Coastal Flooding

Identification

1. Indicator Description

This indicator describes how the number of coastal floods exceeding local flood threshold levels has changed over time. Sea level rise related to climate change is a key driver of the increasing frequency of coastal flooding. The Fifth National Climate Assessment states that the frequency of high tide flooding (also called "nuisance flooding") in the continental United States has doubled over the past few decades in response to rising sea levels (Marvel et al., 2023). The 2022 *Global and Regional Sea Level Rise Scenarios for the United States* report also notes that the impacts from "nuisance floods" are "remarkable throughout dozens of densely populated coastal cities" (Sweet et al., 2022).

Components of this indicator include:

- A map that shows the change in flood days per year along U.S. coasts, comparing the first decade of record with the most recent decade (Figure 1).
- A more detailed graph that shows average flood days per year along U.S. coasts from 1950 to 2023 (Figure 2).

2. Revision History

August 2016:	Indicator published.
April 2021:	Updated indicator with data through 2020 and a new set of flood thresholds.
September 2023:	Updated indicator with data through 2022.
June 2024:	Updated indicator with data through 2023; expanded to include Alaska and Pacific islands.
September 2024:	Updated data for sites in Alaska to incorporate corrections to the underlying source data.

Data Sources

3. Data Sources

Coastal flooding trends are based on measurements from permanent tide gauge stations. The original tide gauge data come from the National Water Level Observation Network (NWLON), operated by the Center for Operational Oceanographic Products and Services (CO-OPS) within the National Oceanic and Atmospheric Administration's (NOAA's) National Ocean Service (NOS). Daily maximum water levels are derived from the hourly data set maintained by CO-OPS. Mike Kolian of EPA developed this indicator in collaboration with William Sweet of NOAA. The analysis was adapted from Sweet et al. (2018), which was an update to an analysis published by Sweet and Marra (2015), NOAA (2014), and Sweet and Park (2014).

4. Data Availability

Individual tide gauge measurements can be accessed through NOAA's "Tides and Currents" website at: https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels. This website also presents an interactive map that illustrates sea level trends over different timeframes.

EPA obtained the 1950–2023 analysis from NOAA. Data from all sites except those in Alaska came from NOAA's publicly accessible derived product data interface at: https://api.tidesandcurrents.noaa.gov/dpapi/prod. Results for stations in Alaska were provided directly by NOAA personnel (NOAA, 2024). Station-specific flood thresholds for locations presented in this indicator, as well as other locations, are listed in Table A1.3 of Sweet et al. (2022). Updated flood thresholds for Pacific island stations, which were implemented in 2023, are listed in Table 1 of NOAA (2023). Updates to this indicator are likely to coincide with NOAA's interactive product, *The State of High Tide Flooding and Annual Outlook*, which is updated each spring at: https://tidesandcurrents.noaa.gov/high-tide-flooding/annual-outlook.html.

Methodology

5. Data Collection

This indicator presents the change in flood days, which are defined as days in which a tide gauge records water levels that exceed a threshold that NOAA has derived from the gauge data at each location. This indicator captures all flooding events that exceed each location's threshold, which means it captures floods that may range from small "nuisance" floods to much larger but less frequent major floods.

Coastal water levels have traditionally been measured using tide gauges, which are mechanical measuring devices placed along the shore. These devices measure the change in sea level relative to the land surface, which means the resulting long-term analysis reflect both changes in flood frequency occurring from changing absolute sea surface height and local land levels.

Tide gauge data for this indicator come from NWLON, which is composed of 210 long-term, continuously operating tide gauge stations along the U.S. coast, including the Great Lakes and islands in the Atlantic and Pacific Oceans. This indicator shows trends for a subset of stations along the ocean coasts that met the following criteria for sufficient data:

- A total of at least 10 "flood days" during the entire period of analysis (1950–2023). This criterion eliminates sites that have too few observed floods to support an analysis of change over time.
- At least 60 years of data during the period of analysis. This criterion eliminates sites that are missing too many years of data to allow for a reasonable analysis of change over time.
- At least six years of data within each decade (1950–1959, 1960–1969, etc.). This criterion eliminates sites with large gaps that might bias the results, including sites that might have come online in the late 1950s but technically met the criterion for 60 years of data. The criterion is prorated for the most recent decade if it is a partial decade.

Although many stations collected data before 1950, NOAA and EPA selected 1950 as a reasonable starting point for this indicator to ensure adequate data for analysis. Choosing a much earlier starting point would have greatly reduced the number of stations with sufficient data for a scientifically defensible analysis, which in turn would have led to an indicator with less complete geographic coverage.

NOAA (2014) describes tide gauge data and how they were collected. Data collection methods are documented in a series of manuals and standards that can be accessed at: https://tidesandcurrents.noaa.gov/pub.html. This indicator uses hourly averages based on each tide gauge's continuous measurements.

6. Indicator Derivation

This indicator was derived by calculating each day's maximum water level based on hourly water level data, then comparing these daily maxima with threshold levels for flooding at each tide gauge.

NOAA derived a consistent set of location-specific flood thresholds using a statistical regression model. This model sets each location's flooding threshold at a specific height above the average local tide range. NOAA determined the regression coefficients by analyzing flood impact levels (minor, moderate, major) that have been established for selected coastal cities by local National Weather Service (NWS) weather forecasting offices, based on many years of impact monitoring. NOAA's derived thresholds for this indicator are based on NWS minor flood impact levels and the observed relationship between these NWS thresholds (where they exist) and the corresponding long-term local tide range. Sweet et al. (2018) and Sweet et al. (2022) describe the derivation of thresholds for this indicator in detail.

NOAA determined that 155 of the 210 NWLON tide gauges had adequate data for an initial analysis, as of a 2023 data download. Accordingly, NOAA derived thresholds for these 155 locations. Data from 15 stations in Alaska were subsequently excluded from the analysis due to NOAA experts' concerns about flood count accuracy, bringing the number of stations to 140. Applying the more restrictive criteria described in Section 5 above led to the selection of 42 sites with adequate 1950–2023 data for inclusion in this indicator.

The total number of days exceeding the derived flooding threshold was calculated for each tide gauge and for every meteorological year. A meteorological year is defined as May of one year to April of the following year (NOAA, 2014). For example, the year "2010" includes data from May 2010 to April 2011. Annual totals were averaged together over multi-year periods for Figures 1 and 2. Figure 1 provides a simple comparison between the first and last decades of record: the 1950s (1950–1959) and the most recent decade (2014–2023). Figure 2 covers the entire period of record by sorting the data into bins, most of which are 20 years in length.

Indicator Development

A previous version of this indicator used a different set of flood thresholds: location-specific "minor flooding" thresholds established by local NWS weather forecasting offices. Direct use of NWS thresholds offered the advantage of leveraging local knowledge tied to observed impacts, but this approach also had disadvantages:

- Because thresholds were derived differently for each location, results did not lend themselves to comparison across multiple locations.

- Only 75 of the 210 NWLON tide gauges have corresponding NWS thresholds, which meant that trends in coastal flooding could not be analyzed for other locations that otherwise had ample data.

Source publications before 2018 all describe the original, NWS-threshold-based method. In 2018, NOAA published a new methodological approach that used the derived thresholds described at the beginning of this section (Sweet et al., 2018). This approach results in broader applicability (more sites) and more comparability between sites. EPA adopted this method for the 2021 indicator update to be consistent with NOAA's new recommended approach. This change expanded the indicator to cover 33 sites, compared with 27 using the previous method. Updated protocols and thresholds published by NOAA in 2022 and 2023 allowed the indicator to grow to 43 sites in the June 2024 update. After the June 2024 update, NOAA informed EPA that the downloadable annual counts of flood days on NOAA's web portal were based on inaccurate flood thresholds for the sites in Alaska. NOAA provided EPA with revisions to the data for three sites in Alaska that had been part of the June 2024 update (Ketchikan, Sitka, and Adak Island). Due to an insufficient number of floods over the period of record (based on the new threshold), the Ketchikan site was removed, leaving a total of 42 sites in the September 2024 update.

7. Quality Assurance and Quality Control

Quality assurance and quality control procedures for U.S. tide gauge data are described in various publications available at: https://tidesandcurrents.noaa.gov/pub.html.

Analysis

8. Comparability Over Time and Space

All of the tide gauges included in this indicator have used the same methods for determining hourly water levels. These methods remained constant over time and across gauges, except as documented in NOAA (2014). Tide gauge measurements at specific locations are not indicative of broader changes over space, however, and the network is not designed to achieve uniform spatial coverage. Rather, the gauges tend to be located at major port areas along the coast, and measurements tend to be more clustered in heavily populated areas like the Mid-Atlantic coast. Nevertheless, in many areas it is possible to see consistent patterns across numerous gauging locations—for example, increases in the frequency of flooding along the Atlantic Coast, the Gulf Coast, and Hawaiʻi.

Flooding thresholds have been established using the statistical model described in Sweet et al. (2018) that applies the same formula across all locations. These flooding thresholds have been used for all U.S. coastlines outside Alaska and the Pacific islands. Thresholds were determined for stations in Alaska using a separate model outlined in Sweet et al. (2020). Updated thresholds for the Pacific islands region were introduced using a separate calculation described in NOAA (2023). For more information on these differences in flood threshold derivation, see Section 9. Each location's flood threshold has been applied consistently throughout the period of record, which supports this analysis of trends over time.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Coastal flooding relates to relative sea level change, which is the height of the sea relative to the height of the land. Changes in coastal flooding frequency cannot be solely attributed to absolute sea level change, but instead may reflect some degree of local changes in land elevation (e.g., subsidence). Tide gauge measurements generally cannot distinguish between these two influences without an accurate measurement of vertical land motion nearby.

2. Some changes in coastal flooding may be due to multiyear cycles such as El Niño/La Niña and the Pacific Decadal Oscillation, which affect coastal ocean temperatures, water density (due to salt content), winds, atmospheric pressure, and currents.

3. The flood thresholds used for this indicator are derived from a statistical model, not directly based on local conditions, so they do not necessarily correspond to a consistent level of observed disruption or damage across different locations. Every location has its own unique characteristics in terms of land cover, topography, elevation of critical infrastructure, and the presence or absence of flood defenses such as seawalls. Thus, flooding that reaches the derived threshold in one city might correspond to much more damage and disruption than a flood that reaches the threshold in a different location. For this reason, when considering the impacts of flooding, it is more useful to compare change over time at a single location than it is to compare patterns across different locations.

4. The statistical model used to derive flood thresholds for the contiguous 48 states (Sweet et al., 2018) is not valid for Alaska. Therefore, in NOAA's updated methodology, a quadratic regression model developed in Sweet et al. (2020) was used to determine thresholds for stations in Alaska. This regression only included NWS flood heights along the U.S. Pacific coastline, and flood thresholds were only considered for stations in Alaska with tide ranges below 6 meters (Sweet et al., 2022).

5. The statistical model for deriving thresholds in the contiguous 48 states (Sweet et al., 2018) did not work well for the Pacific islands, as water levels observed at Pacific island gauges have rarely exceeded the nationally derived thresholds despite on-the-ground reports of flooding. Therefore, the methodology outlined in Sweet et al. (2018) was modified for the Pacific islands region to better align with local observations of flood events. NOAA (2023) describes how a lower flood threshold was calculated for the Pacific islands region by averaging existing NWS minor flood thresholds. In 2023, the annual flood count data for Pacific island stations were recalculated to reference this updated threshold, which resulted in an increase in the number of flood days at these locations.

6. Impacts are localized and not necessarily readily observable. When water levels are expected to exceed an official NWS flooding threshold, coastal flood advisories are typically issued. Minor impacts typically, but not always, manifest.

7. Local topography may affect the relative influences of various environmental processes on a specific site's flooding. For example, offshore barriers such as coral reefs or barrier islands may help to buffer certain contributing effects, such as wind. By contrast, other areas may have topographical features that amplify the flooding caused by slight changes in the environment. Although these differences do not negate the site-specific trends observed, they do contribute to differences between stations.

10. Sources of Uncertainty

Error measurements for each tide gauge station are described in NOAA (2009), but many of the estimates in that publication pertain to longer-term time series (i.e., the entire period of record at each station, not the exact period covered by this indicator). Uncertainties in the data do not impact the overall conclusions. Tide gauges provide precise, reliable water level data for the locations where they are installed.

11. Sources of Variability

Changes in sea level and corresponding changes in coastal flooding can be influenced by multi-year cycles such as El Niño/La Niña and the Pacific Decadal Oscillation, which affect coastal ocean temperatures, salt content, winds, atmospheric pressure, and currents.

12. Statistical/Trend Analysis

This indicator does not report on the slope of the apparent trends in flood frequency, nor does it calculate the statistical significance of these trends. Separately, Sweet et al. (2018) presented statistical trend analyses for four example locations using quadratic and linear fits for data from 1950 to 2016. NOAA reported that two East Coast locations (Atlantic City, New Jersey, and Norfolk, Virginia) fit a quadratic regression, representing acceleration. San Diego, California, and Seattle, Washington, each fit a linear increasing trend. All four regressions were significant to at least a 90 percent level.

In a previous analysis using NWS minor flood thresholds, NOAA (Sweet & Park, 2014) analyzed trends in the annual number of flood days from 1950 to 2013 at 27 of the locations included in the current indicator. Of the 27 stations, 19 had significant quadratic fits and four had significant linear fits, where significance was defined at the 90 percent level.

References

Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripati, A., & Vose, R. S. (2023). Chapter 2: Climate trends. In USGCRP (U.S. Global Change Research Program), *Fifth National Climate Assessment*. https://doi.org/10.7930/NCA5.2023.CH2

NOAA (National Oceanic and Atmospheric Administration). (2009). *Sea level variations of the United States 1854–2006* (NOAA Technical Report NOS CO-OPS 053). www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

NOAA (National Oceanic and Atmospheric Administration). (2014). *Sea level rise and nuisance flood frequency changes around the United States* (NOAA Technical Report NOS CO-OPS 073). https://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf

NOAA (National Oceanic and Atmospheric Administration). (2023). *Notice of methodology update: NOAA high tide flooding outlooks* (NOAA Technical Service Publication NOS CO-OPS 001). https://tidesandcurrents.noaa.gov/publications/HTF_Notice_of_Methodology_Update_2023.pdf

NOAA (National Oceanic and Atmospheric Administration). (2024). *Personal communication: Alaska site data, 1950–2023*.

Sweet, W. V., Dusek, G., Obeysekera, J., & Marra, J. J. (2018). *Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold* (NOAA Technical Report NOS CO-OPS 086). NOAA/NOS Center for Operational Oceanographic Products and Services. https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

Sweet, W. V., Genz, A. S., Obeysekera, J., & Marra, J. J. (2020). A regional frequency analysis of tide gauges to assess Pacific coast flood risk. *Frontiers in Marine Science*, *7*, 883. https://doi.org/10.3389/fmars.2020.581769

Sweet, W. V., Hamlington, B. D., Kopp, R. E., Weaver, C. P., Barnard, P. L., Bekaert, D., Brooks, W., Craghan, M., Dusek, G., Frederikse, T., Garner, G., Genz, A. S., Krasting, J. P., Larour, E., Marcy, D., Marra, J. J., Obeysekera, J., Osler, M., Pendleton, M., … Zuzak, C. (2022). *Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along U.S. coastlines* (NOAA Technical Report NOS 01). National Oceanic and Atmospheric Administration. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report.html

Sweet, W. V., & Marra, J. J. (2015). *2014 state of nuisance tidal flooding*. National Oceanic and Atmospheric Administration. www.ncdc.noaa.gov/monitoring-content/sotc/national/2015/aug/sweet-marra-nuisance-flooding-2015.pdf

Sweet, W. V., & Park, J. (2014). From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, *2*(12), 579–600. https://doi.org/10.1002/2014EF000272