Section 3: Extreme Water Levels and Changing Coastal Flood Exposure

Since Sweet et al. (2017), some objectives of the Task Force have been to define and develop for the U.S. coastline 1) a set of coastal-climate flood-resilience standards and 2) a gridded set of extreme water level (EWL) probabilities that span flood frequencies with associated impacts to assess these standards. Together, these sets of information are used to describe how flood exposure within coastal floodplains are slated to change from rising sea levels (i.e., without mitigative action). Specifically for 1), we use a nationally calibrated set of the coastal water-level-impact-severity thresholds from the NOAA National Weather Service (Sweet et al., 2018), which are used in public communications. For 2), a regional frequency analysis (RFA) of tide-gauge observations is developed by adapting methods for exposure assessments within the Pacific Basin (Sweet et al., 2020b) and for the U.S. Department of Defense coastal installations worldwide[11] (Hall et al., 2016). Regional frequency analysis can provide many types of geospatial information based on limited sets of local observations, such as rainfall characteristics published by NOAA[12] (Perica et al., 2018), which are widely used in stormwater design and management within the United States. Both the RFA-based extremes and NOAA flood-threshold information are discussed below.

There are a few important notes about terminology for this section (and the report as a whole). First, "average event frequency" terminology is used throughout (except in Section 4.2 to build off of relevant papers/concepts) to describe extreme water level probabilities instead of the more traditional "return period" terminology. This is done primarily to address best practices (or avoid bad practices), which have been reviewed by the United States Corps of Engineers (USACE; USACE, 1994). Although "frequency" and "period" are related (they are reciprocals), the use of "periods" can be misconstrued; e.g., the so-called 100-year event can be easily confused or communicated (e.g., IPCC, 2021b) as an event that "occurs once per century." Such an interpretation could be assumed to imply a static and permanent water level that happens, on average, 100 years from the last event. In reality, such coastal water levels have and will continue to change with sea level rise, among other potential factors, and can occur (albeit with low probability) several times over the span of a few years. Second, although annual exceedance probability terminology is often used to describe average event frequencies (e.g., 0.1 events/year frequency expressed as the 10% annual chance event), we again stick to events/year frequency terminology, partly due to underlying method but also because events occurring more often than once a year are also being quantified and communicated (a 5 events/year frequency is poorly conveyed as a 500% annual chance event). Finally, the use of the word "occurrence" in this section means "has the probability of equaling or exceeding," as it applies to a particular water level or flood height.

3.1. Overview of Extreme Water Levels and Coastal Flooding

As sea levels continue to rise, coastal water levels—from the mean to the extreme—are growing deeper and reaching farther inland along most U.S. coastlines. Where local relative sea level (RSL) is rising, the wet–dry land delineation (i.e., mean higher high water [MHHW] tidal datum; NOAA, 2003) is encroaching landward, causing more permanent inundation and land loss (e.g., in Louisiana); affecting groundwater levels (Befus et al., 2020), stormwater systems' effectiveness (Habel et al., 2020), and water quality (McKenzie et al., 2021); and altering the intertidal zone and its ecosystems (Kirwan and Gedan, 2019). Where local RSL is falling relative to the land surface, other problems can occur, such as changes in coastal erosion processes, incision of tributaries, decreased draft for waterborne transport, decreased sedimentation in saltwater marshes, and alterations in intertidal zones and estuaries (Larsen et al., 2004; Sweeny and Becker, 2020). Especially problematic for society's coastal footprint is that the entire spectrum of flood exposure is also growing where RSL is rising, from minor high tide flooding (HTF) to more severe major flooding during storms (Sweet and Park, 2014; Fox-Kemper et al., 2021). For example, the national rate of minor HTF is accelerating and is now (circa 2020) more than double what it was in 2000 due to RSL rise (Figure 3.1), with projections suggesting

[11] https://drsl.serdp-estcp.org/

[12] https://www.weather.gov/owp/hdsc

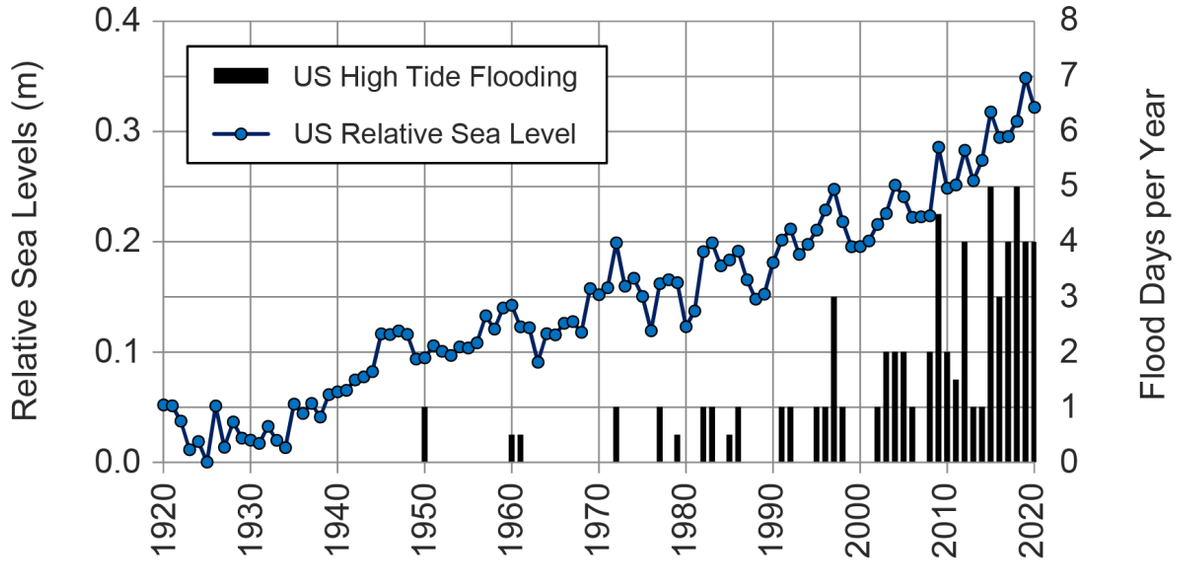

Figure 3.1: National median rate of minor high tide flooding and relative sea level, in meters, from 98 NOAA tide gauges along U.S. coastlines outside of Alaska used to monitor and track flood-frequency changes (from Sweet et al., 2021). Relative sea levels reference the lowest annual (1925) level.

a doubling of its current rate by 2030 (Sweet et al., 2018, 2021; The State of High Tide Flooding and Annual Outlook[13]; Thompson et al., 2021; Flooding Days Projection Tool[14]).

Assessments of current and future changes in minor to major HTF using RSL projections require probabilistic information about local water level variability. Specifically, they require the envelope of variability encapsulating EWLs that define the magnitude and frequency of events capable of causing a range of known or assumed impacts (Tebaldi et al., 2012; Church et al., 2013; Hall et al., 2016; USGCRP, 2017; Oppenheimer et al., 2019; Fox-Kemper et al., 2021). The basis for quantifying EWLs along U.S. coastlines originates with NOAA's tide-gauge network, which measures water level responses from multiple processes operating over a range of frequencies (Table 3.1). However, due to their general placement (e.g., in harbors), protective housings that dampen wave effects, and their multi-minute sampling rates, tide gauges typically do not measure or report values that include higher-frequency wave effects (Sweet et al., 2015; see Box 3.1). Other sources of useful tide level information for the U.S. and globally include USACE inventories (e.g., USACE MRG&P, 2017), the University of Hawaii Sea Level Center,[15] and the Global Extreme Sea Level Analysis database.[16]

Extreme water levels are often used as a proxy for impacts, such as the 0.01 events/year frequency level, better known as the "once per century" event (Oppenheimer et al., 2019), with connotations of the "flood of the century." However, such a probabilistically defined event can be both misleading about its true frequency (USACE, 1994) or might go mostly unnoticed in some locations (Sweet et al., 2020b). High tide flood heights, on the other hand, are absolute heights that are calibrated to the depth-severity impact thresholds of the NOAA National Weather Service and local emergency managers to trigger public notification of impending flood risks (NOAA, 2020). NOAA minor, moderate, and major HTF is defined as a water level reaching or exceeding about (national median values) 0.55 m, 0.85 m, and 1.20 m above current MHHW, respectively (Sweet et al., 2018). Put another way, an EWL is only a "flood" if it actually impacts the public in some manner and is not necessarily a description of a meteorological event.

[13] https://tidesandcurrents.noaa.gov/HighTideFlooding_AnnualOutlook.html

[14] https://sealevel.nasa.gov/data_tools/15

[15] https://uhslc.soest.hawaii.edu/

[16] https://www.gesla.org/

But the NOAA tide-gauge network is relatively sparse compared to the density of coastal communities, and the tide gauges have varying record lengths. From the perspective of a particular coastal community, this may result in either 1) a lack of local data (often data that are simply extrapolated from the closest NOAA tide gauge) or 2) a data record that is biased by lack of or overexposure to regionally significant rare events such as storm surges from landfalling tropical cyclones. Probabilistic assessments using atmospheric/ocean circulation models can increase spatial coverage (Vousdoukas et al., 2018), but they often perform poorly in areas with high tropical storm activity or with complex bathymetries (Muis et al., 2016). Targeted deployments of in situ sensors by communities to monitor changes in sea level, tide heights, and flood exposure (McCallum et al., 2013) can be informative but still lack the necessary longer-term regional perspective.

Table 3.1: Physical processes affecting U.S. coastal water levels and their temporal and spatial scale properties (modification of Sweet et al., 2017). Extreme water levels, which, as measured by tide gauges, generally exclude high-frequency wave effects, include processes between tsunami and ocean-basin variability and, to a lesser extent, low-frequency changes or trends associated with land ice melt/discharge, thermal expansion, and vertical land motion.

Physical Process	Spatial Scale			Temporal Scale	Potential Magnitude (yearly)
	Global	Regional	Local		
Wind Waves Effects	—	—	X	seconds to minutes	<10 m
Tsunami	—	X	X	minutes to hours	<10's of m's
Storm Surge (e.g., tropical and extra-tropical storms)	—	X	X	minutes to days	<10 m
Tides	—	X	X	hours to years	<15 m
Ocean/Atmospheric Variability (e.g., ENSO response)	—	X	X	days to years	<0.5 m
Ocean Gyre and Over-turning Variability	—	X	X	years to decades	<0.5 m
Land Ice Melt/Discharge	X	X	X	years to centuries	mm's to cm's
Thermal Expansion	X	X	X	years to centuries	mm's to cm's
Vertical Land Motion	—	X	X	minutes to centuries	mm's to m's

For the U.S., there are two primary sources of federally provided EWL probabilities. The first comes from the Federal Emergency Management Agency (FEMA, 2016b), which provides sets of regional solutions using a combination of NOAA storm-tide observations, historical high-water marks,[17] synthetic storm simulations (e.g., Nadal-Caraballo et al., 2020; ERDC Coastal Hazards System[18]), and wave effects to estimate the regulatory floodplain and its exposure to the rarest of events (e.g., 1% and 0.2% annual chance events). FEMA provides this information for national flood insurance purposes[19] but does not consider future sea levels. Another set of EWL probabilities is from NOAA's Center for Operational Oceanographic Products and Services (Zervas, 2013), which currently uses a generalized extreme value (GEV) distribution fit to annual highest water levels for tide-gauge records of >30 years).[20] The U.S. Army Corps of Engineers and their Sea Level Change Calculator[21] provide the NOAA EWL probabilities (Zervas, 2013) with several projections of future RSL to help in project planning but only for specific long-term tide-gauge locations.

A primary goal of the following subsections is to introduce a new set of EWL probabilities to support sea level rise and flood-exposure assessments and planning. The EWL set is applicable for most of the U.S. coastline and further resolves (both in physical and probability space) the EWL information currently available from

[17] https://stn.wim.usgs.gov/FEV/

[18] https://chs.erdc.dren.mil/

[19] https://www.fema.gov/flood-maps/national-flood-hazard-layer

[20] https://tidesandcurrents.noaa.gov/est/

[21] https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

FEMA and NOAA; although again, the EWL data here, which are derived from tide-gauge data, generally do not include wave effects (see Table 3.1 and Figure 1.1). Section 3.2 briefly describes the RFA of NOAA tide-gauge data with pointers to the Appendix for a fuller description. In Section 3.3, data for all NOAA tide gauges with >10 years of record are used to compute EWL probabilities, and these results are compared to NOAA and FEMA datasets. Section 3.4 discusses methods on how local EWL probabilities can be 1) computed using other records, such as those of shorter duration (<10 years) from NOAA or other (user supplied) sources, and 2) estimated approximately every 500 m along the U.S. coastline based on local tide range information from NOAA models (e.g., VDatum[22]). Lastly, Section 3.5 assesses current and future flood exposure within the coastal floodplain using NOAA's height-severity categories of minor, moderate, and major HTF (Sweet et al., 2018), which broadly define water levels where U.S. infrastructure becomes impacted and are used in weather forecasting to trigger emergency responses (NOAA, 2020). Estimates of how flood exposure is projected to change by 2050 (assuming no additional adaptation or risk-deduction measures) are provided using the upper-bounding scenarios of the regional observation-based extrapolations along U.S. coastlines (see Table 2.2).

3.2. Regional Frequency Analysis of Tide-Gauge Data

Extreme water level probabilities and their 95% confidence intervals are provided at a 1-degree spacing along nearly the entire U.S. coastline (Figure 3.2). The EWL information is based on an RFA (Hosking and Wallis, 1997) of NOAA tide gauges within a 400-km radius of the center of each individual 1-degree grid and fit with a Generalized Pareto Distribution (GPD) of threshold exceedances (Coles, 2001). The RFA process not only better assesses EWL exceedance probabilities from a regional perspective as compared to a single-gauge assessment but also can supply information where no tide gauges exist. Furthermore, a GPD fit to exceedances above a high threshold as compared to a GEV fit to annual maxima uses more of the data record (e.g., two or more significant events within a particular year), not just those maxima within a certain (e.g., annual) time block. This approach, using RFA-based GPD fits, better resolves both the low- and high-frequency spectrum with output in this report ranging from 0.01 events/year to 10 events/year frequencies. Combining an RFA with GPD fits to obtain EWL probabilities is unique for U.S. coastlines, although there are other statistical methods such as the joint probability method (Baranes et al., 2020) and Bayesian hierarchical modeling (Calafat and Marcos, 2020), which may also prove useful in assessing rare event probabilities or providing information where no tide gauges exist.

[22] https://vdatum.noaa.gov/

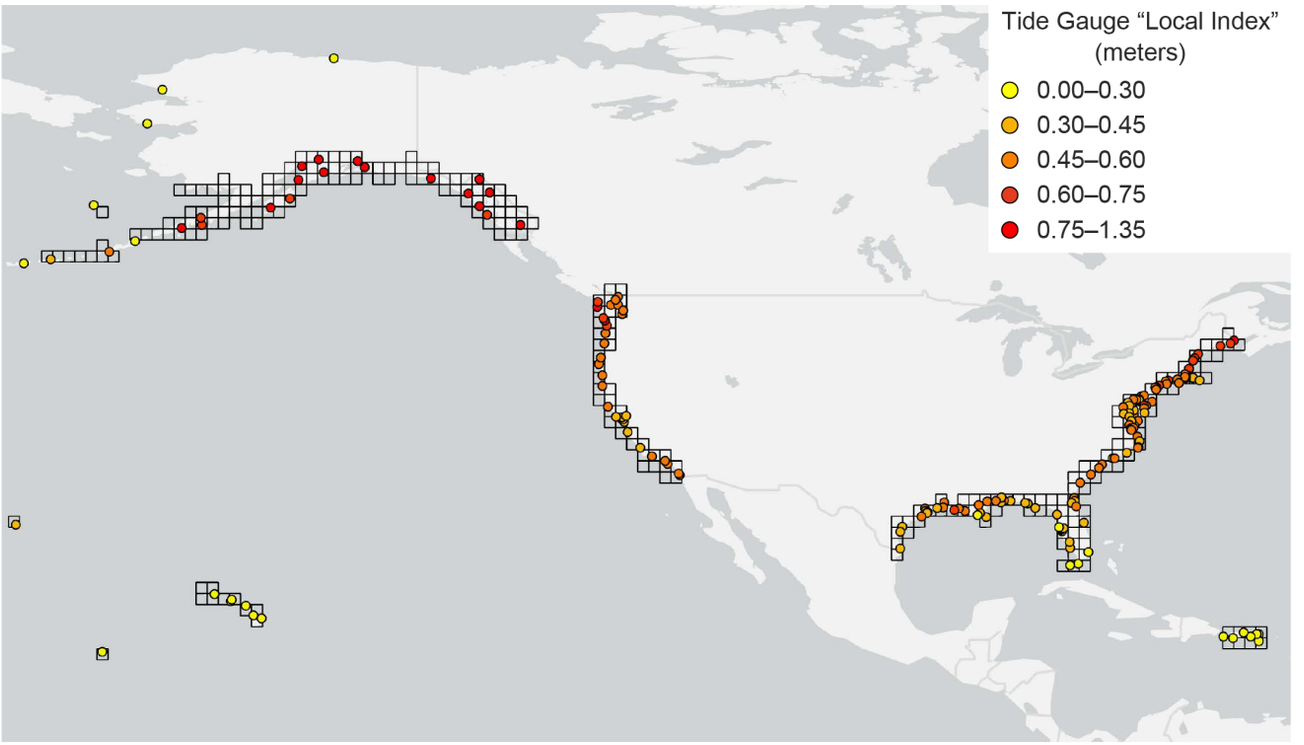

Figure 3.2: Regional Frequency Analysis 1-degree grids and local index values (u) relative to local mean higher high water tidal datum at the NOAA tide gauges used in this study.

To be useful for local decision-making, the gridded EWLs ($EWL_{gridded}$) derived by RFA need to be further localized (EWL_{local}), which is achieved via a “local index” (u) estimated at a particular tide gauge (u values are shown in Figure 3.2) or for a particular location and converted to the vertical control datum on the land surface, normally the North American Vertical Datum of 1988 (NAVD88). The following equation is used to estimate EWL_{local} probabilities (median and 95% confidence intervals):

$$1) \qquad EWL_{local} = EWL_{gridded} * u_{local} + u_{local}$$

where $EWL_{gridded}$ is the gridded EWL composed on normalized (unitless) sets of tide-gauge data, and u_{local}, referred to simply as “u,” are the same value and represent the height of the 98th percentile of daily highest water levels with a 4-day filter applied and are relative to the 1983–2001 (or 5-year modified epoch; Gill et al., 2014) MHHW tidal datum. For statistical independence when quantifying the EWL probabilities, the filtering process is needed to isolate and only include the peak water level value from a particular storm or “event,” rather than including multiple consecutive daily peak levels resulting from the same event (e.g., a multiday storm surge). See Section A2 for more details.

3.3. Average Event Frequencies of Extreme Water Levels

The focus of this analysis is on EWL events and their probabilities that span the frequency space associated with coastal flooding under current sea levels (Sweet et al., 2018). An example for the NOAA tide gauge at The Battery in New York City (NYC) in Figure 3.3a shows the NOAA HTF heights and probability distributions for hourly water levels and also for their daily maxima.[23] Also shown is the local index (u = 0.55 m above MHHW) computed for this tide gauge, which is used to estimate EWL_{local} from the $EWL_{gridded}$ probabilities for this location (Figure 3.3b). See Figure A2.2f for the gridded probabilities applicable for NYC. At higher frequencies, such as those associated with the height of the minor HTF level (0.56 m above MHHW), the EWL_{local} probabilities for ”events” (about 4–5 events/year) are close but slightly underestimate flood frequency estimates for “days” (about 11 days/year; not shown), which are based on a multidecadal distribution

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

of daily highest water levels (shown in Figure 3.3a) used by NOAA when making projections of minor HTF (Sweet et al., 2018). This difference reflects the 4-day event filter in estimates of the EWL_{local} probabilities discussed above. A similar ratio (about 2 days per event) exists in NOAA's HTF Outlook (about 11 days/year for 2020 at NYC, which is based on an extrapolation of quadratic or linear fits to annual counts of minor HTF days (Sweet et al., 2020a). The ratio of minor HTF "events" to "days" estimated at NOAA tide gauges as a whole is further discussed later in this section. The main point is that, typically, the duration of a minor HTF "event," as in NYC and along U.S. coastlines, spans about 2 days and multiple tide cycles on average.

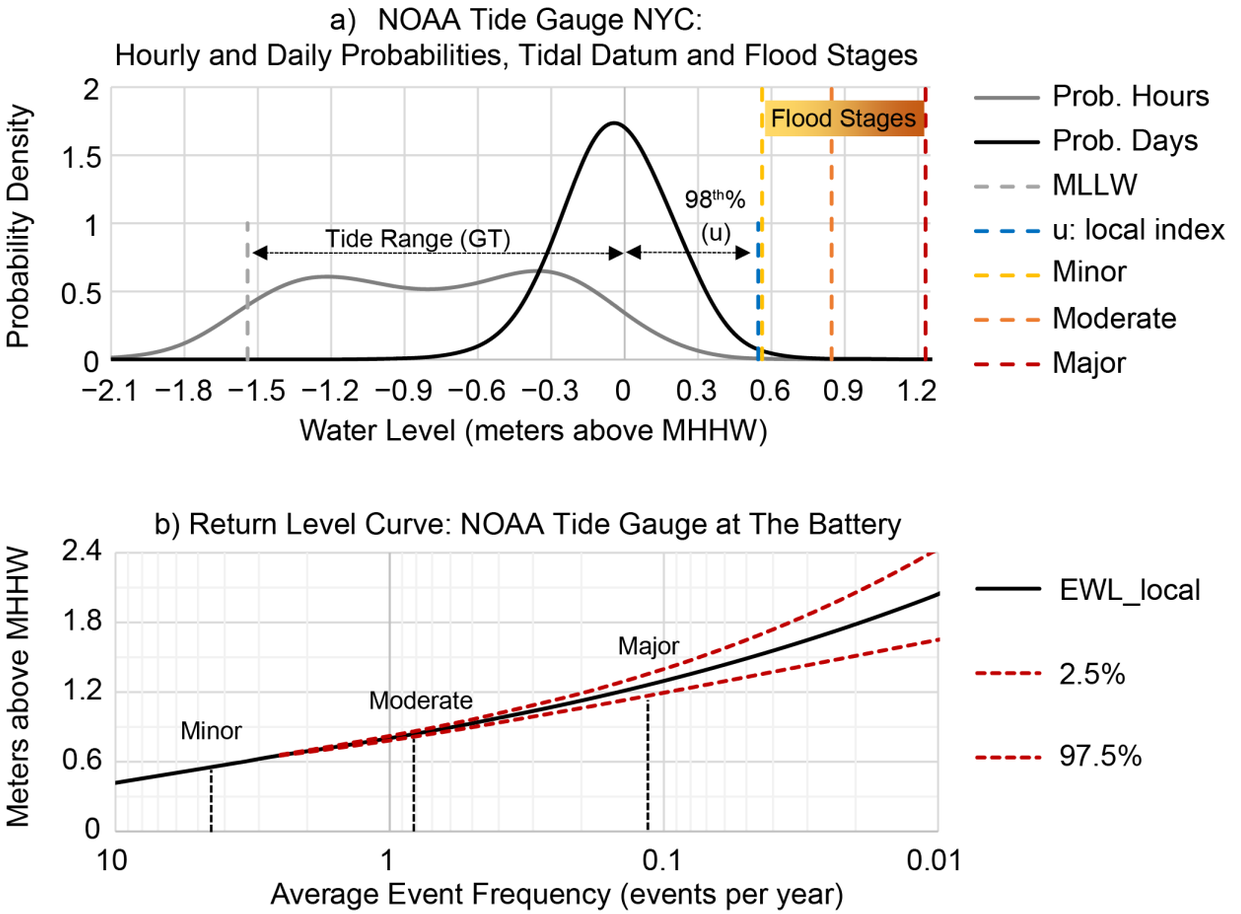

Figure 3.3: a) Empirical probability densities of hourly water levels and their daily maxima measured by the NOAA tide gauge at The Battery (New York City), as well as the tidal datums of mean lower low water (MLLW), great diurnal tide range (GT), local high tide flood (HTF) heights, and the local index (u) used to localize the RFA-gridded EWL for this location (see Figure A2.2f). All values are referenced to the mean higher high water (MHHW) tidal datum and shown in b) as a return interval curve with the 95% confidence interval (2.5% and 97.5% levels) normalized to year 2020 RSLs.

Some general patterns emerge in regional $EWLs_{local}$ with 1 event/year (Figure 3.4a) and 0.01 events/year frequencies (Figure 3.4b). Locations with higher 0.01 events/year EWL_{local} are found adjacent to wide, shallow continental coasts that are exposed to frequent tropical or extratropical storm surges, such as occur along the Eastern and Western Gulf coastal regions at 2.5 ± 1.1 m and 2.8 ± 0.8 m (median ± 1 standard deviation), respectively. In contrast, the U.S. Pacific/Hawaiian Islands and Southwest Pacific coastal regions have lower 0.01 events/year $EWLs_{local}$ due to deep, narrow continental shelves and generally calmer conditions (0.8 ± 0.1 m and 1.0 ± 0.1 m, respectively), although wave effects not inherent to the EWL probabilities are often the primary factor causing flooding, overwash, and erosion along natural landscapes in these locations (Barnard et al., 2019; see Box 3.1). In terms of the 1 event/year heights, tide ranges become influential (correlation of ~0.7 between great diurnal tide range [GT] and u across all locations), as is the case in the Northwest Pacific coastal region and the southern Alaska coasts, where the highest 1-year EWLs occur (0.8 ± 0.1 m and 1.0 ± 0.3 m, respectively) and larger tide ranges are found.

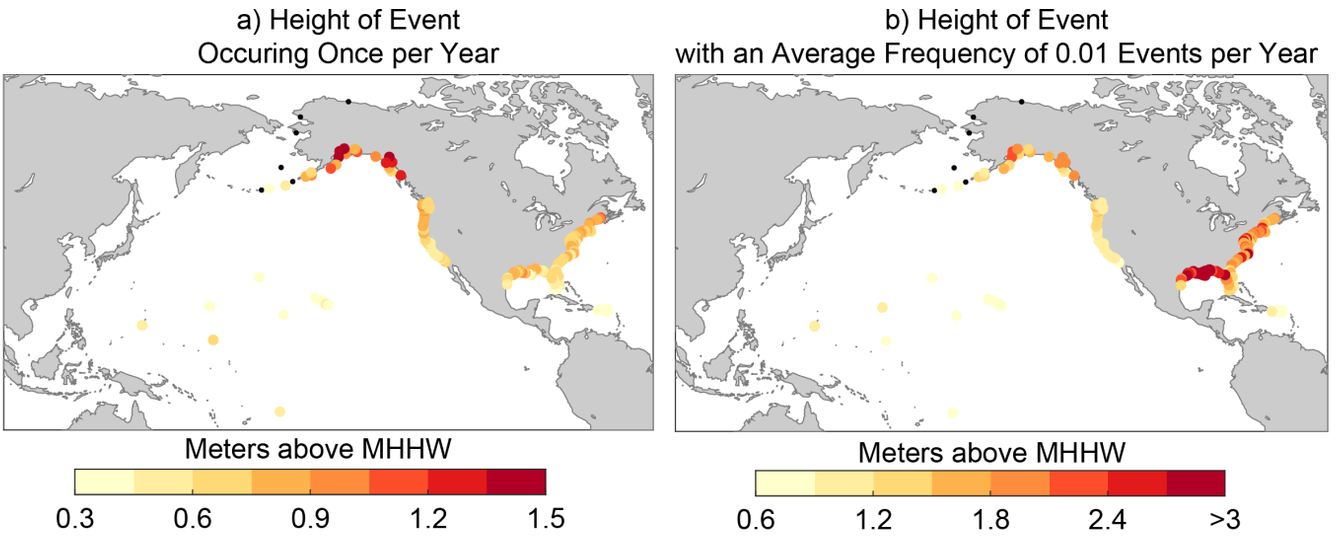

Figure 3.4: Current (circa 2020 relative sea levels) EWL_{local} that a) occur annually on average and b) have a 0.01-year average event frequency. Note: the scales in the two figures are not the same, and to be useful for decision-making, a conversion to land-based heights (e.g., NAVD88) should be made.

There are differences when comparing the RFA-based $EWLs_{local}$ from this study to current FEMA and NOAA governmental datasets. Comparisons to NOAA EWLs (Zervas, 2013) in Figure 3.5a–c show that the RFA-based 0.01, 0.1, and 0.5 events/year levels are about 6%, 9%, and 13% higher across the board based on linear regression, respectively. The bias between datasets is not unexpected, as an RFA typically results in higher EWL probabilities with narrowed confidence intervals due to the regionalization process as compared to a single-gauge analysis (Sweet et al., 2020b). Overall, there is strong correlation between datasets, although less so at the 0.01 events/year EWL_{local} (R^2 = 0.49) due in part to the large differences occurring along the Gulf coastlines of Alabama, Mississippi, and Louisiana, where the RFA-based 0.01 events/year EWL_{local} (~4 m above MHHW) values are substantially higher (>1 m) than the NOAA GEV estimates in a few locations.

The RFA-based EWL_{local} probabilities are also compared to the tide-gauge-equivalent "stillwater" component (tides, storm surge, and limited wave set-up, but not wave swash; see Figure 1.1) generated by FEMA and used within their regional Flood Insurance Studies[24] (Figure 3.5d–f). The FEMA EWLs vary in their construction by region, using a combination of singular and RFA tide-gauge analyses, storm-surge modeling, and synthetic tropical storm modeling (for the Northeast, Southeast, and Eastern and Western Gulf coastal regions) via a joint probability method–optimal sampling (JPM–OS) procedure (FEMA, 2016a, 2016b). The 0.01 and 0.1 events/year EWL_{local} are slightly lower (7% and 4%, respectively), with differences again noted along the Eastern and Western Gulf and Caribbean coastal regions. At the 0.5 events/year levels, both sets of EWLs are nearly the same based on linear regression. The goodness-of-fit (R^2) values are about the same as with the NOAA (2013) GEV results, although a little less at the 0.01 events/year levels—likely due to the inclusion of synthetic storm-surge modeling in the FEMA estimates, compared to the NOAA (2013) values, which are based on tide-gauge observations. Thus, it is concluded that the RFA-based EWL provides higher estimates than a single-gauge analysis (Zervas, 2013) but less than those of FEMA stillwater values at lower probabilities, since FEMA's data also include storm-surge modeling, synthetic storms, and high-water marks in addition to tide-gauge data.

[24] https://www.fema.gov/glossary/flood-insurance-study-fis

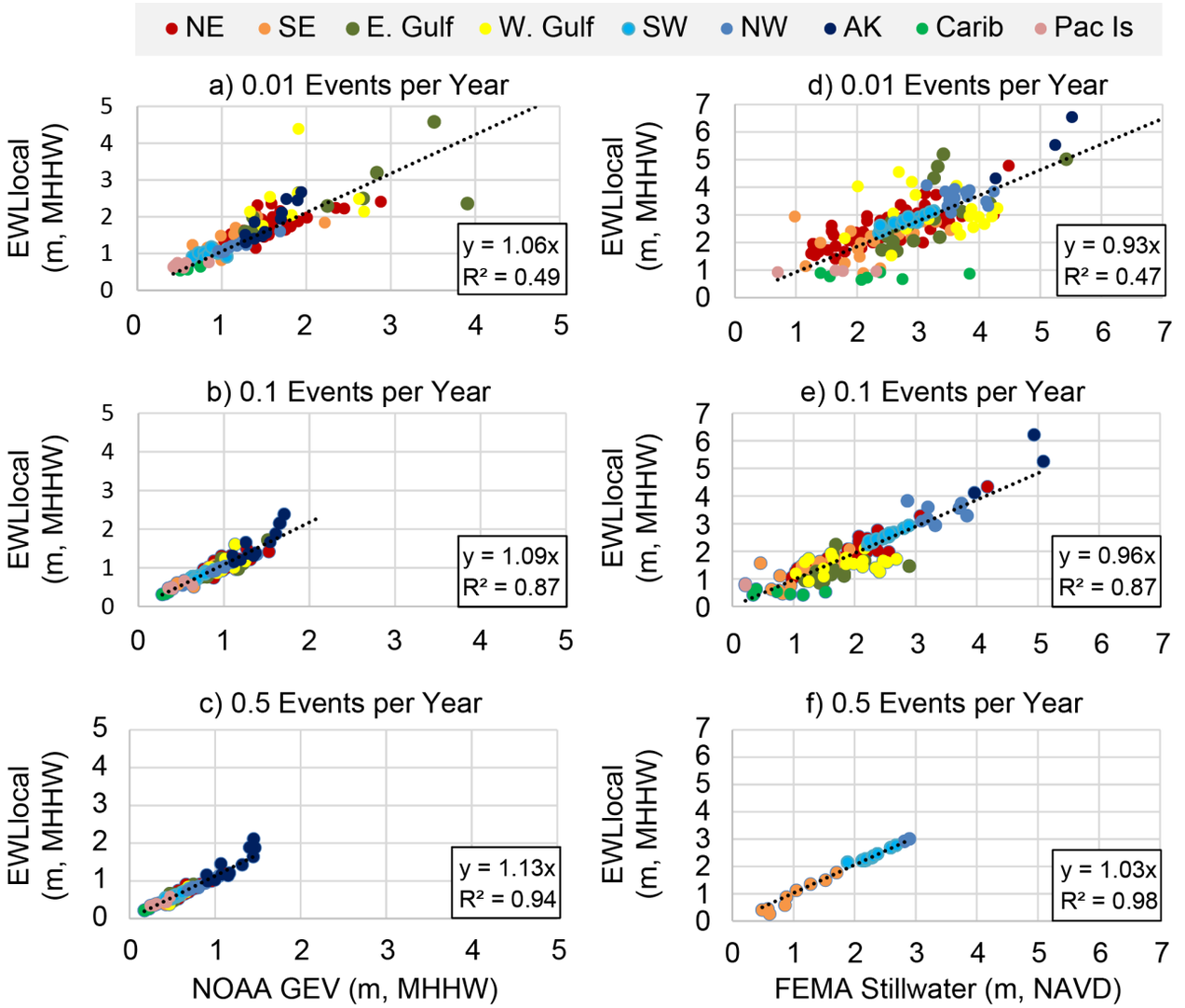

Figure 3.5: Comparison between (a–c) this study's EWL_{local} to those of NOAA (Zervas, 2013) based on a GEV fit of annual highest water levels and to (d–f) the stillwater (storm surge, tides, and wave set-up) components of FEMA used in their Flood Insurance Study at the 0.01-year, 0.1-year, and 0.5-year average event frequency levels.

3.4. Methods to Localize the Gridded Extreme Water Level Event Probabilities

There are several ways to obtain EWL_{local} from the $EWL_{gridded}$. All require a local index (u), which can be obtained from 1) a NOAA tide gauge used in this study (Figure 3.2; Table A1.3); 2) alternative sources of water level/tide-gauge data not used in this study (e.g., see Figure A2.3); or 3) tide range knowledge from measurements or models. When using short-term water level measurements (Figure A2.4), additional uncertainty, dependent on record length, is factored into the 95% confidence interval of the EWL_{local} estimate (see Equation 4 in the Appendix). This additional uncertainty relates to the fact that the local index (u) will vary from year to year akin to how RSL varies through time.[25] On a national scale (and for most regions as well; see Figure A2.4), the root mean square error (RMSE) in local index estimates is about 6–7 cm after 5 years and falls to less than 3 cm at 10 years, which is close to the standard error in tidal datum calculations themselves (see datum errors in Bodnar, 1981).

Where local water level measurements are not available, another option is to estimate a local index (u) and EWL_{local} probabilities based on an underlying relationship between local index values and tide range along U.S. coastlines. Additional uncertainty using this method will need to be factored into the results as well.

[25] https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

This relationship (Figure A2.5) builds off of the findings of Sweet et al. (2020b) within the Pacific Ocean and of Merrifield et al. (2013) globally, who found a strong global correlation between the range of water level variability and average annual highest water level across the globe. Nationally, there exists a strong positive relationship (R^2 = 0.72 in Figure A2.5), although with fairly large uncertainty (RMSE of 0.11 m). But when tide range and local index values are regressed regionally, all the fits' RMSEs are less (see Figure A2.5). Across all U.S. regions, it takes about 6 years of data for the RMSE (see Figure A2.4) in local index (u) estimates to match the RMSE values based on measured tide range (see Figure A2.5). Tide range information can be obtained from NOAA Vertical Datum Transformation (VDatum).[26] Comparison of RMSEs based on multiple years of record versus tide range estimates of a local index (u) will vary by region (see Figures A2.4 and A2.5), and the lesser of the two is considered the better option in estimating an EWL_{local} for any specific location not associated with a tide-gauge location used in the study.

Here we provide an example of how to obtain EWL_{local} probabilities for a location not used in this study. The location for this example is the NOAA National Estuarine Research Reserve in Grand Bay, Mississippi (Figure 3.6a), which has a NOAA tide gauge, but the hourly record is only about 4 years long.[27]

1. The first step is to identify the specific EWL grid where the location resides, which in this case is grid number 42811 (Figure 3.6a), and obtain the $EWL_{gridded}$ probabilities.
2. Next, a local index needs to be estimated for an EWL_{local} to be computed, either by the tide-range-based method (Figure 3.6b) or using the existing short data record (Figure 3.6c) for the specific region, depending on the smaller RMSE of the two methods. The RMSE based on the tide range regression is 0.078 m (Figure 3.6b) and is less than the 0.099 m RMSE based on a 4-year water level record for this region (solving the equation shown in Figure 3.6c).
3. Using the published NOAA tide range value at this location (0.49 m) leads to an estimated local index value of 0.47 m through the regional regression (solving the equation shown in Figure 3.6b).
4. An EWL_{local} return level curve (Figure 3.6d) relative to the 1983–2001 tidal epoch is generated by substituting a local index value of 0.47 m and an RMSE of 0.078 m (with a variance of 0.078^2) into Appendix Equations 1 and 4 (see Section A2), respectively.
5. Finally, to update the curve to current conditions (circa 2020) from the midpoint of the 1983–2001 epoch (1992), 0.12 m is added to the return level curve values. The 0.12 m value represents the regional-median trend in u of 4.3 mm/year multiplied by 28 years (see Table A1.3 and Section A2.3.4 for more information). Alternatively, 0.15 m could be added instead by applying the RSL offsets from the regional observation-based extrapolations for this region (Table A1.2).

The resultant EWL_{local} probabilities estimated for Grand Bay are similar to others at nearby tide gauges that share the same 1-degree $EWL_{gridded}$ (see Figure 3.4). Less noticeable is that the 95th confidence intervals are more inflated (i.e., 0.5 m vs. 0.1 m at the 1 event/year EWL) because of the additional uncertainty from using the tide-range-based method to obtain a local index. Nationally, the spread of the 95% confidence interval at the 1 event/year EWL_{local} using a local index (u) estimated by tide range (Figure 3.6b and Figure A2.5) is 0.32 m as compared to 0.03 m when assessed across all NOAA tide gauges.

[26] https://vdatum.noaa.gov/

[27] https://tidesandcurrents.noaa.gov/stationhome.html?id=8740166

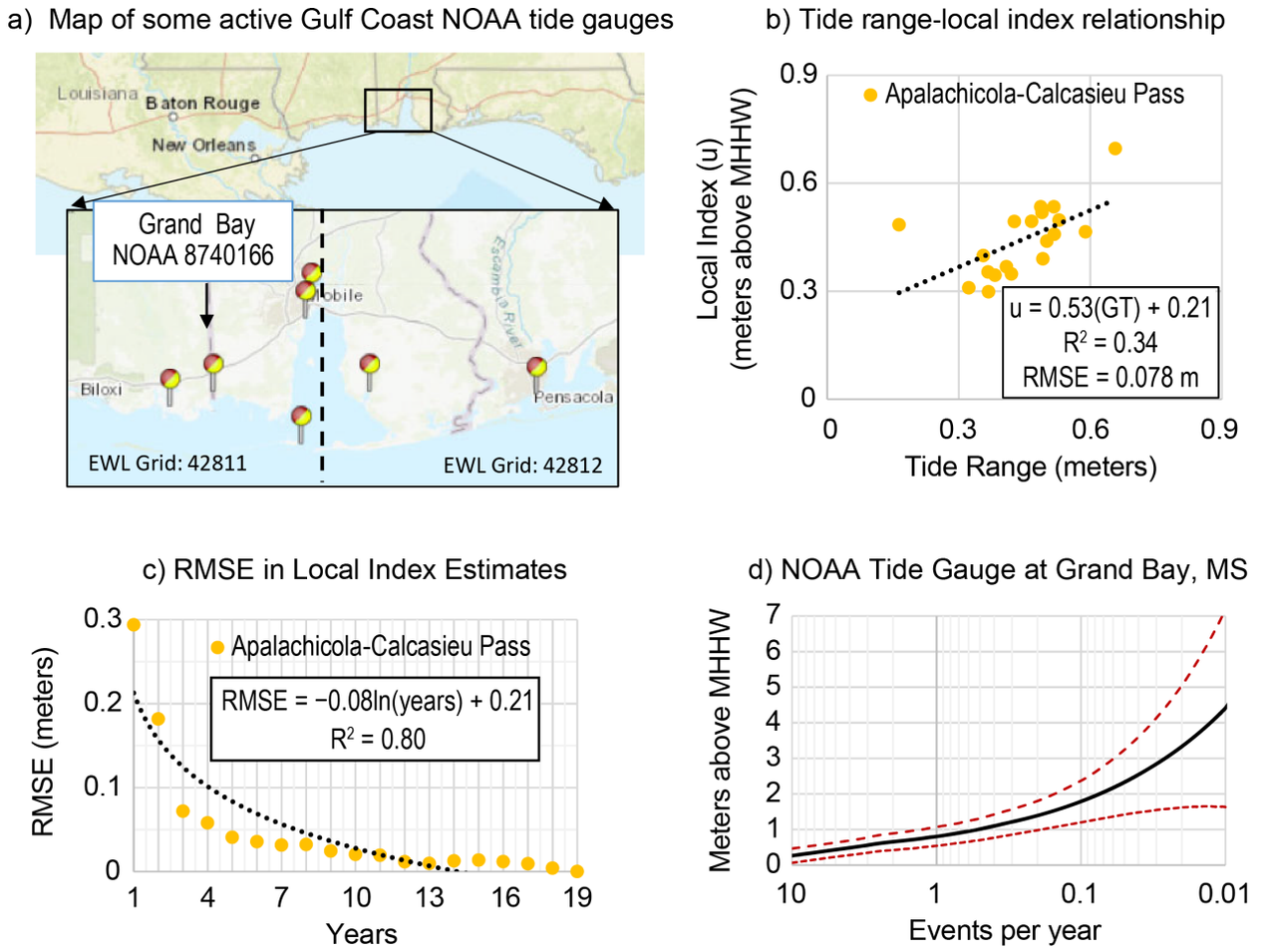

Figure 3.6: a) Map showing active NOAA tide gauges indicating Grand Bay, Mississippi, which has about 4–5 years of hourly data, b) tide range to local index (u) regression relative to the 1983–2001 tidal datum epoch with fit equation, goodness of fit (R^2), and associated root mean square error (RMSE) for the surrounding region, c) RMSE for estimates of u based on 1–19 years of consecutive data over the 2001–2019 period based on the regional tide gauges for the surrounding region; and d) a 2020 EWL_{local} return level curve for Grand Bay using a local index (u) from tide range regression. Note: to be useful for decision-making, a conversion to land-based heights (e.g., NAVD88) should be made.

3.5. The Changing Nature of Coastal Flood Exposure

To assess U.S. coastal flood exposure using the EWL_{local} probabilities, we use the nationally calibrated coastal HTF heights of NOAA (Sweet et al., 2018) and a modification of Sweet et al. (2020b) for Alaska coastlines (see Section A2.4). The NOAA HTF heights include three categories: minor, moderate, and major (national median) starting at about 0.55 m, 0.85 m, and 1.20 m, respectively (Figure A2.6), whose impacts are disruptive, typically damaging, and often destructive, respectively, under current flood defenses. NOAA provides data (e.g., Flood Frequency [MapServer][28]) and maps (Figure 3.7) in its SLR Viewer of exposure to HTF to help communities recognize potential flood exposure associated with weather–water level forecasts and for vulnerability assessments associated with sea level rise.

Currently (with EWL_{local} relative to year 2020 trend levels), minor HTF events occur (median value) about 3 times per year along U.S. coastlines and are most frequent along the Northeast, Western Gulf, and Northwest coastlines (about 4 events/year) and along the Southeast and Eastern Gulf coastlines (about 2 events/year; Figure 3.8a). A similar pattern emerges when comparing the 2020 NOAA minor HTF outlook (Sweet et al., 2020a) for the number of flood "days" at about 100 of the tide gauges (Figure 3.8b). The NOAA outlook for

[28] https://coast.noaa.gov/arcgis/rest/services/dc_slr/Flood_Frequency/MapServer

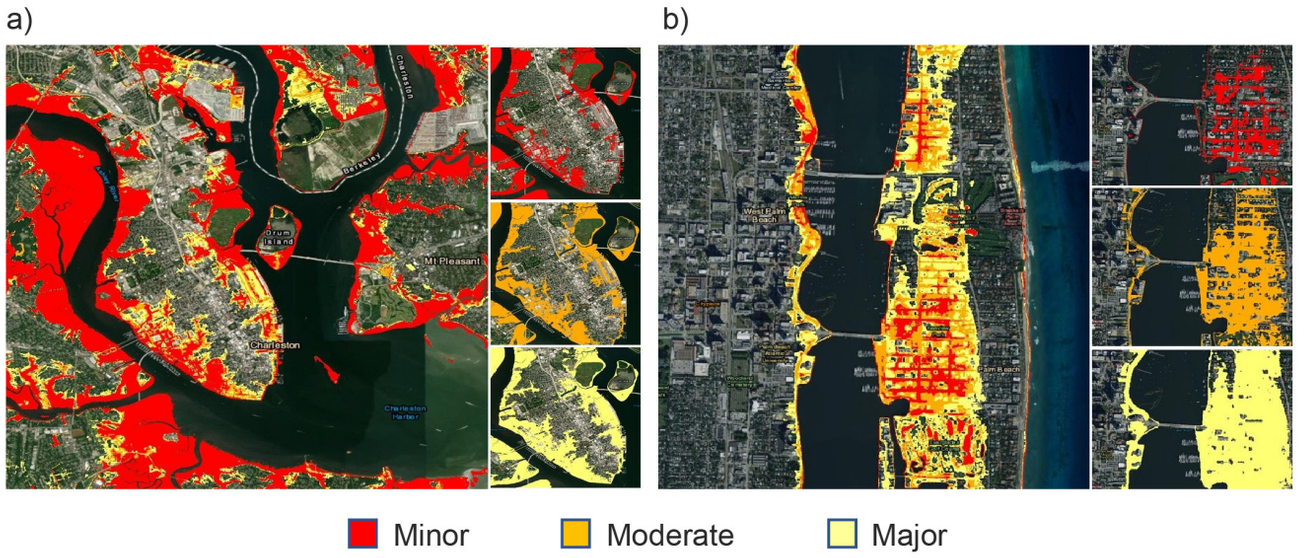

Figure 3.7: NOAA minor (red layer: land between mean higher high water [MHHW] and minor high tide flood [HTF] height above MHHW), moderate (orange layer), and major (yellow layer) HTF maps showing a regional layered map with individual layer panes to the right for a) Charleston, South Carolina, and b) West Palm Beach, Florida. MHHW for 1983–2001 is the shoreline edge. Note: to be useful for decision-making, a conversion to land-based heights (e.g., NAVD88) should be made.

minor HTF days uses extrapolations of linear and/or quadratic fits to days per year with a water level at or above the flood height. As a whole, there are about twice the number of days of minor HTF than the number of discrete events (Figure 3.8b inset), which is largely reflective of typical synoptic-scale (temporal) variability and the 4-day event filtering used in the RFA process and GPD fitting. The national (median) outlook for minor HTF in 2020 was 4–5 days, with about 8–9 days each along the Northeast and Western Gulf coastlines and 3–5 days each along the Southeast and Eastern Gulf coastlines (Sweet et al., 2020a).

Currently, moderate HTF in 2020 (Figure 3.8c) has about a 0.3 events/year frequency (median value) nationally and a similar 0.2–0.4 events/year frequency along the Southeast, Eastern Gulf, and Northwest coastlines. Moderate HTF is most likely along the Western Gulf coastlines (0.6–0.7 events/year). Major HTF (Figure 3.8d) nationally and along the Southeast coastline has about a 0.04 events/year frequency. Major HTF is most likely along the Western Gulf coastline (0.15 events/year) and along the Northeast and Eastern Gulf coastlines (0.08–0.09 events/year). For a more local perspective (see Figure 3.7), 2020 annual frequencies of minor, moderate, and major HTF in Charleston, South Carolina, and West Palm Beach, Florida, were about 2–3 events/year, 0.15–0.25 events/year, and about 0.02–0.04 events/year, respectively, based on the nearest tide gauge (see Table A1.2).

Changes in flood exposure are projected to 2050 considering no additional flood risk reduction or adaptation (e.g., via improved stormwater system functionalities) at NOAA tide gauges (Figure 3.9). The EWL_{local} probabilities are brought to 2050 levels by adding the local RSL projections initiating in year 2005 associated with the upper-bounding sea level scenario identified by the regional observation-based extrapolations (Table 2.2). Other scenarios could be used, but we opted for this particular set because it uses observational evidence—extrapolation of fits over the last 50-years (i.e., 1970–2020) to provide some level of prediction for the next 30 years. For instances where the extrapolations are the same as a particular scenario (e.g., Northeast), the adjacent (higher) scenario is used (e.g., the Intermediate is considered the upper-bounding scenario for the Northeast), which also serves to partially compensate for natural variability that is not reflected in the extrapolations.

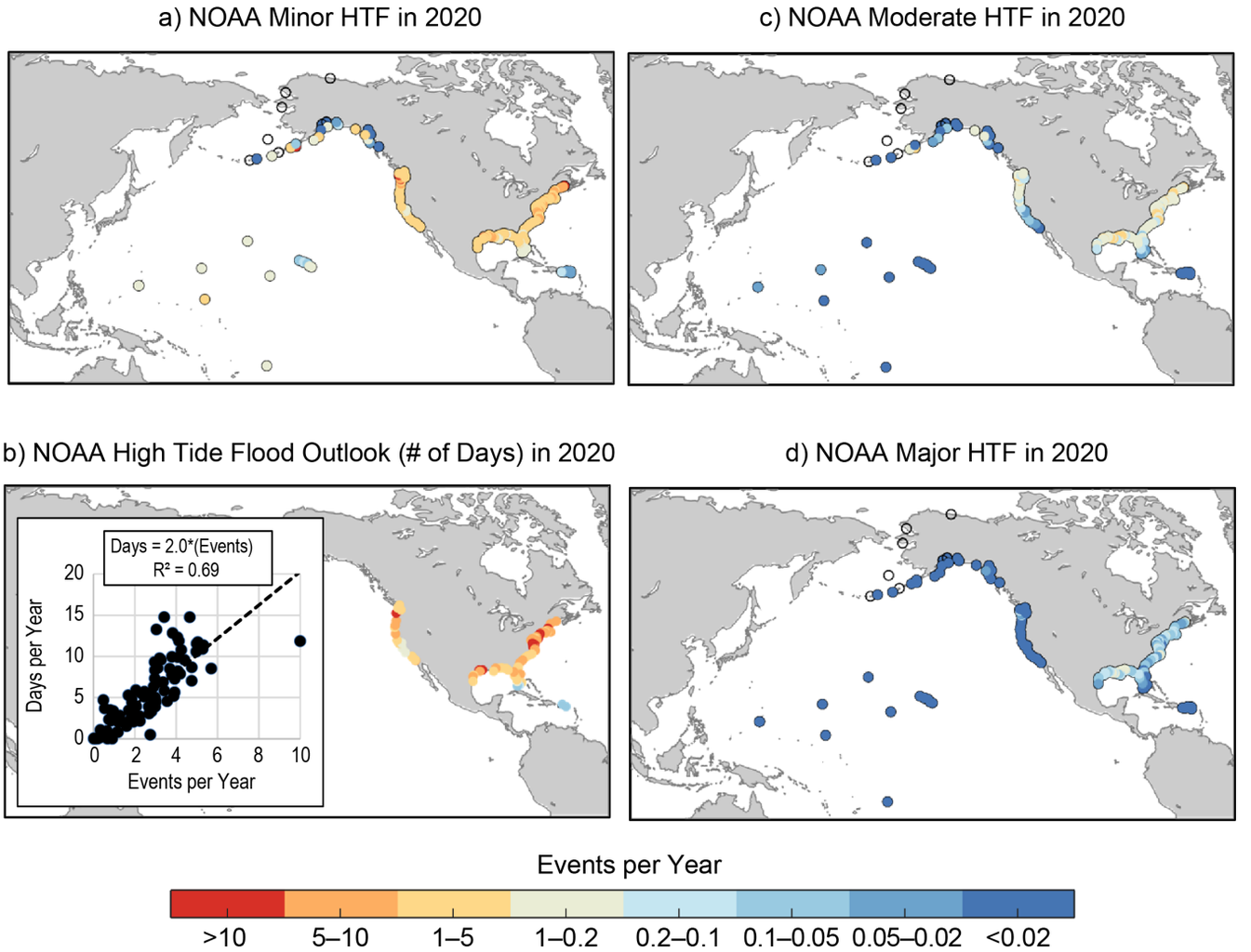

Figure 3.8: Average event frequencies in 2020 of a) minor high tide flooding (HTF); b) number of "days" (as compared to "events") of HTF estimated in NOAA's annual outlook (Sweet et al., 2021) and regression between events and days; c) average event frequencies in 2020 of moderate HTF; and d) average event frequencies in 2020 of major HTF. Flood height-severity definitions are from NOAA (Sweet et al., 2018) and, specifically for Alaska locations, from Sweet et al. (2020b).

Nationally and along all regions except the Hawaiian/Pacific Islands (about 9 events/year), the Caribbean (about 6 events/year), and Alaska (0.7 events/year) coastlines, the median event frequency in minor HTF is projected to increase to >10 events/year (Figure 3.9a). Moderate HTF (median) frequencies (Figure 3.9b) are projected by 2050 to increase nationally to about 4 events/year; >10 events/year along the Western Gulf coastline; 3–6 events/year along the Northeast, Southeast, and Eastern Gulf coastlines; about 1 event/year along the Northwest coastline; and 0.7 events/year along the Southwest coastline. Major HTF frequencies (Figure 3.9c) are projected to increase to about 0.2 events/year nationwide (median), with 1 event/year along the Western Gulf coastline, 0.5 events/year along the Northeast coastline, and 0.2–0.3 events/year along the Southeast Atlantic and Eastern Gulf coastlines. For a local perspective, the 2050 projections of annual frequencies of minor HTF in Charleston and West Palm Beach are >10 events/year, with 4–5 of those events reaching or exceeding moderate HTF and the possibility (0.1–0.2 events/year) of major HTF.

For perspective and a summary assessment by region, Table 3.2 quantifies how minor, moderate, and major HTF frequencies have changed and are projected to change considering the local RSL scenarios associated with the upper-bounding scenario of the regional observation-based extrapolations (Table 2.2) using 1990, 2020, and 2050 time slices. Nationally, minor HTF frequencies nearly tripled between 1990 and 2020, growing from about 1 to 3 events/year. They are projected to more than triple by 2050 to

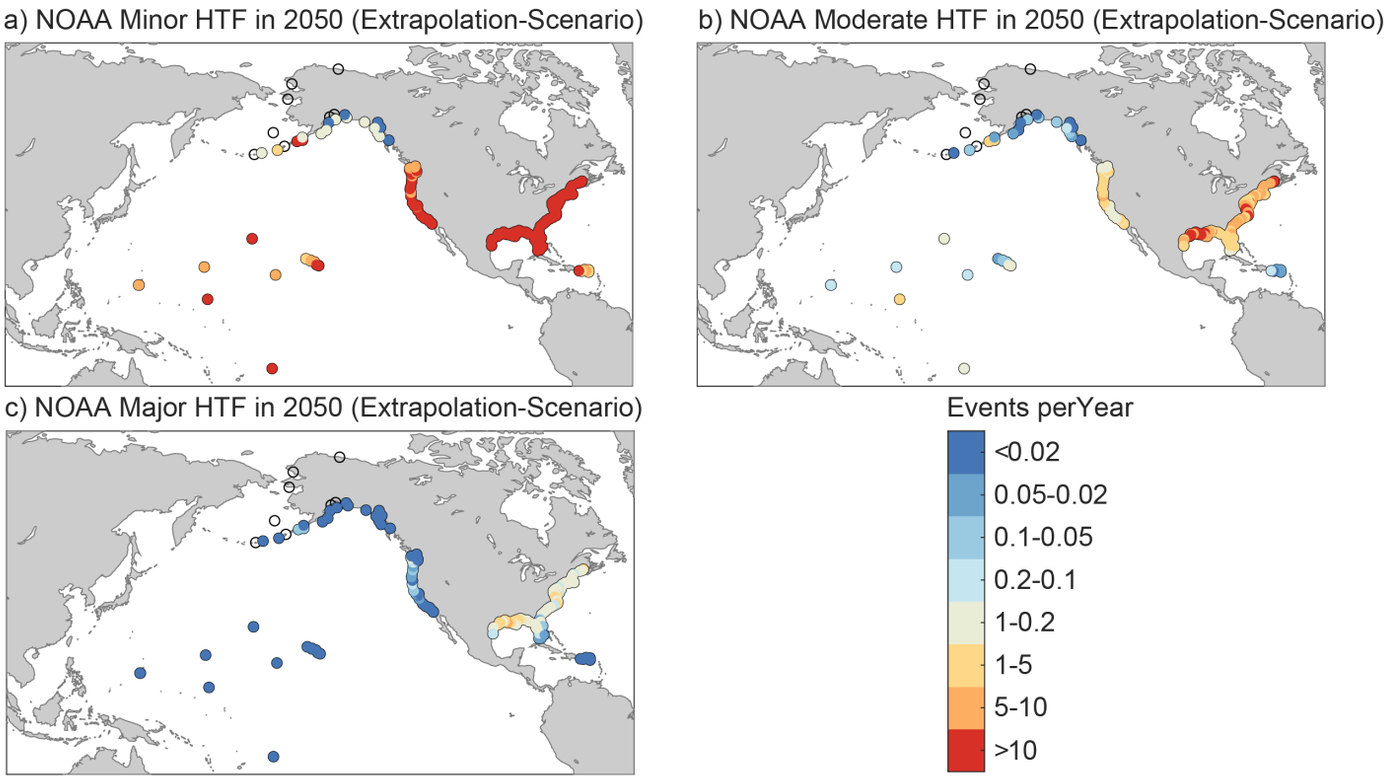

Figure 3.9: Coastal high tide flooding (HTF) frequencies projected at 2050 applying the sea level scenario that upper-bounds the regional observation-based extrapolations for NOAA a) minor, b) moderate, and c) major HTFs.

>10 events/year. Moderate HTF frequencies nationally experienced about a 50% increase (0.2 events/year growing to 0.3 events/year) from 1990 to 2020, which is slightly higher than the frequency increase in major HTF frequencies. By 2050, moderate HTF frequencies nationally are projected to increase by more than a factor of 10, with about a factor of 5 increase in major HTF frequencies. In short, assuming continuation of current trends and summarized at the national level, a flood regime shift is projected by 2050, with moderate HTF occurring a bit more frequently than minor HTF events occur today and major HTF events occurring about as frequently as moderate HTF frequencies occur today.

Table 3.2: Annual average event frequencies for NOAA-defined minor, moderate, and major HTF heights by region that were typical (median values) in 1990, under current (circa 2020) sea levels and projected to occur considering the upper-bounding scenario of the observations-based extrapolations in 2050 (see Table 2.2).

U.S. Region	1990			2020			2050		
	Minor Flood	Moderate Flood	Major Flood	Minor Flood	Moderate Flood	Major Flood	Minor Flood	Moderate Flood	Major Flood
National	1	0.2	0.03	3	0.3	0.04	>10	4	0.2
*Hawaii/Pac Is	0.06	<0.02	<0.02	0.2	<0.02	<0.02	9	0.1	<0.02
NE Atlantic	2	0.3	0.06	4	0.6	0.09	>10	6	0.4
SE Atlantic	0.9	0.1	0.03	2	0.2	0.04	>10	4	0.2
E Gulf	0.7	0.2	0.06	2	0.3	0.08	>10	3	0.3
W Gulf	1	0.3	0.1	4	0.7	0.2	>10	>10	1
SW Pacific	0.8	0.02	<0.02	1	0.04	<0.02	>10	0.7	<0.02
NW Pacific	3	0.3	<0.02	4	0.4	<0.02	>10	1	0.03
**Alaska	0.7	<0.02	<0.02	0.2	<0.02	<0.02	0.7	0.03	<0.02
US Carib	0.02	<0.02	<0.02	0.04	<0.02	<0.02	6	0.04	<0.02

*The Pacific Island locations use the same scenario assigned to the Hawaiian Islands (see Table 2.2); **Alaska locations, which as a whole could not be regionalized due to large differences in VLM, use the lower-bounding scenario per CONUS, which is the Intermediate-Low scenario (see Table 2.1). The lower-bounding scenario for Alaska is used to reflect the significant deviations below the Intermediate scenario (Figure A1.2b).

Box 3.1: Wave Contributions to Extreme Water Levels

Water level heights are a common proxy for coastal flooding (e.g., Sweet et al., 2018) and consist of a variety of components (see Figure 1.1). This report focuses primarily on projections of relative sea level (RSL) rise together with tides and storm surge contributions to extreme water levels (EWLs). However, along exposed coasts, wave-driven water levels can play a significant role in EWLs during storm events and during lesser storm conditions as exacerbated by sea level rise. Here we illustrate the relative influence of wave-driven water levels, broken down into the components of set-up and swash during extreme events across the United States, compared to tide and surge contributions.

Wave set-up is the quasi-static rise in water level at the shoreline due to breaking waves (Longuet-Higgins and Stewart, 1963). Swash is the time-varying elevation of the leading edge of wave uprush, which varies in frequency from seconds (due to incident waves) to minutes (e.g., surf beat; Guza and Thornton, 1982). Wave set-up and swash components, collectively known as wave run-up, are dependent on wave height, period, and beach slope (Stockdon et al., 2006) and are therefore controlled by local beach morphology and transient ocean conditions. To perform regional assessments of present-day or future wave-driven water level contributions, wave conditions are typically determined via global wave models forced by wind-reanalysis studies (e.g., Reguero et al., 2012) or historical/future wind fields produced by global climate models (e.g., Hemer et al., 2013).

Leveraging the global total water level assessment of Vitousek et al. (2017), which combines reanalysis models for waves, surge, and tides ("total water level" implying that all relevant components in Table 3.1 are included), we demonstrate the relative influence of waves on coastal water levels during extreme events (Figure Box 3.1). Even though the coarse resolution of this study (1° x 1° grid cells) cannot fully resolve tropical cyclones, which play a significant role in EWL events for the Southeast, Eastern and Western Gulf, Caribbean, and Hawaiian/Pacific Islands regions, this analysis demonstrates the relevance of waves in contributing to EWLs. Across the United States and its territories, using the 0.1 events/year EWL event as an example, this study estimates that wave set-up ranges from about 20–75 cm (Figure Box 3.1a) and swash from 35–125 cm (Figure Box 3.1b), together accounting for 25%–90% of EWLs (Figure Box 3.1c and based on Vistousek et al., 2017—not this study's RFA-based EWLs) for open-coast beaches (i.e., not for embayments protected from ocean waves). Wave-driven water levels (i.e., wave run-up) represent ~50% or more of the EWL contributions (again, not from this study) in areas with narrow continental shelves (reduces surge potential) and/or small tidal ranges, in particular the Hawaiian and Pacific Islands, the Caribbean, the Outer Banks (North Carolina), most of Florida, the entire U.S. West Coast, and portions of Louisiana, Texas, and Alaska. But swash oscillations only amplify coastal EWLs over short periods (i.e., seconds to minutes), whereas wave set-up represents a relatively sustained

contribution during storm events with about a 10% to 80% contribution to EWLs, with the highest values in the tropics (Figure Box 3.1d). As these examples indicate, when omitting wave-driven processes, coastal flood risk can be significantly underestimated for open-coast beaches, especially along U.S. island coastlines. Including wave-driven processes will be a focus of subsequent Task Force attention leading up to the Sixth National Climate Assessment (NCA6).

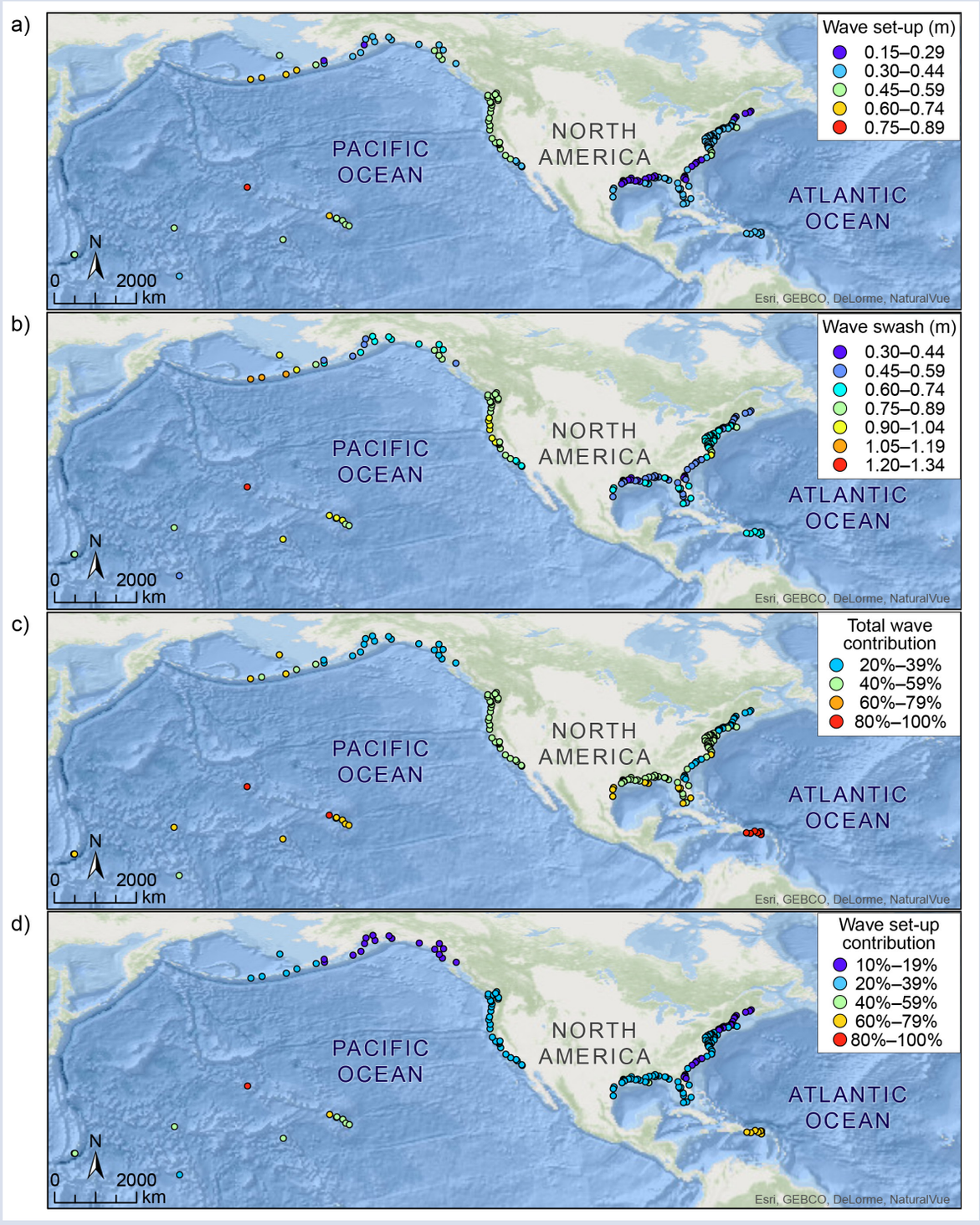

Figure Box 3.1. Water level contribution due to a) wave set-up and b) wave swash; c) percent contribution of wave-driven water levels (i.e., wave run up = wave set-up and swash) relative to all components: tide, storm surge, and waves; and d) percent contribution of wave set-up relative to the sum of tide, storm surge, and wave set-up based on model reanalysis of Vitousek et al. (2017).