NOAA Technical Service Publication NOS CO-OPS 001

NOTICE OF METHODOLOGY UPDATE: NOAA HIGH TIDE FLOODING OUTLOOKS

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

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U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U. S. harbors, and the National Current Observation Program consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real time buoys. The Center establishes standards for the collection and processing of water level and current data; collects and documents user requirements, which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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Notice of Methodology Update: NOAA High Tide Flooding Outlooks

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NOTICE

1. OVERVIEW

High tide flooding is the overflow or excess accumulation of ocean water on low lying land at high tide. It is increasing in frequency and severity due to sea level rise. As relative sea levels rise, high tide flooding (HTF) is occurring more frequently, even on sunny days. HTF creates short term impacts like road closures, overflowing storm drains, and temporary business closures. Over the long term, recurrent HTF causes more severe impacts like damage to below-ground infrastructure and degraded wetlands.

As the authoritative source for accurate, reliable, and timely water-level and current measurements, the Center for Operational Oceanographic Products and Services (CO-OPS) within NOAA’s National Ocean Service (NOS), provides a suite of interactive products, reports, and datasets that help communities understand when, where, and how often HTF may occur to better inform coastal flood planning and mitigation efforts. The suite includes a summary of historical HTF days, Monthly and Annual HTF Outlooks at seasonal to annual time scales, and longer-term decadal projections.

The methodology for creating these products is reviewed routinely by CO-OPS scientists. When a significant procedural or scientific change is made, those updates are documented in a Technical Services Update. The following changes have been made this year that impact the HTF products:

- The NOS flood thresholds for the Pacific Islands have been updated to better fit what stakeholders are observing on the ground. The new approach is a modified version of methodology outlined in Sweet et al. 2018.
- This year, relative sea level trends incorporated in the Monthly Outlook were recalculated using a new methodology that accommodates changing rates in trends at long-term water level gauges over the period of record.
- Dissemination of daily HTF likelihood information within the Monthly Outlook is limited to specific stations based on the results of a retrospective skill assessment evaluating model performance for the most recent 20 years of observations.
- Decadal projections used to calculate annual HTF events are enhanced by integrating updated Sea Level Rise (SLR) Scenarios outlined in the 2022 U.S. Interagency Sea Level Rise Technical Report (Sweet et al. 2022).

2. METHODOLOGY UPDATES

Updates to Flood Thresholds for the Pacific Islands

Dusek et al. (2022) indicates that nationally derived NOS flood thresholds (Sweet et al. 2018) are not representative of the conditions observed at Pacific Island gauges. Despite local reports of flood events by stakeholders, observed water levels have rarely exceeded NOS flood thresholds established at each gauge. For this reason, a new flood threshold of 0.304 m was introduced for the Pacific Islands region effective on June 1, 2023. Of the 11 gauges, seven have existing local minor flood thresholds set by the National Weather Service (NWS) (see **Table 1**). The new regional Pacific Islands flood threshold was derived by calculating the average of the existing NWS minor flood thresholds, omitting the American Samoa NWS threshold. American

Samoa was excluded because subsidence from the 2009 earthquake makes its flood threshold an outlier for the region.

Table 1. The NWS and NOS minor flood thresholds at Pacific Island NOS water level gauges. The previously used NOS minor flood thresholds were derived nationally. The updated NOS minor flood thresholds were derived for the Pacific Island region.

St ID	Station Name	NWS minor (m, MHHW)	Previous NOS minor (m, MHHW)	Updated NOS minor (m, MHHW)
1611400	Nawiliwili, Hi	0.335	0.522	0.304
1612340	Honolulu, Hi	0.213	0.523	0.304
1612480	Mokuoloe, Hi	0.396	0.526	0.304
1615680	Kahului, Hi	0.244	0.527	0.304
1617433	Kawaihae, Hi	0.360	0.597	0.304
1617760	Hilo, Hi	0.274	0.529	0.304
1619910	Midway Island	Undetermined	0.515	0.304
1630000	Apra Harbor, Guam	Undetermined	0.529	0.304
1770000	Pago Pago, American Samoa	0.183*	0.533	0.304
1820000	Kwajalein Island	Undetermined	0.548	0.304
1890000	Wake Island	Undetermined	0.529	0.304

*Excluded from the calculation of the updated NOS flood threshold.

Lowering minor flood thresholds for the Pacific Islands impacts NOAA's HTF products, including: the Historical Flood Days, Monthly Outlook, Annual Outlook, and the Decadal Projections. Statistics on the number of days that exceeded the minor flood threshold are compiled monthly and displayed in the Historical Flood Days product. Effective on June 29, 2023, these statistics were recalculated to reference the regional Pacific Islands minor flood threshold, resulting in an increase in the number of flood days displayed that more accurately represents the impacts observed locally by stakeholders. Updating the minor flood threshold for the Pacific Islands also resulted in an increase in the number of days of potential flooding indicated by the Monthly HTF Outlook and an increase in the frequency of flooding projected in the Annual HTF Outlook for the 2023-2024 meteorological year, which will make both products more applicable to users in the Pacific Islands.

Recalculated Sea Level Trends

Relative sea level trends for each station are incorporated into Monthly HTF Outlook statistical models. Linear trends were recalculated based on at least 40 years of monthly mean data. Many stations have collected observational data for more than 40 years and need to be adjusted for changing rates of sea level rise. To calculate 40-year trends for these stations, the starting point is based on the preceding 40 years. Plotted values are relative to the 1983-2001 mean sea level reference datum. Several stations have separate trends determined pre- and post- earthquake time periods, and their values are plotted relative to the station's most recent epoch. The relative sea level trends are updated annually in May and the updated rates will be included in subsequent updates to the Monthly Outlook.

Determining Stations to Include in Monthly HTF Outlooks

The Annual Outlook and Monthly Outlook models are run for 98 NOAA water level gauges across the coastal U.S. The gauges were included in the analysis if they had relatively continuous, verified hourly data since at least 1997 and had established NOS minor flood thresholds.

All model output was included for the Annual Outlook. Model output for the Monthly Outlook was based on the results of a retrospective skill assessment evaluating the most recent 20 years of observations. The model output for a particular station was included if the Brier Skill Score (BSS) (Wilks, 2010) was greater than the BSS standard error for 1 month of persistence, indicating that the model was skillful at predicting when the HTF threshold was exceeded when compared to climatology alone. If the BSS was less than the BSS standard error (Bradley et al. 2008), then the station was included if all of the following criteria were met, indicating that the modeled results provided useful information:

- Flood thresholds were exceeded greater than 10 times during the 20-year assessment period.
- Flood events were correctly predicted greater than 10% of the time.
- The percentage of correct predictions was four times greater than the percentage of false alarms.

The model was run for 14 NOAA water level gauges in Alaska, but the station-specific output was not disseminated because the national NOS minor flood thresholds may not be adequate for predicting HTF. They do not align with established NWS minor flood thresholds at Alaska stations, and many of the Alaska stations have no existing NWS thresholds. More investigation is needed to develop appropriate thresholds for the flooding in the region. Appendix I shows the 67 stations where the Monthly Outlook model performance criteria were met, as of publication. Dusek et al. (2022) found that the model underperformed in certain locations that were not included in the Monthly Outlook, such as the Gulf Coast and the Chesapeake Bay, where tidal contributions to HTF were relatively small compared to other drivers like weather and climate variability. The spatial variation of water levels in some regions is significant, especially in enclosed bays and estuaries, which also impacts the skill of the model on a local scale. Monthly Outlook output may become available at these additional locations as future research leads to improvements in the model methodology.

Annual HTF Predictions

The Annual Outlook is run for each meteorological year, May to April, to preserve the combined impacts from El Niño Southern Oscillation (ENSO) events. The model is run once water level observations have been verified for dissemination following the methodology explained in Sweet et al. 2018. This time period allows for a 12-month count of HTF during the previous meteorological year, and coincides with the monthly release of the ENSO forecast by the NOAA Climate Prediction Center (CPC)/International Research Institute (IRI) for Climate and Society at the Columbia Climate School, which usually takes place around the 19th of each month.

Very few changes were implemented for the 2023 Annual Outlook model runs.

- The ENSO forecast by IRI includes predictions of Oceanic Niño Index (ONI) from several dynamic (process-based) and statistical models, the list of which may change each month or year. IRI averages all monthly model forecasts for the next 9 months. The Annual Outlook then averages each monthly 'all-model' average into a single value, rounded to a single decimal point, representing the ONI forecast for the next meteorological year.

- As previously stated, NOS-derived HTF thresholds have been adjusted for the Pacific Island stations. This change significantly increases the number of historically observed HTF days, which may alter the statistical behavior of the observed trend and/or the correlation to ONI compared to previous outlooks. Past Annual Outlooks were produced based on the established NOS thresholds in place at the time and care must be taken when evaluating past Annual Outlooks.

Decadal Projections

HTF projections are based on a statistical fit of highest daily water levels from 1990-2022 (Figure 1a). Empirical probability distributions (Figure 1b) of the highest daily levels are used to form probability curves (Figure 1c) to predict annual estimates of daily exceedances for NOAA HTF height thresholds.

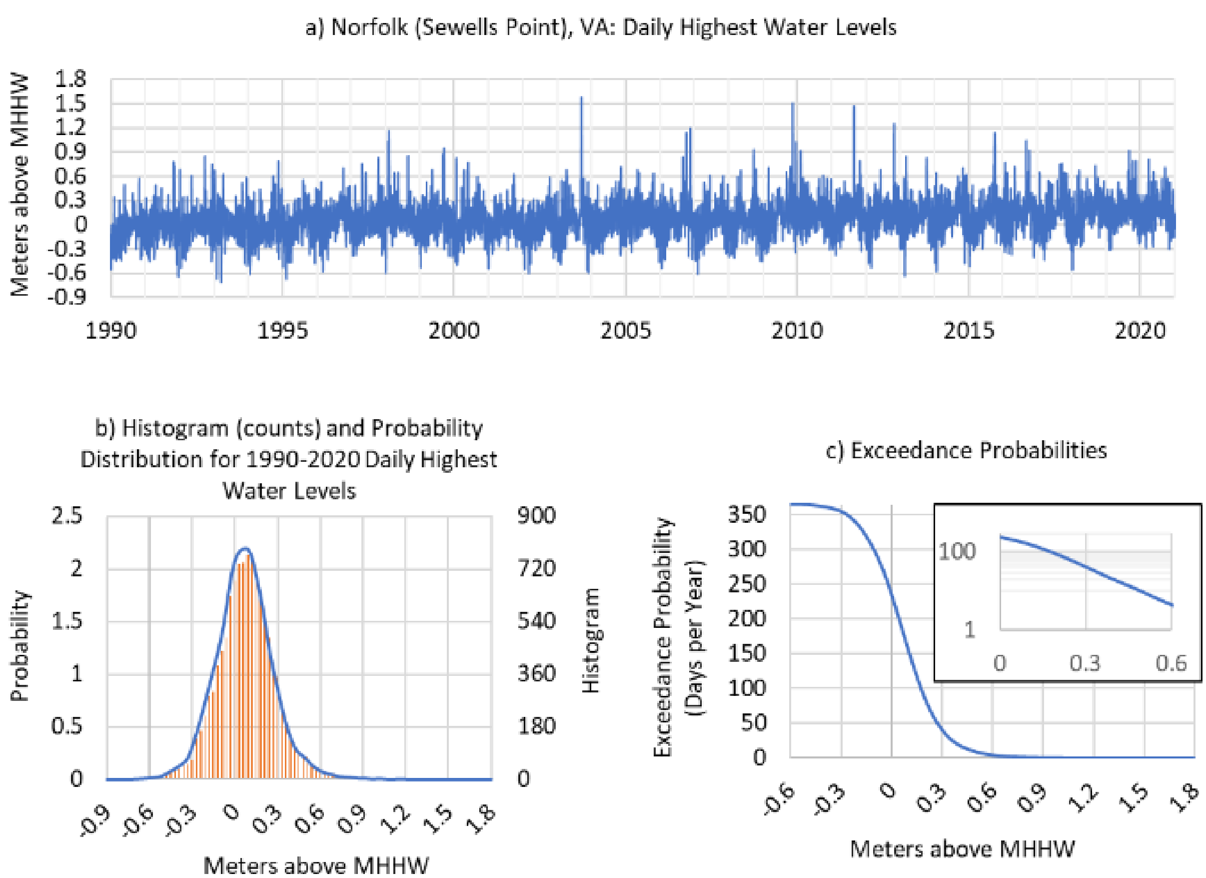

Figure 1. (a) Highest daily water levels from 1990 through 2020 at NOAA water level gauge Sewells Point, VA, shown as (b) a histogram of counts and associated empirical kernel probability distribution; and (c) exceedance probabilities, or 1 minus the cumulative probability distribution. The high tide flooding (HTF) height threshold for Sewells Point is 0.534 m above mean higher high water (MHHW).

Future projections are calculated around an exceedance probability curve (Figure 1c) relative to 2005 - the midpoint of data from 1990 - 2020 (Sweet et al. 2022). Curves are shifted to become relative to location-specific sea level rise trends. Decadal SLR scenario values are annualized through linear interpolation to estimate the amount of SLR per year for each scenario (Figure 2a). Decadal projections of HTF days per year are based on an average of annual values calculated from observations from the previous ten years. For example, the number of HTF days per year expected by 2050 are based on averages from 2041-2050, for each SLR scenario. See the number of expected high tide flooding days per year and by scenario for Norfolk, VA in Figure 2b.

An additional subset of scenarios is used to define a range of expected HTF days per year by 2050. This range is location-specific and derived from the lower and upper bounds of SLR trend extrapolations from regional water level records between 1970 and 2020 (Table 2.2 in Sweet et al. 2022). For example, the Atlantic coastline SLR trajectory from Maine to Virginia falls within the Intermediate and Low bounding scenario based on the extrapolated 2050 trend. The median value of HTF days estimated across the country is used to determine a National Outlook of 45-70 HTF days per year. At Sewells Point, this bounding range equates to a 37-44 cm rise by 2050 for both the Low and Intermediate Scenarios (Figure 2a), and about 85-125 days/year of HTF on average expected by 2050 (Figure 2b). This is a shift from previous estimates based on emissions scenarios outlined in the 4th National Climate Assessment[1] that predicted Sewells Point, VA would experience 165-170 HTF days per year; 25-75 HTF days at the national level.

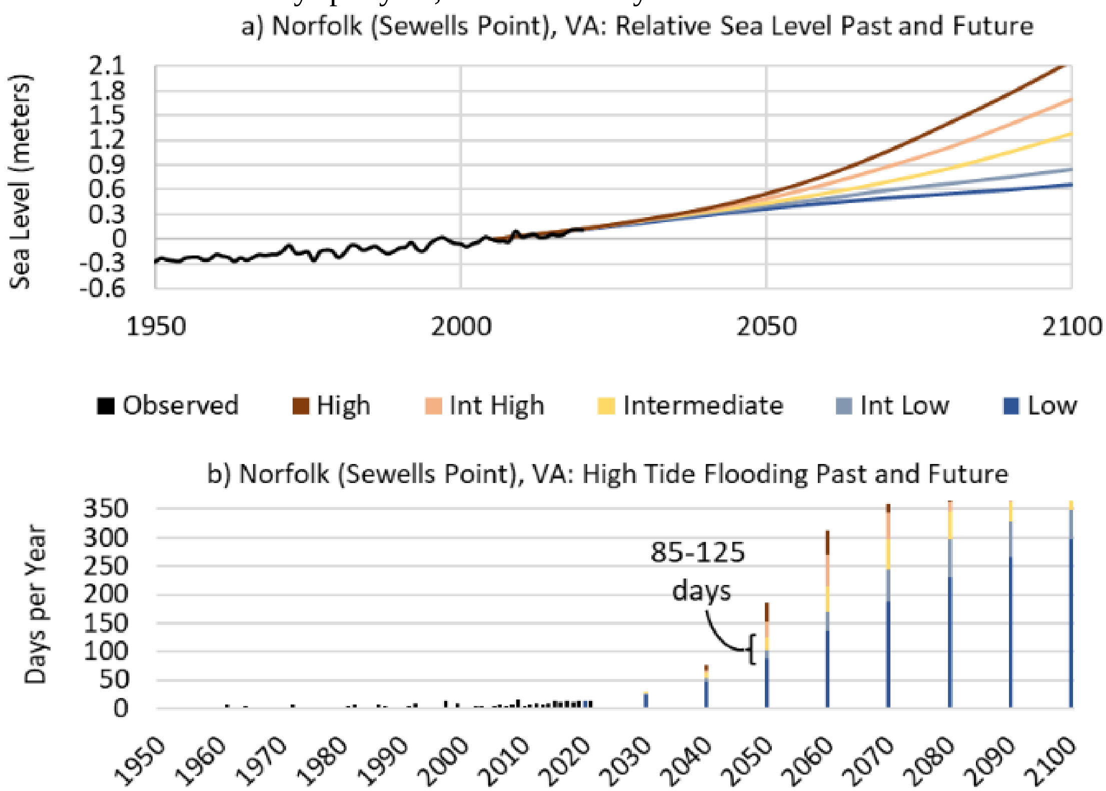

Figure 2. (a) Annual relative sea level at Sewells Point and its 5 sea level rise scenarios with (b) the annual average high tide flooding (HTF) days/year for each scenario and decade with the HTF days/year expected by 2050 highlighted.

[1] Fourth National Climate Assessment (https://nca2018.globalchange.gov/chapter/appendix-3/)

Decadal HTF projections provide estimates of the annual average of expected HTF days per year, by scenario, and decade. Year-to-year HTF variability will continue to occur based on varying climate patterns, like those associated with the ENSO (Sweet et al. 2018); or long tide cycles outlined in NASA's Flooding Analysis Tool (Thompson et al. 2021). The variability of "next season" and "next year" predictions remains and should be considered as part of coastal resilience planning efforts and annual flood-response budget formulation, which is the focus of NOAA's Monthly Outlooks and Annual Outlooks.

3. REFERENCES

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APPENDIX I

The model to generate the daily likelihoods is run for locations with defined NOS flood thresholds that have collected data since 1997 or earlier. The daily likelihoods are disseminated for a subset of stations in the Monthly Outlooks based on results from a retrospective skill assessment evaluating model performance for the most recent 20 years of observations.

Station ID	Station Name	Monthly Outlook Model
1611400	Nawiliwili, HI	Yes
1612340	Honolulu, HI	Yes
1612480	Mokuoloe, HI	Yes
1615680	Kahului, HI	Yes
1617433	Kawaihae, HI	Yes
1617760	Hilo, HI	Yes
1619910	Midway Island	Yes
1630000	Apra Harbor, Guam	Yes
1770000	Pago Pago, American Samoa	Yes
1820000	Kwajalein Island	Yes
1890000	Wake Island	Yes
8413320	Bar Harbor, ME	Yes
8418150	Portland, ME	Yes
8443970	Boston, MA	Yes
8447930	Woods Hole, MA	No
8449130	Nantucket Island, MA	No
8452660	Newport, RI	Yes
8454000	Providence, RI	Yes
8461490	New London, CT	No
8467150	Bridgeport, CT	Yes
8510560	Montauk, NY	No
8516945	Kings Point, NY	Yes
8518750	The Battery, NY	Yes
8519483	Bergen Point, NY	Yes

8531680	Sandy Hook, NJ	Yes
8534720	Atlantic City, NJ	Yes
8536110	Cape May, NJ	Yes
8545240	Philadelphia, PA	No
8551910	Reedy Point, DE	No
8557380	Lewes, DE	Yes
8571892	Cambridge, MD	No
8573364	Tolchester Beach, MD	No
8574680	Baltimore, MD	No
8575512	Annapolis, MD	No
8577330	Solomons Island, MD	No
8594900	Washington, DC	No
8631044	Wachapreague, VA	Yes
8632200	Kiptopeke, VA	Yes
8635750	Lewisetta, VA	Yes
8636580	Windmill Point, VA	Yes
8638610	Sewells Point, VA	Yes
8651370	Duck, NC	Yes
8652587	Oregon Inlet Marina, NC	No
8656483	Beaufort, NC	Yes
8658120	Wilmington, NC	No
8661070	Springmaid Pier, SC	Yes
8665530	Charleston, SC	Yes
8670870	Fort Pulaski, GA	Yes
8720030	Fernandina Beach, FL	Yes
8720218	Mayport, FL	Yes
8721604	Trident Pier, FL	Yes
8723214	Virginia Key, FL	Yes
8723970	Vaca Key, FL	No
8724580	Key West, FL	No
8725110	Naples, FL	Yes

8725520	Fort Myers, FL	No
8726520	St. Petersburg, FL	No
8726724	Clearwater, FL	No
8727520	Cedar Key, FL	Yes
8728690	Apalachicola, FL	No
8729108	Panama City, FL	No
8729210	Panama City Beach, FL	No
8729840	Pensacola, FL	Yes
8735180	Dauphin Island, AL	Yes
8747437	Bay Waveland, MS	Yes
8761724	Grand Isle, LA	No
8770613	Morgans Point, TX	Yes
8771013	Eagle Point, TX	Yes
8771450	Galveston Pier 21, TX	Yes
8774770	Rockport, TX	Yes
8779770	Port Isabel, TX	Yes
9410170	San Diego, CA	Yes
9410230	La Jolla, CA	Yes
9410660	Los Angeles, CA	Yes
9410840	Santa Monica, CA	Yes
9412110	Port San Luis, CA	Yes
9413450	Monterey, CA	Yes
9414290	San Francisco, CA	No
9414750	Alameda, CA	Yes
9415020	Point Reyes, CA	Yes
9415144	Port Chicago, CA	No
9416841	Arena Cove, CA	Yes
9418767	Humboldt Bay, CA (North Spit)	Yes
9431647	Port Orford, OR	Yes
9432780	Charleston, OR	Yes

9435380	South Beach, OR	Yes
9440910	Toke Point, WA	Yes
9444090	Port Angeles, WA	Yes
9444900	Port Townsend, WA	Yes
9447130	Seattle, WA	Yes
9449424	Cherry Point, WA	Yes
9449880	Friday Harbor, WA	Yes
9450460	Ketchikan, AK	No
9451600	Sitka, AK	No
9452210	Juneau, AK	No
9452400	Skagway, AK	No
9453220	Yakutat, AK	No
9454050	Cordova, AK	No
9454240	Valdez, AK	No
9455090	Seward,AK	No
9455500	Seldovia, AK	No
9455760	Nikiski, AK	No
9455920	Anchorage, AK	No
9457292	Kodiak Island, AK	No
9459450	Sand Point, AK	No
9461380	Adak Island, AK	No
9462620	Unalaska, AK	No
9463502	Port Moller, AK	No
9751401	Lime Tree Bay, VI	No
9751639	Charlotte Amalie, VI	No
9755371	San Juan, PR	No
9759110	Magueyes Island, PR	No