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Can We Make Coastal Communities Resilient to Sea-Level Rise?

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ABSTRACT

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"Resilient" is a term that has gotten increasingly widespread usage in recent years as a solution or response for coastal communities to the well-documented global rise in sea level. The message that is usually conveyed seems to be that if we can make coastal communities resilient, everything will be fine and we will have solved the challenge of how to adapt to a rising sea. The federal government and some coastal state government agencies are providing grant money to encourage coastal communities to develop plans to become more resilient. This is an appropriate time to ask what would a resilient coastal community look like and can we actually make a community resilient to future sea-level rise, and if so, for how long?

ADDITIONAL INDEX WORDS: *Coastal protection, coastal zone management, sea-level rise, shoreline erosion.*

SEA-LEVEL RISE RESILIENCE

There are many dictionary definitions of resilient, but most of these refer to human resilience rather than community resilience. Perhaps the most relevant in this context is from the National Oceanic and Atmospheric Administration (NOAA)'s National Ocean Service (NOS):

> *Coastal resilience means building the ability of a community to "bounce back" after hazardous events such as hurricanes, coastal storms, and flooding—rather than simply reacting to impacts. Resilience is important everywhere because all communities face hazard threats such as droughts and flooding. Coastal areas have additional hazard risk from storms such as hurricanes and increased population pressures, making resilience particularly important in those locations.*
>
> *Because all communities are going to face hazards, resilience is important. Resilience is our ability to prevent a short-term hazard event from turning into a long-term community-wide disaster. While many communities effectively prepare themselves to respond to emergency situations, many are not adequately prepared to recover in the aftermath.*
>
> *We cannot overrule Mother Nature, but there are actions that we can take together to build resilient communities and support a healthy ocean, sustainable fisheries, and thriving communities and economies. NOAA provides businesses, resource managers, decision makers, community planners, and individuals the tools and environmental intelligence to build resilience, adapt, and thrive.*

Communities or cities, however, are complex systems with interlinked physical, natural, social, cultural, political, and economic dimensions. Some would define or interpret resilience as building back exactly what was lost; others suggest it requires adjusting or even completely transforming urban systems. This is an important distinction in perceptions.

Sea-level rise is real, now and everywhere. The science is clear, the debate is over, and the jury is in (IPCC, 2023). Today, hundreds of tide gauges around the coastlines of the world are recording ocean water levels, with the earliest measurements dating from the mid-1800s. Tide gauges track local sea level, which is the elevation of the sea relative to land motion at some specific location, and the land may be rising, sinking, or stable.

Globally averaged tide gauge records documented sea-level rise values ranging from ~1.2 to ~1.7 mm/y (4.7 to 6.8 in/century) over much of the 20th century (Griggs *et al.*, 2017; IPCC, 2023; NOAA, 2021). These tide gauges are not evenly distributed, however, with most of them situated in the Northern Hemisphere (United States and Europe). Although tide gauges provide relative or local sea-level rise rates, a recent evaluation of 32 tide gauge records from all U.S. coastlines revealed that, with the exception of the U.S. Northeast coast and Alaska, every coastal location in the continental United States has experienced an upturn in relative sea-level rise rate since 2013–14, despite wide differences in the magnitude and trending direction of relative sea-level rise acceleration (Boon *et al.*, 2018). The rates of relative sea-level rise from 32 U.S. tide gauges on the Atlantic, Gulf, and Pacific coasts from

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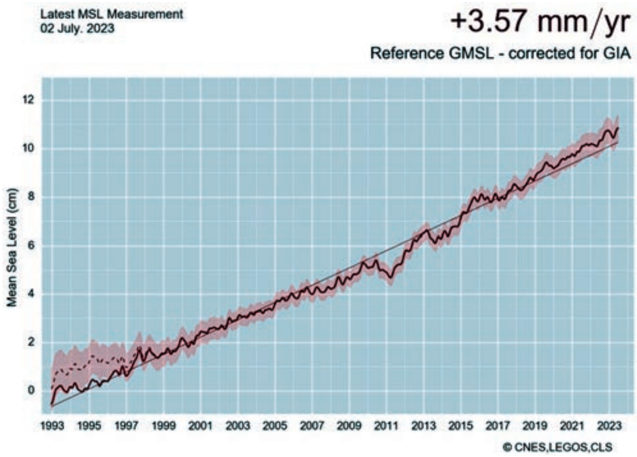

Figure 1. Global mean sea level from satellite altimetry 1993–2023. The average rate of rise of 3.57 mm/y over the 30 y of satellite records is equivalent to 14 in/100 y.

1969 to 2017 range from −14.0 mm/y (Juneau, Alaska, which is rising) to 7.72 mm/y (Grande Isle, Louisiana, which is subsiding).

Thirty years ago (1993) two satellites were placed in orbit (Topex and Poseidon), followed by Jason-1, -2, and -3 in subsequent years, with the objective of measuring global or absolute sea level accurately and precisely from space using lasers. The average sea-level rise rate from these satellite measurements over their 30 years of operation is now 3.57 mm/y (14 in/century) (Figure 1), but this rate is accelerating (Nerem *et al.*, 2018) as Earth continues to warm with increasing anthropogenic production of greenhouse gases. Over the past decade the average rate has increased to approximately 5 mm/y or nearly 20 in/100 y. The warmer the planet gets, the more ice melts and the more seawater expands, both raising global sea levels. Were all the global ice to melt, sea level could rise somewhere between ∼195 feet (National Aeronautics and Space Administration, https://sealevel.nasa.gov/understanding-sea-level/global-sea-level/icemelt#:∼:text=If%20all%20glaciers%20and%20ice,Follow%20On%20satellites%20since%202018) and ∼230 feet (U.S. Geological Survey], https://www.usgs.gov/faqs/how-would-sea-level-change-if-all-glaciers-melted#:∼:text=There%20is%20still%20some%20uncertainty,Science%20School%3A%20Glaciers%20and%20Icecaps). Although all of that ice is not going to melt this century or the next, just 5 or 10 feet of additional sea-level rise will create very substantial impacts in coastal communities and cities around the world. The predictions or projections for sea-level rise by 2050 are in good general agreement (∼25–30 cm or ∼10–12 in), but estimates for end of century vary between models depending upon greenhouse gas emission scenarios (representative concentration pathways) and the specifics of individual models, with increasingly wider uncertainties and ranges by 2100. The latest projections for the end of the century range from a low of ∼60 cm (∼24 in) to as high as 220 cm (∼8.7 ft) as a function of greenhouse gas emissions and various probabilities or uncertainties, especially concerning the extent of Greenland ice melt and Antarctica ice-sheet collapse (Sweet *et al.*, 2022; Figure 2).

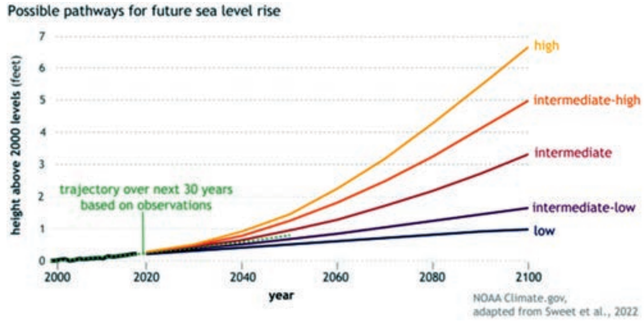

Figure 2. Observed sea level from 2000 to 2018, with future sea level through 2100 for six future pathways. The pathways differ on the basis of future rates of greenhouse gas emission and global warming and differences in the plausible rates of glacier and ice sheet loss. NOAA Climate.gov graph, adapted from Sweet *et al.* (2022).

Looking to the future, the potential loss of public infrastructure and private development due to sea-level rise will have enormous economic impacts on coastal communities, cities, and nations globally. Individual coastal environments face different hazards, however, because of their geology and topography, regional climatic settings, and development patterns and intensities. Coasts display a variety of landforms (*e.g.*, estuaries, barrier islands, beaches, dunes, low bluffs, high cliffs, and steep mountains) and differing development patterns (low to high density) (Griggs and Reguero, 2021).

Lower-lying shoreline areas (Florida and much of the Atlantic Coast of the United States, for example) are more vulnerable to flooding from wave action, hurricanes, large storm waves arriving simultaneously with very high tides, and atop the higher sea levels of the future. Higher-elevation areas, such as bluffs, cliffs, and coastal mountains (which characterize much of the Pacific Coast of California and Oregon, for example) are more vulnerable to coastal erosion or recession from wave attack during high tides or elevated sea levels. Nonetheless, higher sea levels in the future will mean: (1) more frequent, greater-elevation, further-inland penetration and longer-duration flooding of low-relief shoreline areas, followed by permanent inundation and loss of beaches and coastal wetlands in developed areas; and (2) waves reaching and impacting the base of coastal cliffs, bluffs, and dunes more often, leading to increased retreat rates with damage or loss of both public infrastructure and private development.

The economic impacts of coastal hazards will also vary with the degree and type of development and whether public or private. Although precise numbers are difficult to determine, best estimates are that under a high-emission scenario, up to 230 million people around the planet live on land below projected annual flood levels at present. This will increase up to 340 million people by 2050, and as many as 630 million people by 2100 (Kulp and Strauss, 2019). Twenty of the planet's 33 megacities (>10 million people) are sited in low-lying coastal areas. Many of the large cities along the Atlantic Coast of the United States are already experiencing frequent high-tide flooding (Boston, New York City, Baltimore, Atlantic City, Norfolk, Charleston, and Miami, for example; UCS 2014, 2017), and these events will increase in frequency, depth, duration, and extent as sea levels continue to rise at an accelerated rate throughout the 21st century and beyond. Cities in Southeast Asia and Indo-Pacific islands are already experiencing the effects of extreme weather events combined with other factors that increase coastal risk. Although short-term extreme events such as hurricanes, El Niño events (NOS-NOAA, 2023), and severe storms and high tides come and go and will be more damaging in the short term, sea-level rise is a long-term permanent change of state.

As sea-level rise could lead to displacement of hundreds of millions of people, this may be one of the greatest challenges that human civilization has ever faced. Impacts will include inundation of major cities, destruction or loss of coastal infrastructure, increased saltwater intrusion and damage to coastal aquifers and ecosystems, and many other global impacts, as well as geopolitical and legal implications (Sweet *et al.*, 2022). Although there are several short-term responses or adaptation options, we need to begin to think longer term for both public infrastructure and private development.

The options available to coastal communities or megacities are limited, however, and all come with costs, benefits, and impacts. Depending on location, some of these may require successfully navigating and negotiating through a complex, expensive, and time-consuming permitting and environmental review process as well as the very significant challenge of funding. Future losses will be high. The threat from future sea-level rise to coastal cities and low-lying areas around the world, combined with storms, erosion, and inundation, will be one of the major societal and infrastructure challenges of this century.

Throughout the 20th and early 21st centuries, developed coastlines around the world have been responding to the hazards of shoreline flooding and coastal erosion in several ways. Each of these options has its positives and negatives and different geographic areas, political entities, communities, cities, states, or nations have either intentionally or unintentionally made decisions to use one or several approaches (Anderson *et al.*, 2020; Griggs 2017, 2021; Lester *et al.*, 2022):

(1) Denial, do nothing, or wait and see.
(2) Beach nourishment or renourishment.
(3) Shoreline armoring, with either hard or soft structures.
(4) Managed or unmanaged retreat or realignment.

In recent years there have been numerous workshops and conferences, articles, and presentations, as well as government funding programs for developing resilient coastal communities. What does this mean in the context of an accelerating rise in sea level that is almost certainly going to continue for the rest of this century and beyond (IPCC, 2023)? How do you make a coastal community physically resilient and for how long? Does this mean rebuilding what was just damaged or destroyed, or does this mean rethinking our vulnerable communities and planning for relocating assets, whether public or private, away from the shoreline when they are repeatedly damaged?

The first three responses listed above need to be understood as short- or perhaps intermediate-term solutions—possibly to mid-century. Denial or no action is only going to be successful until the next high tide, storm, or hurricane arrives.

Beach nourishment has become an annual or repeated process along many Atlantic and Gulf Coast beaches. Over 1.35 billion m^3 of sand have been placed on the beaches of 475 U.S. communities since 1923 at a 2020 real cost of $10.8 billion (https://beachnourishment.wcu.edu/). Whether New Jersey, New York, or Florida, literally billions of federal dollars have been spent moving sand from offshore to the shoreline for both recreational and shoreline protection benefits, but the life span of the sand added artificially to these beaches in many cases has been relatively short, in some instances less than a year or until the next storm or hurricane hits. For some perspective on life spans of individual nourishment projects, Florida has 15 beaches that have each been nourished 15 or more times; Palm Beach has been nourished 51 different times. It should be clear that beach nourishment is not sustainable and should not be seen as a permanent or even long-term solution to beach or bluff erosion, but simply as a way to buy a little more time at great public expense. Does beach renourishment make a coastal community resilient and for how long? At some point, hurricanes, nor'easters, and rising sea level will overtake all nourished beaches.

Whether rock revetments, seawalls, levees, or floodwalls, or any of a variety of other engineered or nonengineered structures, hardening or armoring the shoreline has been the most common historical approach to coastal erosion, shoreline retreat, or flooding. These solutions aim to protect the shore by defending against elevated water levels or wave impacts. There are, however, several effects of hardening the shoreline, including visual impacts; loss of public beach due to placement of the structure on the beach; loss of the sand to the beach previously provided by the eroding cliff, bluff, or dune being armored; and passive erosion or the gradual loss of the beach fronting the armor with a continuing rise in sea level (Griggs, 2005). It is important to understand that coastal armoring (including seawalls and revetments) protects what is behind the armor, at the cost of the fronting beach. Combating erosion with a hard structure parallel to the shoreline is a choice to not protect the beach at that location. It is only a matter of time before beaches in front of hard armoring structures will be flooded or disappear with a rising ocean (Vitousek *et al.*, 2017), along with all the recreational and ecological benefits provided by the beach.

In addition to rock revetments or seawalls built to protect individual homes, groups of homes, or public infrastructure, the U.S. Army Corps of Engineers has recently proposed extensive and expensive walls to protect a few of the many Atlantic and Gulf Coast cities threatened by rising sea levels and short-term extreme events (Griggs, 2021). The list of cities and projected costs includes Charleston (~$2 billion), Miami (~$4.6 billion), New York City/New Jersey (~$119 billion), and the Houston–Galveston metro area (~$57 billion). These proposed megaprojects raise several significant questions:

(1) What and who will be protected by these walls and what and who gets left out?
(2) What would these walls look like, how high would they be, and do the residents of these cities want to live behind walls?

Figure 3. California State Route 1 was relocated inland at Gleason Beach, 50 miles north of the Golden Gate, after the older highway was threatened by continuing bluff retreat. Sixteen of the homes perched on the bluff edge along the older highway have now been destroyed—in white rectangle (Google Earth June 2023 image).

(3) Are these proposed walls planned for protection against extreme events such as hurricanes, future sea-level rise, or both? If the latter, how many years of future sea-level rise will they protect against and what future sea levels are being used for planning?
(4) Who will pay for these structures? What is the local share, and how will this be financed? Should federal dollars be used to protect these large cities, which are large economic engines themselves?
(5) Protection, whether flood walls or river levees, encourage additional development in the now-protected areas and thereby increases future liabilities. What happens when the combination of higher future sea levels and extreme events (hurricanes, for example) overtops the walls or leads to complete failure, as happened during Hurricane Katrina in New Orleans in 2005?
(6) Would these areas proposed for protection be considered resilient after the construction of these proposed walls?

With a changing climate, the history and magnitude of hurricane and flood events can no longer be considered a realistic guide for what might take place in the future. Building walls around those coastal cities that are already experiencing high tide, storm, or hurricane flooding is certainly one short- or perhaps intermediate-term option (~25 y), although the questions listed above need to be thoroughly vetted at all levels of government before any decisions are made and plans developed, funded, and implemented. The mortgage, insurance, and reinsurance industries also have a vested interest in being involved in any solutions (Hill, 2023).

Any discussion of future long-term responses and building resiliency needs to also agree on a time frame. It's one thing to plan for the next decade, for example, and quite another to plan for 25 to 50 years or longer. This is particularly challenging with terms for elected officials ranging from 2 to 6 years. Where high-value and critical infrastructure is involved—such as international airports, electrical generating stations, wastewater treatment plants, or major transportation corridors—the long-term risks need to be considered carefully, which is

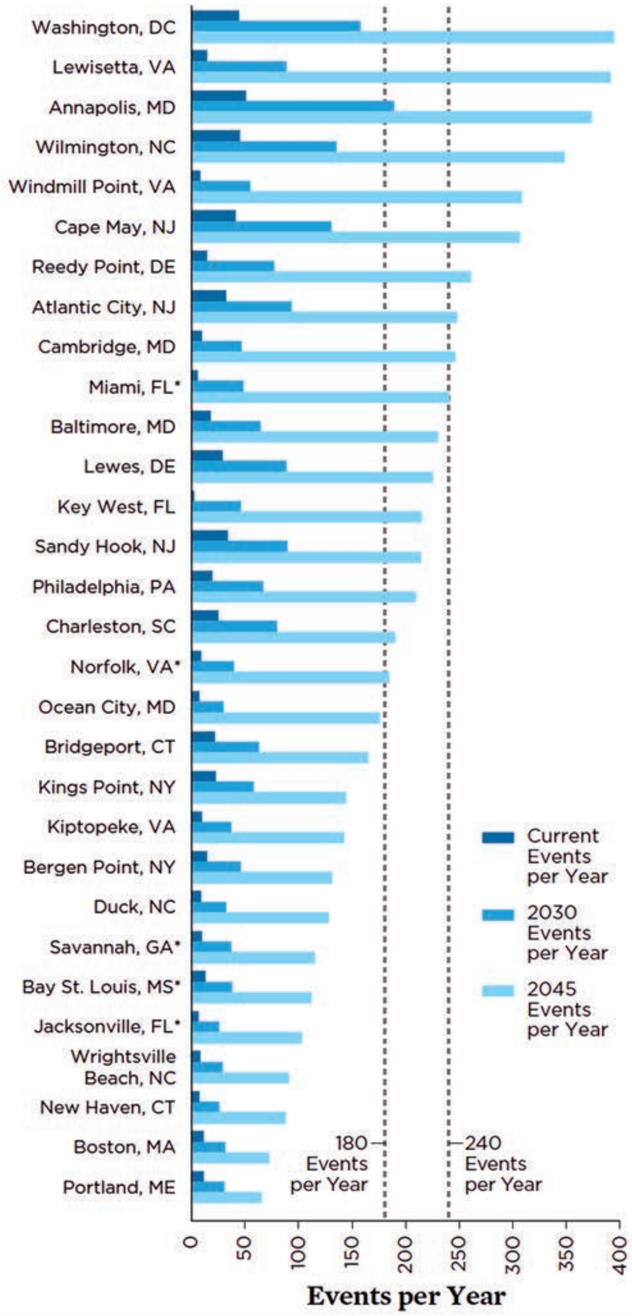

Figure 4. These 30 cities can expect at least 2 dozen tidal floods annually, on average, by 2030. By 2045, one-third of the locations can expect 1980 or more tidal floods/y. Nine locations could average 240 or more tidal floods/y by 2045. Tidal flooding is defined as when at least 10% of the city is flooded (from UCS, 2014).

made more challenging by the increasing uncertainty in sea-level rise projections as we approach mid-century and beyond. At present the projections for 2100, for example, range from <1 m to nearly 3 m (Sweet *et al.*, 2022).

Because of the carbon dioxide and other gases that have already accumulated in the atmosphere, there is general

Figure 5. Collapse of a second house at Rodanthe, North Carolina on 10 May 2022. Five houses were eventually destroyed. Photo courtesy of National Park Service.

agreement among climate scientists that sea level will continue to rise for the rest of this century and well beyond, regardless of our intentions to reduce greenhouse gas emissions (IPCC, 2023). In the long run, there is absolutely nothing we can do to hold back the Atlantic or the Pacific Ocean.

This realization argues for a long-term vision and planning horizon and will lead to the likely conclusion that a progressive or gradual relocation or retreat from the shoreline will become necessary at some future date, with that time being a function of the local or regional sea-level rise rate, the topography, and the vulnerability of each individual coastal community or city. This may well be the greatest challenge that human civilization has ever faced, and to date we have very little experience with such an undertaking, although we are beginning to see an increasing number of examples of relocating threatened infrastructure away from the shoreline (Figure 3).

With all of the above in mind, can any coastal community or city be made truly resilient to future sea-level rise as well as short-term extreme events? What would it require to make Miami Beach, Charleston, Long Beach, or Newport Beach resilient to 5 or 6 feet of sea-level rise? Seawalls and revetments can only be built so high, will be very costly, and will lead to passive erosion or the loss of any fronting beach. Living shorelines sound very appealing, but many of the planet's large cities are not situated at latitudes where mangroves and coral reefs can flourish, and with the infrastructure associated with these large cities (ports, railways and highways, industrial facilities, *etc.*), is it realistic to think that living shorelines are practical or feasible? Additionally, very recent research (Saintilan *et al.*, 2023) indicates that during past periods of rapid global mean sea-level rise, mangrove forests, tidal marshes, and coral reefs were all drowned. In the long run, we need to begin to plan for creative relocation of coastal infrastructure and development away from the shoreline and the opportunities this may provide.

As a first step, communities or cities need to come together and delineate their most vulnerable private development and public infrastructure. The next step will be to agree on trigger points or thresholds when resisting sea-level rise, high-tide flooding, or extreme events is simply no longer feasible. This might include when some portion of the community or city (10%, 20%, for example) is flooded at a certain frequency (monthly or weekly, for example) or a certain number of times per year. The Union of Concerned Scientists (UCS) has made the determination for several Atlantic Coast cities of how often at least 10% of each city would be flooded in 2014, 2030, and 2045 (UCS, 2014; Figure 4).

Although there is understandably very significant resistance from coastal homeowners to managed retreat or realignment, the alternative will be unmanaged retreat, which is already taking place at several locations along U.S. shorelines (Figure 5).

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