Section 1: Introduction

Sea level rise driven by global climate change is a clear and present risk to the United States today and for the coming decades and centuries (USGCRP, 2018; Hall, Weaver et al., 2019). Sea levels will continue to rise due to the ocean's sustained response to the warming that has already occurred—even if climate change mitigation succeeds in limiting surface air temperatures in the coming decades (Fox-Kemper et al., 2021). Tens of millions of people in the United States already live in areas at risk of coastal flooding, with more moving to the coasts every year (NOAA NOS and U.S. Census Bureau, 2013). Rising sea levels and land subsidence are combining, and will continue to combine, with other coastal flood factors, such as storm surge, wave effects, rising coastal water tables, river flows, and rainfall (Figure 1.1), some of whose characteristics are also undergoing climate-related changes (USGCRP, 2017). The net result will be a dramatic increase in the exposure and vulnerability of this growing population, as well as the critical infrastructure related to transportation, water, energy, trade, military readiness, and coastal ecosystems and the supporting services they provide.

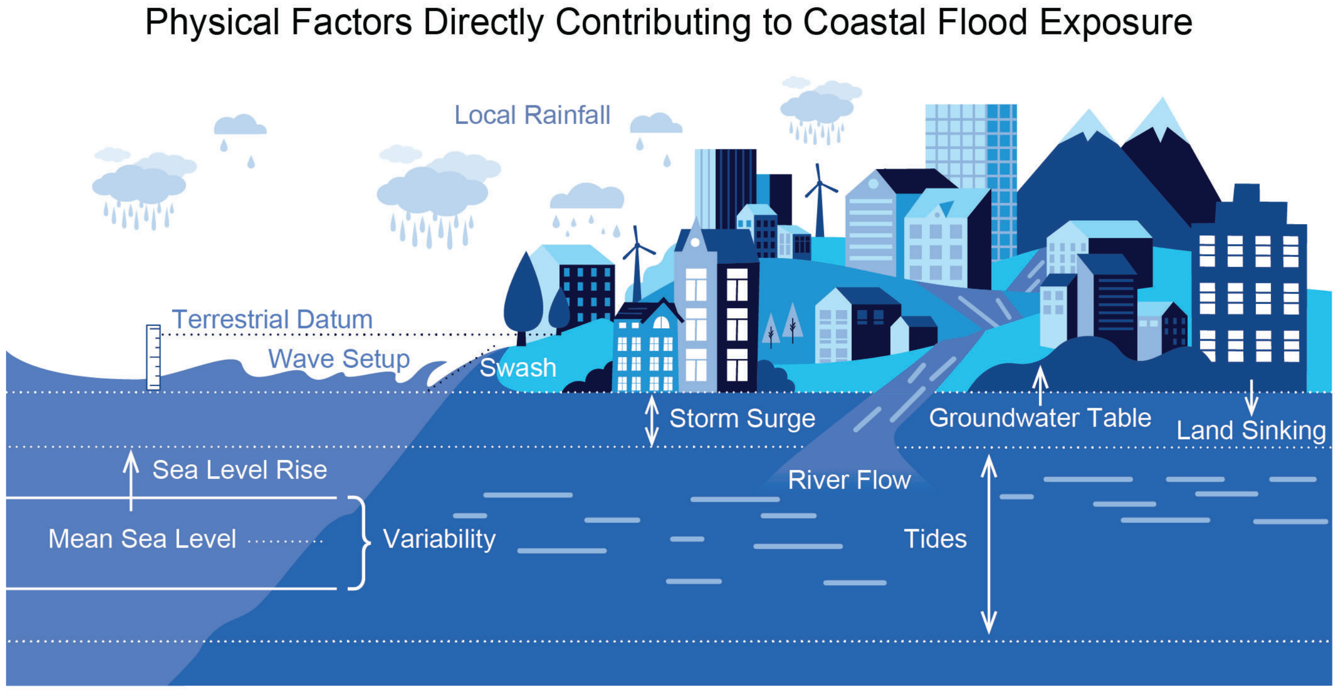

Figure 1.1: Schematic (not to scale) showing physical factors affecting coastal flood exposure. Due to the clear and strong relative sea level rise signal (i.e., combination of sea level rise and sinking lands), the probability of flooding and impacts are increasing along most U.S. coastlines.

Global mean sea level (GMSL) rise is a direct effect of climate change, resulting from a combination of thermal expansion of warming ocean waters and the addition of water mass into the ocean, largely associated with the loss of ice from glaciers and ice sheets. These processes are well understood for the recent past, and their contributions have been estimated for the 20th century (Figure 1.2a). With regard to increasing sea levels associated with climate change, the questions are when and how much, rather than if (USGCRP, 2017; Hall, Weaver et al., 2019). Increases in GMSL provide an important indicator of the changing climate, but it is the sea level rise on local and regional scales—measured by the global network of tide gauges and satellites—that is most relevant for coastal communities around the world. Regional and local sea level rise has not been and will not be uniform in time or space. Rather, sea levels change locally for a variety of reasons, such as vertical land motion (VLM), which can exacerbate the effects of the rising ocean. For context, whereas GMSL has risen by about 17 cm over the last 100 years (1920–2020), with noted acceleration since about 1970, relative sea level (RSL) averaged along the contiguous United States (CONUS) has risen about 28 cm over the same period with similar onset of acceleration (Figure 1.2b).

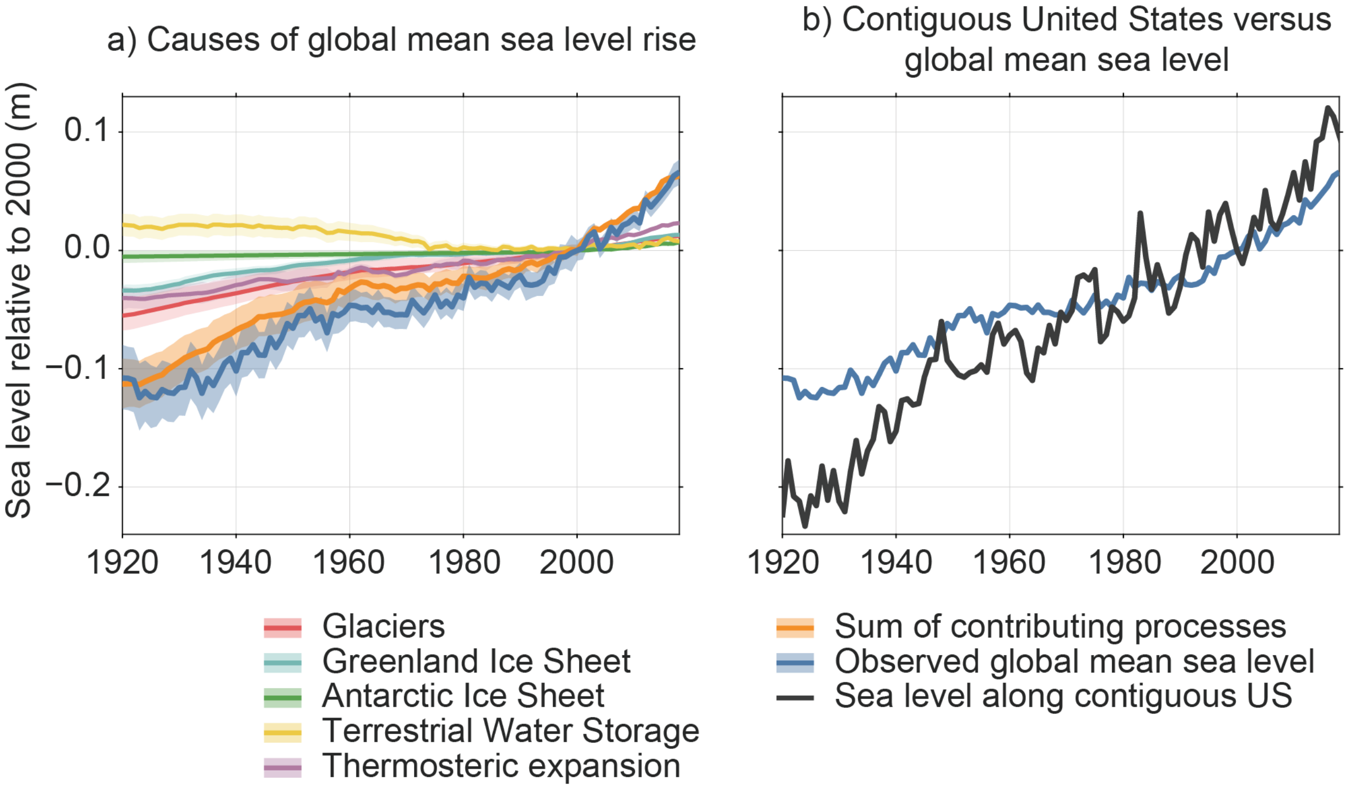

Figure 1.2: a) Observed annual global mean sea level (GMSL) change from global tide gauges (blue line), along with the sum (orange line) of contributions from thermal expansion (thermosteric) and four distinct water-mass-driven increases in GMSL. b) GMSL change (blue line) as shown in a) with the annual average relative sea level change measured by tide gauges around the contiguous United States (black line; with a linear regression estimate of 28 cm of sea level rise from 1920 to 2020). (Adaptation of Frederikse et al., 2020).

While this long-term and upward shift in mean RSL is the underlying driver of changes to the Nation's coasts, extreme water levels (EWLs) occurring against the background of this shifting sea level baseline are responsible for many of the recurring and event-based impacts. In this report, EWLs are explicitly assumed to be ocean-related changes measured by tide gauges (e.g., high tides and storm surges), which typically do not measure other contributors such as direct rainfall or river flow unless they are positioned upstream of major river systems (Moftakhari et al., 2016). Specifically, EWLs are considered as those occurring with an average event frequency between 0.01 events/year (often referred to as the 1% annual chance event) and 10 events/year. This range mostly spans the flood frequency of NOAA high tide flood (HTF) severity levels (minor, moderate, and major). HTF levels are nationally calibrated against NOAA's National Weather Service and local emergency managers' depth-severity thresholds used in weather forecasting and impact communications (NOAA, 2020) to provide a consistent coastal-climate resilience standard (Sweet et al., 2018).

Higher sea levels amplify the impacts of storm surge, high tides, coastal erosion, and wetland loss, even absent any changes in storm frequency and intensity. Because of threshold effects related to changes measured relative to a fixed elevation (Figure 1.3a), even the relatively small increases in sea level over the last several decades have led to greatly increased frequency of flooding[6] at many places along the U.S. coast (Figure 1.3b). Much of the coastline is already close to a flood regime shift, with respect to flood frequency (and presumably damages). That is, only about a 0.3–0.7 m height difference currently separates infrequent, moderate/typically-damaging and major/often-destructive HTF from minor/disruptive "nuisance" HTF (Sweet et al., 2018), whose impacts are already remarkable throughout dozens of densely populated coastal cities (Moore and Obradovich, 2020). Decades ago, powerful storms were what typically caused coastal flooding,

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[6] The definition of a "flood" in this report is typically meant to refer to a water level associated with impacts rather than the occurrence of natural phenomena.

but today, due to RSL rise, even common wind events and seasonal high tides regularly cause HTF within coastal communities, affecting homes and businesses, overloading stormwater and wastewater systems, infiltrating coastal groundwater aquifers with saltwater, and stressing coastal wetlands and estuarine ecosystems.

At multiple locations along the U.S. coastline, the annual frequency of minor HTF is accelerating and has more than doubled over the past couple of decades, turning it from a rare event into a recurrent and disruptive problem (Sweet and Park, 2014; Sweet et al., 2018; USGCRP, 2018). For example, the trends in minor/disruptive HTF have grown from about 5 days in 2000 to 10–15 days in New York City and Norfolk, Virginia, in 2020; in Miami, Florida, and Charleston, South Carolina, annual frequencies have grown from 0–2 days to about 5–10 days over the same period. These increases will continue, further accelerate, and spread to more locations over the next couple of decades (Sweet et al., 2021; Thompson et al., 2021). Thus, accurate projections of ongoing and future sea level rise and assessments that integrate across processes and temporal and spatial scales are key inputs to planning efforts and a key goal of this report.

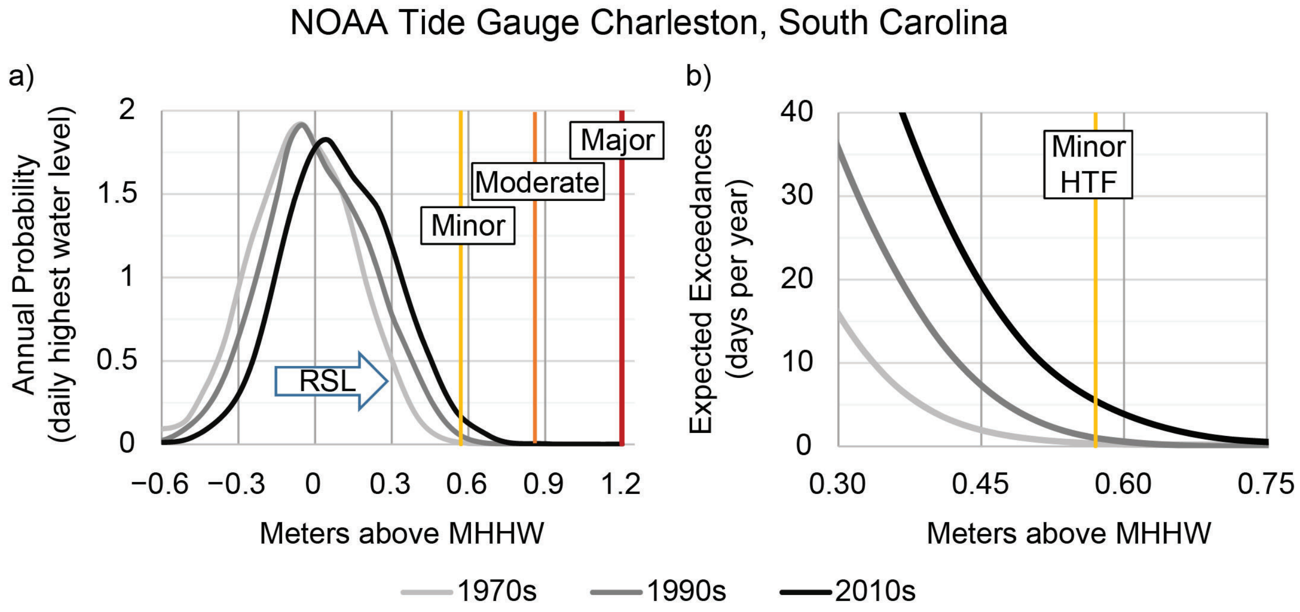

Figure 1.3: a) Annual probability density and b) annual expected exceedances for daily highest water levels relative to the 1983–2001 mean higher high water (MHHW) tidal datum showing increases in NOAA minor, moderate, and major high tide flooding (HTF) probabilities/frequencies due to relative sea level (RSL) rise at the NOAA tide gauge in Charleston, South Carolina.

The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force (hereafter “Task Force”) was jointly convened at the direction of the White House Resilience Council in 2015 under the U.S. Global Change Research Program (USGCRP), the Subcommittee on Ocean Sciences and Technology (SOST), and the National Ocean Council (NOC). This was in recognition of the strong need and demand for authoritative, consistent, and accessible sea level rise and associated coastal hazard information for the entire U.S. coastline, coordinated across the relevant Federal agencies, to serve as a starting point for on-the-ground coastal preparedness planning and risk management activities. The goal of the Task Force, since its inception, has been to develop the necessary products through sustained and coordinated participation of key agencies, based on the best available science, including regional science and expertise when possible and appropriate. The goal has also been to incorporate those products into user-friendly mapping, visualization, and analysis tools made easily accessible through existing agency portals serving specific partners and stakeholders, as well as interagency venues such as the National Climate Assessment (NCA), the U.S. Climate Resilience Toolkit, and others.

The Task Force focused its initial efforts on the development of an interagency report (Sweet et al., 2017), providing updated GMSL rise scenarios focused primarily on 2100 and integrating these GMSL rise scenarios with regional factors contributing to sea level change to produce, for the first time, a set of RSL scenarios for the entire U.S. coastline. These scenarios were also a major technical input to Volumes I and II of the Fourth NCA (NCA4; USGCRP 2017, 2018) and have been widely used in the development of state (e.g., Florida[7] and Virginia [CCRM, 2019]) and local agency adaptation plans (e.g., Pensacola, Florida,[8] and Portland, Maine [One Climate Future, 2019]), and processes for anticipating and managing future coastal risks.

The Task Force's first report (Sweet et al., 2017) built upon the most current scenarios at that time (e.g., Parris et al., 2012; Kopp et al., 2014; Hall et al., 2016) and estimated the full possible range for GMSL rise by 2100 as being bounded by 0.3 m on the low end, representing a simple linear extrapolation of the GMSL rate since the early 1990s, and by 2.5 m on the high end, representing an extreme ice-sheet melt/discharge scenario. This 0.3–2.5 m range was discretized and aligned with emissions-based, conditional probabilistic storylines and global model projections into six GMSL rise scenarios: Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme, corresponding to GMSL rise by 2100 of 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m, respectively. These GMSL rise scenarios were then used to derive regional RSL responses on a 1-degree grid covering the coastlines of the U.S. mainland, Alaska, Hawai‘i, the Caribbean, and the Pacific Island territories, as well as at the precise locations of tide gauges along these coastlines.

This current report takes the Sweet et al. (2017) report as its starting point, updating the GMSL scenarios and the associated local and regional RSL projections to reflect recent advances in sea level science, as well as expanding the types of scenario information provided to better serve stakeholder needs for coastal risk management and adaptation planning. As with the 2017 report, this iteration will also serve as a key technical input to the NCA, in this case NCA5. Specific updates in this report include the following:

- While this report still uses the same nomenclature as the NOAA 2017 GMSL scenarios, it draws upon new science of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6; Fox-Kemper et al., 2021; Garner et al., 2021) to provide updated temporal trajectories and exceedance probabilities based on different levels of global warming. One effect is that the associated RSL projections for the U.S. coastline (gridded and at individual tide-gauge locations) differ in timing and magnitude as compared to the NOAA 2017 projections.
- In addition, in leveraging this updated science, including a longer observational record, improved understanding of ice-sheet dynamical processes, and better-constrained models, this report provides a more comprehensive and detailed assessment of the distinct types and range of uncertainties associated with the GMSL rise scenarios, particularly at the high end.
- By utilizing 50-year regional sets of tide-gauge data, observation-based rates and accelerations are extrapolated to the year 2050 to identify the scenario projections aligning with current RSL trajectories.
- Lastly, gridded EWL probabilities are provided, along with methods to localize them along most U.S. coastlines, to contextualize each of the regionalized sea level scenarios across a range of flood frequencies under current standards, from recurrent tidal flooding to major storm-surge flooding, out to 2050.

To frame the remainder of this report, it is important to emphasize the distinction between describing scientific progress, in terms of current understanding and key uncertainties, and translating such advances in the scientific knowledge base into actionable science. The latter requires sustained engagement by groups such as NOAA's Office of Coast Management and the Sea Grant program with users, stakeholder groups, and associated boundary organizations regarding their specific planning and decision contexts. Our development

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[7] https://floridadep.gov/rcp/florida-resilient-coastlines-program/documents/proposed-rule-development-draft-62s-7-sea-level

[8] https://storymaps.arcgis.com/stories/e812723f69ad4a618c8f5f8b08cb208e

of scenarios in this report is grounded in the principles of risk-based framing for climate assessment (King et al., 2015; Weaver et al., 2017; Sutton, 2019; Kopp et al., 2019) and is consistent with adaptation pathways approaches for long-term planning. What we thus aim to provide are screening-level (suitable for first-order assessment) products appropriate for framing and bounding important problems in coastal risk assessment and management, along with contextualization of the underlying science and illustrative case studies. For example, consistent with this purpose, this report aims to provide the underlying scientific information to develop both planning- and bounding-type scenarios across the full spectrum of coastal risk; that is, 1) planning scenarios intended to frame near- to mid-term decision contexts and/or longer-term decisions with high-risk tolerance or ability to adjust plans, which address the question, What is most likely to happen? and 2) bounding scenarios designed to set the envelope of possible future outcomes, which can be used to stress-test long-term objectives, gauge the “when, not if” a given level of sea level rise might be reached, and address the question How bad could things get? *What this report does NOT provide is official guidance nor design specifications for a specific project.*

Section 2 describes advances in the understanding of the drivers of mean sea level since the 2017 report, discusses the use of observations for a near-term trajectory assessment, and provides the updated GMSL rise scenarios and their associated regional RSL projections. Section 3 focuses on high-frequency EWLs, including a regional frequency analysis of historical NOAA tide-gauge data to develop a set of EWL probabilities for assessing and projecting (to 2050) across a range of flood levels. Section 4 applies these scenarios and projections in illustrative use-case examples. Section 5 provides a summary of the report findings, as well as conclusions and next steps.