; SSPEED, 2020; Sustainable Solutions Lab, 2018). In total, these projects are estimated to cost between \$70 and \$193 billion USD (Table 6.1). To date, none of these coastal flood protection megastructures[1] have broken ground, despite most being designated as technically feasible (from an engineering standpoint), economically beneficial (i.e., benefits > costs), and generously funded. For example, in the eight years since Hurricane Sandy caused roughly \$19 billion USD of direct damage to New York City and claimed the lives of 43 people (City of New York, 2013), no major megaproject to address coastal flooding has broken ground (Daily News Editorial Board, 2020) [although two shore-based megaprojects have recently been cleared to begin construction (Cohen, 2019; Smith, 2019)]. This is in spite of roughly \$15 billion USD (NYC Comptroller, 2019) in federal funds for coastal risk reduction measures and multiple proposals for technically feasible and economically justifiable adaptation works, such as storm surge barriers (USACE, 2019a) (Fig. 6.1), levees (USACE, 2016a), and floodable public spaces (City of New York, 2020). Generous financing, sound engineering, and favorable economics appear to be necessary, but, by themselves, insufficient for implementation.

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[1] Structured, engineered public initiatives that involve huge commitments of public resources in terms of finances (> \$0.5 billion USD) and planning (Altshuler and Luberoff, 2003; Flyvbjerg et al, 2003b)

Coastal flood protection megaprojects designed and built by the Corps and other government agencies are not evaluated and implemented in a political vacuum (Adger et al, 2009; Dolšak and Prakash, 2018; Eakin et al, 2017; Eriksen et al, 2015; Leiserowitz, 2006; Moser and Ekstrom, 2010; Rasmussen et al, in review; Sovacool and Linnér, 2016). They are guided by an extensive body of laws, regulations, and polices and involve coordination and cooperation between elected officials at all levels of government, federal agencies (e.g., the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service), and a variety of stakeholders that may be inherently biased in supporting (e.g., contractors, professional associations, academics) or opposing projects (e.g., NGOs and academics) (Samet, 2009). Recent media attention has highlighted the political contentiousness of these projects. In Miami, a Corps proposal for a levee system received strong opposition from the public and government officials who instead advocated for nature-based solutions. The chair of Miami's Downtown Development Authority proclaimed, "[n]obody wants to see the Berlin wall in the middle of Biscayne Bay" (Allen, 2020; Harris, 2020). In New York City, a detailed plan developed over several years between city officials and several Lower East Side advocacy groups was abruptly replaced with a new design that was less popular with local residents. City officials defended the new plan saying it could be completed quicker (three years, as opposed to five) and would not lead to costly traffic restrictions that would have been necessary under the original proposal (Araos, 2020; Hanania, 2019). In February 2020, an in-progress Corps study of coastal flood protection within New York Harbor and its tributaries was abruptly halted just weeks after President Trump expressed his disapproval of the project, leading to speculation that his opinion may have influenced agency staff (Barnard, 2020).

Political scientists have long studied both the complexity and difficulty of translating public policy into practice (deLeon and deLeon, 2002; Elmore, 1979; Ferman, 1990; Pressman and Wildavsky, 1984), including cases where there exists both viable technical solutions and financial resources (Pressman and Wildavsky, 1984). In the case of infrastructure, siting conflicts (sometimes referred to as "not-in-my-backyard" or NIMBY) can arise when governments attempt to construct public works that aim to increase the general welfare of their citizens but coincidently impose adverse impacts on some groups (e.g., eminent domain, decreases in property value, deterioration of the natural environment, and lost amenities)

(Aldrich, 2008; Devine-Wright, 2011; Kraft and Clary, 1991; McAvoy, 1999; Munton, 1996; Smith and Klick, 2007). Army Corps megaprojects that are not favored by the public are unlikely to generate both the necessary support needed to pass referendums to finance local cost shares or encourage their congressional delegates to support project authorization (Samet, 2009). Additionally, regulatory battles in courts between the public and federal agencies can lead to project deadlock, delays, and failures (Bligh, 2006; Buzbee, 2014; Kagan, 1991; Kysar and McGarity, 2006; Luther, 2006; Murchison, 2007). If storm surge barriers, levees, and other coastal flood protection megastructures are to remain politically feasible climate adaptation strategies, a better understanding of complexity that politics adds to these projects is needed (Javeline, 2014).

Empirical case studies can open up the "black box" of politics and identify plausible causal processes that may determine when projects do and do not break ground (Biesbroek et al, 2014; Bisaro and Hinkel, 2016; Hinkel et al, 2018; Measham et al, 2011; Sieber et al, 2018; Wellstead et al, 2014). This may give coastal managers a priori information regarding the political feasibility of projects. While some studies exist for Dutch flood projects (Bijker, 2002; Disco, 2002), to our knowledge, no such assessment has been performed specific to Army Corps coastal megastructures. The Corps has been well-studied (Ferejohn, 1974; Maass, 1951; Mazmanian and Nienaber, 1979; O'Neill, 2006; Pilkey and Dixon, 1996), including some political aspects of conceiving, designing, and implementing coastal flood protection megastructures (US National Research Council, 1999, 2004, 2011, 2014). However, detailed case studies have not been presented, and little attention has been given to siting-related opposition. Much remains to be learned. The ways in which politics can derail coastal projects has even puzzled retired USACE employees.[2] Given the current level of national interest in these strategies for managing sea-level rise (City and County of San Francisco, 2016; City of New York, 2013; Sustainable Solutions Lab, 2018; USACE, 2016a, 2018a,b, 2019a, 2020c), such an effort is warranted. Additionally, the Army Corps figures to play a prominent role in coastal adaptation given their wealth of technical expertise, more

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[2] Morang (2016) states, "Despite a decade of intensive study, the Narragansett Bay barriers were never built. I was unable to find documents stating the final reason why the project never came to fruition…"

than 60 years[3] of experience with coastal risk reduction efforts, and coastal jurisdiction in terms of navigation, dredging, and filling (Moritz et al, 2016; Samet, 2009).

6.1.2 Research approach and summary of findings

To understand the reasons for starting but ultimately not breaking ground on a technically feasible and economically justifiable coastal adaptation project, we ask, "what are the specific political reasons why coastal flood protection megaprojects both do and do not progress beyond the planning stage?" Because in-progress Corps projects are too recent to provide a complete overview of the political process from conception to implementation and because archive materials are scarce, we consider two Rhode Island storm surge barriers simultaneously planned between the mid-1950s and mid-1960s: the Fox Point Hurricane Barrier and the Narragansett Bay Barriers (Figs. 6.2 and 6.3; Section 6.2). We recovered nearly a thousand documents related to these storm surge barriers (Section 6.3.2). The Corps designated both projects as technically feasible and economically justifiable, but ultimately, only the Fox Point Hurricane Barrier broke ground (dedicated in March 1966). Despite these projects appearing prior to modern environmental laws, many of the stages between conception, authorization, and appropriation remain the same (Section 6.2.4).

Using process tracing and archival materials, we show that the Fox Point Hurricane barrier progressed beyond the planning stage as a result of minimal environmental concerns and strong, sustained support from both the public and Rhode Island's elected officials (Section 6.4.2). On the other hand, we find that the Narragansett Bay barrier project failed to break ground due to strong public opposition, related, in part, to forecasted increases in channel currents that had the potential to complicate maritime navigation, uncertain impacts on marine life, and an almost decade long planning period during which the public's flood concerns declined (Section 6.4.1).

Our assessment may appear to take the normative stance that building a megastructure is universally preferred over not doing so. This is not our intent. Knowing why projects fail to break ground is also useful for those who wish for a particular project to not get built.

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[3] The Corps was involved in two projects in the early twentieth century (Table 6.2) but studying coastal flood protection was not officially added to their jurisdiction until 1955 (Public Law 71, 84th Congress, 1st Session).

There may be several valid reasons why a Corps project should never break ground (Section 6.2.2), despite the well-intentioned effort to improve societal welfare by reducing coastal flood risks. While projects are labeled feasible and economically beneficial by government agencies, their analyses may not identify undesirable outcomes, such as encroaching upon environmental protection efforts, worsening social inequalities, transferring funds from public to private groups, or being maladaptive (Barnett and O'Neill, 2010; Sovacool and Linnér, 2016).

In the following section (Section 6.2), we give an overview of the Corps' history and role in coastal flood protection, discuss plausible justifications for both supporting and opposing storm surge barriers as flood protection strategies, and introduce the Fox Point and Narragansett Bay barrier projects. Next, we describe the archival data sources used for this study and describe our case study and process tracing methodological approach (Section 6.3). From a detailed timeline of the Rhode Island storm surge barrier projects reconstructed from archive materials (given in the appendix, Section 6.8), we identify the mechanisms that led to the outcomes of each project (Section 6.4). When then propose four ways in which politics adds complexity to Corps megastructures and provide supporting examples from current efforts to build these projects in U.S. coastal cities (Section 6.5). We discuss our findings (Section 6.6), and then conclude with recommendations for how the Corps could limit project delays, deadlocks, and failures (Section 6.7).

6.2 Background: the Army Corps, storm surge barriers, and the Rhode Island projects

6.2.1 The U.S. Army Corps of Engineers: a short history of both coastal flood management and local engagement prior to NEPA

Since the early 19th century, Congress has assigned the responsibility to the federal government to either undertake or assist in the development of water resource projects (John Lonnquest et al, 2014). This eventually included flood protection (Joseph L. Arnold, 1988). However, the Corps did not specifically get involved in coastal flood protection until after

World War II[4], following a series of destructive and deadly hurricanes in New England and elsewhere. In 1955, Congress authorized hurricane studies of coastal areas on the Eastern Seaboard and Gulf Coast in recognition of the need to consider protection against coastal floods.[5] Assigning the responsibility of flood protection to the government is not unusual. Welfare states have long built floodwalls and levees to keep their citizens safe (John Lonnquest et al, 2014). In the U.S., the Corps has largely been the facilitator of flood protection public works. With the support of a non-federal sponsor, the Corps' job is to present the engineering solution and the economic facts as a basis for decision. The decision to move forward with projects is up to the public, local and state government, and Congress (Samet, 2009). For example, after a project has been formulated, the public can pressure elected officials to support or oppose projects, and the public can (after 1970) file lawsuits that can lead to formal judgements (Luther, 2008). Over the years, Congress has increasingly broadened the agency's responsibilities, leading to a shift to operations, maintenance and restoring aquatic ecosystem functions (US National Research Council, 2011, 2014). Despite the de-emphasis on new construction, the Corps is occasionally directed to undertake new, high-priority projects, such as those in the greater New Orleans region following Hurricane Katrina.

In the 1950s and 60s, the Corps was largely viewed as a construction-oriented organization with a strong commitment to economic development (Mazmanian and Nienaber, 1979; US National Research Council, 2011). It was heavily involved with the construction of megaprojects (Altshuler and Luberoff, 2003; Flyvbjerg et al, 2003b). Altshuler and Luberoff (2003) describe period of the Rhode Island storm surge barriers as the "great mega-project era" (1950s to late 1960s), a period of "unprecedented" federal investment in public works (e.g., urban renewal, highway construction, and airport development). During this time, public confidence in government was high, and because they aimed at generating economic activity, many of these megaprojects were supported by businesses, labor groups, and the media. However, megaprojects often entail significant threats to some interests and values, even as they promise great benefits to others. By the mid 1960s, it became apparent that

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[4] Some of the earliest coastal flood protection projects carried out by the USACE were the Galveston Seawall in 1902 and hurricane control gates and barriers in Lake Okeechobee, Florida in 1938.

[5] Public Law 71, 84th Congress, 1st Session

many of these projects were negatively impacting communities and the natural environment. The Corps was a frequently cited offender. In the late 1960s and early 1970s, the agency came under scrutiny for an increasingly poor track record of giving little consideration to the natural environment and also sustaining decision-making protocols that ignored oppositional viewpoints (Douglas, 1969; Drew, 1970; Mazmanian and Lee, 1975; Porter, 1971; Reuss, 1971; Sargent, 1972; St. Louis Globe-Democrat, 1971). As a result, the Corps was forced to re-evaluate their approach to public engagement and planning (Mazmanian and Nienaber, 1979).

Prior to the mid 1960s, the USACE's megaproject planning process largely consisted of local proponents, the USACE, and project allies in Congress. It was more or less exclusionary to project opponents and communities. Engineers were often the only experts involved in deciding both how to define the flood problems communities were experiencing and also the objectives and goals of the plan to address the problem. Additionally, alternative plans were rarely produced. Oppositional viewpoints from concerned publics began to disrupt the Corps' megaprojects that had previously appeared to be unstoppable in other parts of the country. This movement led to a number of project turndowns by governors and other state authorities, the Narragansett Bay barriers being among them (Isé, 1965). Ultimately, the amassing of similar project failures across the U.S. started an organizational shift within the Corps that was further solidified with the passage of the National Environmental Protection Act (NEPA) in 1970. The NEPA allowed for citizens and other groups to secure significant litigation powers (who have otherwise had no direct say in projects) and also facilitated transparency in terms of the potential negative impacts of projects through environmental impact statements (EISs).

6.2.2 Storm Surge Barriers as Coastal Flood Protection Strategies

Storm surge barriers (sometimes called hurricane or harbor barriers) are engineered barriers placed within bodies of water (usually tidally influenced rivers or estuaries) that have openings (either permanent or gated) to allow for tidal flushing and maritime navigation (Mooyaart and Jonkman, 2017; Morang, 2016). Barriers with gates close during forecasted high-water events (e.g., coastal storms). In the U.S., the Corps has built roughly seven storm surge barriers of various sizes (Morang, 2016), including the Fox Point Hurricane Barrier (Table 6.2). The last to be constructed was the Inner Harbor Navigation Canal Lake Borgne Surge Barrier near New Orleans, Louisiana (completed in 2013). Prior to the Lake Borgne project, the agency had not built a major surge barrier since the Charles River Dam in 1978 (Morang, 2016). Internationally, storm surge barriers have been built in Russia, Japan, England, the Netherlands, and Germany. A newly constructed massive barrier in Italy recently protected Venice during a high water event (Mooyaart et al, 2014; Silvestri, 2020).

Common criticisms of storm surge barriers include their potential harms to natural ecosystems (Nienhuis and Smaal, 1994; Orton et al, 2019; Swanson et al, 2012), high cost ($>$ \$100 million USD)(Mooyaart and Jonkman, 2017), lengthy planning and implementation periods (often several decades, see appendix, Section 6.8), their unsightly presence that degrades the natural appeal of coastal waterways, inability to address frequent floods that do not trigger gate closure (e.g., sunny-day flooding), perverse secondary effects such as encouraging further development in hazardous areas (i.e., the "levee effect")(Di Baldassarre et al, 2018; White, 1945), and the inherent long-term commitment to a largely irreversible and inflexible investment. In spite of this list of unfavorable attributes, there is evidence that storm surge barriers can provide net benefits in terms of avoided damages (Comiskey, 2005; Lavery and Donovan, 2005; US National Research Council, 2014; USACE, 2013a)[6], even in the context of sea-level rise (Aerts et al, 2014). In a review of existing coastal protection practices in the U.S., the National Research Council found that "[h]ard structures are likely to become increasingly important to reduce coastal risk in densely populated urban areas", partly because urban areas lack the space to take advantage of nature-based strategies (e.g., mangroves, sand dunes, ect.) and the value of property usually justifies the high cost of the barriers[7] (US National Research Council, 2014). When placed across narrow inlets on major waterways, surge barriers can protect large regions from extreme water levels. In other words, surge barriers placed across small distances can address long stretches of shoreline that may otherwise require its own protection. As such, we argue that storm surge barriers

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[6] Admittedly, independent, ex-post empirical assessment of storm surge barrier performance is lacking. More evidence-based studies are needed to better quantify the reductions in damages that are facilitated by storm surge barriers. Evidence presented is from the USACE and may be vulnerable to institutional biases

[7] Benefit-cost analysis driven by property values is inherently regressive and will disfavor low-income populations (Sovacool and Linnér, 2016)

remain an economically viable and technically feasible option to manage coastal flood and sea-level rise impacts in urban areas within a broad and diversified suite of coastal risk reduction strategies that include engineered and nature-based measures as well as policies such as insurance and building codes.

6.2.3 The Fox Point and Narragansett Bay Barriers

Information on the political aspects of coastal flood protection megastructures is rare, in part because only a few large projects have gotten built in the U.S. In researching this topic, we discovered that among these, there are even fewer available primary and secondary sources for studying non-technical aspects of projects. Ultimately, we were able to recover materials for the Narragansett Bay barriers and Fox Point barrier projects to aid in exploring the political reasons why their respective outcomes occurred. Two projects arising simultaneously with different outcomes can help identify reasons why each outcome occurred.[8] If both projects were successful in breaking ground (i.e., no variation in outcome), then it could not be deduced what may lead to projects not breaking ground. It would be an "analytic dead end" (King et al, 1994b).

The Fox Point and Narragansett Bay storm surge barriers were among the first coastal flood protection public works megaprojects proposed in the U.S. (Morang, 2016). They both possessed an imposing physical presence, a combined price tag of close to a billion dollars (2020 USD$) and required substantial involvement of public resources. The Fox Point Barrier was completed by the USACE in January 1966 at a cost of $16.2 million (Fig. 6.2) (Frederiksen, 1966). It lies 1.4 km south of downtown Providence and sits across the Providence River, adjacent to the Providence River Bridge that carries Interstate 195. The Fox Point Barrier currently protects roughly 1.1 km^2 of downtown Providence and $2 billion worth of property (Kuffner, 2019) against a storm surge of 6.25 m (above mean sea level)[9] (Engineering News-Record, 1963). The projected benefit-cost ratio in 1958 was 2.37 (Secretary of the Army, 1958). The barrier itself consists of a 213 m long concrete gravity

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[8] Variation is on independent variables is more constrained, while the dependent variable is different (built or not).

[9] Or about 5.0 m above MHHW (after adjusting for SLR), roughly the height of the 1000-yr event (not accounting for wave setup or swash)

dam with three sluice gates to pass normal flows from the river and tides, a pumphouse to discharge the Providence River when the gates are closed to prevent flooding behind the barrier, and two earthen levees that flank each end of the dam (eastern levee is 238 m in length and the western levee is 427 m in length). In total, the barrier spans roughly 0.8 km. Removable gates were also installed in sewer pipes below ground to prevent backflow (Engineering News-Record, 1963). While the Fox Point Barrier achieved broad public support and eventually broke ground, the Narragansett Bay Barriers did not make it past the planning stage.

The Narragansett Bay Barriers were a Corps flood protection project designed to provide flood protection for cities and towns in and around Narragansett Bay. The Chief Engineer of the Corps' New England Division described the Bay barriers as "unrivaled in scope and magnitude by any similar project in the world—a project equally as imaginative as the St. Lawrence Seaway or the International Passamaquoddy Tidal Power Project, and a project that has. . . posed some of the most challenging problems of professional engineering research" (Sibley, 1959). While the Fox Point barrier served those in Rhode Island's capital city, those below were still left exposed to coastal floods. The project was comprised of three massive rock barriers with an ungated, navigational opening large enough to allow sufficient maritime travel, but small enough to constrict the flow of storm surges into the bay. The "East" barrier was planned for across the eastern bay passage in the vicinity of Castle Hill in Newport, Rhode Island, the "West" barrier was planned for across the western bay passage at Bonnet Shores, and the third earth-fill barrier was to be placed across the Sakonnet River between Tiverton and Portsmouth (Fig. 6.3). Both the East and West barriers were to have 40 sluice gates to reduce the current velocity through the navigational opening and to lessen any impact on the normal tidal interchange and flushing of Narragansett Bay. Supplemental levees were planned for Bonnet Shore, Mackerel Cove, and Castle Hill. Unlike the Fox Point barrier, the lower bay project did not completely close off the waterway. As such, it merely attenuated storm surge coming into Narragansett Bay.[10] It was estimated that the barriers would eliminate 93 percent of the damage from future hurricanes. The

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[10] Local officials were required to notify residents at least once a year that the barriers did not provide complete protection from hurricane tidal surges.

projected cost was $90 million, roughly 30 percent of which was to be paid for by Rhode Island and Massachusetts. The projected benefit-cost ratio was reported to be 1.4, less than that of the Fox Point project (Secretary of the Army, 1966).

6.2.4 Applicability of older projects as case studies

While these projects were conceived over six decades ago, many aspects of the Corps' decision-making process leading up to breaking ground on megastructures have largely remained the same, including close involvement with Congress, state and local elected officials, and other federal agencies. For example, local interests are still required to initiate all surveys performed by the Corps. The Corps cannot act unilaterally.[11] The law that authorized the Corps to carry out the study of the Rhode Island barriers is still invoked today.[12] Secondly, Corps projects are still required to be reviewed by the public, including informing them of proposed designs and their potential impacts. However, environmental protection laws, such as NEPA, the Clean Water Act (CWA), and the Endangered Species Act have made this step a much more complex legal process (Mazmanian and Nienaber, 1979; US National Research Council, 2011). For example, under NEPA, Corps projects that pose significant harms to the quality of the natural environment must analyze and publicly disclose a proposal's environmental impacts through an environmental impact statement and receive public comment on the proposal and its alternatives (Luther, 2008). Some states and cities duplicate powers and add more project hurdles (e.g., New York City and California) (Buzbee, 2014; Side et al, 2005). While this process is not a direct legal barrier to project implementation per se, the transparency of potential ecological harms it provides can trigger public opposition (Buzbee, 2014). On the other hand, some environmental laws can block projects altogether. Under the CWA, projects cannot be built in coastal waterways unless 1) the sponsoring agency proves they need to be built in the water or 2) the project will not cause "significant degradation" to important aquatic habitats (Copeland, 2016). Third, state and federal agencies are still required to review Corps plans (Samet, 2009). Fourth, the cost of Corps projects is still split between the federal government and local interests (although

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[11] Congress can order the Corps to act in an emergency (e.g., flood protection in New Orleans post-Katrina)

[12] Public Law 71, 84th Congress

the local share has increased from 30 to 35 percent). Fifth, congressional authorization is still required for all projects (now through Water Resources Development Acts, previously River and Harbor or Flood Control Acts), and congress must still appropriate funds (Carter and Stern, 2010).

6.3 Methods

In this study, we use a case-oriented approach to help illustrate how political complexity played a role in both the Fox Point and Narragansett Bay storm surge barriers. For both projects, we use within-case process tracing to describe the series of events that led to the outcome of each project (i.e., breaking ground or not). Because there is no published information on the projects, we reconstructed the events around each barrier using thousands of documents found in archives (see Appendix, Section 6.8). Our ambitions for this study are to produce "minimally sufficient explanations" (Beach and Pedersen, 2013) for each storm surge barrier outcome using recovered archive materials. In other words, our research strategy is descriptive and exploratory, rather than confirmatory or inferential. It is based on the details learned from both storm surge barrier cases and does not attempt to identify causal mechanisms or produce causal inference. For both projects, we use within-case process tracing to identify and describe multiple plausible causal mechanisms that led to each project outcome. These plausible causal mechanisms serve as hypotheses that can be tested in a subsequent study.

6.3.1 Within-case process tracing approach

In the social sciences, process tracing seeks to analyze sequences of events as they unfold over time, from initial conditions to a given outcome. This involves searching for evidence about the process by which a certain outcome was produced, such as reading written records from archives, in this study's case. However, process tracing is more than simply just giving a chronology of events or an historical narrative. By observing the underlying relationship between actors and other variables, process tracing can uncover what plausible causal mechanisms could be at work in order to explain cause and effect (Beach and Pedersen, 2013;

John Gerring, 2007). This can lead to producing plausible hypotheses and also to finding observations that refute a given hypothesis. While process tracing can identify plausible causal mechanisms, King, Keohane, and Verba argue that it is unlikely to produce strong causal inference because 1) it does not identify the counterfactual situation to what was observed and 2) it does not differentiate between the various effects of causes in the case that more than one causal mechanism could be activated. The latter includes making clear the relative strength of the explanatory variables.

For each Corps project, we perform a within-case analysis. The decision of when to start process tracing is an import question that must be answered for every process tracing analysis (Beach and Pedersen, 2013). We use the aftermath of Hurricane Carol as the "critical juncture" at which the Corps, the City of Providence, and the State of Rhode Island all began to consider coastal flood protection in earnest. While projects can fail during the construction process itself, we limit our analysis to the events leading up to breaking ground on a project.

6.3.2 Data collection and methods

For good process tracing, a detailed and complete description of event sequences is key. Almost no information related to the political process of the Fox Point or Narragansett Bay Hurricane Barriers is located online or in published secondary sources. The only information on political aspects were found in a series of small paragraphs in Morang (2016), where the author offers several hypotheses from personal communication with retired USACE employees, including environmental concerns. We use nearly 2000 primary documents collected at public and private archives between September and November 2019 (a handful are secondary in nature). Documents included projected-related materials and newspaper clippings from the New England District of the USACE archived at the U.S. National Archives and Records Administration facility (Waltham, Massachusetts), personal papers from Congressman John E. Fogarty, Senator John Pastore, and Governor Dennis J. Roberts archived at Providence College, over a decade of newspaper articles on microfilm from the Providence Journal and Evening Bulletin archived at both the Rhode Island Historical Society and the Providence

Public Library, and additional materials associated with the Fox Point Hurricane Barrier at the Providence City Archive (all Providence, Rhode Island).

The collected documents included primary sources such as memos between government agencies and elected officials, technical reports from federal agencies and academic institutions, speeches, transcripts of congressional hearings and town hall meetings, letters to senators and congressman, newspaper articles that recounted the previous day's events, editorials, and op-eds. A key contributor to the analysis was more than 540 unique newspaper articles that served as a play-by-play on the entire process of bringing coastal flood protection to Rhode Island. These articles covered the aftermath of Hurricane Carol in 1954 to the final decision to shelve the Narragansett Bay barrier project in 1966.

6.3.3 Methodological caveats

Our methodological approach closely resembles that of historical scholarship. However, that should not prevent this study from adding value to both the climate adaptation and natural hazards literatures. First, King, Keohane, and Verba 1994a note that mere description is one of the two primary goals of social science (in addition to causal inference). Second, detailed case studies, while being limited to context-dependent knowledge, can provide a lens through which to view real-life situations, and multiple case studies taken together can form the basis of expert knowledge for practitioners (Flyvbjerg, 2006a). Case studies may provide depth that generalizable theories cannot (Gerring, 2004; Peattie, 2001). Additionally, they serve as a natural bridge between rich empirical evidence and theory building (King et al, 1994b). Because our findings are not generalizable, we recommend that this study's lessons and conclusions be limited to other comparable cases. Additionally, historical case studies are subject to external validity concerns.

6.4 Plausible explanations for the Rhode Island storm surge barrier outcomes

6.4.1 The Narragansett Bay Barriers: killed by public opposition

What are the specific political reasons why coastal flood protection megaprojects do not progress beyond the planning stage? The experience with the Narragansett Bay barriers suggests that the public's reaction to perceived/intuited or expertly forecasted adverse impacts is a strong predictor of a project's ultimate fate. These impacts include the risk of degrading an area of its unique natural beauty (e.g., structures themselves are aesthetically displeasing, increased water pollution), threats to maritime travel (recreational, commercial, and military), and risks of adverse impacts on complex ecosystems (including marine life). In response to the public opposition, elected officials were unwilling to move the project forward, despite them not explicitly opposing the barriers outright. Support from a state's congressional delegation proved to be critical for pushing the Fox Point Barrier through Congress (Section 6.4.2); without it, the project had no chance of being authorized or appropriated. The Chief of Rhode Island's Division of Harbors and Rivers requested stopping the Narragansett Bay barriers because they were unable to foresee voters passing future referendums to pay for the roughly $20 million non-federal share of the costs (e.g., through a voter-approved government bond issue). Additionally, deliberation over the specifics and likelihood of the impact of the barriers carried on for almost a decade, during which public interest in permanent flood protection diminished (Jacobs and Matthews, 2012). Some who had initially favored the barriers ended up changing their minds.

6.4.2 The Fox Point Barrier: three factors why projects get done

Knowing why some projects get built is as at least as useful as knowing why they failed to get built. Because it was constructed and the political process was well-documented leading up to breaking ground on the project, the Fox Point Barrier is a good case for understanding when, why, and how flood protection megaprojects get built in the U.S. We identify three unique factors that contributed to the success of the Fox Point Barrier breaking ground: 1) strong and consistent public demand for flood protection, 2) strong and consistent support from elected officials, and 3) little to no opposition from local organized interests.

Damages sustained by businesses from Hurricane Carol in 1954 increased attention in permanent flood protection well above that produced by the hurricanes in 1938 and 1944. Businesses were ready to invest their own money in a permanent solution if the federal government was not able to help. Local businesses also formed a hurricane protection committee in the hopes of maintaining interest in Providence's flood problem and to also serve as a link to elected officials. Many close calls with other storms in the years after Carol helped to sustain public interest in flood protection in Providence. Additionally, state and local election drives kept attention on flood protection high enough to pass two referendums needed to cover the non-federal share of the barrier cost. A key element in obtaining statewide approval (i.e., from those who would not directly benefit from protection) was the promoting the belief that Providence was of significant importance to the overall economic well-being of the state.

Elected officials heeded the demands from local businesses for permanent flood protection by continuing to support the effort many years after Hurricane Carol. Support from the Rhode Island congressional delegation was critical for pushing the Fox Point Barrier towards congressional authorization and appropriation, particularly from Congressman Fogarty and Senator Pastore. The congressional process for approving and funding the Fox Point Barrier was a long, slow obstacle course, in part because of the many policy issues that the U.S. government was giving attention to at the time (e.g., rising Cold War tensions). At multiple decision points, the fate of the project seemed to hang in the balance, only to have Rhode Island's congressional delegates keep the projects in play. Obtaining approval from President Eisenhower also was necessary.

Lastly, the absence of opposition from community boards, civic organizations, and environmental groups proved beneficial. Little local opposition must be present in order for projects to move beyond the planning stage. This aspect of the Fox Point barrier vastly differed from that of the Narragansett Bay project. The siting of the barrier in Providence impacted few of the same organized interests that opposed the Bay barriers (e.g., environmental interests). The Providence River, across which the barrier was built, was already polluted, so there was no increased threat to marine life. The water behind the barrier was also of little use to boating interests. The only organized opposition that was observed came from a group of property owners that were outside of the planned protection area.

6.5 Empirically determined ways in which politics adds to coastal flood protection megastructure complexity

6.5.1 Project risks to the natural environment are likely to incite opposition

Significant opposition to the Narragansett Bay barrier project resulted from worry over environmental degradation. The placement of storm surge barriers across waterways continues to raise concerns regarding their environmental impacts (Royte, 2019; Ong, 2018; Roff and Gallay, 2018; Stringer, 2019; USACE, 2019b), including but not limited to impeding natural tidal flows, habitat destruction, changes in sedimentation rates, trapping pollutants, and degrading water quality (salinity, temperature, circulation, dissolved oxygen, nutrient concentrations, and algal blooms). Studies conducted on the environmental impacts of Delta Works Projects in the Netherlands support these concerns (Bakker et al, 1994; Eelkema et al, 2011; Nienhuis and Smaal, 1994; Smaal and Nienhuis, 1992; van der Tol and Scholten, 1997), but impacts remain hard to forecast with the accuracy and precision desired by both modern environmental laws and those in opposition (e.g., environmental NGOs)(Flyvbjerg et al, 2003a; Fukuyama, 2017; Ortolano and Shepherd, 1995). The Narragansett Bay barrier experience showed that even close to a decade of study is sometimes not enough to arrive at a conclusive outcome. As such, the potential for environmental harm remains a viable veto point for any storm surge barrier or other coastal flood protection megastructure.

Today, modern environmental laws empower minority interests by authorizing them to legally challenge federal projects. Much in the same way that Rhode Islanders criticized the Corps presentation of the barrier's impacts, opposition for modern Corps projects now comb through Feasibility Studies and/or environmental impact statements (EISs) to find technical flaws that can be used as arguments against a project (Buzbee, 2014; Flyvbjerg et al, 2003a; USACE, 2019a). As long as critics believe that a project fails to meet scientific and legal criteria, the EIS can be challenged in court (Buzbee, 2014; Kagan, 1991; Luther, 2006). In some cases, this has led to long delays in bringing about coastal risk reduction (Bligh, 2006; Kysar and McGarity, 2006; Luther, 2006). Multiple on-going Army Corps proposals for surge barriers have recently come under scrutiny by environmental NGOs and other government officials during the feasibility stage, even before their EISs have been completed. This includes proposed storm surge barriers in New York City (Royte, 2019; Ong, 2018; Roff and Gallay, 2018; Stringer, 2019), Miami (Allen, 2020; Weber, 2020), and Houston (Cusick, 2020). The Bay barrier experience suggests that these early environmental concerns may be a harbinger of a project that is doomed to fail.

However, the fact that the Narragansett Bay barrier experience pre-dated modern environmental laws suggests that the current, more strict process is not necessarily to blame for past and ongoing megaproject delays, deadlocks and failures. In the mid 1950s, Brig. Gen. Fleming, at the time the Chief Engineer of the New England Division, observed that many projects aimed at addressing flood issues in Rhode Island had not been dealt with in the past because of objections from “certain minority groups” (“minority” meaning small, political interests) and that public opinion had been the “determining factor” in the fate of any flood control effort (Goodrich, 1956). Some scenic regions such as Narragansett Bay may be inherently politically unfit for coastal flood protection megastructures due to heavy recreational boating use, commercial fisheries, and cherished natural beauty. The importance of preserving unique natural beauty has been brought up by those opposed to engineered projects both in New York City past (Nolan, 1972; US National Research Council, 1971) and present (Royte, 2019; Ong, 2018; Roff and Gallay, 2018; Stringer, 2019), where the environmental NGO Riverkeeper declared that recent Corps storm surge barrier proposals would “threaten the very life of the Hudson River”(Riverkeeper, 2018) and in Miami, where critics argued that a seawall would block views and hinder access to the water (Allen, 2020; Weber, 2020). Similar claims were made during the planning of the Eastern Scheldt Barrier in the Netherlands, suggesting that these experiences are not unique to the U.S. (Bijker, 2002; Disco, 2002).

6.5.2 Alternatives to storm surge barriers that are more environmentally friendly and faster to implement are sometimes the preferred coastal risk reduction approach

Several Rhode Islanders who opposed the Narragansett Bay barriers stated that they were still in support of coastal risk reduction by suggesting alternative strategies that would comparatively involve fewer environmental harms, would be cheaper (i.e., lower tax burden), and would be faster to implement. This included retreat, re-zoning, establishing a public flood insurance program, shore-based strategies like levees, and building-by-building measures such as flood proofing and temporary flood walls. During the time when the Narragansett Bay barriers were being considered, the Corps was not required to propose alternative strategies. When the barriers failed to advance, coastal risk reduction efforts failed with it. There was not another active project alternative to consider.

Today, critics of storm surge barriers in Boston, New York, Miami, and Houston have supported alternative flood risk reduction approaches that comparatively involve fewer environmental harms, are cheaper, and are faster to implement. Under NEPA, the Corps is required to consider multiple project alternatives, some of which may be favored by interests that oppose surge barriers. For example, environmental NGOs have expressed support for nature-based risk reduction measures (e.g., dunes, oyster beds, mangroves) as well as engineered structures along the shoreline (e.g., levees) (Ong, 2018; Riverkeeper, 2018; USACE, 2019c). In Boston, a study unaffiliated with the Corps found that shore-based strategies would be more cost effective, provide flexibility and adaptability, offer social-justice co-benefits, and cause minimal impact to the environment (Kirshen et al, 2020; Sustainable Solutions Lab, 2018). However, the purpose of nature-based strategies is primarily to reduce wave energy and limit erosion, not provide flood protection from extreme storm surges (Narayan et al, 2016; Oppenheimer et al, in press; USACE, 2015), and shore-based strategies like levees have also sometimes failed to gain support due to concerns over aesthetics and environmental degradation (Harris, 2020; Nolan, 1972).

The slow speed at which storm surge barriers and other Army Corps megaprojects move from the initial proposal to implementation has also encouraged support for alternative strategies that some believe can be implemented faster (Cusick, 2020; PlaNYC, 2013; Stringer, 2019; Sustainable Solutions Lab, 2018). Even in the 1950s, the media and public viewed the Corps' megaproject protocols as notoriously slow. In the wake of the third major flood in under two decades, Rhode Islanders lamented at the thought of a long, political "obstacle course" that would accompany any Corps-led flood protection effort (Dunbar Jr., 1956). Businesses in Providence were particularly eager for protection. Some went as far as to suggest that the City of Providence proceed without the help of the federal government, even if it meant footing a larger bill. Today, environmental laws have added even more steps to what some water infrastructure experts have described as a "remarkably inefficient" process (Knopman et al, 2017). Lengthy planning times can cause flood concerns to fade (Fanta et al, 2019; Jacobs and Matthews, 2012) and projects can stall. The Providence Journal wrote, "…the biggest immediate danger facing the barrier project is public apathy fostered by the passage of time… [the Bay barriers] deserves a better fate than death by disinterest" (Providence Journal, 1956e). The Army Corps was also aware of the impact of time on project interest. The Assistant New England Division Engineer had said, "…experience shows that the public in the past has had a tendency to lose interest in flood control as the last major disaster fades in their memory" (Providence Journal, 1956a). Ultimately, no other projects received seriously consideration besides the Bay barriers. When the barriers failed, the public and elected officials had lost interest and ultimately nothing was done to reduce coastal flood risk.

Today, concerns over how quickly storm surge barriers could be constructed (following approvals) have resulted in calls for support for alternative strategies. In a letter to the Corps, Scott Stringer, the New York City comptroller, advocated for shore- and nature-based approaches that could be built faster, "I also am concerned that the long timeline associated with the construction of these barriers – amounting to 25 years – will leave our City all too vulnerable to storms in the decades ahead." Mr. Stringer used the example of Venice's MOSE barriers to support his argument, which took nearly two decades of construction before they became functional (Stringer, 2019). Such delays are common with megaprojects throughout the world (Flyvbjerg et al, 2003b; Flyvbjerg, 2006b, 2007).The Thames Barrier in England also took almost a decade of construction to construct (following roughly two decades of planning; Horner, 1979). In Houston, designers of a smaller-scale surge barrier argued for their design over the Corps', under the belief that their project could be built faster, "[o]ur biggest concern is the length of time it will take to build. We get a major storm in here about every 15 years. The last one was 2017, so we could see another one before this project is complete" (Cusick, 2020).

6.5.3 Elected officials play an intricate and important role in leading Army Corps megaprojects through a complex maze of legal procedures

The Rhode Island storm surge barrier projects highlight the intricate and important role that elected officials play in Army Corps megaprojects. Support from congressional delegates is needed to shepherd projects through Congress (Knopman et al, 2017). Senator Pastore and Congressman Fogarty played critical roles in amassing support in Congress, while Governor Roberts and Mayor Reynolds were dedicated to bringing flood protection to Providence and elsewhere in Rhode Island. The Corps' ongoing South Shore Staten Island Project in New York City (a system of levees and raised embankments estimated to cost $615 million)(USACE, 2016a) recently highlighted the importance of congressional support in federal projects. New York Congressman Max Rose and Senator Chuck Schumer led an effort to pass new legislation that allowed the Corps to build a section of the seawall in Great Kills Park, part of Gateway National Recreation Area (Michel, 2020), and in Virginia, the entire congressional delegation recently requested additional planning funds for a series of Corps projects in Norfolk (13News Now Staff, 2020). On the other hand, a lack of support from congressional and local leadership for the Corps' coastal flood protection proposal for New York Harbor and its tributaries may have led to its demise. No New York Senator or Representative for a congressional district in New York City provided comment on the Corps' plans. Nor did the mayor of NYC (USACE, 2019a).

Endorsements from state-level leadership is also important for obtaining support outside the areas that are planned to be protected by storm surge barriers and other flood protection megaprojects. As the Providence barrier experience showed, those outside of the protected area are sometimes less willing to support referendums to pay for the state's share of project costs. Recently, New York Governor Andrew Cuomo declared his support for the Corps' South Shore Staten Island Project, calling it "innovative" and that it would "bring peace of mind to the diverse communities that live along the coastline" (Cohen, 2019).

6.5.4 Public trust in the Corps impacts project outcomes

The Narragansett Bay experience also showed how public trust in the Corps as an organization can impact project outcomes. Several residents became agitated after noting an obvious bias in the Corps' depiction of both the Bay barriers and themselves as an agency during the public hearings; this included showing a film in which the Corps is depicted as the "hero" in the fight against villainous New England hurricanes (Hawkes, 1964). A resident expressed their displeasure to the Corps, "I resent the biased presentation of the project. . . the presentation turns out to be a massive campaign to force the barrier upon us; distorted opinions and exaggerated damage figures compiled by persons whose main concern is to assure themselves of continued employment. Your agency should serve the taxpayers, not force your will upon us (at our expense)" (Thomas, 1964). Despite overwhelming public opposition, the Corps continued to push the Bay barriers towards authorization, citing the irrationality of project critics. Brig. Gen. Fleming called the opposition "self-appointed" flood control experts, promoting their own "woefully inadequate" views of technical aspects of projects, rather than relying on the conclusions of the Corps' studies. Previous Corp leadership even openly called the public a "threat" to their projects (Goodrich, 1956).

Today, environmental NGOs and other critics still expresses animosity towards the Corps and cite the Corps' history with their over-emphasis on concrete and steel projects. Some argue that the Corps' use of benefit-cost analysis as a basis for comparison between project alternatives is inherently biased against nature-based strategies (Koller, 2019; Weber, 2020) because the Corps does not monetize ecosystem services (Davis et al, 2009; USGAO, 2019) and other hard-to-monetize benefits and costs (e.g., biodiversity and culture) (Chambwera et al, 2014). For example, a representative for Miami Waterkeeper, an Environmental NGO, claimed, "This [proposed levee system] is really reflective of an agency that has a hammer and sees everything as a nail" (Allen, 2020). Critics of the storm surge barriers planned for

New York and New Jersey derided the Corps for a lack of transparency, poor public outreach, and short comment period (Fallon, 2018; Hellauer, 2018), and Riverkeeper called the Corps' public outreach process "woefully inadequate" (Riverkeeper, 2018). However, environmental NGOs have supported Corps proposals for shore-based measures, such as dunes, groins, and buried seawalls (Roff and Gallay, 2018).

6.6 Discussion

In the U.S., the conception, design, and implementation of storm surge barriers, levees, and other coastal flood megastructures is simply not a matter of federal agencies drawing up technically feasible designs that are economically justified. The experience with the Rhode Island storm surge barriers indicates that such projects are immersed in legally fixed decision-making procedures that involve coordination and cooperation from the public, all levels of government, and organized interests (e.g., professional and civic organizations, NGOs). Social conflict can result and lead to deadlocks, delays, and failures that wastes tax-payer money and the time of government agencies and their technical expertise. These scarce resources could instead be going towards projects that are deemed more palatable by the public, elected officials, and organized interests, thus improving the efficiency with which coastal risk reduction strategies are deployed.

6.6.1 Environmental harms do not always prevent projects from moving forward

Both the Bay barriers and current Corps projects suggest that environmental degradation is the most commonly cited objection. However, these concerns are not always present. The Fox Point Barrier is a unique case in that the Providence River in the mid-1950s was so polluted that environmental harms from the barrier were not seriously considered. Such conditions are unlikely to exist after over a half-century of improvements in water quality (Robinson et al, 2003; Smith et al, 1987). Therefore, it is unclear how far the Fox Point Barrier would progress with a cleaner Providence River and the current web of complex environmental laws, regulations, and reviews. The progression of some recent adaptation works beyond the planning stages also supports the claim that environmental concerns do not block all coastal flood protection megaprojects outright, or even emerge at all. For example, the South Shore Staten Island Project has progressed from an initial feasibility report in 2015 to congressional approval, and construction is slated to begin in early 2021 (Goodrich, 1956). Also in New York City, the East Side Coastal Resilience Project (not affiliated with the Corps) recently received approval from the City to begin construction, and in Norfolk, a Corps project consisting of a series of structural defense measures, including storm surge barriers, received support from Virginia's congressional delegates and currently awaits authorization[13]. Future work should examine these cases and better understand why these projects progressed without significant environmental concerns while others did not [e.g., other projects in New York City, such as storm surge barriers in Jamaica Bay (Secretary of the Army, 1965; US National Research Council, 1971) and New York Harbor (Barnard, 2020) and a levee proposed for Coney Peninsula (Nolan, 1972)]. For example, Naval installations in Norfolk may have increased the federal government's interest in flood protection.

6.6.2 Siting disputes and government bureaucracy

The Narragansett Bay barrier experience could be categorized as a siting dispute. Infrastructure siting disputes are part of a broader debate in the political science literature over the role of bureaucracies, experts, and the public in policy making (Aldrich, 2008; Dear, 1992; Devine-Wright, 2011; Dewey, 1927; Fischer, 2000; Inhaber, 1998; Kraft and Clary, 1991; Lindblom, 1990; Lippmann, 1922; Mazmanian and Morell, 1994; McAdam and Boudet, 2012; McAvoy, 1999). Some scholars view siting difficulties as mere hurdles that need to be overcome in order to achieve an optimal policy outcome (Beckmann, 1973; Inhaber, 1998; Ophuls, 1977). On the other hand, some view such disputes as value trade-offs between the public and experts and that priority should be given to the views of the public (McAvoy, 1999). Likewise, concerns over environmental harms incite debate over how to balance environmental protection with the socioeconomic benefits from infrastructure projects. Some

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[13] Sec. 401. Project Authorizations in H.R. 7575, 116th Congress, 2nd Session https://www.congress.gov/bill/116th-congress/house-bill/7575/text

scholars who study infrastructure argue that there is too much emphasis on environmental regulation over public safety and economic growth (Fukuyama, 2017; Howard, 2015; Kagan, 1991, 2001), while others suggest it is warranted (Ortolano and Shepherd, 1995), particularly in light of the Corps' history of understating environmental impacts (Taylor, 1984). The Corps often finds itself trying to achieve goals and objectives that are not always consistent or compatible with one another (e.g., credible protection from rare, storm surge events and improvement in environmental quality)(US National Research Council, 2011).

Modern democracies often rely on federal agencies, like the Corps, to administer technical decisions that can impact the public in adverse ways (e.g., a higher tax burden, degrading environmental quality). These agencies are filled with policy experts that attempt to make informed, good-faith decisions on the behalf of citizens. However, conflict can arise when experts, elected officials, and the public come to a different understanding of what "good" policy solutions are (Lindblom, 1990). For example, variation in risk perception (Huber, 1986; Kahan et al, 2011; Kunreuther and Slovic, 1996; May, 1991; Slovic et al, 1982) can make it challenging to amass a majority who agree that costs associated with a given project are justified. This could be risks that the project purports to reduce (e.g., coastal flood risks) or potential adverse outcomes associated with the project itself (e.g., risk to marine life and recreational boating). In op-eds and letters to the Corps and elected officials, several Rhode Islanders made it clear that they would rather live with the risk of a repeat disaster than pay for expensive flood protection that also comes with the potential to degrade their experience of living on the water, frequently citing the low probability of another destructive storm as an argument to not pursue protection. Such risk perception behaviors have been well documented in the psychology literature (Slovic, 2000). Elected officials and the public may also be more likely to make decisions on timescales that are shorter and more relevant to their needs (Gasper and Reeves, 2011; Healy and Malhotra, 2009; Jacobs, 2016; Mayhew, 1974). Climate adaptation efforts could be challenged by similarly reasoned opposition, especially in the presence of disincentives such as generous federal disaster aid and public flood insurance premiums that are below actuarial values (Burby, 2001; Knowles and Kunreuther, 2014; Posner, 2006).

6.6.3 Reconciling trade-offs in protection levels between alternative strategies

Opposition to storm surge barriers and other coastal flood protection megastructures has implications for reducing coastal flood risk. More specifically, alternative projects supported by such opposition may involve tradeoffs in levels of protection. Projects that are more politically palatable (i.e., those less likely to invoke strong opposition) may not always provide an equivalent reduction in flood hazard. For example, nature-based solutions lauded by environmental NGOs (e.g., mangroves, dune building, wetland restoration) that primarily reduce wave energy may not offer the same level of protection as concrete and steel approaches that have historically been politically contentious (Oppenheimer et al, in press). Additionally, more politically feasible projects have tended to be smaller-scale, "end-of-the-pipe" strategies, such as stormwater improvements, pumps, elevation of critical utilities, and temporary flood barriers that provide marginal increases in safety (City of New York, 2013). In the U.S., these projects are often justified using benefit-cost analysis (U.S. Water Resources Council, 1983), as opposed to meeting a specific regional risk protection standard (e.g., the Delta Works in the Netherlands). The result of pursuing projects characterized by little political opposition could be an over-emphasis on hazard reduction from more frequent, less costly flood events and an under-emphasis on projects that address the most dangerous coastal storms (i.e., those that are more often subject to political opposition). Reducing frequent floods may correspondingly limit the reminders that a location is exposed to potentially catastrophic events, thus encouraging development (e.g., the "safe development paradox")(Burby, 2006; Kates et al, 2006).

Experience with large-scale relocation efforts suggest that other alternative projects, such as managed or voluntary buyouts, may be even more politically contentious than storm surge barriers and other coastal megastructures (Aldrich, 2008). For instance, while neighborhood-scale buyouts have occurred in New York City (e.g., Oakwood Beach in Staten Island), some of its mayors and other city officials have firmly supported a commitment to continued development along the city's coastline (City of New York, 2013), including expanding into the harbor (NYC Mayor's Office of Recovery and Resiliency, 2019). No plan has been made for massive-scale coastal relocation, and the City has instead suggested that properties in the floodplain privately invest in resiliency measures (City of New York, 2013). However, future disasters, rising insurance premiums, and escalating costs of private flood protection may change this position.

Opposition to politically contentious projects could lead to an outcome in which no risk reduction project is constructed. As the Narragansett Bay barrier experience showed, project opposition can ultimately lead to no action to reduce coastal flood risk. After nearly a decade of detailed study had been completed, many Rhode Islanders had discounted the threat of flooding and preferred to live with the chance of a repeat disaster. As of 2020, Hurricane Carol remains the last major storm to strike Rhode Island[14]. Many of the citizens who opposed the Narragansett Bay barriers ultimately never experienced a storm as destructive. However, climate change may make a "no action" outcome less palatable (Demski et al, 2017; MacInnis and Krosnick, 2020). Experience has shown that future storms provide opportunities to reboot failed Corps projects with renewed interest [e.g., Jamaica Bay barrier (Secretary of the Army, 1965; US National Research Council, 1971; USACE, 2016b), Saugus River Flood Barrier (The Regional Saugus River Floodgate Project, 2020; USACE, 1989)]. It may only take another destructive storm before the Narragansett Bay barrier plans are reconsidered.

6.7 Conclusions and recommendations for the Corps

Sea-level rise, as a result of global warming, is increasing the frequency and severity of coastal floods (Sweet et al, 2017; Sweet and Park, 2014). A growing list of more than $70 billion in coastal flood protection megaprojects suggests that state and local governments are taking these threats seriously (Table 6.1). However, historical and contemporary experiences with efforts to build coastal flood protection have demonstrated the political complexity in moving from a project proposal to breaking ground. Corps projects often die on the vine, sometimes after a decade of planning and millions of dollars spent. We are pessimistic that storm surge barriers will be politically feasible climate adaptation options for most

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[14] While not officially classified as a major hurricane at landfall, Hurricane Bob in 1991 was a Category 2 storm when it struck Rhode Island.

U.S. cities as a result of 1) modern environmental laws that elevate oppositional viewpoints, 2) the allure of alternative options that are more aesthetically pleasing and cheaper and faster to implement (even though they don't offer the equivalent level of protection), and 3) lengthy and complex decision-making procedures that coincide with fading memories of floods. Corps efforts to reduce coastal flood risks require strong leadership (especially to shepherd projects through Congress), limited opposition by the public and environmental NGOs, and substantial funding [usually provided through emergency supplemental appropriations acts (Carter, 2018; Kousky and Shabman, 2017; US National Research Council, 2014)].

The U.S. Army Corps of Engineers is well positioned to manage sea-level rise and coastal flooding given that it has a wealth of knowledge in scientists, engineers, and more than 60 years of experience with coastal risk reduction. The Corps has also expressed its commitment to adaptation by adding consideration for sea-level rise and other climate change impacts in its assessments (Moritz et al, 2016; USACE, 2013b, 2019c). While the Corps is limited in its ability to unilaterally undertake coastal risk reduction under its current authorities (Carter and Normand, 2019; Samet, 2009), its direct connections to Congress and the President and its coastal permitting authority legally equip the agency with the potential to play a significant role in coastal climate adaptation efforts. Despite this, the Corps is arguably not yet viewed as a climate adaptation leader (Brandon, 2016; Flatt and Tarr, 2011), in part because its projects often die on the vine. A Corps project manager in New York recently acknowledged this inefficiency, "I've been with the Corps for 30 years. It's very difficult to get projects constructed. There are a lot of challenges, technical and institutional" (Kensinger, 2018). From our analysis of past and present experiences with storm surge barriers and other coastal flood protection megastructures, we give the following recommendations:

1. *The Corps should improve relations with state and local non-governmental entities to better understand local opposition before proposing strategies*

   The Corps should work more closely with state and local non-governmental entities. More specifically, prior to proposing structural risk reduction measures in feasibility studies, the Corps should identify potential local opposition and work to engage them in dialogues over ways to reduce coastal flood risk while improving or protecting environmental quality. Before undertaking an initial proposal/reconnaissance study, local nonfederal sponsors could provide information to the Corps regarding local stakeholders, their interests, desires, and potential to delay planning. Better working relationships between the Corps and environmental NGOs has helped to reach compromises (Hickey and Warner, 2006; US National Research Council, 1999). Such an approach has been recommended before by the U.S. National Research Council (US National Research Council, 1999), and even the Corps has acknowledged an increased need for collaboration and partnerships (USACE, 2015). However, the immediate opposition by environmental NGOs, the public, and government leaders to recent Corps proposals in the New York-New Jersey harbor area and in Miami suggests that this task remains.

2. *The Corps should prioritize nature- and shore-based strategies*

   Modern environmental laws such as NEPA, the CWA, and the Endangered Species Act have all created new responsibilities and requirements for the Corps. These have also greatly constrained new construction efforts. The Corps should focus their attention on implementing shore- and nature-based strategies (USACE, 2015) in light of these constraints, even if they do not offer the level of protection that storm-surge barriers can provide. Storm surge barriers may be more likely to emerge as serious contenders if there were regional flood risk protection standards (such as the Netherlands) because nature-based strategies are unable to provide an equivalent level of protection, especially in densely populated cities (Oppenheimer et al, in press). Such was the situation that led to the construction of the Lake Borgne Surge Barrier. Following Hurricane Katrina, Congress mandated a 100-yr protection standard for the New Orleans area and relaxed some environmental laws to expedite approvals and implementation (Luther, 2006). As long as the Corps continues to appraise alternatives using benefit-cost analysis, they must acknowledge that their methodology likely does not capture all benefits from nature-based strategies. Nature-based strategies are also cheaper and better reflect the Corps' budget realities (Scodari, 2014).

3. *The Corps should build trust with environmental NGOs and the public*

The Corps must build trust with environmental NGOs and the public. Over the years, public trust in the Corps has been tenuous, largely as a result of the Corps' history of exaggerating the economic benefits from projects (Ferejohn, 1974) while simultaneously downplaying environmental impacts (Buzbee, 2014; Mazmanian and Nienaber, 1979; Pilkey and Dixon, 1996; Taylor, 1984) Environmental NGOs may still view the Corps as an advocate of concrete and steel solutions. If the public lacks confidence in their government's ability to deliver benefits, they will have little reason to pay for the costs of such actions (Chanley et al, 2000; Hetherington, 2005; Jacobs and Matthews, 2012; Simonsen and Robbins, 2003). Collaborations between the Corps and the Nature Conservancy in the area of river water quality and ecosystem restoration has strengthened relations and helped to reach consensus agreements (Hickey and Warner, 2006). The Corps has acknowledged the need for improved relations (USACE, 2015), but recent experiences in New York and Miami have pointed to the need for more work to be done. Additionally, the levee failures during Hurricane Katrina have led to wide-spread criticism of the Corps' expertise that still persists today.

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Archive Materials

Upon publication, archive materials used to support the findings of this study are available will be available on Zenodo. Until then, materials are available upon request.

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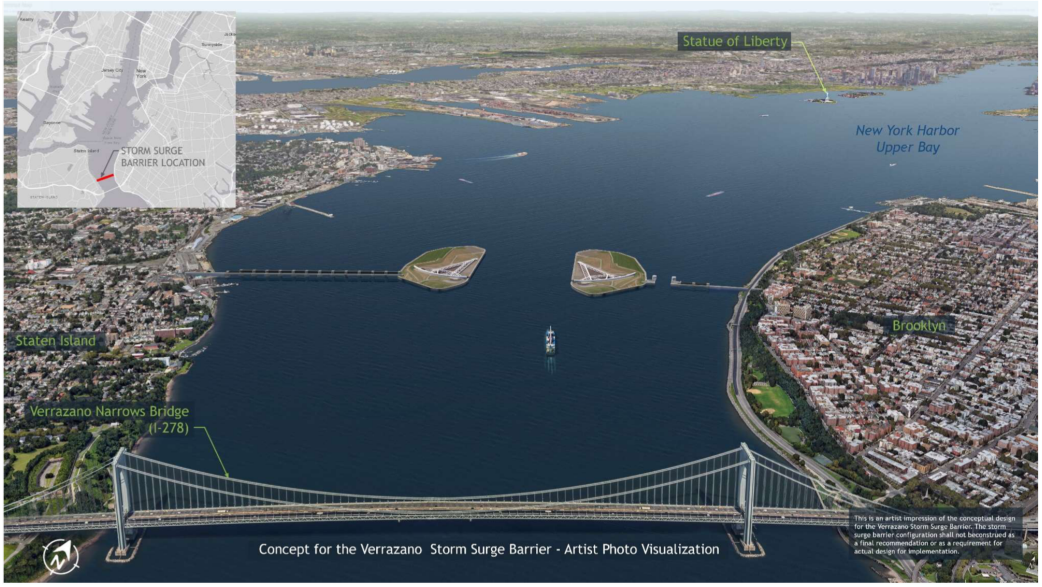
Figures and Tables



Concept for the Verrazano Storm Surge Barrier - Artist Photo Visualization

This is an artist impression of the conceptual design for the Verrazano Storm Surge Barrier. The storm surge barrier configuration shall not beconstrued as a final recommendation or as a requirement for actual design for implementation.

Figure 6.1: Artist rendering of a proposed storm surge barrier at the entrance to New York Harbor. Source: The New York Division of the U.S. Army Corps of Engineers, New York-New Jersey Harbors and Tributaries Feasibility Study

Figure 6.2: The Fox Point Hurricane Barrier following completion in March 1966 (Providence, Rhode Island). Photo taken by the New England Division of the U.S. Army Corps of Engineers (Waltham, Massachusetts).

Figure 6.3: Revised plans for the Narragansett Bay barriers, April 1964. Source: New England Division of the U.S. Army Corps of Engineers (Waltham, Massachusetts).

Table 6.1: An incomplete list of proposed public works coastal flood protection projects in the U.S. (USACE is the U.S. Army Corps of Engineers; CSRM is Coastal Storm Risk Management; HUD is Department of Housing and Urban Development; NYC is New York City; SSPEED is the Severe Storm Prediction, Education, and Evacuation from Disasters Center)

Project	Location	Strategy	Proposed	Lead Agency	Project Cost	Status (as of 2020)
Boston Harbor Surge Barrier	Boston, MA	Levee/Barrier	2018	UMass-Boston	$6.5 to 11.0 billion	Proposed
East Side Coastal Resiliency Project	New York, NY	Levee/Nonstructural	2014	NYC/HUD	$1.5 billion	Approved by the City
Lower Manhattan Climate Resiliency Project	New York, NY	Coastal Advance/Fill	2019	NYC	$10 billion	Proposed
Embarcadero Seawall	San Francisco, CA	Seawall	2018	City of SF	$5 billion	Proposed
Red Hook Integrated Flood Protection System	New York, NY	TBD	2013	NYC	$0.1 billion	Undergoing a redesign
Coastal Texas Protection and Restoration Project	Coastal Texas	Levee/Barrier/Nonstructural	2015	USACE	$23.1 to 31.8 billion	Proposed
Galveston Bay Park	Galveston, TX	Levee/Barrier/Nonstructural	2020	SSPEED	$2.3 to 2.8 billion	Proposed
South Shore of Staten Island CSRM Project	New York, NY	Levee/Nonstructural	1993	USACE	$0.6 billion	Ready to break ground
Charleston Peninsula: A Coastal Flood Risk Management Project	Charleston, SC	Levee/Seawall	2020	USACE	$1.7 billion	Proposed
City of Norfolk CSRM Project	Norfolk, VA	Levee/Barrier/Nonstructural	2015	USACE	$0.9 to 2.3 billion	Awaiting authorization
Miami-Dade Back Bay CSRM Project	Miami, FL	Levee/Barrier/Nonstructural	2020	USACE	$0.9 to 5.2 billion	Proposed
Collier County CSRM Project	Naples, FL	Levee/Barrier/Nonstructural	2020	USACE	$2.2 billion	Proposed
Fairfield and New Haven Counties, CT CSRM Project	Fairfield/New Haven, CT	Levee/Seawall/Pumps	2019	USACE	$0.05 to 0.3 billion	Proposed
New York – New Jersey Harbor and Tributaries Project	New York, NY	Levee/Barrier/Nonstructural	2019	USACE	$15 to 119 billion	Planning suspended

Table 6.2: An incomplete list of completed public works coastal flood protection projects in the U.S. (USACE is the U.S. Army Corps of Engineers).

Public Works Flood Protection	Location	Completed	Agency	Cost (unadjusted)
Galveston Seawall	Galveston, TX	1904	USACE	$1.5 million
Herbert Hoover Dike	Lake Okeechobee, FL	1938	USACE	Unknown
Pawcatuck Hurricane Protection Barrier	Pawcatuck, CT	1963	USACE	$851,000
New Bedford Hurricane Barrier	New Bedford, MA	1966	USACE	$18.6 million
Fox Point Hurricane Barrier	Providence, RI	1966	USACE	$16.2 million
Stamford Hurricane Protection Barrier	Stamford, CT	1969	USACE	$14.5 million
Charles River Dam	Boston, MA	1978	USACE	$61.3 million
New London Hurricane Protection Barrier	New London, CT	1986	USACE	$12.0 million
Lake Pontchartrain and Vicinity Hurricane Protection (Levee/Dike)	New Orleans, LA	Destroyed during Katrina, 2005	USACE	$760 million
Inner Harbor Navigation Canal Lake Borgne	New Orleans, LA	2013	USACE	$1.1 billion

6.8 Appendix: A Tale of Two Army Corps Megastructures: Fox Point and the Narragansett Bay Storm Surge Barriers

A period of active hurricane activity in New England creates demand for flood protection

The late 1930s through the early 1960s was a period of elevated hurricane activity in New England (Boose et al, 2001) (Fig. 6.4) during which all levels of government gave serious consideration to coastal flood protection. Over $4 million (unadjusted)[15] was spent on planning and design of coastal protection (Providence Journal, 1964b) and ultimately five USACE projects were constructed in the region, including the Fox Point storm surge barrier (Rhode Island) (Morang, 2016). Plans were also being made for hurricane protection elsewhere in Rhode Island (Fig. 6.5), but many of these projects failed to break ground, despite some of them being congressionally authorized (Frederiksen, 1975). This included hurricane protection around Point Judith and the Misquamicut area (Providence Journal, 1964a). Hurricane protection planned for Narragansett Pier also faced strong public scrutiny(Providence Journal, 1965b) and failed to progress beyond the planning stage. Outside of Rhode Island, storm surge barriers were completed in New London (Connecticut), Pawcatuck (Connecticut), New Bedford (Massachusetts), and Stamford (Connecticut).(Morang, 2016; Warner, 1963) In New York City, a surge barrier across Jamaica Bay barrier received congressional authorization in 1965 (Secretary of the Army, 1965). At the time, the Corps' New England Division Engineer called the flood control efforts in the region, "one of the biggest joint federal, state and local flood control operations in the country" (Goodrich, 1956).

The recorded history of coastal storms in Rhode Island (both tropical and extra-tropical cyclones) dates back to 1635. This 400-year timeline is marked by periods of various levels of hurricane activity. After the "Great September Gale"[16] of 1815, the next major storm would not occur until the "Great New England Hurricane" of 1938, over 120 years later (Donnelly et al, 2001). The '38 storm caused $57.8 billion in damage (2017 normalized USD$) to New England (Brown, 1938; Weinkle et al, 2018) and was particularly devastating

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[15] all dollar amounts given are unadjusted for inflation, unless otherwise noted

[16] The word "hurricane" was not yet used in American English at the time of the storm.

to Rhode Island. Much of downtown Providence flooded in the ‘38 storm, and damages accounted for roughly one-third of the state’s total (ASCE, 1959). Over 250 Rhode Islanders drowned (U.S. Army Engineer Division, 1963). Just six years after the ‘38 storm, another hurricane ravaged the region, the “Great Atlantic Hurricane” of 1944. The ‘44 storm was not a destructive, causing just $19.6 billion in damage (2017 normalized USD$) across several east coast states, including Rhode Island (Weinkle et al, 2018). While Rhode Island began to consider flood protection after the ‘44 storm (Providence Journal, 1954d), serious and sustained government action did not occur until the next major hurricane ten years later.

On August 31st, 1954, Hurricane Carol brought devastating floods again to Rhode Island (Fig. 6.6) (Brooks and Chapman, 1945). More destructive than the ‘44 storm but not as damaging or deadly as the ‘38 storm, Hurricane Carol caused roughly $23.5 billion in damage across New England (2017 normalized USD$) and killed 19 in Rhode Island alone (Hale, 1955a). The destruction in Rhode Island amounted to roughly 7.4% of the state’s GDP (Fogarty, 1959). Much of the damage came as a result of extreme storm surges throughout Narragansett[17] and Mt. Hope Bays (Secretary of the Army, 1966). In Providence (Upper Narragansett Bay), the flood levels reached 4.5 m above mean sea level (MSL; the ‘38 storm produced flood levels of 4.8 m above MSL). Flood levels were lower farther down the bay. In the Newport area, Carol raised MSL by 3.0 m (Secretary of the Army, 1966). At the time, the 1954 hurricane season turned out to be the most damaging in U.S. history (Brown, 1954). Just over a week and a half after Carol, Hurricane Edna struck neighboring Massachusetts, further emphasizing the need for permanent hurricane protection in New England. Later in the 1954 hurricane season, Hurricane Hazel[18] hit the Carolinas and drew further national interest in managing hurricanes and coastal floods (Dunbar Jr., 1955a), at the time not yet in the purview of the Corps (Providence Journal, 1956e) or scientifically well understood.

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[17] Narragansett Bay is a coastal estuary consisting of 456 km^2 of total water area and about a dozen islands of various sizes. Roughly 26 cities and towns (17 in Rhode Island and 9 in Massachusetts) dot the shoreline of Narragansett Bay. Providence, the capital and most populated city of Rhode Island, sits at the head of the bay, while the city of Newport lies at the entrance to the east passage. Narragansett Bay is noted for its shell fishing industry, prevalence of vacation homes, boaters, and being home to a large naval base in Newport. President Eisenhower’s Summer White House was also located in Newport in 1958 and 1960 (Hitchcock, “The Age of Eisenhower: America and the World in the 1950s”)

[18] Hurricane Hazel caused severe damage and death in the Carolinas ($33.2 billion 2017 normalized USD$)

Elected officials loudly demand for federal coastal flood protection

The demand for the construction of permanent flood protection emerged locally in the days following Hurricane Carol and quickly made its way up through the ranks of elected officials: from local and state officials to Congress and eventually the U.S. President. The Providence City Planning Commission was the first governing body to act. Just one week after the hurricane, the Planning Commission asked Mayor Walter H. Reynolds to request help from Rhode Island Governor Dennis J. Roberts, who then wrote to President Eisenhower (Providence City Planning Commission, 1954; Roberts, 1954). In his letter to President Eisenhower, Gov. Roberts inquired if the president had the authority to direct the Corps to conduct a "prompt, preliminary survey of the construction and other means needed to protect Rhode Island Shore areas."[19] In the same letter, Gov. Roberts also mentioned that he would ask the Rhode Island congressional delegation to introduce a resolution in Congress to authorize a thorough study of flood protection. Gov. Roberts also emphasized the specific goal of protecting downtown Providence (Roberts, 1954). The Rhode Island congressional delegation ultimately heeded both the Governor's and the public's demands for flood protection (Providence Journal, 1958c). Congressman John E. Fogarty wrote in his replies to letters from the public calling for action, "... [flood control] is uppermost in the minds of the Rhode Island congressional delegation..."(Fogarty, 1955) and "... I will certainly do everything I possibly can to see to it that the United States Government gives the City of Providence and the State of Rhode Island every possible assistance"(Fogarty, 1954). In the weeks and months after Carol, Gov. Roberts also instructed the Rhode Island Development Council to produce a report on how to best manage recurring hurricane damages (Fogarty, 1954; Rhode Island Development Council, 1955).[20] Specifically, on the Governor's mind were permanent flood defenses. He said, "[t]he enormity of the loss suffered by our people justifies a substantial investment in protection" (Providence Journal, 1954a).

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[19] Governor Roberts justified the request by citing Public Law 875 of the 81st Congress, which facilitates federal assistance in developing state and local plans to cope with major disasters.

[20] The Rhode Island Development Council report ultimately drew together inputs from federal agencies, several consulting engineering organizations, and the Rhode Island Development Council's own staff. The Rhode Island Development Council report compared and evaluated them as the basis for proposing a solution of the flood problem.

Local businesses lead the public in the call for flood solutions

Elected officials were not the only ones demanding that something be done about recurring flooding in both Providence and elsewhere in the state. Several waterfront property owners (Residents of Touisset, 1954), business associations such as Chambers of Commerce (Gilbane, 1954), individual businesses in and outside of Providence (Quinn, 1954) wrote to the Rhode Island congressional delegation expressing a strong desire for government action on the flood issues, including those that specifically called for building permanent flood protection (Providence Journal, 1954f). After Carol and the previous '38 and '44 storms, downtown Providence had developed a reputation for being vulnerable to costly coastal floods. Local businessmen, industrialists, and property owners wanted to avoid such experiences in the future, even if it meant a heavy cost to them, going as far as to proclaim that unless action was taken, the financial risk would be too great to continue to do business in downtown Providence (Providence Journal, 1954c). In the first few months after Carol, the Providence Chamber of Commerce passed a resolution calling for an official plan for flood control "at the earliest possible time" and the need for flood control to be "kept upper-most in our minds until a control project becomes a reality" (Providence Chamber of Commerce, 1954). In response, the Chamber of Commerce sponsored a series of public meetings to publicize flood control projects and keep citizens informed and engaged in discussions (Gilbane, 1954). A hurricane protection committee was also formed by Mayor Reynolds, comprising of nine business and industrial leaders to study potential hurricane protection options (Providence Journal, 1955i).

Local businesses in downtown Providence were very motivated to push for permanent, government-provided flood protection. First, affordable public flood insurance was not yet available. While a congressional effort was made in the late 1950s for a federally-backed flood insurance program (Evening Bulletin, 1955a; Providence Journal, 1955f; Dunbar Jr., 1955b; Smith, 1955; Providence Journal, 1957b,a), it would not emerge until 1968 (Brown, 2016).[21] Private insurance was often not available, but in cases where it was, premiums were reported to be "exceedingly high" (Evening Bulletin, 1955a). Second, federal disaster aid in

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[21] The National Flood Insurance Program was established by the National Flood Insurance Act of 1968 (NFIA, 42 U.S.C. §4001 et seq.)

the 1950s was much more meager than it is today. In the wake of Carol, President Eisenhower appropriated just $1.5 million in federal disaster aid to Rhode Island (Shanley, 1954), while total damages were in excess of $200 million (Hale, 1955a). Relief amassed to just 6% of total damages, much less than relief given for recent hurricane disasters. For example, in 2012, the federal government provided disaster aid for roughly 75% of total hurricane damages (US National Research Council, 2014). Third, building-by-building interim flood protection measures employed by businesses proved to be expensive. In Providence, the use of temporary sandbag barricades, the installation of pumps and generators, the relocation of some businesses to higher ground, and the flood-proofing of basements and first floors all totaled more than $1 million. Some of these costs were incurred each hurricane season (Hale, 1955a). A permanent tidal dam was seen as a way to provide long-term economic relief to these businesses (Cray, 1955; Providence Journal, 1955d). Gov. Roberts echoed the sentiments of many Providence business owners, "[p]eople cannot be expected to make large capital investments in an area where their investments are threatened by recurring disaster. The only thing we can do to make Rhode Island safe for the investment we need—is to begin actual construction to prevent flooding of our river valleys and shores" (Evening Bulletin, 1955c).

The need for swift action on hurricane protection

Not only was there a wide-spread desire for action, but there was demand for these actions to occur quickly. This feeling was frequently expressed in the Providence Journal-Bulletin throughout the planning phase for both the Fox Point and Narragansett Bay Barriers (Providence Journal, 1955g, 1956e, 1960a, 1955h). It was strongly felt that another devastating storm could flood Providence and other parts of Rhode Island in any given hurricane season. During the planning and construction of the Fox Point and Narragansett Bay barriers, close calls with other hurricanes continually put Rhode Islanders and elected officials on edge, specifically Hurricanes Connie, Diane, and Ione (1955), Cindy (1959), Donna (1960), Esther (1961), and Ginny (1963) (Providence Journal, 1960b,a, 1961b, 1963, 1955d,e,c). Speaking to the Senate Public Works Committee, Gov. Roberts said, "We must have a complete study and adequately documented, authoritative engineering recommendations at the earliest possible date. . . we cannot tell how soon the next major hurricane will strike...the record shows that on average, severe tropical storms have struck the North Atlantic coast every three to four years...with full scale hurricanes every eleven years" (Roberts, 1955).

While it was discussed, it was also anticipated that involvement of both the Corps and Congress would lead to a long and slow "obstacle course" for any project (Hale, 1954d,e; Dunbar Jr., 1956; Hale, 1955b). It was locally known that it took 19 years and multiple disasters to begin flood control for the Blackstone River in the Woonsocket Valley (Providence Journal, 1959b). The desire for quick action was so much so that many private engineering firms and state and town officials came forward with proposals in case the federal government was not able to get involved in construction in a timely manner (Providence Journal, 1954c,g,e; Hale, 1954e; Editorial, 1954). The president of a Providence engineering firm proclaimed, "[t]he Army people are great hydraulic engineers. . . but they are very busy. I think it would take them from five to eight years to complete the project once it had been authorized while private engineers, I believe, could have it completed in four years" (Providence Journal, 1954d). There was little public objection voiced against the presented plans devised by private engineers, particularly for Providence. However, some criticism was aimed at an early proposal crafted by two engineers (Dahl and Anderson) for a series of barriers at the head of Narragansett Bay. The arguments were that such a monumental effort might detract from building flood protection in Providence as soon as possible (Editorial, 1954), that residents might be unwilling to cover a bond issue of tens of millions of dollars to finance the project, and that increases in the currents at the entrance to the bay may lead to opposition from the Navy and recreational boaters (Hull, 1955). Some experts suggested further study would be needed for such a project (Hale, 1954b). In hindsight, these initial concerns were a harbinger that the project was doomed to fail.

The idea of Providence and Rhode Island proceeding with flood protection without the Corps' help had precedent. Providence had previously considered a privately funded proposal for the construction of a barrier in downtown Providence as recently as the year before Carol. However, it was reported that state officials were "skeptical" and ultimately decided against pursuing the idea (Tillman, 1954; Providence Journal, 1954f). With that experience in mind, Rhode Islanders seemed committed to taking action instead of letting the issue "die" as had occurred after the storms in 1938 and 1944 (Providence Journal, 1954d). The Providence Journal wrote, "…the biggest immediate danger facing the barrier project is public apathy fostered by the passage of time and the absence of storm threats. It took 20 years to get action on river flood projects that might have made Hurricane Diane a harmless rainstorm. The bay project deserves a better fate than death by disinterest" (Providence Journal, 1956e). The Corps also knew that time was not on their side for getting something built. Lt. Col. Miles L. Wachendorf, the Assistant New England Division Engineer, said, "…experience shows that the public in the past has had a tendency to lose interest in flood control as the last major disaster fades in their memory" (Providence Journal, 1956a).

The Corps enters coastal flood protection

The aftermath of Hurricane Carol eventually led to Congress adding coastal flood protection to the Corps' list of authorized duties. In the spring of 1955, multiple bills were introduced in Congress an effort to initiate and fund a large, interim hurricane survey, which included authorization for the Corps to investigate coastal flood protection. A bill was ultimately passed and signed into law by Eisenhower on June 16, 1955 (Public Law 71, 84th Congress; or P.L. 71-84). Today, P.L. 71-84 is still invoked to authorize examination and surveys of coastal and tidal areas in the U.S., including surveys of coastal flood protection options that give serious consideration to sea-level rise [e.g., the New York-New Jersey Harbors and Tributaries Focus Area Feasibility Study (USACE, 2019b)]. The New England Division Engineer proclaimed, "…the protection of coastal areas from hurricane induced tidal inundation constitutes a revolutionary development in flood control in the U.S." (ASCE, 1959).

The Corps was a natural choice for involvement in coastal flood protection for multiple reasons[22]. First, the Corps had decades of experience with inland flood protection (Evening Bulletin, 1955d). The Providence Journal highlighted Corps projects in Hartford (Connecticut) and Cincinnati (Ohio) as examples of urban flood protection success stories (Hale, 1954c,a). The Rhode Island General Assembly noted that the Corps has the "…staff, the

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[22] Unless directed by Congress to take action, local interests are required to initiate help from the Corps. The Corps cannot act unilaterally.

know-how, and the experience to make the necessary studies and to formulate and carry out an effective protective program". The Rhode Island Development Council also recommended that "...every effort be made to secure promptly the definitive study of the entire hurricane flooding problem in the State, which can best be done by the USACE." (Rhode Island Development Council, 1955). Second, at the time, roughly 90% of the cost of inland flood protection built by the Corps was paid for by the federal government, an attractive approach when considering that the proposed flood protection solutions in Rhode Island were projected to run into the tens to hundreds of millions of dollars (Providence Journal, 1956e). Third, the fact that any surge barrier project would alter navigable waters required the Corp to issue a permit[23], thus making it a federal issue. Fourth, Narragansett Bay was home to naval installations at Newport, Quonset Point, and Davisville (Providence Journal, 1955b). For these reasons, the Rhode Island congressional delegation was unanimous in its conclusion that there was a federal interest and responsibility in coastal flood protection which affected the navigable waters of Narragansett Bay and its tributaries.

At the time, the Corps had little prior experience with coastal flood protection (Evening Bulletin, 1955d)[24], and more generally, very little was scientifically known about the characteristics of hurricane tidal flooding, especially Narragansett Bay where limited tidal data existed (Evening Bulletin, 1955b). Furthermore, Rhode Island's hurricane protection problem was described by the New England Division's chief engineer, Brig. Gen. Robert J. Fleming, Jr., as "unique", declaring that there is "...no problem I know of anywhere in the world like that of Narragansett Bay, where you have an inverted funnel pointed like a dagger at a built-up industrial area" (Providence Journal, 1955a). Joseph R. Brennan, chief of planning of the Corps' civil works section, noted that the agency had never built tidal protection – only river protection – and mentioned that the authority of the Corps to

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[23] See Rivers and Harbors Appropriations Act of 1899, 30 Stat. 1121, 1151 (codified in 33 U.S.C. §401) ("It shall not be lawful to construct or commence the construction of any bridge, causeway, dam, or dike over or in any ... navigable water of the United States until the consent of Congress shall have been obtained . . . ."); An Act to Provide Security for the Lives of Passengers on Board of Vessels Propelled by Steam, 5 Stat. 304 (1838) (providing that "it shall not be lawful for the owner . . . of any steamboat . . . to transport any goods, wares, merchandise or passengers, in or upon ... navigable waters of the United States . . . without having first obtained . . . a license").

[24] The Corps was involved in two projects in the early twentieth century (Table 6.2) but studying coastal flood protection was not officially added to their jurisdiction until 1955 (Public Law 71, 84th Congress, 1st Session).

engage in tidal flood control had not yet been clearly established. Brennan noted that new legislation was needed to specifically allow surveys of tidal flood measures and construction of tidal flood structures. Two precedents for coastal flood control were cited – Galveston and Florida levees. However, those projects proceeded under beach erosion and navigation laws, respectively, not flood control (Hale, 1954d). The authors of this study did not evidence was found that suggested that there was strong opposition to at least carrying out a survey on flood protection, at least not locally. Some members of Congress objected to not having their state included in the hurricane survey bill. South Carolina Senator Strom Thurmond wanted his state to also receive Corps' attention after being heavily ravaged by Hurricane Hazel (Dunbar Jr., 1955a).

Public Law 71-84 was passed and signed into law in June 1955 to address the issues of scientific understanding and the Corps' authority to undertake coastal studies. More specifically, Public Law 71-84 called for an interim hurricane survey to compile data on the behavior and frequency of hurricanes, improve hurricane warning services along Atlantic and Gulf coasts, and to give the Corps the authority to examine both the technical feasibility and economic justification for hurricane protection measures in Rhode Island and Massachusetts, including storm surge barriers, levees, and seawalls. The hurricane survey began the following month (Providence Journal, 1955j). Notably, the bill did not yet place the responsibility of paying for hurricane protection on the federal government; this was left for later debate. After about a year and three months of study, the Corps presented an initial draft of plans for two projects, a storm surge barrier at Fox Point and a series of rock barriers in lower Narragansett Bay (Times, 1956). Storm surge barriers were not the only proposed solution in the months following Carol. Also discussed was re-zoning and retreating from the coastline (Providence Journal, 1954b), temporary flood protection measures (e.g., sandbags), and flood proofing lower levels of buildings, the latter two done building-by-building. There was also a failed attempt at establishing a public flood insurance program (Providence Journal, 1957a).

Public input on the Corps' storm surge barriers

Vocal public opposition to the Fox Point and Narragansett Bay barrier projects did not become widely apparent until the Corps formally revealed them to the public. Holding public hearings is standard Corps practice before projects are eligible to continue towards receiving congressional authorization. In all Corps projects—both historically and presently—the public is given a chance to provide comment in such forums (Luther, 2008; Mazmanian and Nienaber, 1979). Public interest shown at these hearings is an important factor in congressional consideration of project approval and financing, and meeting transcripts commonly accompanied the engineering reports to Congress (Providence Journal, 1956c). In addition to these standard hearings, engineers from the New England Division of the Corps attend numerous gatherings of service clubs and other civic and private organizations to speak on the survey and the various plans of protection that were being studied (Providence Journal, 1956d; Secretary of the Army, 1966). Congressman Fogarty also arraigned a cruise of the bay barrier sites with Corps engineers, members of the House Public Works Subcommittee, the Navy, the Rhode Island Development Council, and various local marine interests (Providence Journal, 1956j). Roughly a week before the public hearings were held, the Rhode Island Hurricane Survey Advisory Committee voted in favor of the Corps' plans, but concluded that more study should be undertaken in order to ascertain the effects of lower bay barrier construction (Isé, 1956).

Public hearings were held in Providence, Newport, and Fall River (Massachusetts) in October 1956. In total, nearly 380 people attended the meetings (Secretary of the Army, 1966). Henry Isé, Chief of Rhode Island's Division of Harbors and Rivers, noted that, "[i]t is very important for the success of this project that we get as good a turnout as possible. A poor turnout, I know, would have a very bad effect in Washington" (Providence Journal, 1956c). In addition to business owners and other members of civil society, those in attendance included the New England Division's Chief Engineer, Gov. Roberts, members of the Rhode Island congressional delegation, Mayor Reynolds, and engineers who headed the survey of Narragansett Bay (Providence Journal, 1956h). In Providence alone, more than 200 people turned out for the two-and-a-half-hour hearing that included 17 presentations.

Senator Pastore said the turnout was, “one the finest expressions of good citizenship I have seen in many a day” (Providence Journal, 1956g).

Public reception to Fox Point and Bay Barriers

Public feedback for both projects was mixed. An overwhelming (but not unanimous) majority urged immediate construction of the Fox Point Barrier, while the reception for the Bay barriers was lukewarm, at best. The only recorded dissenter for the Fox Point project was the Allens Avenue Businessmen’s Association, a group of 122 Providence businesses. They opposed the Fox Point Dam because their properties were not in the planned protection zone. The Association instead advocated for an alternative design that included their properties, which were heavily impacted by flooding from hurricane Carol (Dinsmoor, 1956).

Several concerns were raised regarding the Bay barriers. Among them were related to the effects of the barriers on maritime navigation, water quality, salinity, fish and wildlife, and recreational activities in the bay (Providence Journal, 1956b). The presented studies at the hearings had been heavily focused on engineering design; little attention was given to assessing environmental impacts. As such, there was almost no scientific support available for arguments that the public could make to use against the barriers, particularly in light of their potential effects on marine life. Several attendees wanted assurance that the barriers would not ruin commercial and sport fishing in Narragansett Bay (both shell and fin fish). As such, further study was recommended, particularly for impacts on marine life, which had been noticeably underfunded and understudied. In an op-ed in the Providence Journal, Donald J. Zinn of the Rhode Island Wildlife Federation noted that “… the Corps thus far has a generally sad record with their more or less public-wishes-be-damned policy when it has come to a question of dam construction versus natural resources.” Zinn pointed out the imbalance of preliminary study funds for a biological investigation from the U.S. Fish and Wildlife Service ($6,000) and Corps’ budget ($500,000) (Zinn, 1956). The Evening Bulletin also raised concerns about marine life, “…until questions about the effect of the dam on marine life are answered satisfactorily hundreds of residents of this state are bound to oppose construction of a dam that might put them out of business or ruin a major source of salt-water recreation. The way things are going right now, it will be impossible to find out what the effect will be until plans are so far along the way that construction will be the next step. Let's get the answers now and re-draw preliminary plans, if necessary, to save that marine life" (Evening Bulletin, 1956b). Leaders in the seafood industry also called for more studies of the barrier's effect on natural resources (Blount, 1956).

While the environmental impact of the Narragansett Bay barriers was subject to heavy scrutiny, these concerns were noticeably absent from discussions around the Fox Point project. One possible reason is that the Providence River was already heavily polluted. A report on pollution of the waters in Rhode Island from 1946 indicated that the water around Providence had attained "grossly polluted" levels, the highest category on the report's pollution assessment scale. In the same report, most of the water in Narragansett Bay was assigned to the cleanest water category (Rhode Island State Department of Health, 1946). More recent reports also indicated pollution issues. In early 1955, it was mentioned that the Providence River was too polluted to be used for the cooling condensers on the Narragansett Electric Company's South Street Station, a coal-fired power plant adjacent to the proposed site of the Fox Point Barrier (Cool, 1955). By 1956, dramatic improvements in sewage treatment had reduced the amount of effluence being fed into the Woonasquatucket and Moshassuck that emptied into the Providence River. But even after these efforts, there still remained what was called, "the problem of foul morass of mud and trash" (Providence Journal, 1956i).

Maritime navigation concerns associated with the Bay barrier's East Passage were also raised by the Navy. It was believed that the initially planned opening in the barrier would not be wide and deep enough to accommodate some of the Navy's largest ships. The night of the Corps' Newport hearing, the Newport City Council voted (5-2) to turn down the Bay barrier project, citing infrequent use of flood protection (i.e., floods are rare) and daily use of the East Passage by the Navy (Evening Bulletin, 1956a). The Newport City Council instead favored the construction of roughly two miles of dikes and seawalls along the Newport Harbor line (Cyganowski, 1956). Other calls for barrier alternatives were made elsewhere in the state (Providence Journal, 1956f) and some individuals even preferred no government action. A former sewer commissioner from Warren, RI wrote in an op-ed, "I'd much rather take my chances on hurricanes without barriers. Anyone living close to the bay who stands to suffer damage from hurricanes should take steps to prevent such damage and leave the barriers for the birds" (Cyganowski, 1956). It was ultimately concluded that the USACE's plans for the Narragansett Bay barriers required more study, particularly the impact of the barriers on marine life (Providence Journal, 1956h). Almost a full eight years would pass before a more complete study was ready to be presented to the public. In the meantime, the Fox Point barrier would continue towards breaking ground.

Public support for bond referendums to pay for local share of Fox Point Barrier

After a long, up-hill battle in Congress (Providence Journal, 1958c)(Fig. 6.7), the Fox Point hurricane barrier was authorized in 1958 (Providence Journal, 1958a), roughly two years after the public hearings. After the hearings, several Army Corps and congressional hurdles needed to be cleared prior to project authorization, including arriving at a 70-30 federal-local cost sharing agreement (Providence Journal, 1958b,c).[25] Following authorization, another three years of detailed engineering by the Corps would occur before construction of the Fox Point barrier would begin. Additionally, two state and local referendums were needed to issue government bonds that would pay for the 30 percent non-federal share of the project. In November 1959, Providence voters showed just how seriously they wanted flood protection. A special election was held, and Providence voted to approve three bond issues to pay for $4.6 million of the non-federal share. While the voters overwhelmingly supported the referendum (margin of 6 to 1), the turnout was noticeably meager (slightly less than 9 percent of Providence's eligible voters). Mayor Reynolds was disappointed at the lack of voter interest. He said it represented "terrible apathy" towards such important matters (Providence Journal, 1959a). A year later, all of Rhode Island was eligible to vote to approve a state bond needed to pay the remaining local share of the hurricane barrier (Providence Journal, 1960c). However, this time there was some public opposition to supporting the state referendum by communities outside of Providence who would not directly benefit from the Fox Point Barrier. Central Falls City Council asked legislators and citizens of Blackstone Valley to band together against the Providence hurricane barrier. The opposition

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[25] As of 2020, the federal-local cost sharing split for structural coastal projects is 65-35 (per the Water Resources Development Act of 1986), but in extreme cases the full cost has been paid for by the federal government (NOLA post Katrina)

was intended to be retaliation against the state for failing to give relief to higher sewer rates in the Valley, which had come from the construction and maintenance of a new Valley sewer system (Evening Bulletin, 1959). In a firm rebuke, the Providence Journal editorial board argued the Fox Point situation was different. The Journal asserted that protecting Providence meant protecting the economic heart of the state, therefore the Fox Point Barrier was simply not a local issue but rather one the entire state must support (Providence Journal, 1960d, 1959c). In the lead up to the statewide referendum, an "all-out" campaign was waged to generate state-wide approval for the Fox Point Barrier. The state received a timely reminder of how badly flood protection was needed just before the election when a half-million dollars in damages from Hurricane Donna occurred in downtown Providence (Evening Bulletin, 1960). Ultimately, the $1.75 million bond issue was approved by state voters(Providence Journal, 1960c), and the Fox Point Barrier broke ground in July 1961 (Providence Journal, 1961a).

After further study, Bay barriers again ready for public scrutiny

After nearly eight years of further study, the Corps released revised plans for the Bay barriers in late 1963 (U.S. Army Engineer Division, 1963). The Fox Point and Bay barrier Army Corps hearings in 1956 had concluded that the Bay barrier project required more study to 1) determine the effects of the Lower Bay Barriers on natural resources, 2) to secure further data on velocities through the navigation openings, and 3) to further study the design of the barrier foundations (Hyzer, 1964c; U.S. Army Engineer Division, 1963). The Corps' updated plans were designed to meet the objections that had been previously voiced (Providence Journal, 1964d). Brig. Gen. Peter C. Hyzer, the new Chief of Engineers of the New England division of the Corps, wrote, "During the eight years we have studied this proposal, primary consideration has been given to determining the possible effects of the barriers and to refining the design so as to eliminate or minimize those found to be undesirable" (Hyzer, 1964b). Ultimately, more than 15 barrier plans were considered at 25 different locations throughout Narragansett Bay using a 1:1000 horizontal and 1:100 vertical scale model (Hyzer, 1964a). The final three barrier locations were selected as a result of 1) extensive testing of changes in the tidal flow, 2) recommendations by the Navy, and

3) economic assessment of alternative structures. The most significant changes focused on minimizing the restriction of the normal tidal flow in and out of the bay in order to limit impacts on marine life and boating. The final designs used navigational openings whose width had been doubled and also incorporated dozens of sluice gates that would close when high water was forecast. Overall, the openings in the barriers had been increased by 270 percent over the old plan (Providence Journal, 1964d). The Corps insisted that the new design would not have an impact on marine life since they claimed the same volume of water would flow in and out during each tidal cycle (Evening Bulletin, 1964e). However, the larger navigational openings meant that protection afforded by the barriers would be reduced. As a result, local officials would be required to notify residents at least once a year that the barriers did not provide complete protection from hurricane tidal surges. The estimated cost of the revised barrier plans was $90 million (unadjusted) (Secretary of the Army, 1966).

Assessments performed by other federal agencies that accompanied the Corps' report were either inconclusive (i.e., suggested more study required) or found adverse impacts were likely. The U.S. Public Health Service determined that the barriers would not have a noticeable effect on the water quality in the upper region of the Bay but said that more study was needed to reach a confident conclusion on possible increases in pollution in the lower Bay (Secretary of the Army, 1966). Studies on marine life were less supportive of barrier construction. The U.S. Fish and Wildlife Service claimed that the Corps' revised plan had the potential to "...significantly alter the aquatic environment and adversely affect the fin fish and shellfish resources of the area." The U.S Fish and Wildlife service also concluded that the proposed barriers could have an adverse effect on recreational boating in the lower Bay due to increased tidal currents (Nelson, 1965).

Despite the mixed reviews from other federal agencies, the Corps continued to claim that the new design would not adversely impact the bay. In a letter to Fogarty, New England Division Engineer Brigadier General Seymour A. Potter, Jr. wrote that "The problems of effects on pollution and water quality, fisheries and wildlife...have been satisfactorily resolved...the lower bay barriers would cause no important effect on water quality, oxygen and pollution in the bay" and "...the U.S. Fish and Wildlife Service, concluded that the overall impact of the Lower Bay barriers on fishery resources would be small" (Potter Jr., 1961). John B. McAleer, the head of the Corps' hurricane unit, stressed that there would not be a change in the volume of water entering and leaving the bay each tidal cycle. As such, McAleer argued that no change in flushing time, salinity, or temperature would result. He cited experiments with the Corps' scale model of the Bay (Evening Bulletin, 1964a). Brig. Gen. Hyzer also claimed that the effects of the barriers would be dwarfed by that of the normal seasonal changes within the bays (Providence Journal, 1964d). Despite the Corps' attempt to cast doubt on the findings of the other agencies, opposition to the revised plans not only remained, it grew louder.

Revised Narragansett Bay barrier plans met with overwhelming public opposition

Public hearings were once again held to inform local interests of the Corps' updated plans for the Bay barriers (Providence Journal, 1964d). The hearings took place in April 1964 in Newport, Providence, and Swansea (Massachusetts). A total of 611 people attended (232 in Newport, 237 in Providence, and 142 in Swansea)(Secretary of the Army, 1966), a markedly higher turnout than the previous hearings in 1956, which had also included consideration for the Fox Point barrier. While the Fox Point project received with near unanimous support at the hearings in 1956, this time the Bay barrier project was met with near unanimous opposition. In addition to the hearings, opposition also was expressed through letters to the Governor, the Rhode Island congressional delegation, and the Corps. Senator Pastore reported he had received letters to his office at a rate of at least 10 to 1 against the barriers. Congressman Fernand J. St. Germain said he answered at least 200 letters from Rhode Island residents opposed to the project and had received none in favor (Van Dusen, 1964). Brig. Gen. Hyzer also reported that more than 300 letters from Rhode Islanders had been received at the Corps' New England office in Waltham, Massachusetts (Providence Journal, 1964c). In addition to letters, a number of editorials and op-eds were printed in the Providence Journal-Bulletin, most of them sounding off against the barriers. Generally, grievances were similar to those expressed at the earlier Corps hearings, namely objections over the impact on recreational boating, tides, pollution, marine life, and the high cost of the non-federal share of the project (Evening Bulletin, 1964e,b; Providence Journal, 1964f; Evening Bulletin, 1964f,a).

Even before barriers were formally introduced and discussed at the public hearings in April 1964, several boaters (both professional and amateur) spoke out against the project (Dawson, 1964; Upham, 1964; Hagglund, 1964; Whitehead, 1964; Davis, 1965), including those who had called for flood protection in the wake of Hurricane Carol in 1955 (Cobb, 1955). Many boaters did not believe the Corps' claim that the currents in the openings in the new barrier design would not exceed three knots for a mean tide and four knots during a high tide (the latter being roughly double the existing velocity)(Evening Bulletin, 1964f; Providence Journal, 1964d). Preston R. Gladding, a Barrington, Rhode Island resident and a naval architect and partner in the Gladding-Hearn Shipbuilding Corporation believed that the Corps' calculations were, "...ridiculously less than foreseen by local pilots...", and contended that high velocities and turbulence of flowing water would make passing through any of the three navigational openings extremely dangerous and at times virtually impossible, except for large ships. Rhode Island Governor John H. Chafee, a himself a sailor, also voiced strong opposition to the barrier plan, "I am against it. I vote no" (Evening Bulletin, 1963). The Corps admitted that the top tide velocities would pose problems for sailboats but pointed out that the conditions would not be dissimilar from those of the approach to Galilee in Point Judith Pond, a popular Rhode Island sailing spot (Evening Bulletin, 1964a). Halsey Herreshoff, crewman of the 1958 champion America's Cup team and of the famous Bristol yacht-building family, believed the barriers would constrict the tidal flow into the Bay and create currents that would be "too strong for most sailboats to navigate" (Evening Bulletin, 1964c,g). The America's Cup had taken place in Newport since 1930 and was again slated to host the event in 1964; at the time, Narragansett Bay was described as the "yachting center of the world." (Dyer, 1964). Herreshoff stated that he personally would recommend that future America's Cup races be held elsewhere if the barriers were built (Providence Journal, 1964f). A counter point to the yachtsmen's claims was made by the Corps. The Corps claimed that yacht races were often held in Long Island Sound, where water velocities were sometimes 50% greater than those projected to occur in the area of the barrier's navigational openings (Evening Bulletin, 1964a).

In addition to impacts on recreational boating, many cited concerns related to the barrier's potential to cause ecological damage to the Bay. Conservationists and marine biologists echoed the U.S. Fish and Wildlife's conclusions (Nelson, 1965). Dr. Theodore J. Smayda, a marine biologist at the University of Rhode Island Narragansett Marine Laboratory [a yachtsman (Providence Journal, 1964f) and also had assisted the U.S. Fish and Wildlife service in their report to the Corps], argued that the barriers should not be built until more is known about potential impacts on marine life. Dr. Smayda believed that the barriers could warm the waters in the bay in the summertime, lead to decreases in salinity that could cause the bay to freeze over, increase the number of red tides in the bay, and also cause additional shellfish pollution (Evening Bulletin, 1964a; Providence Journal, 1964d). In a Providence Journal editorial, Smayda claimed that, "[e]ven the most minute changes (e.g., a degree or two of temperature change) could have profoundly adverse effects in an ecology in which all factors operate in the most delicate balance." On a morning radio broadcast, Dr. Nelson Marshall, professor of oceanography at the University of Rhode Island, questioned the Corps' conclusions regarding possible changes in sedimentation on the bottom of the bay, and described the revised plans as, "at best, a gamble" (Evening Bulletin, 1964e). Dr. Marshall also opposed the barriers on esthetic grounds (Evening Bulletin, 1964a).

However, other experts believed that there was little to worry about regarding impacts on marine life. Julian H. Gibbs, a chemistry professor at Brown University, spoke in favor of the barriers at one of the Corps' hearings, arguing that tidal exchange in the bay would not be reduced. Additionally, Ralph A. Schmidt, a regional supervisor of river basin studies for the U.S. Fish and Wildlife Service, also supported the conclusion that marine life would not be harmed (Providence Journal, 1964f). But these counter arguments were very much in the minority. Alfred L. Hawkes, Executive Director of the Audubon Society of Rhode Island, noted that there is "almost no agreement among engineers and biologists we rely upon as to the real effects of these barriers" (Hawkes, 1964). Overall, it was clear that most believed Rhode Island could not afford to run the risk of irreversible ecological damage to Narragansett Bay. Much was at stake. Just months before the Corps' hearings, a University of Rhode Island-Kingston study estimated that Narragansett Bay was valued at being worth $145 million annually to the state of Rhode Island (Rorholm, 1963).

The risk of ecological harm also threatened the Narragansett Bay shellfish and fin fish industry. Businesses spoke out to oppose the barriers both loudly and often, including those who had originally desired flood protection (Linehan, 1955). In a letter to Congressman Fogarty, Frederick H. Richardson, Vice President of Blount Seafood Corporation noted that his corporation had suffered "very severe damage" from Carol, but still opposed construction of the barriers because he felt that the "cure would be worse than the disease." Richardson said, "[w]e have thus far been able to recover from hurricane damage, but we would be put out of business completely if our bay is ruined for shellfishing" (Richardson, 1964). At the hearings in 1956, the Blount Seafood Corporation did not outright oppose the project, but did express desire for further study of barrier impacts (Blount, 1956). The Rhode Island Shellfish Industry opposed the construction of the barriers until, "it is proven conclusively by Biologists, Bacteriologists and the U.S. Fish & Wildlife Service, that erection of said Barriers will not be detrimental to the natural resources of Narragansett Bay" (Industry, 1956). Francis B. Manchester of Manchester Seafoods, Inc. wrote, "...I would rather take the risk of storm damage than risk the possible pollution of our Bay Areas, the loss of fishes in our Bays and Rivers, and the damage to our shellfish due to increased silting, pollution, and reduced salinity. We deal directly with approximately one hundred fishermen during the year, and I do not know of one who is in favor of these proposed barriers" (Manchester, 1964).

Opposition also emerged from residents with waterfront properties who stated that they were aware of the risks of living on the water and simply did not want the government's help. In several op-eds and letters to Rhode Island's congressional delegation, residents noted that they had experienced disastrous flooding from both the '38 Storm and Hurricane Carol but decided they would rather take their chances with having a repeat disaster than degrade their experience of living on Narragansett Bay. In an op-ed in the Providence Journal, Irving C. Sheldon took a stand against the barriers and claimed that, "[t]hose who would be protected by the barriers are those who invested in locations with full knowledge that they were taking a chance on water damage from hurricanes" (Sheldon, 1964). In another case, a Rhode Island resident wrote to Congressman Fogarty, "...I've recently bought a house on the water, which was partially flooded in the 1954 hurricane, but I am not asking Uncle

Sam to bail me out" (Henderson, 1964). The Narragansett Bay Home Owners Association said it would be better to "accept the possibility of a devastating storm once or twice every hundred years rather than tamper with Narragansett Bay" (Evening Bulletin, 1964d). Some residents attempted to discredit the need for flood protection by claiming that wind was the most damaging peril associated with hurricanes in Rhode Island (Sheldon, 1964).

Those who opposed the bay barriers were not necessarily against all flood damage reduction measures. Many gave suggestions for alternative solutions. The Audubon Society of Rhode Island proposed re-zoning, purchasing of endangered areas for public recreational facilities and open space, obtaining easements to limit or control development in the flood plain, and encouraging private property owners to maintain the natural state of their lands (Hawkes, 1964). Byron Blount of Blount Seafood Corporation mentioned that he was not opposed to certain types of safety measures to reduce flood damage, but barriers that he believed threatened the conditions of the bay were, "out of the question" (Blount, 1964). In an editorial in the Evening Bulletin, it was mentioned that, "...much can be done in those communities to prevent flood damage without a dam, as in zoning to prevent building in flood-prone, low-lying areas" (Evening Bulletin, 1964f). In lieu of barriers, Barrington, Rhode Island resident Preston R. Gladding proposed improved weather forecasting and warnings, federal flood insurance, temporary barriers erected on a seasonal or ad hoc basis, and shore-based protection measures that provide local protection without changing tidal flow patterns (Evening Bulletin, 1964a). The Newport Redevelopment Agency also suggested that new building developments incorporate flood mitigation as opposed to relying on the bay barriers (Providence Journal, 1964e).

Some opposed to the Bay barriers expressed that they had supported the Corps' Fox Point project. The Providence Journal editorial board was a strong supporter of the Fox Point barrier, but cautioned against the Bay barriers without further certainty of their environmental impacts (Evening Bulletin, 1964f,b). They asserted that the Fox Point project was a different situation because it protected downtown Providence, "at no risk of any kind to marine life or boating" due to the water above the barrier not being, "suited for boating or marine life" (Evening Bulletin, 1964f). The Providence Journal also described the Fox Point Barrier as, "badly wanted", and claimed there was no active desire in any community around Narragansett Bay or Mt. Hope Bay, for a $90 million series of barriers (Providence Journal, 1975). Others made similar comparisons. In an op-ed, Irving C. Sheldon noted that the Fox Point Barrier is entirely different because it protects a business center that affects the livelihood of a majority of Rhode Islanders (Sheldon, 1964), and in a letter to Brig. Gen. Hyzer, a Providence resident wrote that he has, “...always rooted for the Fox Point Dam“, but was opposed to the Bay Barriers (Unknown, 1964). Manchester Seafoods also noted no objection to the Fox Point Barrier (Manchester, 1964). Some also argued that hurricane damage in the future should be much less serious if the Fox Point barrier would prove to be effective given that a large part of damage from the ‘38 storm and Hurricane Carol was in Providence (McGowan, 1964). Without given a reason, Governor Chafee also doubted that the Bay barriers would receive the same statewide appeal that the Fox Point project did (Providence Journal, 1965c).

Despite the overwhelming opposition, there were supporters of the Bay barrier project. The Allens Avenue Businessmen’s Association (Providence Journal, 1964f) was the lone reported supporter at the Corps’ Providence hearing (Dinsmoor, 1956). They were a group of 122 Providence businesses who had voiced opposition to the Fox Point Barrier proposal at the 1956 meeting (Providence Journal, 1956h) because they had been left out of the planned protection area. After widening the navigational opening of the East barrier, the Navy became supportive of the revised plan (Providence Journal, 1956h), and at the meeting held in Swansea, residents representing the shores of Mt. Hope Bay and the bands of the Taunton River expressed a desire and willingness to support the project (Secretary of the Army, 1966). In an op-ed, a resident of Fall River, Massachusetts argued that opponents of the Bay barriers need to recall the disastrous effects of both Carol and the ‘38 storm and then “re-examine their position” (Conroy, 1964).

Despite public opposition, the Corps advances plans for Narragansett Bay barriers

Even in the face of strong public opposition, the Corps continued to advance the Bay barrier project (Fig. 6.8). Rhode Islanders took note and continued to voice their objections. Charles B. McGowan of the Narragansett Bay Home Owners Association said, “. . . it is impossible to understand the position taken by the Corps in the face of practically unanimous local opposition" (Providence Journal, 1965e). Some even began to attack the Corps as an organization. The public vocalized their issues with the Corps' presentations and lackluster rapport with those in the community. Some even interpreted the Corps actions as subversive tactics intentionally performed in order to get their projects built. For example, after clear public disinterest, the Corps floated the possibility that the barriers could be fully paid for by the federal government, although Brig. Gen. Hyzer admitted that he was "not yet sure" how to recommend the full financing (Evening Bulletin, 1964g). This gesture was interpreted by some as a ploy to generate public support. A resident from Barrington expressed his displeasure in a letter to the Army Corps, "I resent the biased presentation of the project. . . the presentation turns out to be a massive campaign to force the barrier upon us; distorted opinions and exaggerated damage figures compiled by persons whose main concern is to assure themselves of continued employment. Your agency should serve the taxpayers, not force your will upon us (at our expense)" (Thomas, 1964). The Narragansett Bay Home Owners Association said that the Corps' studies on the effect of the barriers on natural resources were, "superficial and completely inadequate for the purpose" (McGowan, 1964). Dr. Nelson Marshall, an oceanographer, suggested that a scientific body "completely neutral" make a "more thorough cost-benefit analysis" (Evening Bulletin, 1964e). In an op-ed in the Providence Journal, Robinson C. Locke wrote, "[I]t is frightening that government bureaucrats against the wishes of the people concerned, are still trying to force an unpopular project upon us. . . After months of hearings on this matter around the bay it would seem that the Army engineers would realize that the great majority of people do not want this noble experiment forced down their throats. To me this is far from a democratic move" (Locke, 1965). Lincoln Cone, a representative of the American Merchant Marine Institute (an association of steamship companies) took issue with the Corps because they had not consulted with his institute on the possible effects of the barriers, despite the obvious potential to impact the commercial shipping industry (Evening Bulletin, 1964g). However, not all were critical of the Corps. Some commended them for presenting "an extremely honest appraisal" of the barriers (Boss, 1964).

Brig. Gen. Hyzer had written about his frustrations with the public to Congressman Fogarty, arguing that those opposed to the projects were filled with "misconceptions, lack of understanding and fears". Brig. Gen. Hyzer contended that some of the opposition had come from those who had previously supported the barriers, "I am puzzled that memories are so dimmed that few now appear to want the protection which, in 1956, they considered so necessary in the bay areas." He believed these fears were a largely a result of "misunderstood engineering and technical considerations" (Hyzer, 1964b). In an attempt to clear up any confusion, Brig. Gen. Hyzer wrote a summary, published by the Providence Journal, in which he, in question and answer format, responded to ten of the most common complaints and fears that had been expressed about possible long-range adverse effects of the barrier system (Providence Journal, 1964c). He also questioned why the opposition was so strong when the purpose of the Lower Bay barriers was the same as that of the Fox Point project—to reduce hurricane damage (Hyzer, 1964a). The Corps accepted only two valid points made by the public during the hearings, 1) that the barriers were expensive and 2) that the barriers would increase the tidal velocities through the ungated navigation openings in the East and West Passages (Evening Bulletin, 1964a). The Corps continued to insist that no changes would take place in the bay if barriers were installed.

In the wake of the opposition, Brig. Gen. Hyzer saw three options, 1) drop the project if opposition continued, 2) request funds for further studies, 3) go ahead and recommend construction under the belief that the expressed public opposition does not reflect a regional consensus (Evening Bulletin, 1964g). Brig. Gen Hyzer believed the latter to be true, and he decided to advance the plans in the hope that a clearer understanding of the "purposes and effects" of the project would come to light upon congressional authorization. The Board of Engineers for Rivers and Harbors agreed stating, "[i]n similar cases, these problems are resolved as the purposes and effects of the plan become more clearly understood. Although full support of the plan is not now apparent, authorization of the plan by Congress would be a major step in this direction" (Young, 1965). While the Corps was able to advance the project for approval from the Board of Engineers for Rivers and Harbors (Young, 1965), they were well aware that support from elected officials would be needed prior to receiving congressional authorization. Brig. Gen Hyzer admitted that he had become "quite concerned" about this particular step (Hyzer, 1964b). Unlike the Fox Point project, not a single Rhode Island congressional delegate promoted the barriers. They were quite alarmed by the mail they were receiving at their offices. Senator Pastore described the response as, "heavy and overwhelmingly opposed". Congressman Fernand J. St. Germain said, "...I see no reason for promoting or pushing for the construction of this barrier." Senator Claiborne Pell had similar thoughts, "...I do not believe a project of this sort should go ahead unless a majority of the community wishes it." Congressman Fogarty said that because an estimated $26-27 million dollars would be required from local sources (30 percent share), he "[would] let the people decide" if the project should go ahead. Senator Pastore agreed, "[w]ithout [the willingness of the public to share the cost], I don't think it's got a ghost of a chance" (Van Dusen, 1964).

After state officials object, the Bay barrier plans are shelved

The lack of public support ultimately doomed the Bay barrier project. Upon receiving approval by the Army's Chief of Engineers, the next step was for the Corps to obtain comments from state officials in both Rhode Island and Massachusetts. The Rhode Island congressional delegation believed that the decision on the barrier should be made by the state government since the state would be required to put up most of the local share of the cost (Providence Journal, 1965a). Ultimately, the State of Rhode Island requested that the construction of the bay barriers be postponed until, "citizens of the state have expressed approval of the project." In a letter to the Army's Chief of Engineers, Henry Isé, the Chief of the Rhode Island Board of Engineers and Rivers and Harbors, wrote, "There is considerable fear among a great number of people in Rhode Island that the proposed barriers would adversely affect navigation, the quality of water inside the barriers, fish and wildlife resources of the state, and recreation in the bay. Grave doubts have also been expressed by many citizens regarding the efficiency of the project to provide sufficient protection and damage reduction to justify the large financial outlay necessary for construction and maintenance. In view of the widespread opposition to what is considered by many a 'questionable project', it is extremely doubtful that appropriation of funds for the local share of the cost would be approved. Therefore, the State of Rhode Island hereby urgently requests that no construction of the hurricane barriers be undertaken until such time as the citizens of the state have expressed approval of the project. Such approval has not been given to date" (Isé, 1965). The defeat of the Bay barriers was celebrated by the Providence Journal-Bulletin, but the editorial board cautioned that Rhode Islanders should not be, "too rough on the Army Engineers", for it was many of them who had so desperately called for the Corps' help in undertaking the studies which led to the barrier proposal that was so widely disliked. The Journal wrote, "Rhode Islanders should not completely close their minds to the possibility that the day may come when some kind of a hurricane barrier at the mouth of the bay is feasible and desirable... Another blow like the doubleheader the state received 11 years ago might change a lot of minds" (Providence Journal, 1965d). The Army Corps' Chief of Engineers, Lt. Gen. William F. Cassidy, responded to Isé's letter and stated that his report to congress will "recommend that no project be authorized for the lower Narragansett Bay Area at this time." Lt. Gen. Cassidy stated that future authorization would be dependent on upon future local agreement for participation (Providence Journal, 1966; Secretary of the Army, 1966) (Fig. 6.9).

Discussion of the Bay barriers in the Providence Journal-Bulletin did not end in 1966. In the mid-1970s, the lower Narragansett Bay hurricane barrier project re-emerged as possibly being included in a new $6.1 million round of Corps water resource studies. The plan was to update the project to meet new environmental protection standards in the event that interest in the project re-emerged (Frederiksen, 1975), a possibility foreseen by some groups opposed the project. Both the Narragansett Bay Home Owners Association and the Jamestown Protective Association were worried that the barriers, "might be authorized in a moment of panic after a severe storm or as a boondoggle" (Providence Journal, 1965f). The mentioning of the Bay barrier project did not go unnoticed. In an editorial in the Providence Journal, the Corps was accused of acting in their own self-interest to use tax-payer dollars in order to make grandiose plans for projects no one wants. The editorial further stated there was no "whisper of desire" from anyone to take a second look at the barriers and described the original Corps plan as "...ultimately never generat[ing] any support in the cities and towns the dams were supposed to protect" (Providence Journal, 1975).

Figures

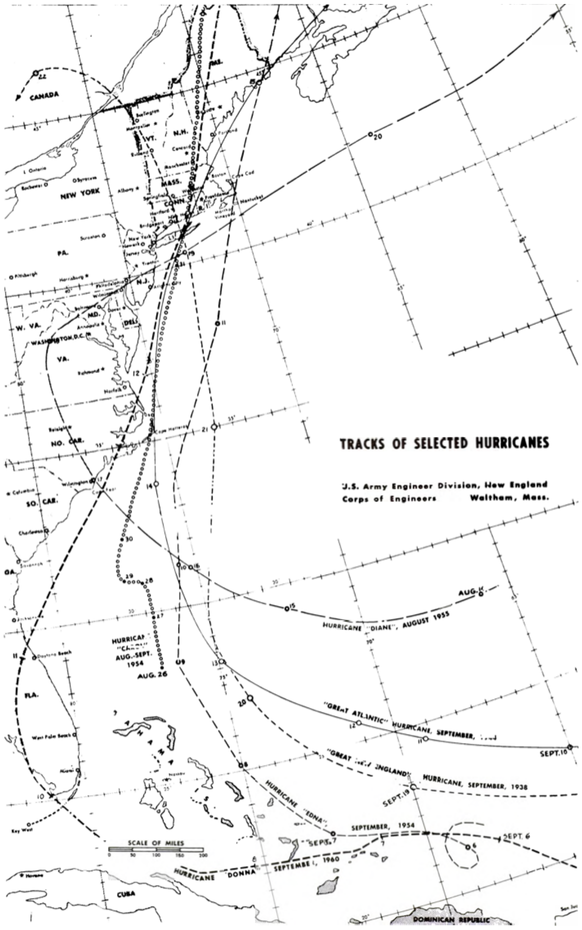

Figure 6.4: Tracks of hurricanes impacting New England (1938 to 1960). Source: the U.S. Army Corps of Engineers, New England Division. Waltham, Mass.

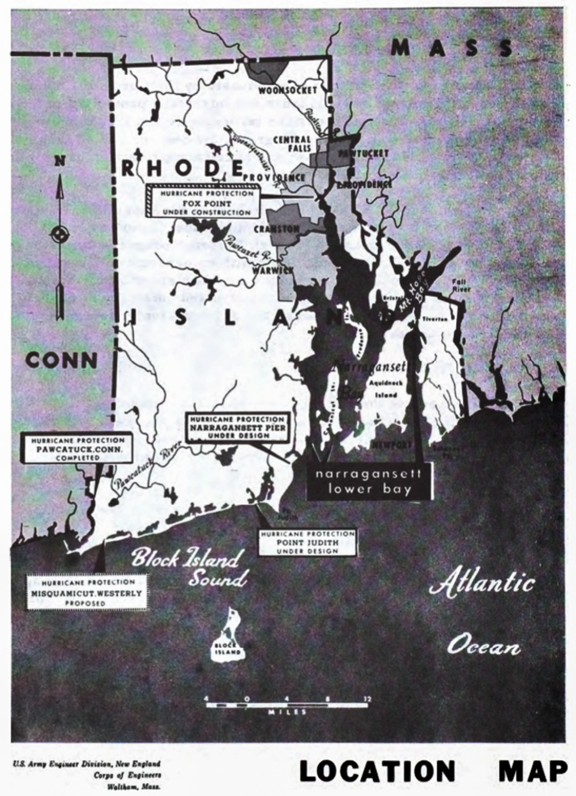

Figure 6.5: A map showing coastal flood protection projects in Rhode Island in the early 1960s that are either under design, have been proposed, or are currently under construction. Source: the U.S. Army Corps of Engineers, New England Division. Waltham, Mass.

Figure 6.6: A) Flooding in downtown Providence, Rhode Island during Hurricane Carol on August 31, 1954; B) Flooded offices of the Providence Journal-Bulletin; C) Photo of flooding in downtown Providence, Rhode Island looking up Westminster Street towards the business section; D) Aerial photo of destruction from Hurricane Carol in Oakland Beach, Rhode Island. Source: "Hurricane Carol Lashes Rhode Island", Published by the Providence Journal-Bulletin.

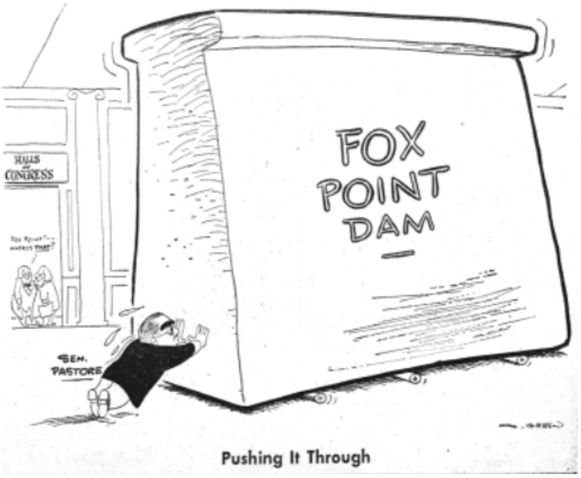

Figure 6.7: A political cartoon depicting the struggle that Rhode Island's congressional delegation endured in pushing the Fox Point Barrier through Congress. Source: Providence Journal-Bulletin, 5/24/1957.

It Can't Happen Here

Figure 6.8: A political cartoon depicting the how Rhode Islanders felt after the U.S. Army Corps of Engineers was attempting to continue to advance the Bay barriers following strong and consistent public opposition. Source: Providence Journal-Bulletin, 11/18/1965.

R.I.P.

Figure 6.9: A political cartoon depicting the Army Corps grieving the loss of the Narragansett Bay Barrier project after more than a decade of planning and deliberation. Source: Providence Journal-Bulletin, 1/6/1966.

Chapter 7

Conclusion

While each chapter gives both concluding remarks and policy recommendations, I will repeat and summarize them here, with an emphasis on how they apply to coastal risk reduction efforts in New York City.

7.1 Summary of Findings and Recommendations

Local sea levels will rise along most global coastlines over this century, regardless of whether or not international climate agreements are met. Therefore, individuals, businesses, and coastal communities should plan for changes in the frequency of extreme sea levels and coastal floods (Chapter 2)

The selection of the level at which to stabilize the global mean surface air temperature (GSAT) will guide the committed amount of future global mean sea level rise. For the majority of locations along global coastlines, the frequency of extreme sea levels will increase, even under the most optimistic GSAT stabilization target currently being considered on the international climate negotiation stage. For instance, I estimate that there is roughly an 86 percent chance that local mean sea level at the Battery in Lower Manhattan will increase by at least 0.5 m by 2100 under a stabilized GSAT of 2.0°C, a target consistent with the long-term goals of the Paris Agreement. Under this stabilization scenario, the expected frequency of the 100-yr extreme sea level event in Lower Manhattan will increase from once every 100 years, on average, to once every 5 years, assuming coastal storm frequency, track, and severity all remain constant. Importantly, I also note that a stabilized GSAT scenario will not coincidentally stabilize the frequency of an extreme sea level event, in part due to the thermal inertia of the deep ocean and the slow response of the cryosphere to warming.

Extreme sea level metrics that only consider the physical heights of water may misrepresent exposure to floods (Chapter 3)

Estimating changes in the frequency or height of extreme sea levels (e.g., the 100-yr event) is a popular approach for communicating future coastal flood exposure or risk (i.e., combination of hazard, exposure, and vulnerability) under various climate change scenarios. However, these metrics only account for physical water levels (i.e., the hazard). They do not consider exposure that is societal (e.g., populations, property) or natural (e.g., wetlands), nor do they account for the vulnerability of these components. As a result, extreme sea level metrics that only consider the physical heights of water may give misleading estimates of current exposure to future coastal floods. Linking extreme sea levels to exposure metrics (e.g., population) is more informative of impacts. For example, by 2100, the 100-yr extreme sea level event in Lower Manhattan is expected to increase in height from 1.85 m to 2.67 m above high tide (44 percent increase). However, the corresponding change in the total number of people in New York City exposed to the 100-yr extreme sea level event is greater, roughly a 65 percent increase. Ultimately, the applicability of any metric used to assess and communicate exposure to coastal floods will depend on preferences and management goals.

Flood damage allowances are the design heights of flood protection strategies needed to maintain a given level of coastal flood risk under uncertain sea level change (e.g., the annual average damage from flooding; Chapter 4)

A common coastal flood management strategy seeks to provide a region with a specified margin of safety (e.g., protection against the 100-year extreme sea level event). Without accounting for sea-level rise, the originally selected margin of safety will decrease, potentially leading to increased flood damages and greater numbers of people at risk. Extreme sea level hazard allowances can estimate flood protection design heights needed to maintain a specified margin of safety over a given time period (with uncertain sea level change). However, hazard allowances only consider the heights of extreme water levels and not associated damages. Flood managers may prefer to maintain financial risk over time (e.g., the annual average loss [AAL] due to flooding) rather than a physical hazard (e.g., extreme sea levels). In support of this potential need, I develop damage allowances that link extreme sea levels to financial loss using a damage function that is modified based on the flood protection strategy used.

Using this framework, I find that a hypothetical storm surge barrier constructed between Staten Island and Brooklyn (across the "Verrazzano Narrows") would need to be constructed to a height of 3.4 meters above the high tide line. This protection height would assure that the historical AAL due to flooding is maintained in the year 2100. This also assumes a maximum global mean sea level contribution from the Antarctic Ice Sheet (AIS) of 1.0 meter and equal odds of AIS collapse. My presentation of the damage allowance framework is largely conceptual. It neglects many factors that would need to be taken into account for real-world applications, such as wave set up and swash and funneling effects produced by levees and storm surge barriers that further elevate the water surface. Future work could also account for uncertainties in future changes in tropical cyclone strength and frequency.

Benefit-cost analyses used to appraise flood protection strategies with lifetimes beyond mid-century should consider deep uncertainty[1] *in sea-level rise (Chapter 4)*

Long-lived projects necessitate consideration of present versus future benefits and costs. For example, benefit-cost analysis is a popular approach for appraising flood protection strategies and is a part of the project selection process used by the U.S. Army Corps of Engineers. Such frameworks require consideration of future changes in extreme sea level frequencies, which in turn require probabilistic projections of local

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[1] Deep uncertainty (also synonymous with Knightian uncertainty and Ellsbergian "ambiguity") describes situations where there is either ignorance or disagreement by experts or decision makers over (1) conceptual models used to describe key system processes and (2) probability distribution functions (PDFs) used to characterize uncertainty related to key variables and parameters

sea level change to properly account for low-probability, high-impact outcomes. However, beyond midcentury, the dynamic response of the Antarctic Ice Sheet (AIS) to warming is a key uncertainty in protecting future sea levels. Because AIS melt is characterized by deep uncertainty, unique probability distributions of AIS ice discharge do not exist. In other words, decision-makers must contend with divergent expert judgements of AIS stability.

In order to more accurately depict the true state of knowledge, decision analytic frameworks that weigh benefits and costs for projects with lifetimes beyond midcentury (e.g., benefit-cost analysis) should consider multiple plausible probability distributions of local sea level change. While this approach can better capture the true state of knowledge, it can also result in a large array of possible outcomes. For example, the probability of local sea-level rise exceeding 1.5 meters in Lower Manhattan by 2100 is between roughly 5 and 65%, depending on the assumption for the maximum plausible amount of AIS melt. This uncertainty in local sea level projections also results in starkly different projections for corresponding expected number of 100-yr extreme sea level events (between 0.2/year and 100/year).

Better understanding the social and political factors that enable or hinder the implementation of coastal climate adaptation public works could encourage strategies and policies that are less likely to result in project deadlocks, delays, or failure. This could ultimately save governments valuable time and planning resources (Chapter 5)

In the eight years since Hurricane Sandy caused roughly $19 billion dollars of direct damage to New York City and claimed the lives of 43 people, no major project has broken ground that provides regional coastal flood protection. This is in spite of roughly $15 billion dollars in federal funds for coastal risk reduction measures and multiple proposals for technically feasible and economically justifiable adaptation works, such as storm surge barriers, levees, and floodable public spaces. Generous financing, sound engineering, and favorable economics appear to be necessary, but, by themselves, insufficient for implementation to occur.

The prospects for breaking ground on storm surge barriers, levees, and other coastal adaptation megaproject in the U.S. are not solely a function of technically feasible and economically justifiable plans. Projects are deeply embedded in struggles between diverse groups, organizations, and communities with heterogenous values, beliefs, interests, and influence. Decisions over adaptation works are likely to involve difficult trade-offs between divergent preferences of multiple groups that make it impossible to reconcile equitably or arrive at a Pareto-optimal outcome. I use the literature in natural hazards, infrastructure, political science, and climate adaptation to provide examples of how political challenges may arise during the phases of conception, design, and implementation before breaking ground on a coastal defense megaproject. My analysis also highlights past experiences in which these political obstacles have been overcome and projects have gotten built.

I conclude by highlighting four lessons from historical experience with coastal risk reduction with respect to factors that will enable or impede future adaptation works: 1) multiple floods are often needed to elicit earnest planning; 2) strong and continuous leadership from elected officials is necessary to advance projects; 3) stakeholder participation during the design stage has improved outcomes; 4) legal challenges to procedural and substantive shortcomings under environmental protection statutes present an enduring obstacle to implementing megastructure proposals. Focusing on these factors will improve coastal risk reduction efforts so that they are less likely to result in delays, deadlocks, and failures that can waste valuable time and planning resources.

Storm surge barriers built by the U.S. Army Corps of Engineers face several political and legal challenges (Chapter 6)

Efforts led by the U.S. Army Corps of Engineers to reduce coastal flood risks require strong leadership (especially to shepherd projects through Congress), limited opposition by the public and environmental NGOs, and substantial funding (usually provided through emergency supplemental appropriations acts). Storm surge barriers in particular face several political and legal challenges. This may impact their status as being feasible climate adaptation options for most U.S. cities, including New York City, as a result of 1) modern environmental laws that elevate oppositional viewpoints, 2) the allure of alternative options that are more aesthetically pleasing and cheaper and faster to implement (even though they don't offer the equivalent level of protection), and 3) lengthy and complex decision-making procedures that coincide with fading memories of floods. I recommend that the Corps should 1) improve relations with state and local non-governmental entities to better understand local opposition before proposing strategies, 2) prioritize nature- and shore-based strategies, and 3) build trust with environmental NGOs and the public.