Yesterday's high tide is today's new normal

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Key Points:

- Sea-level rise is altering how we live, work, and play by the sea.
- Elevations that marked high tide only decades ago are now closer to mean sea level.
- This has implications for transportation, construction, and policy.

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Abstract

The daily rise and fall of the tides are intimately familiar to those living on the coast. However, due to sea-level rise, what communities in the United States now experience as the highest, lowest, and average water levels on a typical day no longer corresponds to the official definitions of high tide, low tide, and mean sea level, respectively. Water levels now regularly exceed official high tide along parts of the Chesapeake Bay, Gulf Coast, and Puerto Rico. In other words, yesterday's high tide is becoming today's new normal. This demonstrates how sea-level rise is radically redefining the American shore.

Plain Language Summary

Due to sea-level rise, coastal elevations that we once knew as marking the highest water level over a typical daily tidal cycle now correspond more closely to the average level of the sea: yesterday's high tide is becoming today's new normal. This illustrates how profoundly sea-level rise is altering how we live, work, and play by the sea.

Main text

Four sculptures greet visitors to City Dock in Annapolis, Maryland. Overlooking Annapolis Harbor, author Alex Haley reads from a book. Three children sit before him, listening with rapt attention. The memorial commemorates the arrival of Kunta Kinte, a character from Haley's 1976 novel *Roots*, and represents the author's vision for racial reconciliation and national healing. It is also a poignant illustration of climate change. The author and the children are elevated 20 cm above official highest astronomical tide, which is the highest water level expected under all possible astronomical conditions and normal weather. Yet, contrary to this expectation, Annapolis water levels now regularly exceed this high water mark, even in the absence of storms (Figure 1), and the Kunta Kinte-Alex Haley Memorial is increasingly at risk of flooding (Sweet et al., 2021).

Similar stories are unfolding all across the American shore. Because of sea-level rise (Figure 2), what coastal communities now observe as the highest, lowest, and average water levels over the daily tidal cycle on a typical day no longer correspond to official definitions of high tide, low tide, and mean sea level, respectively, set by the National Ocean Service (2000, 2003) based on historical tide-gauge observations from 1983–2001. In fact, given the rapid pace of sea-level rise in the United States (Sweet et al., 2022), coastal elevations that formerly identified high tide just decades ago are now closer to mean sea level.

These points are illustrated by considering how often coastal water levels exceeded mean sea level and mean higher high water over time. Mean sea level is the average hourly water height whereas mean higher high water is the average higher high water height each tidal day observed by a tide gauge over 1983–2001 (National Ocean Service, 2000, 2003). From these definitions, one expects that water levels will exceed mean sea level about half the time, and exceed mean higher high water only a small fraction of time, over that period on average across phases of the tides (Haigh et al., 2011; Ray and Merrifield, 2019).

Hourly tide-gauge data show that water levels were above mean sea level and mean higher high water 50% and 8% of the time, respectively, on average along the coastal United States during 1990–2000 (Figure 3). Yet, owing to sea-level rise, these percentages have grown higher more recently (Figures 2, 3). On the Gulf Coast, Chesapeake Bay, and Puerto Rico, where tides are smaller and recent sea-level rise more rapid, water levels exceeded mean sea level 68% of the time on average between 2010–2020 (Figures 2, 3). Galveston, Vaca Key, and Annapolis saw water levels above mean sea level more than 80% of the time in 2019–2020. In contrast, there were no appreciable changes in how often water levels exceeded mean sea level on much of the West Coast and in the Gulf of Maine, which feature larger tides and more muted sea-level rise lately (Figures 2, 3). Likewise, water levels were above mean higher high water 15% of the time on average across all tide gauges during 2010–2020, which is nearly a doubling compared to just two decades prior. The increasing frequency of water levels above mean higher high water was strongest along the Gulf of Mexico, Chesapeake Bay, and Puerto Rico, and weakest or absent along much of the West Coast and Gulf of Maine (Figure 3). Galveston, Rockport, and Port Isabel saw water levels above mean higher high water 51–64% of the time during 2015–2020, meaning that yesterday's high water is today's new normal along the Texas coastline. This finding is consistent with the observation that the western Gulf has experienced record numbers of minor, moderate, and major high-tide flooding recently (Sweet et al., 2021).

Right now, the Texas shoreline is an exception to the rule, in that water levels do not exceed current mean higher high water most of the time in most places (Figure 3). Yet that may change in the future depending on the tides, past sea-level rise, and future sea-level scenario (Figure 4). For all sea-level scenarios published in a recent technical report from an interagency sea-level rise task force (Sweet et al., 2022), relative sea level rises above current mean higher high water in the Chesapeake Bay, Gulf of Mexico, and Puerto Rico by ~ 2040 (Figure 4). If and when relative sea level rises above current mean higher high water elsewhere varies. Due to lower past sea-level rates, larger tides, and more muted future sea-level scenarios, locations along the West Coast and Gulf of Maine may witness relative sea level above current mean higher high water by end of century for intermediate-to-high sea-level scenarios (Figures 2, 4). Hawai'i has similarly low past and future sea-level rise rates, but smaller tides, so relative sea level may exceed current mean higher high water as soon as ~ 2040 or as late as ~ 2090, depending on scenario (Figure 2, 4). Elsewhere, observed and projected rates of sea-level are rapid enough, and tides small enough, that the time when relative sea level rises above current mean higher high water is constrained within a relatively narrow window. For example, at Woods Hole, relative sea level will be above mean higher high water between 2041–2054 (Figure 4).

The official definitions of high tide, low tide, mean sea level, and other tidal heights in the United States, collectively known as tidal datums, are updated every 20–25 years (National Ocean Service, 2000). Revised tidal datums, which will soon be issued by the National Ocean Service using more recent data from 2002–2020, will include the effects of sea-level rise over the intervening period, resulting in higher values in general. These updates will temporarily reduce the kinds of differences highlighted here, for example, between official high tide and a typical high tide experienced in the future, but they will not alleviate the issue in the long term. So long as these revisions occur every couple decades, there will continue to be times when water levels exceed official high tide more often than not in some places, due to sea-level rise. In fact, as sea-level rates accelerate, such issues will only grow more acute, since the time it takes relative sea level to rise the distance separating mean sea level and mean higher high water will shorten. This may present practical challenges, since the legal boundary between the land and sea, maritime zones, marine operations, coastal construction, and property rights all depend on the official definitions of high tide, low tide, and mean sea level (Borax Consolidated, Ltd. versus Los Angeles, 1935; Convention on the Law of the Sea, 1982; Pacific Islands Forum, 2021; Pugh, 1987; United States Army Corps of Engineers, 2010).

Our results shine light on one of the many ways that sea-level rise is remaking our shorelines. Given the rapid pace of sea-level rise in the United States (Sweet et al., 2022), official definitions of tidal heights based on historical observations no longer correspond to the daily water levels typically experienced today. This presents legal and political challenges, but perhaps more basically it illustrates how fundamentally and quickly our collective experience of the coast has changed: coastal elevations that only decades ago were recognized as mean higher high water, inundated only acutely during storms or peak seasonal full- or new-moon tides, are now (or will soon be) experienced as mean sea level, underwater as often as not (Figure 1). This has profound implications for how we live, work, and play by the sea, and provides a stark demonstration of how sea-level rise is redefining the American shore.

Open Research

Hourly tide-gauge water-level observations and predictions as well as tidal datums were downloaded from the National Oceanic and Atmospheric Administration Tides and Currents (`https://tidesandcurrents.noaa.gov/`). Future sea-level scenarios from the sea level rise technical report (Sweet et al., 2022) are from the National Ocean Service (`https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-data.html`).

Acknowledgments

The authors were supported by the NASA Sea Level Change Team (grant 80NSSC20K1241). CGP also acknowledges support from the Joint Initiative Awards Fund from the Andrew W. Mellon Foundation, the Ocean and Climate Innovation Accelerator (OCIA), and the President's Innovation Fund at Woods Hole Oceanographic Institution.

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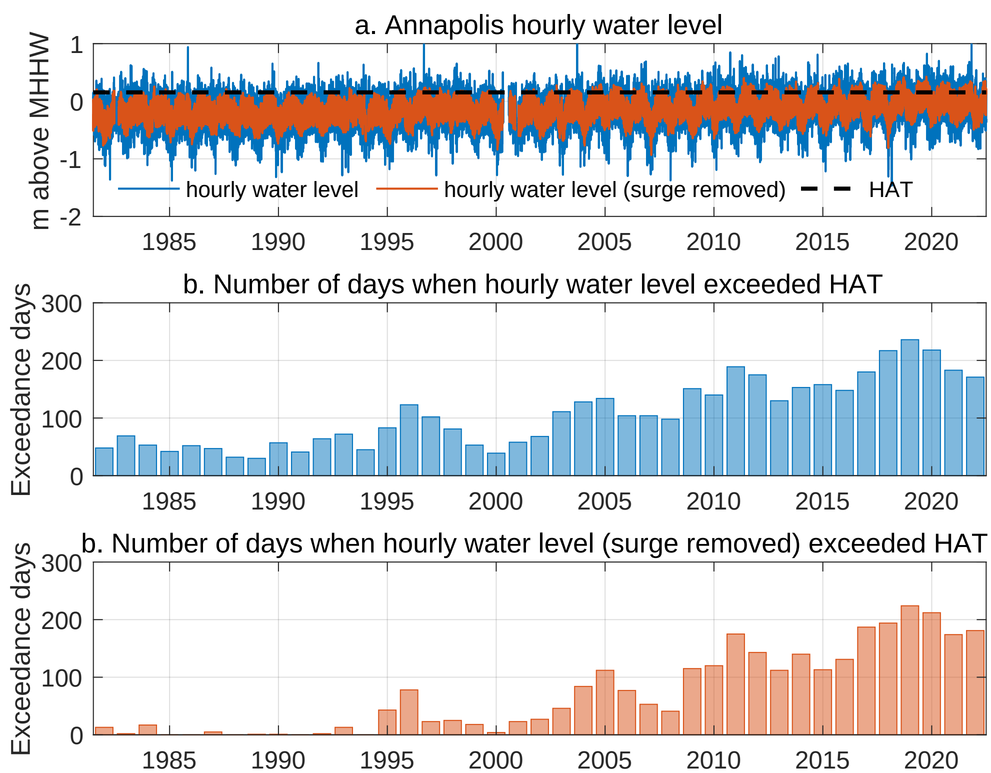

Figure 1. (a.) Blue line shows hourly water-level observations from the Annapolis tide gauge relative to mean higher high water (m). Black dashed line identifies highest astronomical tide (0.154 m above mean higher high water). Orange line shows the same data with surge removed after Piecuch et al. (2022): the predicted tides are subtracted from the water level data in blue; the nontidal residuals are then smoothed with a 20-day moving median filter isolate longer-term mean sea level and remove shorter-term storm surge; finally, the predicted tides are added back to give the orange time series. (b.) Histogram shows the number of days per meteorological year (May–April) when water level exceeded highest astronomical tide for at least one hour based on the full data series shown in blue in (a.). (c.) As in (b.) but based on the hourly observations with storm surge removed shown in orange in (a.).

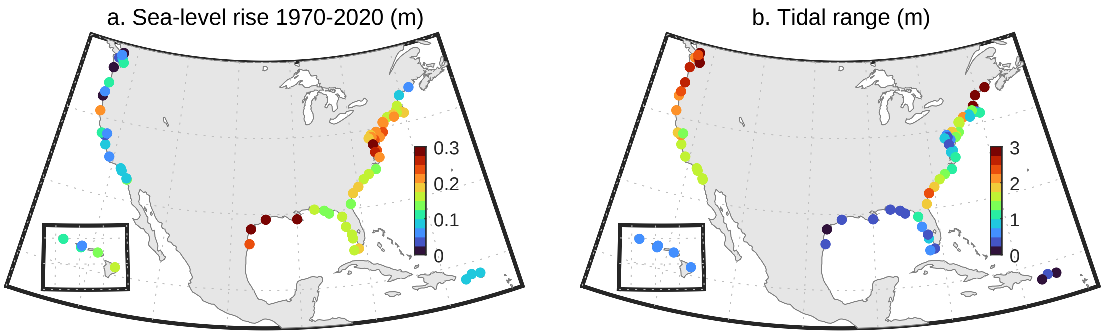

Figure 2. (a.) Relative sea-level rise during 1970–2020 and (b.) tidal range during 1983–2001 based on hourly water-level records from 77 tide-gauge stations. See Figure 1 for an example of the hourly tide-gauge water-level data upon which these calculations are based. Relative sea-level rise is defined as the difference between 2020 and 1970 values of a second-order polynomial fit to annual-mean relative sea-level data during 1970–2020 (cf. Figure 4d–f). Tidal range is the great diurnal range, which is the difference between mean higher high water and mean lower low water.

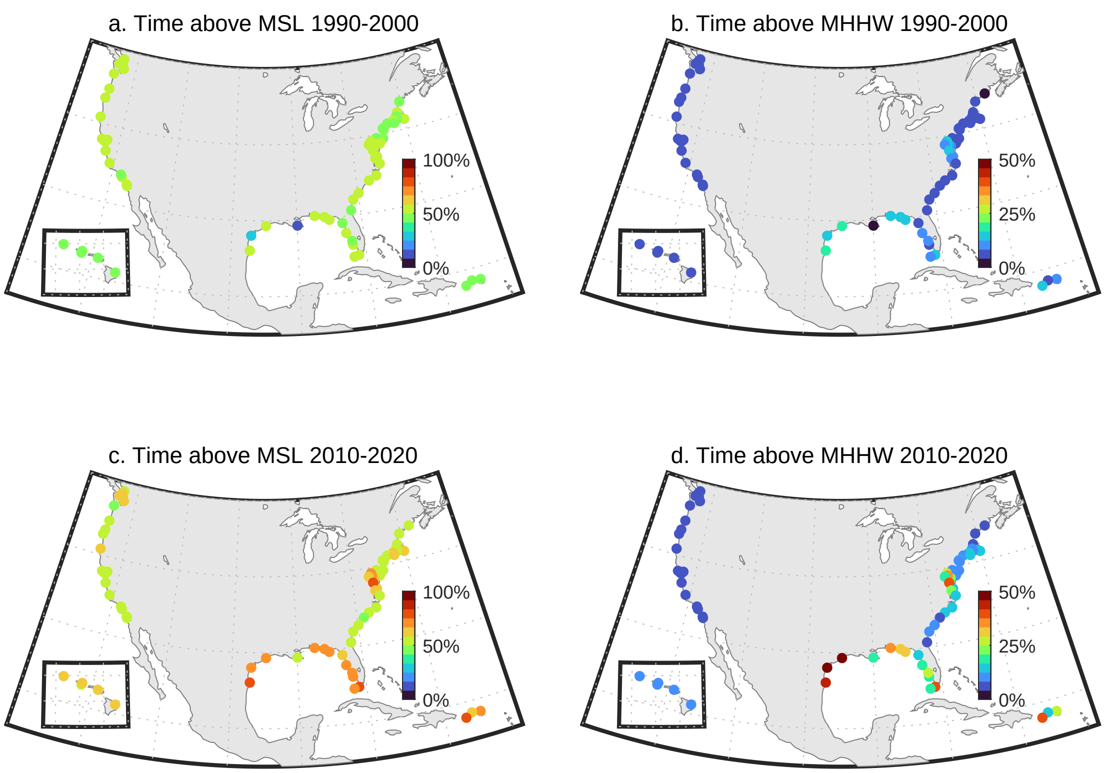

Figure 3. Percent of the time when hourly water-level data exceeded (left) mean sea level or (right) mean higher high water during (top) 1990–2000 or (bottom) 2010–2020 at 77 tide gauges.

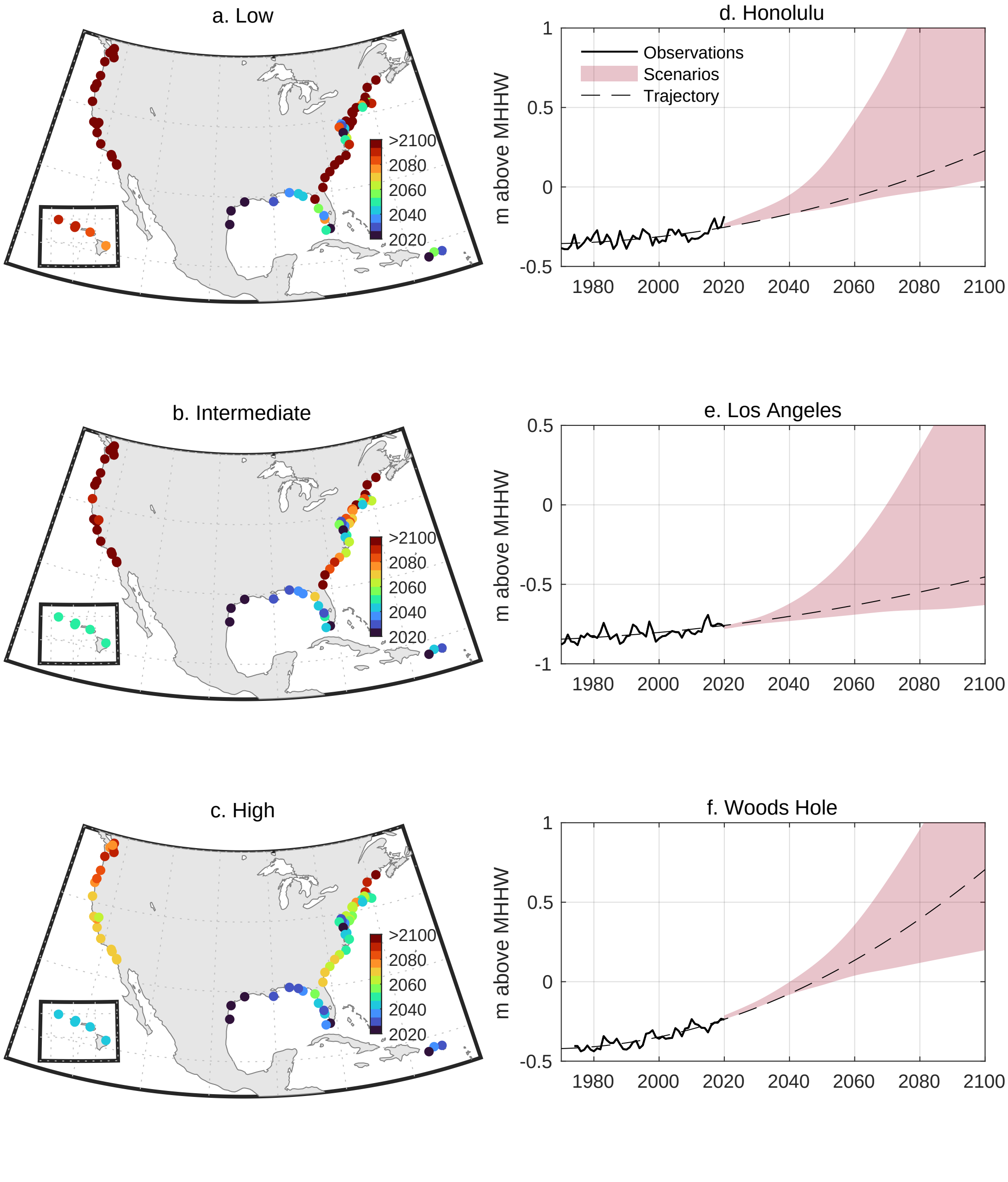

Figure 4. Colored circles on the left identify the future year when annual-mean relative sea level exceeds mean higher high water for the (a.) low, (b.) intermediate, and (c.) high scenarios from Sweet et al. (2022) at 77 tide-gauge stations. Solid black, dashed black, and shaded red on the right respectively represent annual-mean relative sea level from tide-gauge observations during 1970–2020, a second-order polynomial fit to the data and extrapolated forward to 2100, and the bounds of the low and high scenarios at (d.) Honolulu, Hawai'i, (e.) Los Angeles, California, and (f.) Woods Hole, Massachusetts. All values on the right relative to mean higher high water.