NOAA Technical Report NOS CO-OPS 090

2018 State of U.S. High Tide Flooding with a 2019 Outlook

Photo: Charleston, South Carolina

Silver Spring, Maryland
June 2019

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U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

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National Ocean Service
National Oceanic and Atmospheric Administration
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2018 State of U.S. High Tide Flooding with a 2019 Outlook

William Sweet
Greg Dusek
Doug Marcy
Greg Carbin
John Marra

June 2019

U.S. DEPARTMENT OF COMMERCE
Wilbur L. Ross, Jr., Secretary

National Oceanic and Atmospheric Administration
Dr. Neil Jacobs, Assistant Secretary of Commerce for Environmental Observation and Prediction, performing the duties of Under Secretary of Commerce for Oceans and Atmosphere

National Ocean Service
Nicole LeBoeuf, Acting Assistant Administrator

Center for Operational Oceanographic Products and Services
Richard Edwing, Director

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EXECUTIVE SUMMARY

Tide gauges of the U.S. National Oceanic and Atmospheric Administration (NOAA) are measuring rapid increases in coastal flood risk along U.S. coastlines due to relative sea level (RSL) rise. The most noticeable impact of RSL rise is the increasing frequency of high tide flooding (HTF) that in 2018 was 1) disrupting vehicular traffic along the U.S. East Coast due to flooded roadways, 2) inhibiting parking and thus slowing commerce at stores in downtown Annapolis, Maryland, 3) raising groundwater elevations and degrading septic system functionalities in South Florida, and 4) salting farmlands within coastal Delaware and Maryland.

In 2018, the national annual HTF frequency reached 5 days (median value) and tied the historical record set in 2015. HTF was most prevalent along the Northeast Atlantic Coasts (median of 10 days) and broke records within the Chesapeake Bay (e.g., 22 days in Washington D.C. and 12 days in Annapolis and Baltimore) and along the Eastern Gulf of Mexico Coasts with some major flooding from several hurricanes. In all, 12 individual (out of 98 U.S. tide gauge) locations broke or tied their HTF records. There are now over 40 locations whose HTF decadal trends reveal significant acceleration (nonlinear increase) and 25 locations whose HTF trends are linearly increasing, implying that impacts will soon become chronic without adaptation.

HTF in 2019 is projected to be higher than normal at about 40 locations along the U.S. West and East Coasts in part due to a minor El Niño that is predicted to persist until early next year. The national median HTF frequency is projected to be more than 100% greater than it typically was in 2000. Regionally in 2019, the Northeast Atlantic is projected to experience a median of 8 days of flooding, which is a 140% increase since 2000. Flooding along the Southeast (5 days—190% increase over 2000), Eastern Gulf (3 days—100% increase since 2000) and Western Gulf (6 days—130% increase since 2000) Coasts continues to rapidly increase as well. The U.S. Southwest and Northwest Pacific Coasts are projected to see a median 2 and 6 days of flooding (80% and 20% increase since 2000), respectively.

Annual flood records are expected to be broken again next year and for years and decades to come from RSL rise. Projecting out to 2030 and 2050 provides vital information for communities that are already taking adaptation steps to address coastal flooding impacts and those that are beginning to assess future flood risk in their communities. Bounded by a range of RSL rise under a lower and continued-high emission rate, today's national HTF frequency of 5 days (national median) is likely to increase to about 7–15 days by 2030 and 25–75 days by 2050 (HTF range: low emission–high emission values), with much higher rates in many locations.

1. INTRODUCTION

Coastal flood risk causing minor-to-major impacts is changing because of ongoing relative sea level (RSL) rise (Figure 1). Flooding that decades ago usually happened only during a powerful or localized storm can now happen when a steady breeze or a change in coastal current overlaps with a high tide (Sweet et al., 2009; 2014; 2018a). Such high tide flooding (HTF) is happening often, and it is complicating preparedness and planning within coastal communities. The National Water Level Observation Network of the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) has been in place at some locations for over a century. The network defines U.S. maritime boundaries, supports safe maritime commerce with real-time observations and tide predictions, and tracks dangerous storm surge. It now monitors how the steady creep of RSL rise is accelerating the frequency of HTF (Sweet and Park, 2014).

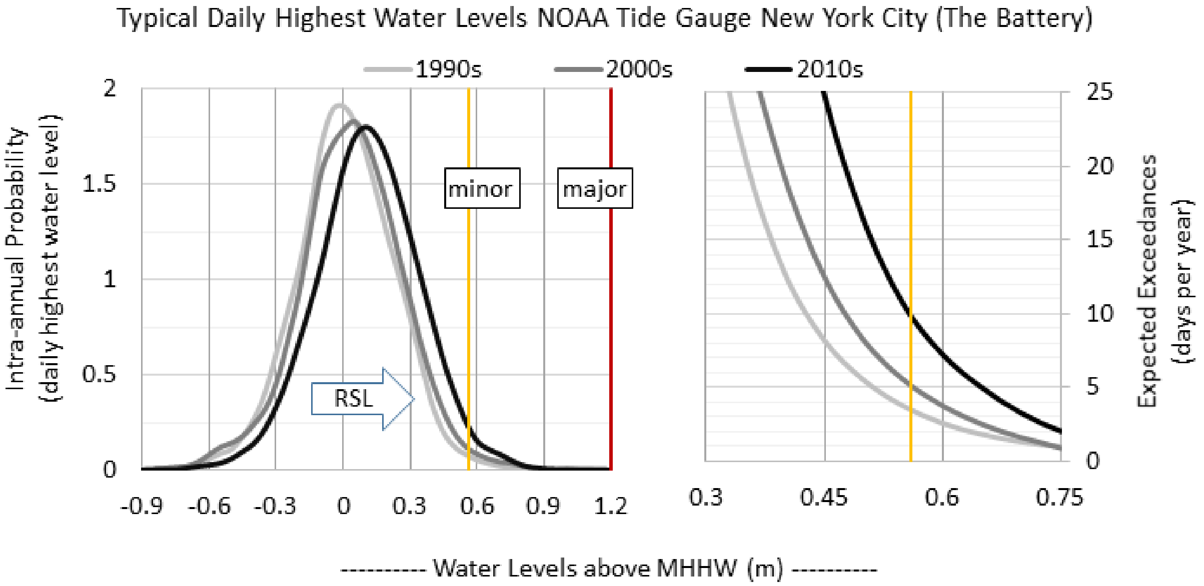

Figure 1. Decadal empirical probability distributions for daily highest water levels in New York City (NOAA tide gauge The Battery) during the 1990s, 2000s, and 2010s changing due to relative sea level (RSL) rise. Shown are the NOAA NOS impact thresholds for minor/HTF and major flooding and corresponding average annual exceedances.

NOAA NOS (Sweet et al., 2018a) defines HTF as heights ranging from about 0.5 meters (m) to 0.65 m above the mean higher high water (MHHW) level (Figure 2a) and varying regionally with tide range. The HTF height thresholds are based upon the minor-flood thresholds set by NOAA National Weather Service (NWS) Weather Forecasting Offices (WFOs) and on-the-ground local emergency managers who prepare for response to impending conditions (NOAA, 2017). WFOs will typically issue a *coastal flood advisory* when NWS minor coastal flood thresholds are expected to be exceeded. Though the NWS flood thresholds are calibrated empirically from years of impact monitoring, they are valid for only particular parts of a city or region that has variable topography, urbanization, and storm-proofing. As a best-fit solution to the NWS thresholds (Figure 2b: regressed with tide range), the NOS HTF thresholds provide a nationally consistent height threshold that broadly defines U.S. coastal infrastructure vulnerabilities to flooding. The amount of land along the U.S. coast exposed to HTF has been mapped by NOAA and is substantial (more than 2,700 square miles or slightly larger than the State of Delaware) as shown for the U.S. East and Gulf Coasts (Figure 2c).

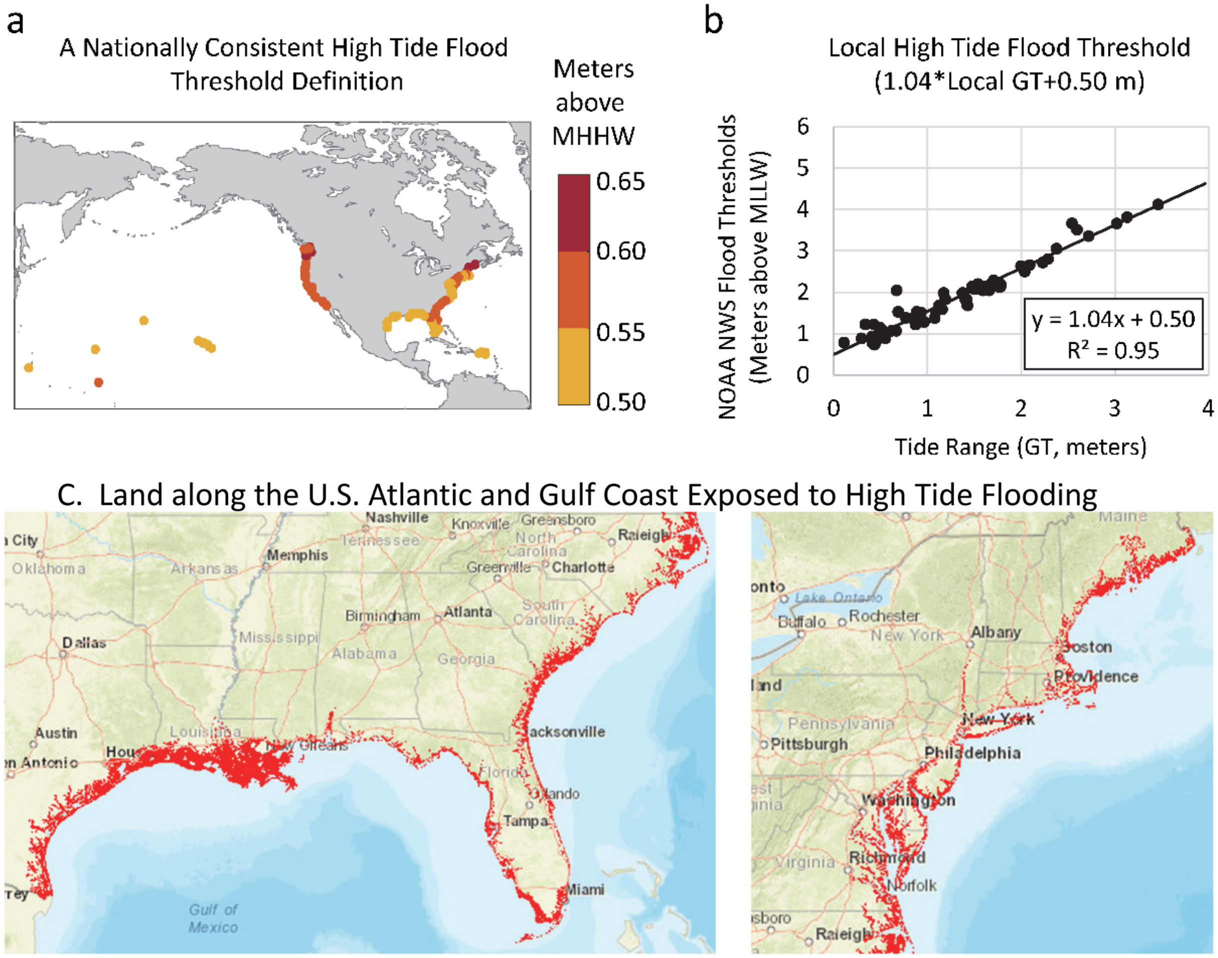

Figure 2. a) HTF height thresholds established at NOAA tide gauges based upon the regression relationship shown in b) as a scatter plot of a national set (about 60 locations) of NOAA NWS flood thresholds for minor impacts (y-axis) shown relative to the mean lower low water (MLLW) tidal datum versus the local great diurnal tide range (GT) on the x-axis. Adapted from Sweet et al. (2018a). In c) is a map of the areas (red) at or below the HTF threshold interpolated between locations for the U.S. East and Gulf Coasts. (Data accessible from NOAA's Digital Coast.)

HTF is often referred to as 'nuisance' or 'sunny-day' flooding, but the impacts are disruptive and sometimes damaging, and its cumulative effects are becoming a serious issue in many coastal communities. HTF events, made worse by RSL rise, are contributing to overwash and beach erosion, overwhelming storm/waste/fresh water systems, disrupting harbor operations, closing roadways, and degrading subsurface infrastructure and property values. These impacts are nearly certain to get much worse this century (Fleming et al., 2018). This past year, reports describe how RSL rise and HTF are flooding roads and disrupting traffic (Jacobs et al., 2018), negatively impacting parking and commerce in downtown Annapolis, Maryland (Hino et al., 2019), raising the water table to ground level (Sukop et al., 2018) and degrading septic system functionality in the Miami region[1], and laying waste to farm lands in the Delmarva Peninsula[2].

This report is the fifth in an annual series that provides annual and multi-decadal projections of HTF and helps keep the focus on important perspectives. It provides 1) an assessment of HTF that occurred in 2018 relative to measured flood-frequency trends, 2) maps of areas potentially exposed to HTF, 3) a 2019 outlook based upon temporal trends and predicted strength of the El Niño Southern Oscillation (ENSO) and 4) projections based upon RSL rise likely to occur by 2030 and 2050. This information is intended to raise awareness of the growing impact of RSL rise through HTF and inform decision-making not only next year (e.g., budgeting and allocating for necessary coastal flood responses) but over the longer term (e.g., major infrastructure upgrades, and land-use planning) to ensure resilience to sea level rise impacts.

2. 2018 CONDITIONS

In 2018[3] the national median annual HTF frequency reached 5 days, which tied the historical record of 2015 as measured by 98 NOAA tide gauges along U.S. coastlines[4] (Figure 3). The rapid increase in HTF is largely in response to the RSL rise occurring along most U.S. coastlines. When assessing only the ocean rise component (separate from any vertical land motion) cumulative RSL rise since 1920 surpassed 25 cm along U.S. coastlines (median value) during 2018. Vertical land motion rates used to estimate the ocean rise component are from Sweet et al. (2017b). Median U.S. RSL rise (ocean rise plus vertical land motion) over the same time period topped 31 cm, which is also the second-highest amount (not shown).

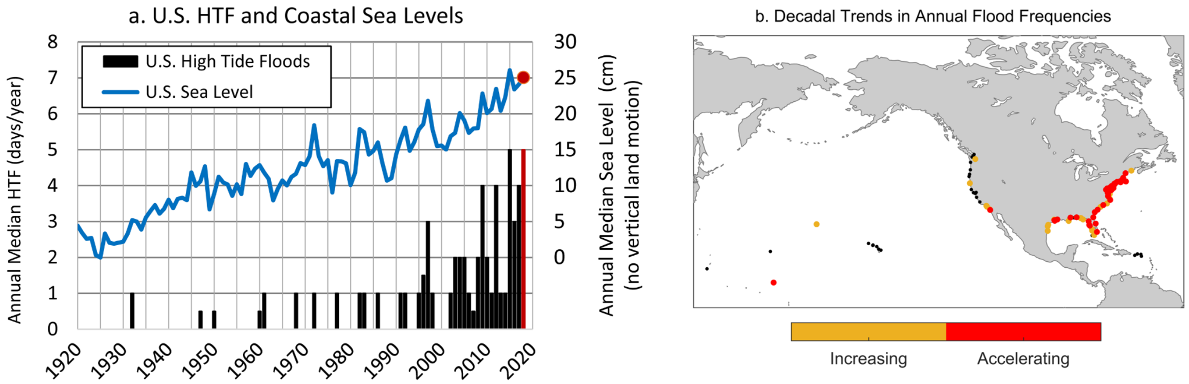

Figure 3. a) Median high tide floods per year (black bars) from 1920-2018. The annual-median rise in coastal sea levels is also shown (blue line), which has the local/gridded vertical land motion amounts removed using rate estimates from Sweet et al. (2017b). 2018 sea level and flood frequency values are shown in red. In b) is the characterization of the trends in annual HTF frequencies, with 42 locations now accelerating and 25 linearly increasing with time.

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[1] https://www.claimsjournal.com/news/southeast/2019/01/14/288708.htm; https://www.miamidade.gov/green/library/vulnerability-septic-systems-sea-level-rise.pdf)

[2] https://www.delmarvanow.com/story/news/local/maryland/2019/03/29/sea-level-rise-saltwater-intrusion-laying-waste-delmarva-farms/3276897002/

[3] Unless otherwise noted, a year in this report is defined as a meteorological year spanning May-April.

[4] Following the reasoning of Sweet et al. (2018a), Alaska and locations with tide ranges greater than 4 meters and where RSL trends are decreasing are not included in this report.

The acceleration of national HTF frequency over the last several decades largely is attributed to U.S. East and Gulf Coast locations where 42 locations have annual HTF frequencies that are now accelerating (Figure 3b). HTF acceleration is and will continue to occur in more locations regardless of whether RSL trends are accelerating (Sweet and Park, 2014). Due to RSL rise, HTF thresholds have entered the bulk (as compared to the 'tail') of the water level probability distribution in numerous locations (e.g., Figure 1), implying that impacts will soon become chronic without adaptation, e.g., upgraded flood defenses. In addition to the 42 locations with accelerating HTF trends (significant nonlinear increase), there are 25 locations with HTF trends linearly increasing. The two locations outside the East and Gulf Coasts with accelerating annual HTF frequencies are San Diego, California and Kwajalein Atoll, Marshall Islands.

There were 12 locations that broke or tied their HTF records during 2018 (Appendix 1). HTF was most prevalent along the Northeast Atlantic coastline with 10 ±4 (median ±1 standard deviation) days, and several HTF records were broken within the Chesapeake Bay (Figure 4). HTF records include 22 days of HTF in Washington D.C. and 12 days each in Annapolis and Baltimore. At least in the case of Annapolis, the record number of days with HTF caused parking and transport disruption in the downtown area and negatively impacted commerce (Hino et al., 2019). The highest number of days overall with HTF within the Northeast Atlantic was Boston with 19 days.

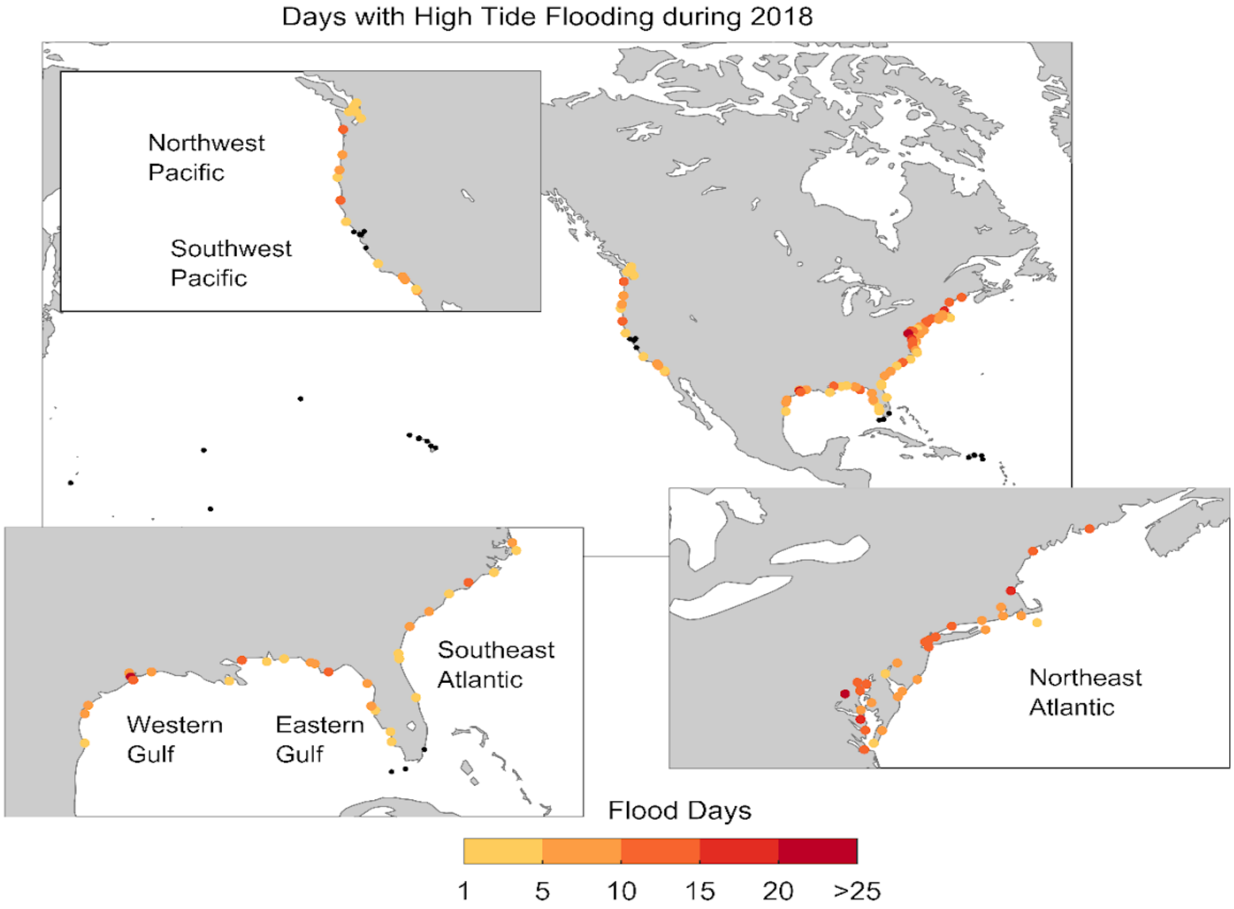

Figure 4. Number of days with HTF at 98 NOAA tide gauge locations; 12 locations broke or tied their all-time records (see Appendix 1 for values).

Like Washington D.C, which is situated up a major river, Wilmington, North Carolina also broke its HTF record with 14 days during 2018. Measurements from these two NOAA tide gauges (and a few others) are affected by both storm surge and also the compounding effects of elevated river discharge (Moftakhari et al., 2017) from regionally heavy rainfall occurring across the watershed. Prolonged elevated discharge often occurs during spring at tide gauges located in East Coast rivers (Sweet et al., 2018a) but is possible at other times. Such an instance happened during and after Hurricane Florence in mid-September 2018 (Figure 5) when water levels near the HTF threshold (about 0.55 m at both locations) persisted for weeks after a localized storm surge of about 1 m above MHHW. The Southeast Atlantic had 4 ±4 (median ±1 standard deviation) HTF days, which is largely reflective of the region between North Carolina and northern Florida where water levels are generally more responsive to weather/ocean forcing and from differing topo-bathymetric characteristics.

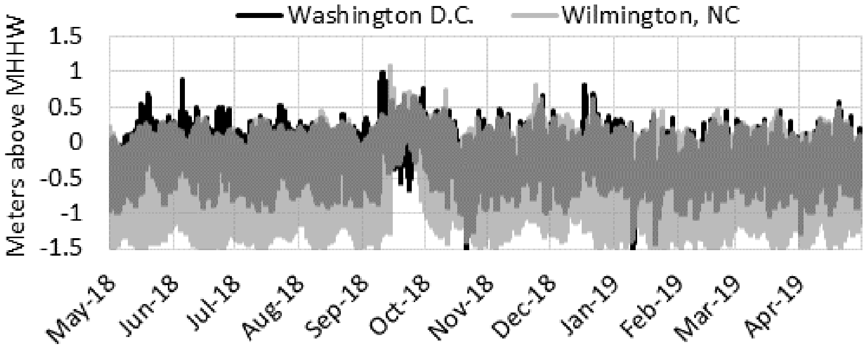

Figure 5. Hourly water level observations at Washington D.C. (black line) and Wilmington, N.C. (semi-transparent gray line) illustrating effects of Hurricane Florence in September 2018 in terms of direct storm surge and subsequent prolonged high waters from elevated river discharge from the upstream watershed.

HTF frequencies along the Eastern Gulf of Mexico (5 ±3 days [median ±1 standard deviation]) also broke or tied records (e.g., 10 days at Apalachicola, Florida and 8 days at Cedar Key, Florida) in 2018. The HTF records also included the effects of Hurricane Michael, a category 5 hurricane that came ashore along the Florida Panhandle in October 2018 and caused major flooding about 2.3 m above MHHW. Hurricane landfalls aside, annual HTF frequencies are mostly represented by smaller events closer to the HTF threshold (e.g., Figure 1). Maximum water levels in 2018 were less than 0.6 m above the HTF threshold along much of the East and Gulf Coasts and less than 0.3 m along the West Coast (Figure 6).

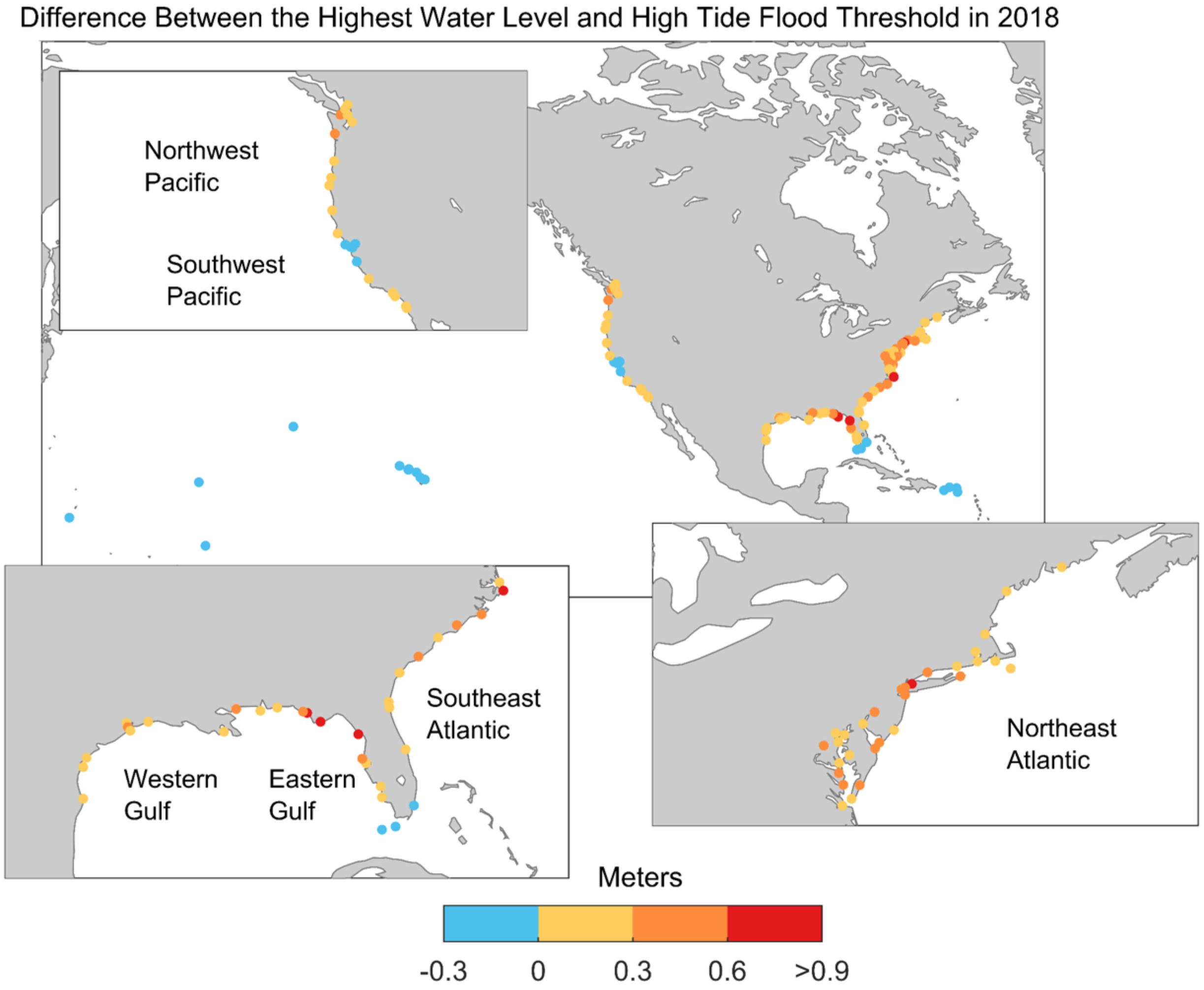

Figure 6. Height difference between highest water level measured during 2018 and the HTF threshold.

The Western Gulf coast experienced 8 ± 8 (median ±1 standard deviation) days of HTF days during 2018 with no land-falling hurricanes. Eagle Point, Texas (Galveston Bay region), however, stands out at 27 days during 2018 and has been an anomaly over the last two decades[5] potentially in response to localized land subsidence with rates on the order of 1 cm/year[6]. It is unclear whether any localized impacts associated with HTF are apparent or disruptive within this community.

In 2018 the U.S. Southwest Pacific Coast experienced 1 ±3 (median ±1 standard deviation) days of HTF with nearly all flooding occurring between Santa Monica and San Diego (Figure 4). HTF was 4 ±4 (median ±1 standard deviation) along the U.S. Northwest Pacific Coast where winter storms are more prevalent and where storm surges are of greater significance to inundation than tidal forcing (Serafin et al., 2017; Sweet et al., 2018a). The HTF threshold is higher than nearly all historical water levels measured by tide gauges along Hawaii, even those that recently caused

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[5] https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.csv
[6] See monthly sea level data at https://tidesandcurrents.noaa.gov/waterlevels.html?id=8771013.

problematic flooding (Thompson et al., 2019). There have only been two instances of water levels in Hawaii exceeding the HTF thresholds: 1) at Nawiliwili during Hurricane Iniki in 1992 and 2) at Hilo following the March 1964 Alaskan earthquake/tsunami (meteorological year 1963). The HTF threshold is similarly extreme (or has not been exceeded) in tide gauge records within the U.S. territorial islands in the Pacific and Caribbean (see Appendix 1). In these locations, waves tend to be a more important contributor to total water levels (Serafin et al., 2017; 2019) that cause erosion, overwash, and related impacts (Barnard et al., 2019). Future assessments might begin incorporating higher frequency/wave effects, which are measured but typically not reported by tide gauges (Sweet et al., 2015).

In terms of public communication alerts of upcoming minor HTF impacts, NOAA NWS WFOs issue *coastal flood advisories*; if moderate or major coastal flooding is imminent, *coastal flood warnings* are issued (NOAA 2017)[7]. NWS minor flood thresholds that trigger coastal flood advisories closely relate to HTF thresholds (Figure 2b), so not surprisingly, the frequency of issuances is increasing as well. Viewed nationally using a traditional calendar year (Jan.–Dec.), WFO advisories (median value) are correlated (r=0.76) and accelerating (Figure 7a) similar to the national HTF trend (Figure 3a). The national trends largely follow those along the U.S. East and Gulf Coasts, which are demonstrated by comparing tide gauge observed HTF to issuances from the encompassing WFO such as those for the New York City (Figure 7b), Norfolk, Virginia (Figure 7d) and the Galveston/Houston (Figure 7f) regions. The relationship between tide gauge HTF and WFO coastal flood advisory issuances is not significant in U.S. West Coast locations, as shown for Seattle (Figure 7c) and Los Angeles (Figure 7e), possibly due to the influence of waves. During 2018 (calendar year), there were seven records broken for the total number of coastal flood advisories issued to the public, mostly along the U.S. East Coast (https://mesonet.agron.iastate.edu/archive/). These results demonstrate the direct effects of RSL rise affecting coastal flood risk and weather forecasting that is guiding day-to-day decision making.

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[7] The NOAA NOS definition of moderate and major flooding uses similar regression analysis as with NWS minor coastal flooding (Figure 2b). Moderate and major flooding equate to heights about 0.8-0.9 m and 1.15–1.3 m above MHHW (Sweet et al., 2018a).

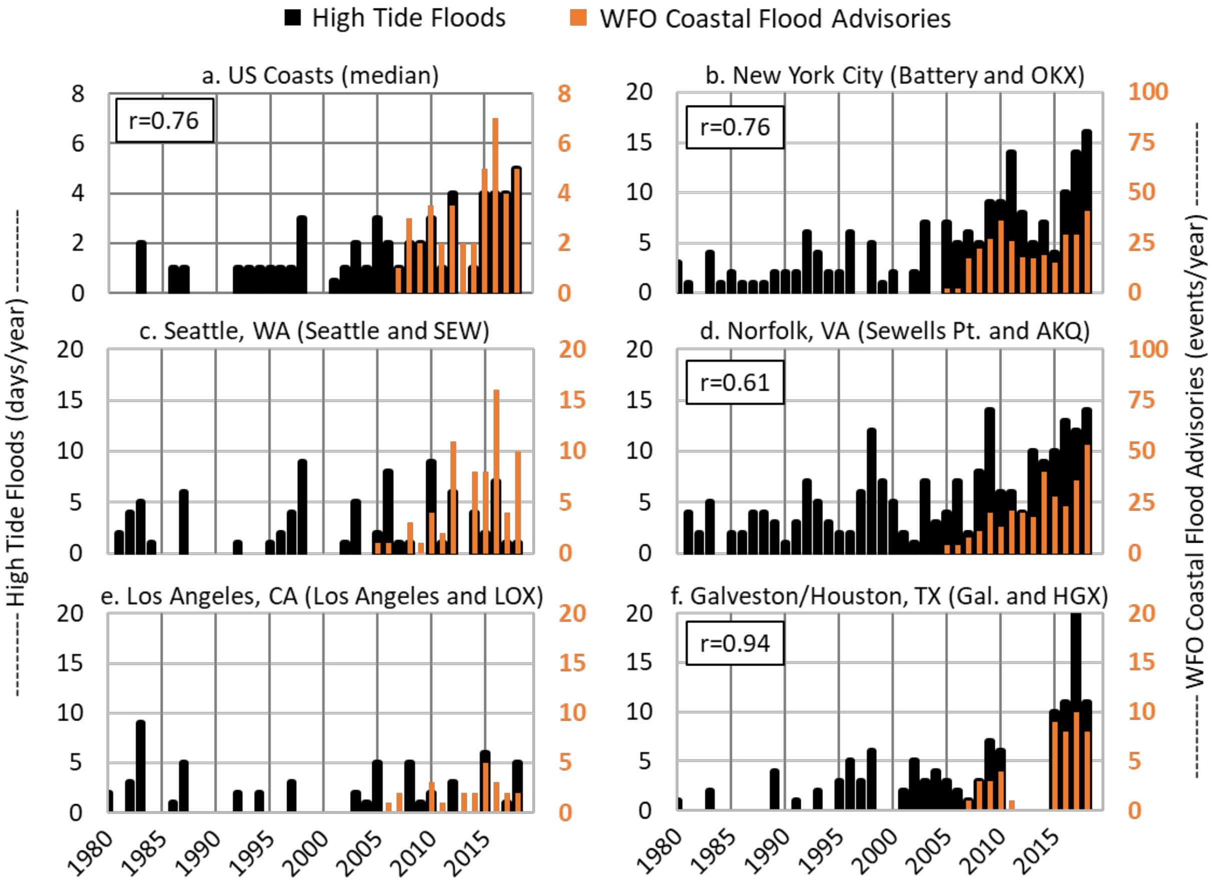

Figure 7. Annual (calendar year) HTF frequencies and coastal flood advisories issued since 2006 by WFOs a) nationally (median values) and in b) New York City, c) Seattle, Washington, d) Norfolk, Virginia, e) Los Angeles, California and f) Galveston/Houston regions showing correlation coefficients where significant. Note: coastal flood advisories were issued prior to 2006, but only those with a Valid Time Event Code starting in 2006 are readily obtainable via archives by the University of Iowa. Shown in the label parentheses is the location of NOAA tide gauge (Appendix 1) and related Coastal WFO[8].

3. 2019 HIGH TIDE FLOOD OUTLOOK

The 2019 outlook is provided as the likely range expected flood frequency ±1 standard deviation) based upon updates of Sweet et al. (2018a). The projection is based on: 1) a 19-year (2000-2018) average where no trends exist, 2) an extrapolated linear or quadratic temporal regression trend fit and/or 3) an extrapolated statistical fit that also uses the strength of ENSO quantified by the Oceanic Niño Index[9] in a bivariate regression. Statistical fits use data from 1950 (or start of hourly observations) – 2018. All trend fits are significant above the 90% level (p value <0.1). Multi-model ensemble predictions of ENSO strength for 2019/2020 were obtained from the International Research Institute for Climate and Society in April 2019[10].

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[8] https://www.weather.gov/srh/nwsoffices

[9] ONI: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

[10] Dynamical and statistical El Niño average of about 0.75 predicted for the rest of 2019 meteorological year https://iri.columbia.edu/our-expertise/climate/forecasts/enso/2019-April-quick-look/?enso_tab=enso-sst_table.

A mild El Niño (ONI modeled at a 0.75 °C value) is predicted to persist into calendar year 2020. In response, higher than expected (above long-term average or trend values) flood frequencies are predicted at 42 locations primarily along the U.S. West and East Coasts (Figure 8a) as illustrated for San Diego, California and Norfolk, Virginia (Figure 8b).

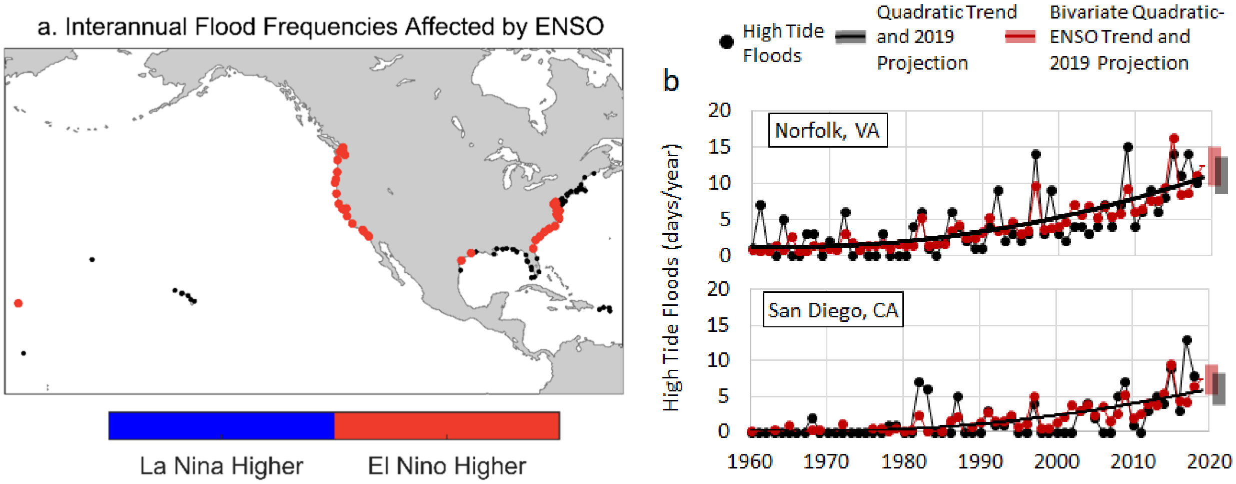

Figure 8. a) Locations where annual HTF frequencies from 1950 (or data start)-2018 are affected by ENSO and b) annual HTF frequencies (black dots) with quadratic regression fits (black line) projected through 2019 (grey shading) in Norfolk, Virginia and San Diego and bivariate regressions (red line-dot) that include ENSO effects (ONI) in addition to the temporal changes. The 2019 ENSO-based Outlooks (red shading) are based on 2019 ONI predicted value of about 0.75 °C.

The 2019 outlook is shown in Figure 9, and for mapping purposes, it illustrates the expected value (not the ±1 standard deviation likely range, Appendix 1) using the ENSO-based predictions where significant. The Northeast Atlantic coast is projected to experience the most HTF in 2019 with the regional-median expected value of 8 HTF days. Individual locations are projected to experience more (likely range): 12–19 days in Boston, Massachusetts, 8–13 days in New York City region, and 10–15 days in Norfolk, Virginia. The Southeast Atlantic Coast is projected to experience 5 days (i.e., median value), with 4–7 (i.e., likely range) HTF days in Charleston, South Carolina and 1–3 days at Virginia Key (Miami, Florida region). Along the Eastern Gulf, 3 days of HTF are projected with most individual locations close to the regional values (e.g., 2–5 days projected at Pensacola, Florida). Higher frequencies of HTF are projected along the Western Gulf (6 days) with some substantial variability (discussed earlier) locally: 6–13 days at Sabine Pass, Texas, 29–40 days at Eagle Point, Texas (outlook is high due to anomalously high trend over the last couple of decades), and 1–6 days at Corpus Christi, Texas.

The 2019 outlook for the U.S. Southwest Pacific coast is 2 days of HTF, with 5–9 days likely at San Diego, 1–4 days in Los Angeles, and 0–2 days at San Francisco. Along the U.S. Northwest Pacific Coast, 6 days of HTF is projected, with the exposed ocean sites projected to experience more (e.g., 6–12 days at Humboldt Bay, California and 9–21 days at Toke Point, Washington) and less within the Puget Sound region (e.g., 2–6 days in Seattle, Washington). HTF flooding is not projected to occur (not considering wave or rainfall effects) along the Hawaiian Islands or the U.S. Caribbean or U.S. Pacific Island territories; the exceptions are Midway Island (0–2 days) and Wake Island and Kwajalein Atoll (0–1 days at both).

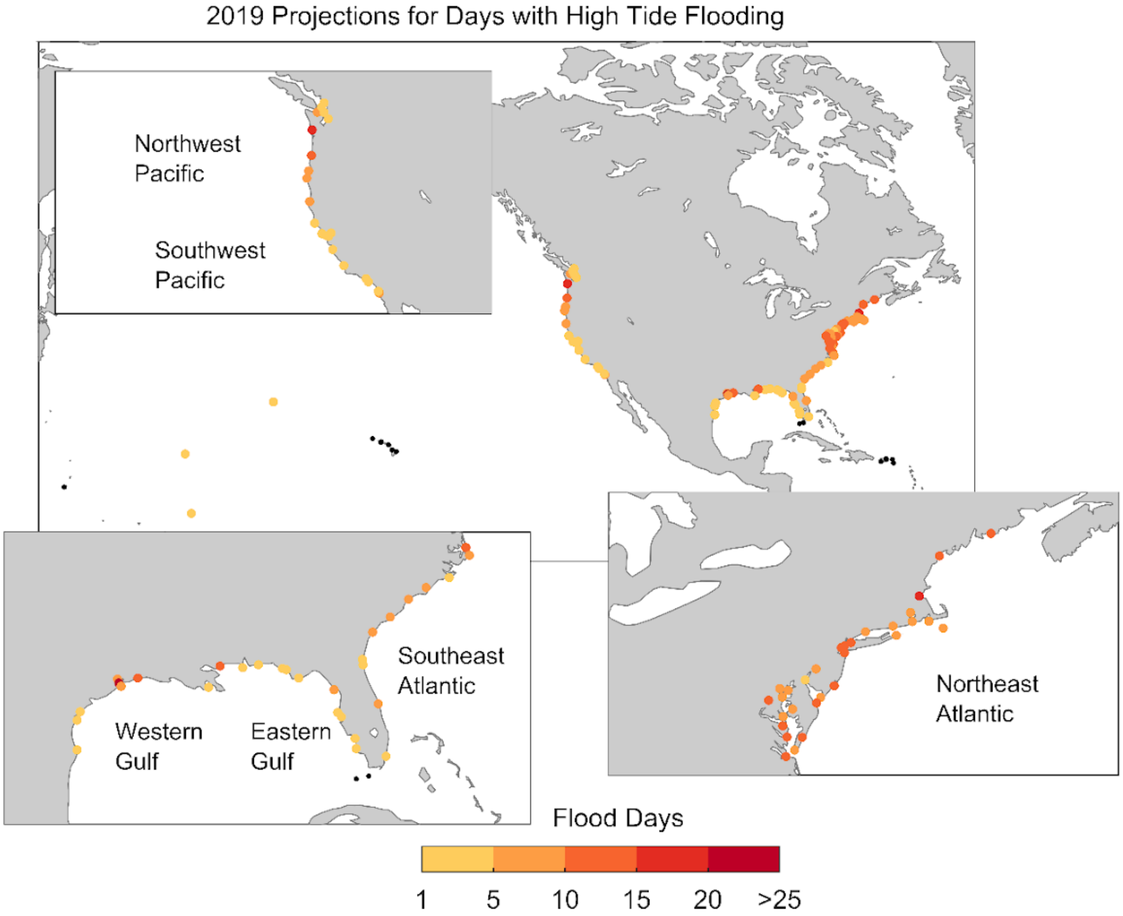

Figure 9. Outlook for number of HTF projected to occur in 2019 (May 2019 – April 2020) with color-codes associated with the 'expected' value, whereas the actual outlooks are based upon the likely range (expected value ±1 standard deviation; see Appendix 1).

The 2019 HTF national outlook is expected to be over 100% greater (median value) than would have been typical in year 2000 (i.e., based upon individual trends fit for ENSO neutral conditions) as shown in Figure 10 (with values listed in Appendix 1). Annual HTF frequencies are rising the fastest along the Southeast Atlantic Coast (median value about 190%) and are also above 100% along the Northeast Atlantic (140%) and the Eastern and Western Gulf (about 100% and 130%, respectively). They are less substantial along the U.S. Southwest and Northwest Pacific Coasts (80% and 20%, respectively). Projected increases along the U.S. West Coast for 2019 largely reflect the predicted influence of El Niño, as for the most part, these locations are not yet experiencing either a linear or accelerating frequency in time (Figure 3b).

Projected frequency increases in HTF are especially problematic in many of the older, low-lying East Coast cities that were built just above average highest tides. As sea levels have risen over the last century, stormwater systems are no longer able to perform as designed. HTF causes tidewater to fill stormwater pipes, which prevents rainwater from entering storm drains and causes increased impacts from flooding. Many of these gravity-driven systems are ceasing to function as designed, causing rainwater to flood streets and neighborhoods until the tide lowers and water can drain normally. This is exacerbated when extreme rainfall events coincide with higher tides (Carter et. al, 2018).

The outlook methodology underpinning the 2019 outlook and earlier ones (e.g., Sweet et al., 2018b) are not intended necessarily to capture effects of rare events like hurricanes or abnormally high storm-surge/storm years. When rare extremes like hurricane landfalls or intense winter storms occur, they are capable of producing not only extreme water levels, but an anomalous number of days of high storm surge and/or high river discharge affecting some NOAA tide gauges. What the outlooks do provide is a method to predict HTF considering RSL effects (Figure 3), typical storm surge climatologies (e.g., Figure 1), and in some cases by utilizing ENSO predictions (Figure 8), which inherently lead to both higher sea levels and higher storm-surge frequency along large portions of the U.S. East and West Coasts. The outlooks will typically under-predict next-year's HTF frequencies due to RSL rise-forced responses to normal weather (storm surge) and tides, since the autoregressive HTF-trend characterization is becoming increasingly nonlinear through time (Sweet and Park, 2014; Figure 1). Seasonal climatological distributions are provided in Sweet et al. (2018a), who note when HTF typically occurs most often and to what degree it is in response to predicted astronomical tidal forcing or (less predictable) stochastic weather effects. Ongoing efforts are underway to provide seasonal predictions directly (e.g., Widlansky et al., 2017).

Comparing the HTF outlook from the previous year's report (Sweet et al., 2018b) to the 2018 observed floods (Appendix 1, Figure 4) gives some indication of expected accuracy of the projections presented here. About two-thirds of the HTF-day counts in 2018 at locations (Figure 4) fell within the 'likely range' prediction (66 out of 98), with about one-third of the locations above prediction (29 out of 98). Only three locations with HTF days along the Southeast Atlantic Coast in 2018 fell below their respective 2018 outlook prediction. Of the 29 locations with HTF frequencies during 2018 above the likely range prediction, about half of those (14 locations) were above 2 standard deviations, including 9 of the 12 locations that broke or tied their historical HTF annual frequencies in 2018. Thus, it is anticipated that nearly all of the HTF days measured in 2019 will likely fall within or above the 2019 HTF outlook presented in this report.

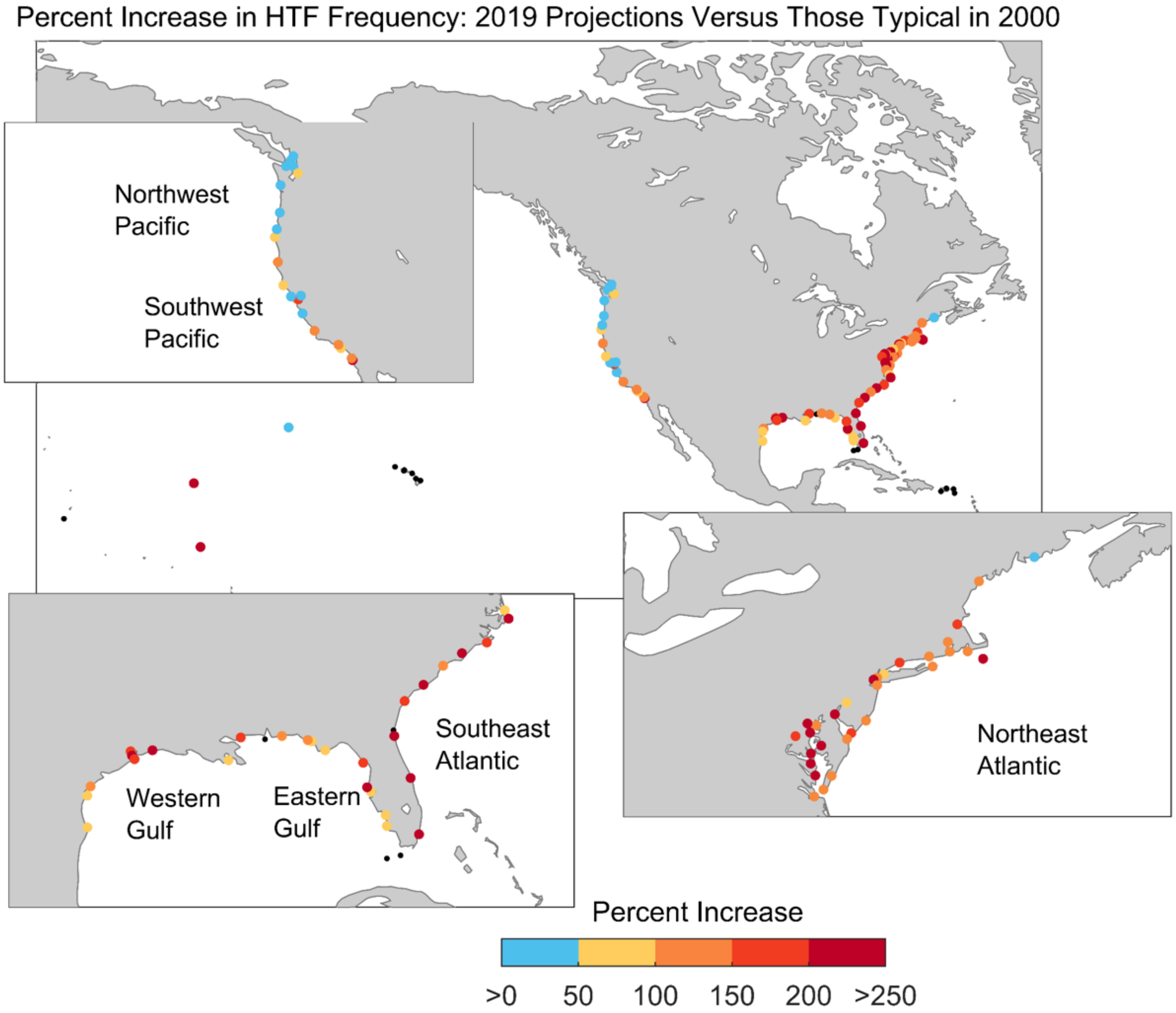

Figure 10. The percent change since 2000 for 2019 outlooks based upon trend fits but for ENSO neutral conditions in year 2000. Black dots denote locations where high tide flooding still occurs less than once a year, or in some cases, has yet to occur.

4. PROJECTIONS OF HIGH TIDE FLOODING LIKELY TO OCCUR BY 2030 AND 2050

The historical and 2019 HTF outlooks can be contextualized to longer-term projections. Changes in HTF frequency are estimated out to about 10 and 30 years (2030 and 2050) using multi-decadal HTF projections of Sweet et al. (2018a). We utilize two scenarios of RSL rise that bound the range considered 'likely' this century in response to a lower and continued-high emission scenario by the U.S. Fourth National Climate Assessment (Sweet et al., 2017a). Specifically, the Intermediate Low and Intermediate Scenarios of Sweet et al. (2017b) are utilized. HTF projections under higher RSL rise scenarios as presented by Sweet et al. (2018a) are possible this century but, if they were to occur, would emerge toward the end of the century. In all cases, decadal values are averages over the preceding decade (e.g., 2030 = 2021–2030 average; 2018 values are 2011–2018 average) since the RSL rise scenarios provide only decadal resolution.

These estimates are intended to characterize HTF frequency typical in most years by 2030 and 2050, though it is recognized here and elsewhere that interannual variability in tide cycles or climate mode variability affects flood frequencies in any given year (e.g., Menéndez and Woodworth, 2010; Wahl and Chambers, 2016; Sweet et al., 2018a).

Examples for San Diego, California and Norfolk, Virginia are shown in Figure 11 for historical and future projections of decadal HTF averages. The HTF frequencies continue to grow rapidly with continued RSL rise and in a very nonlinear fashion as the daily high-water distribution continues to impinge upon and surpass the HTF threshold (Sweet and Park, 2014; as illustrated in Figure 1). Under the Intermediate projection, Norfolk will experience about 170 days/year of HTF, which by definition, suggests that MHHW (about 182 days per year exceeded) will nearly equate to the HTF threshold.

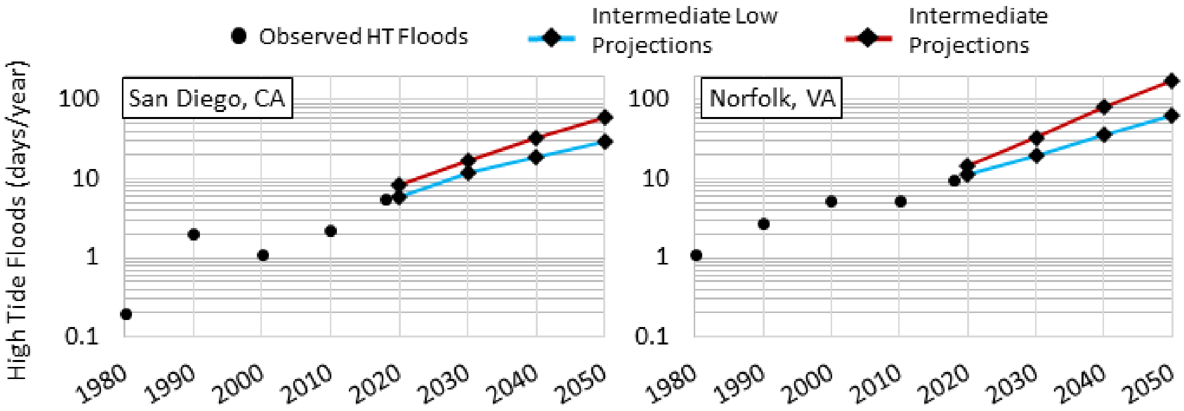

Figure 11. Decadal averages of days with HTF both historical and projected into the future (Sweet et al., 2018a) using RSL rise projections bounding the 'likely' outcomes this century by the Fourth National Climate Assessment (Sweet et al., 2017a).

The likely range of annual HTF frequencies bound by projections of the Intermediate Low and Intermediate Scenarios at U.S. locations is shown in Figure 12 and presented in Sweet et al. (2018a)[11]. By 2030 and 2050, HTF is likely to occur (median regional value) between about:

- 15–25 days and 40–130 days along the Northeast Atlantic
- 7–15 days and 25–70 days along the Southeast Atlantic
- 4–7 days and 15–70 days along the Eastern Gulf
- 10–20 days and 65–165 days along the Western Gulf
- 4–7 days and 10–30 days along the Southwest Pacific
- 8–10 days and 15–25 days along the Northwest Pacific
- 0 days and 3–45 days in the Hawaii/Pacific Islands
- 0 days and 0–5 days along the Caribbean Coasts.

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[11] https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.csv

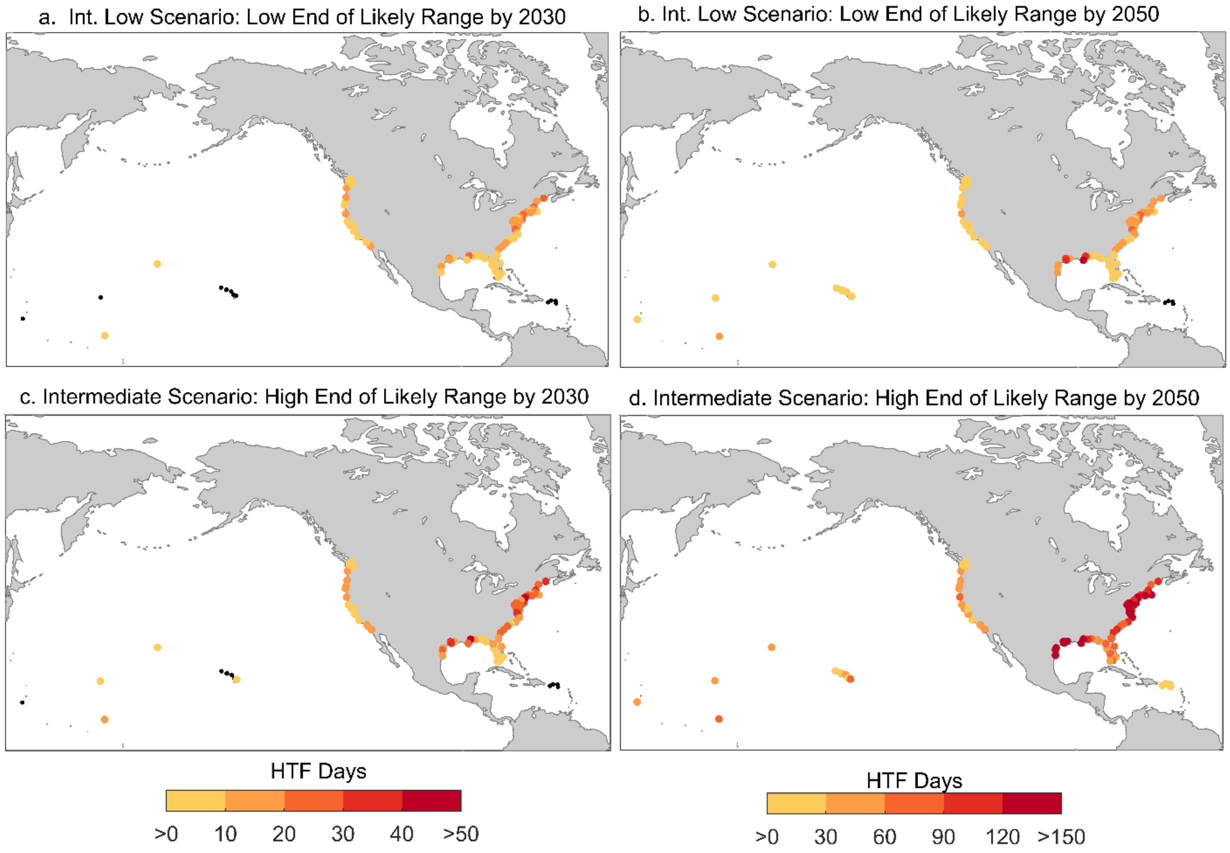

Figure 12. Projections of average HTF by 2030 and 2050 (i.e., 2021–2030 and 2041–2050 averages) of Sweet et al. (2018a) using RSL rise projections that bound outcomes considered likely in the Fourth National Climate Assessment (Sweet et al., 2017a).

5. SUMMARY

NOAA tide gauges are measuring rapid changes across the entire severity-spectrum of coastal flood risk along U.S. coastlines due to RSL rise. The most noticeable impact of RSL rise is the increasing frequency of HTF (sometimes referred to as 'nuisance' or 'sunny day' flooding), which typically causes minor and disruptive impacts. However, within many rural and urban U.S. coastal communities, the cumulative effects of more HTF upon public-works systems, roads, first floors of businesses, and residences (among others) is becoming a serious problem. Because of this, communities need projections for 'next year' and for the coming decades for preparedness and planning purposes to respond to the growing RSL-related HTF threat.

In 2018, the national annual HTF frequency reached 5 days (median value) and tied the historical record set in 2015 as measured by 98 NOAA tide gauges along U.S. coastlines. In all, 12 individual locations broke or tied their HTF records. There are now over 40 locations whose HTF trends reveal significant acceleration (nonlinear increase) and 25 locations whose HTF trends are linearly increasing, implying that impacts soon will become chronic without adaptation. HTF was most prevalent during 2018 along the Northeast Atlantic Coast and broke records along the Chesapeake Bay and the Eastern Gulf of Mexico Coast, where major flooding also occurred from hurricane-induced storm surge and heavy rainfall/river flows.

HTF for 2019 is projected to be more likely than normal at about 40 locations along the U.S. West and East Coasts in part due to a minor El Niño that is predicted to persist until early next year. The national median HTF frequency is projected in 2019 to be more than 100% greater than it typically was in 2000 and regionally HTF is projected to occur:

- 8 days along the Northeast Atlantic (140% increase since 2000)
- 5 days along the Southeast (190% increase over 2000)
- 3 days along the Eastern Gulf (100% increase since 2000)
- 6 days along the Western Gulf (130% increase since 2000)
- 2 days along the Southwest Pacific (80% increase since 2000)
- 6 days along the Northwest Pacific (20% increase since 2000)

Annual flood records are expected to be broken again next year and for years and decades to come. Projecting out to 2030 and 2050 provides vital information for communities who are already taking adaptation steps to address coastal flooding impacts and those who are beginning to assess future flood risk in their communities. Bounded by a range of RSL rise under a lower and continued-high emission rate, today's national HTF frequency of 5 days (national median) is likely to increase to about 7–15 days by 2030 and 25–75 days by 2050 (HTF range: low emission - high emission values), with much higher rates in many locations.

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APPENDIX 1

Location-specific high tide flooding occurrences and projections. U.S. Regions, tide gauge location information and NOAA ID, NOAA NOS high tide flood threshold (meters above MHHW) of Sweet et al. (2018), annual high tide flood frequency record through 2018, high tide flood frequency typical of year 2000 based upon trend fits, high tide flood frequencies measured in 2018 (May 2018–April 2019), the 2019 likely range and range typical in 2030 and 2050.

Region	Tide Gauge Location	Lat	Long	NOAA ID	HTF Height (m, MHHW)	Record HTF (days/year)	Year of Record	Typical HTF days in 2000	HTF days in 2018	2019 HTF Outlook	Peak HTF Season	2030 HTF Projection	2050 HTF Projection
Pacific Islands	Nawiliwili, HI	22.0	-159.4	1611400	0.52	1	1992	0	0	0	---	0-0	1-30
	Honolulu, HI	21.3	-157.9	1612340	0.52	0	---	0	0	0	---	0-0	2-30
	Mokuoloe, HI	21.4	-157.8	1612480	0.53	0	---	0	0	0	---	0-0	3-30
	Kahului, HI	20.9	-156.5	1615680	0.53	0	---	0	0	0	---	0-0	4-55
	Kawaihae, HI	20.0	-155.8	1617433	0.53	0	---	0	0	0	---	0-0	0-15
	Hilo, HI	19.7	-155.1	1617760	0.53	1	1963	0	0	0	---	0-1	10-65
	Midway Island	28.2	-177.4	1619910	0.52	6	2004	1	0	0-2	winter	3-4	7-55
	Apra Harbor, Guam	13.4	144.7	1630000	0.53	1	1992	0	0	0	winter	0-0	2-45
	Pago Pago, Am. Samoa	-14.3	-170.7	1770000	0.53	0	---	0	0	0	---	0-0	0-2
	Kwajalein Island	8.7	167.7	1820000	0.55	3	2017	0	0	0-1	winter	7-15	35-90
	Wake Island	19.3	166.6	1890000	0.53	2	2004	0	0	0-1	summer	0-2	6-55
Northeast Atlantic	Bar Harbor, ME	44.4	-68.2	8413320	0.64	30	1977	7	12	4-15	winter	20-35	45-90
	Portland, ME	43.7	-70.2	8418150	0.62	21	2009	5	11	7-13	winter	15-30	35-80
	Boston, MA	42.4	-71.1	8443970	0.63	22	2017	6	19	12-19	winter	20-35	45-95
	Woods Hole, MA	41.5	-70.7	8447930	0.53	10	2017	2	5	3-7	winter	8-20	35-135
	Nantucket Island, MA	41.3	-70.1	8449130	0.54	11	2017	2	2	3-7	winter	7-15	30-125
	Newport, RI	41.5	-71.3	8452660	0.55	11	2017	2	6	3-7	fall	10-25	40-120
	Providence, RI	41.8	-71.4	8454000	0.56	13	2017	3	8	5-10	spring	15-30	40-105
	New London, CT	41.4	-72.1	8461490	0.54	10	2017	2	7	3-7	fall	8-15	25-120
	Bridgeport, CT	41.2	-73.2	8467150	0.59	11	2017	3	10	6-11	fall	15-30	35-105
	Montauk, NY	41.0	-72.0	8510560	0.53	11	2017	2	7	3-7	fall	10-25	40-150
	Kings Point, NY	40.8	-73.8	8516945	0.60	15	2012	5	10	7-13	fall	20-35	40-110
	The Battery, NY	40.7	-74.0	8518750	0.56	15	2017	5	12	8-13	fall	20-40	50-135
	Bergen Point, NY	40.6	-74.1	8519483	0.57	13	2017	3	10	8-13	fall	15-35	45-130
	Sandy Hook, NJ	40.5	-74.0	8531680	0.56	20	2017	5	12	9-15	fall	25-45	70-160
	Atlantic City, NJ	39.4	-74.4	8534720	0.56	22	2017	5	9	8-14	fall	20-35	65-155
	Cape May, NJ	39.0	-75.0	8536110	0.57	14	2009	3	7	6-10	fall	15-30	55-135
	Philadelphia, PA	39.9	-75.1	8545240	0.58	12	2011	3	8	3-7	fall	10-20	30-105
	Reedy Point, DE	39.6	-75.6	8551910	0.57	5	2012	1	4	2-4	spring	6-15	25-100
	Lewes, DE	38.8	-75.1	8557380	0.56	15	2017	4	8	7-12	fall	15-30	50-135
	Cambridge, MD	38.6	-76.1	8571892	0.53	7	2012, 2018	1	7	4-7	fall	9-20	40-150
	Tolchester Beach, MD	39.2	-76.2	8573364	0.52	12	2018	3	12	4-9	fall	15-25	50-160
	Baltimore, MD	39.3	-76.6	8574680	0.52	12	2018	2	12	6-9	fall	15-25	50-155
	Annapolis, MD	39.0	-76.5	8575512	0.52	12	2018	2	12	6-10	fall	15-25	55-170
	Solomons Island, MD	38.3	-76.5	8577330	0.52	9	2015	1	8	7-9	fall	10-20	45-165
	Washington, DC	38.9	-77.0	8594900	0.54	22	2018	3	22	7-12	spring	10-20	35-120
	Wachapreague, VA	37.6	-75.7	8631044	0.56	17	2017	5	6	7-13	fall	15-25	40-120
	Kiptopeke, VA	37.2	-76.0	8632200	0.54	11	1997	3	4	4-9	fall	10-20	40-120
	Lewisetta, VA	38.0	-76.5	8635750	0.52	15	2018	2	15	8-12	fall	15-25	50-170
	Windmill Point, VA	37.6	-76.3	8636580	0.52	10	2015, 2018	3	10	8-12	fall	15-25	45-160
	Sewells Point, VA	36.9	-76.3	8638610	0.53	15	2009	5	10	10-15	fall	20-25	65-170
Southeast Atlantic	Duck, NC	36.2	-75.7	8651370	0.55	18	2009	5	6	7-12	fall	20-30	55-135
	Oregon Inlet, NC	35.8	-75.5	8652587	0.51	8	2009	1	4	3-6	fall	7-15	35-165
	Beaufort, NC	34.7	-76.7	8656483	0.54	10	2015	1	2	1-4	fall	6-15	25-100
	Wilmington, NC	34.2	-78.0	8658120	0.56	14	2018	1	14	3-7	fall	4-9	15-65
	Springmaid Pier, SC	33.7	-78.9	8661070	0.57	11	2015	3	4	3-8	fall	10-20	30-75
	Charleston, SC	32.8	-79.9	8665530	0.57	9	2015	2	5	4-7	fall	10-20	35-90
	Fort Pulaski, GA	32.0	-80.9	8670870	0.59	12	2016	2	6	4-8	fall	15-25	40-95
	Fernandina Beach, FL	30.7	-81.5	8720030	0.58	9	2015	3	2	0-5	fall	9-15	25-70
	Mayport, FL	30.4	-81.4	8720218	0.56	6	2015	1	2	2-3	fall	5-10	20-65
	Trident Pier, FL	28.4	-80.6	8721604	0.55	12	2015	0	4	6-11	fall	7-15	20-65
	Virginia Key, FL	25.7	-80.2	8723214	0.53	3	2017	0	0	1-3	fall	2-5	10-55
	Vaca Key, FL	24.7	-81.1	8723970	0.51	1	2017	0	0	0	fall	1-3	9-65
	Key West, FL	24.6	-81.8	8724580	0.52	2	1944	0	0	0	fall	0-2	8-60

Region	Tide Gauge Location	Lat	Long	NOAA ID	HTF Height (m, MHHW)	Record HTF (days/year)	Year of Record	Typical HTF days in 2000	HTF days in 2018	2019 HTF Outlook	Peak HTF Season	2030 HTF Projection	2050 HTF Projection
Eastern Gulf	Naples, FL	26.1	-81.8	8725110	0.54	3	2017	1	1	0-2	fall	2-4	9-55
	Fort Myers, FL	26.6	-81.9	8725520	0.52	6	2017	1	1	1-4	fall	3-6	15-80
	St. Petersburg, FL	27.8	-82.6	8726520	0.53	4	2016, 2018	1	4	1-3	fall	3-7	15-85
	Clearwater, FL	28.0	-82.8	8726724	0.53	5	2018	1	5	2-4	fall	2-4	10-55
	Cedar Key, FL	29.1	-83.0	8727520	0.55	8	2018	2	8	3-6	fall	5-10	20-70
	Apalachicola, FL	29.7	-85.0	8728690	0.52	10	2018	2	10	1-5	fall	4-8	10-50
	Panama City, FL	30.2	-85.7	8729108	0.52	7	2005	1	5	1-4	fall	4-7	10-65
	Panama City Beach, FL	30.2	-85.9	8729210	0.52	8	2005	2	6	2-6	fall	4-6	10-50
	Pensacola, FL	30.4	-87.2	8729840	0.52	10	2005	1	4	2-5	fall	4-8	15-70
	Dauphin Island, AL	30.3	-88.1	8735180	0.52	6	2017	3	4	0-5	fall	5-10	30-95
	Bay Waveland, MS	30.3	-89.3	8747437	0.52	14	2017	4	12	8-14	fall	25-40	110-205
Western Gulf	Grand Isle, LA	29.3	-90.0	8761724	0.51*	5	2008	1	3	0-3	fall	9-20	145-270
	Sabine Pass, TX	29.7	-93.9	8770570	0.52	23	2017	0	8	6-13	fall	8-15	60-160
	Morgans Point, TX	29.7	-95.0	8770613	0.52	16	2015	4	8	5-13	fall	30-45	110-215
	Eagle Point, TX	29.5	-94.9	8771013	0.51	47	2015	1	27	29-40	fall	---	---
	Galveston Pier 21, TX	29.3	-94.8	8771450	0.52	18	2017	3	13	5-11	fall	15-30	100-215
	Rockport, TX	28.0	-97.0	8774770	0.50	7	2010, 2018	1	7	1-4	fall	7-15	60-160
	Corpus Christi, TX	27.6	-97.2	8775870	0.52	10	2017	2	5	1-6	fall	10-20	55-150
	Port Isabel, TX	26.1	-97.2	8779770	0.52	6	2017	1	2	0-3	fall	7-15	40-135
Southwest Pacific	San Diego, CA	32.7	-117.2	9410170	0.57	13	2017	2	8	5-9	winter	10-15	30-60
	La Jolla, CA	32.9	-117.3	9410230	0.57	8	2015	2	4	2-5	winter	10-15	25-55
	Los Angeles, CA	33.7	-118.3	9410660	0.57	6	2015	1	5	1-4	winter	6-10	15-40
	Santa Monica, CA	34.0	-118.5	9410840	0.57	7	2015	2	5	2-5	winter	7-15	20-50
	Port San Luis, CA	35.2	-120.8	9412110	0.57	6	1982	1	1	0-3	winter	3-5	8-25
	Monterey, CA	36.6	-121.9	9413450	0.57	7	1982	1	0	0-2	winter	3-5	10-30
	San Francisco, CA	37.8	-122.5	9414290	0.57	6	1982	1	0	0-2	winter	2-3	6-25
	Alameda, CA	37.8	-122.3	9414750	0.58	10	1982	1	0	0-3	winter	1-2	3-15
	Point Reyes, CA	38.0	-123.0	9415020	0.57	8	2016	1	0	0-4	winter	4-7	15-40
	Port Chicago, CA	38.1	-122.0	9415144	0.56	15	1982	1	0	0-2	winter	2-2	4-15
	Arena Cove, CA	38.9	-123.7	9416841	0.57	14	1997	2	2	1-6	winter	5-7	10-30
Northwest Pacific	Humboldt Bay, CA	40.8	-124.2	9418767	0.58	15	2016	4	12	6-12	winter	15-20	45-80
	Port Orford, CA	42.7	-124.5	9431647	0.59	23	1997	5	4	3-12	winter	9-15	15-40
	Charleston, OR	43.3	-124.3	9432780	0.59	27	1997	6	7	4-12	winter	9-15	15-35
	South Beach, OR	44.6	-124.0	9435380	0.60	25	1997	7	9	5-14	winter	15-20	30-50
	Toke Point,WA	46.7	-124.0	9440910	0.61	33	1997	12	12	9-21	winter	15-20	20-35
	Port Angeles, WA	48.1	-123.4	9444090	0.59	12	1982	4	3	2-7	winter	5-7	8-15
	Port Townsend, WA	48.1	-122.8	9444900	0.60	13	1982	3	2	1-6	winter	5-6	9-20
	Seattle, WA	47.6	-122.3	9447130	0.64	11	1997	2	2	2-6	winter	4-6	9-20
	Cherry Point, WA	48.9	-122.8	9449424	0.61	15	1982	4	4	1-7	winter	4-5	5-10
	Friday Harbor, WA	48.5	-123.0	9449880	0.60	17	1982	4	2	1-7	winter	6-7	9-20
Caribbean	Lime Tree Bay, VI	17.7	-64.8	9751401	0.51	1	1999	0	0	0	fall	0-0	0-3
	Charlotte Amalie, VI	18.3	-64.9	9751639	0.51	1	1995	0	0	0	fall	0-0	0-7
	San Juan, PR	18.5	-66.1	9755371	0.52	1	2017	0	0	0	fall	0-0	0-9
	Magueyes Island, PR	18.0	-67.0	9759110	0.51	1	1998	0	0	0	fall	0-0	0-3

ACRONYMS

cm	centimeter
°C	degree Celsius
ENSO	El Niño Southern Oscillation
GT	Great Diurnal Range
HTF	high tide flooding
m	meter
MHHW	mean higher high water
MLLW	mean lower low water
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWS	National Weather Service
ONI	Oceanic Niño Index
RSL	relative sea level
WFO	Weather Forecasting Offices