Encroaching Tides

How Sea Level Rise and Tidal Flooding Threaten U.S. East and Gulf Coast Communities over the Next 30 Years

Union of Concerned Scientists

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Erika Spanger-Siegfried
Melanie Fitzpatrick
Kristina Dahl

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Erika Spanger-Siegfried, a senior analyst in the Climate and Energy Program at the Union of Concerned Scientists (UCS), designs and manages analytical projects that shed light on local climate impacts, adaptation options, and the urgency of action. Her projects include the Northeast Climate Impacts Assessment (NECIA), a multidisciplinary collaboration of more than 50 scientists from across the region that explored future climate change and the effects on key sectors.

Melanie Fitzpatrick is a climate scientist with the Climate and Energy Program at UCS. Dr. Fitzpatrick specializes in glaciology and atmospheric physics, and has conducted science field programs in Antarctica for two decades. Her work with UCS encompasses basic climate research, the local and global consequences of climate change, and communicating scientific findings to policy makers, the media, and citizens.

Kristina Dahl is a climate scientist whose research, analysis, and communication services help make the impacts of climate change on our environment and society more tangible to the public and policy makers. Dr. Dahl, whose background is in paleoclimate research, formerly coordinated the Rutgers Climate and Environmental Change Initiative, and served as an online educator for the American Museum of Natural History.

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This report and supporting technical document are available online at *www.ucsusa.org/encroachingtides*.

Cover photo: © Amy McGovern

Annapolis, MD, in December 2012, when wind, rain, and high tides combined to cause disruptive flooding.

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AUTHORS

Erika Spanger-Siegfried
Melanie Fitzpatrick
Kristina Dahl

FULL TEAM

Project Management: Erika Spanger-Siegfried
Leadership: Angela Anderson, Brenda Ekwurzel, Adam Markham
Additional review: Carina Barnett-Loro, Kate Cell, Rachel Cleetus, Nancy Cole, Rob Cowin, Matt Heid, Lisa Nurnberger, Jean Sideris, Jackie Weidman
Research: Bjorn Grigholm, Alison Loomis
Mapping: Kristina Dahl, Chris Watson
Editorial support: Sandra Hackman, Seth Shulman
Production: Aaron Eckhouse, Andrew Klein, Heather Tuttle, Bryan Wadsworth
Design: Tyler Kemp-Benedict

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Today scores of coastal communities in the United States are seeing more frequent tidal flooding. And as global warming drives sea levels higher over the next 15 to 30 years, flooding from high tides is expected to occur even more often and cause more disruption, particularly on the East Coast and, increasingly, on the Gulf Coast.

This flooding will redefine how and where people in affected areas live, work, and otherwise go about their daily lives. Coastal communities, and the nation as a whole, need to start planning today to cope with sea level rise and unprecedented tidal flooding, and to take swift and decisive action to limit longer-term damage to our coasts.

A Daily Cycle Gains Disruptive Force

High tides are having a greater impact on U.S. communities today than in decades past for two reasons. First, our shores are more heavily developed, so higher tides affect more people and infrastructure. Second, these tides are now occurring on top of elevated—and rising—sea levels.

Global sea level rose roughly eight inches from 1880 to 2009. That rise occurred because global warming accelerated the melting of land-based ice into the oceans, and because seawater expanded as it absorbed heat from a warming atmosphere. Sea level rise is accelerating globally today, and at especially fast rates along parts of the East Coast.

Coastal communities are all too familiar with the catastrophic damage that can result from major storms, storm surge, and flooding, but they have historically seen high tides as routine. Some tides periodically rise higher than the daily average because of the gravitational pull of the moon and sun. Flooding can result, but that has until recent years been infrequent. Today, however, as the reach and effect of the tides is changing as sea levels rise, our thinking about how we live with the tides—indeed, how we live near the sea—must change, too.

COASTAL COMMUNITIES ON THE FRONT LINE OF TIDAL FLOODING

To analyze how often flooding now occurs at locations along the East and Gulf Coasts—and the frequency and extent of flooding that communities along these coasts can expect 15 and 30 years from now—we relied on 52 tide gauges from Portland, ME, to Freeport, TX. We limited our analysis to locations where flooding thresholds, defined at the gauges, correlate well with coastal flood advisories issued by the National Weather Service.

Our analysis shows that many East Coast communities now see dozens of tidal floods each year. Some of these communities have seen a fourfold increase in the annual number of days with tidal flooding since 1970.

When tidal floods occur, water can cover coastal roads for hours, making passage risky or impossible. With water on the street, some residents can be effectively trapped in their

(Left:) Extreme tides, amplified by earlier rainfall, caused flooding in Washington, DC, in August 2014.

> *In the next 15 years, two-thirds of these communities could see a tripling or more in the number of high-tide floods each year.*

homes, and homes can be damaged. Entire neighborhoods can be affected, even isolated. In many communities, retail stores, restaurants, other businesses, and public infrastructure are clustered in low-lying waterfront areas, in easy reach of tidal flooding.

No longer an intangible global trend, sea level rise has arrived on the doorstep of communities scattered up and down the East Coast, delivered by the tides.

Tidal Flooding in the Next 15 to 30 Years: Frequent, Disruptive, Widespread

AN OCCASIONAL EVENT BECOMES CHRONIC, THEN INCESSANT

Using a mid-range scenario for future sea level rise, we find that, by 2030, more than half of the 52 communities we analyzed on the East and Gulf Coasts can expect to average more than two dozen tidal floods per year. Importantly, the rise in the frequency of tidal flooding represents an extremely steep increase for many of these communities. In the next 15 years alone, two-thirds of these communities could see a tripling or more in the number of high-tide floods each year.

The mid-Atlantic coast is expected to see some of the greatest increases in flood frequency. Because many communities are already coping with tidal floods, a tripling in their frequency means that, by 2030, such floods could occur more than once a week. Places such as Annapolis, MD, and

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In Norfolk, VA, tide gates are deployed to keep floodwaters out of the downtown and maintain business as usual. But by disrupting daily life often enough, tides alone can make business as usual in some parts of communities impractical, if not impossible.

> ***As the reach of the tides expands, communities now unfamiliar with tidal flood conditions will start to see such flooding more regularly—a new normal.***

Washington, DC, for example, can expect more than 150 tidal floods a year, and several locations in New Jersey could see 80 tidal floods or more.

By 2045—within the lifetime of a 30-year mortgage—many coastal communities are expected to see roughly one foot of sea level rise. As that occurs, one-third of the 52 locations in our analysis would start to face tidal flooding more than 180 times a year, on average. And nine locations, including Atlantic City and Cape May, NJ, can expect to see tidal flooding 240 times or more per year.

In this future, days without high-tide floods could start to become the exception in certain places. Without sensible preparation for these disruptions, conducting daily life in such flood-prone areas would become, at best, unreliable and, at worst, dangerous.

FLOODING DURING HIGH TIDES BECOMES MORE EXTREME

Today strong winds or a storm system are typically required for coastal flooding to become extensive. But sea level rise is changing that. In the near future, higher seas will mean that high tides can reach farther inland, creating flood conditions that last longer and disrupt daily life for growing numbers of people.

In some East Coast locations, such as Savannah, GA (at Fort Pulaski), and Lewisetta, VA, extensive flooding is expected to occur with tides alone on a regular basis within one or two decades. By 2045, even more places can expect to see extensive flooding, including Ocean City, MD, and Myrtle Beach, SC (at Springmaid Pier). When strong winds or heavy rains do occur on top of elevated seas, the risk of extensive flooding will rise higher still.

MORE COMMUNITIES JOIN THE FRONT LINE OF TIDAL FLOODING

As the reach of the tides expands, communities now unfamiliar with tidal flood conditions will start to see such flooding more regularly—a new normal. In New London, CT, for example, tidal floods now occur just twice per year, on average, and are limited in extent. By about 2045, however, the city can expect more than 35 tidal floods every year. Other locations with fewer than five tidal floods per year today could see a 10-fold increase in the number of floods annually by 2045.

Given the substantial and nearly ubiquitous rise in the frequency of floods expected in our 52 locations, other communities along the East and Gulf Coasts will need to brace for similar changes. Their susceptibility to flooding will depend on the local topography, their natural and physical defenses, and the measures they take to adapt.

Sensible Steps for Building Resilient Coastal Communities

Coastal communities and states, and the nation as a whole, need to prepare for near-term changes in tidal flooding, while working hard to minimize longer-term losses through efforts to both adapt to these changes and limit their extent.

BUILDING COASTAL RESILIENCE IS A LOCAL IMPERATIVE . . .

Over the next few decades—the time frame of our analysis—changes set in motion by our past and present heat-trapping emissions will largely drive the pace of sea level rise. The lag of several decades between the release of carbon into the atmosphere and the response of the ocean means that more tidal flooding is virtually guaranteed, and that communities need to act with urgency. Locally, there are many things we can do to help ensure enduring coastal communities, including:

- **Upgrade the built infrastructure in harm's way.** With help, communities can prioritize and incentivize flood-proofing of homes, neighborhoods, and key infrastructure, such as sewer and stormwater systems.
- **Avoid putting anything new in harm's way.** Communities can use a range of regulatory and planning tools to curtail new development in coastal locations subject to tidal flooding now and in the future.
- **Consider the risks and benefits of adaptation measures.** Some measures to limit the impact of coastal flooding can provide multiple benefits, while others can alter shoreline dynamics and damage neighboring areas and ecosystems. Decision makers need to ensure that a rush to protect coastal communities builds broad-based resilience, rather than helping some areas while putting others at risk.
- **Develop a long-term vision.** Communities that create a vision for both near-term protection and long-term resilience in the face of sea level rise—and craft plans for

building better, safer, and more equitably—will be best positioned to thrive in the years ahead.

. . . AND A NATIONAL ONE

But local communities can't go it alone—coastal challenges are too great, the costs are too steep, and too many people are at risk. Instead, we need a coordinated, well-funded national response to our country's coastal vulnerability involving federal, state, and local collaboration. Federal and state governments can help build local resilience by supporting, incentivizing, regulating, and even mandating action. They can:

- **Build and maintain a coastal monitoring and data-sharing system equal to the threat.** Key federal agencies can sustain and expand efforts to monitor and project sea level rise and flooding, and ensure that local decision makers have access to the data.
- **Encourage or mandate the use of good scientific information.** Agencies can require that communities and other applicants for state and federal funds use the best available data, and demonstrate that new development and redevelopment projects can withstand projected tidal flooding and storm surges.
- **Support planning.** More federal support for state and local planning and collaboration can accelerate efforts to build coastal resilience.
- **Mobilize funding.** Adapting to sea level rise will require major, sustained investment. Federal policy makers need to develop new funding sources to support resilience-building efforts at the state and local level.
- **Improve risk management.** The true costs of living on the coast are not reflected in the price of flood insurance and other risk management tools. But big increases in the cost of insurance are hard for many to bear. Federal incentives to reduce some property owners' risks and costs can aid the transition to a more solvent flood insurance system and better risk management.

> ***Leaders at all levels of government need to take seriously the risks facing people living along our coasts and the urgent need for action.***

- **Ensure equitable investments.** Federal investments in coastal resilience can prioritize households and communities with the greatest needs.
- **Reduce heat-trapping emissions.** A near-term increase in sea level rise and tidal flooding may be locked in, but changes later this century and beyond are not fixed. To slow the rate of sea level rise—and enable coastal communities to adapt in affordable and manageable ways—we must reduce our global warming emissions.

THE HARD TRUTH: WE FACE FUNDAMENTAL LIMITS TO COASTAL ADAPTATION

As sea level rises, even our best protection efforts will not suffice in some areas in the face of rising tides, waves, and storm surges.

In certain locations, shoreline dynamics will make it impossible to build structural defenses. Residents, business owners, communities, and ultimately the nation may reach their capacity to fund costly measures. People may also simply be unwilling to face ever more frequent flood-related disruptions. As we reach these and other de facto limits to coastal adaptation, communities will face the prospect of shifting back from the shore. If we plan well, though, we can sustain our communities by pulling back from the most affected areas before flooding becomes too disruptive.

These limits will arrive sooner in those areas exposed to greater risks, those with more fragile ecosystems and limited natural buffers, and those that are less well-off economically. Our coasts will also face these limits sooner if we allow climate change and sea level rise to grow into an even greater crisis.

TO LIMIT FUTURE SEA LEVEL RISE AND SUSTAIN COASTAL COMMUNITIES, WE MUST CURB CARBON EMISSIONS

Global emissions are rising rapidly, and are on a trajectory to push surface temperatures more than 2°C (3.6°F) above the preindustrial average—the threshold beyond which scientists say "dangerous" climate change becomes unavoidable. To stay below this threshold, and slow the rate of sea level rise later this century and beyond, global carbon emissions need to peak and begin to decline by the end of this decade.

Leaders at all levels of government need to take seriously the risks facing people living along our coasts and the urgent need for action. And communities faced with tidal flooding need to hold their local, state, and national leaders accountable for taking strong action to both adapt to rising seas and mitigate global warming. As a nation, we need to commit to the challenge today, treating the resilience of our coasts as a century-long project—one that requires a concerted early push, one to which we commit for the long haul, and one that enables communities to thrive even in the face of encroaching tides.

Sea Level Rise and Tidal Flooding: Encroaching on Our Coasts, Affecting Daily Life

On October 27, 2011, a sunny day in coastal New Hampshire, the tide shifted shoreward in its daily cycle, filling the salt-marshes of Seabrook, covering the beaches of Hampton and Rye, and rising along the Portsmouth harbor waterfront. On that mild fall day, no storm drove water ashore, and no rains swelled coastal waterways. However, the water kept inching higher, peaking at two feet above the normal high-tide mark.[1] Along the state's 19-mile shoreline, seawater overtopped some roadways and submerged parking lots, and signs warning that "this area may flood during high tide" stood in ankle-deep water (PREP 2011).

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A causeway in coastal New Hampshire, in October 2011—inches from the reach of high tide.

1 Recorded by the National Oceanic and Atmospheric Administration's inundation analysis tool as 0.626 meter (2.05 feet) above the "mean higher high water" (MHHW) mark. In locations with two high and two low tides daily, one of the high tides is typically higher than the other. MHHW is the average higher high-water mark over the 1983–2001 National Tidal Datum Epoch (NOAA 2013).


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Sea level rise has arrived on the doorstep of communities around the world, complicating daily life during extreme high tides, and providing a glimpse of the future for other locations.

This day on the New Hampshire seacoast was by no means unique: the ocean now reaches farther inland during certain high tides in locations up and down our coasts. As the recently released Third U.S. National Climate Assessment observed, "Climate change, once considered an issue for a distant future, has moved firmly into the present." Indeed, recent analyses by the National Oceanic and Atmospheric Administration (NOAA) and Reuters show that tidal flooding has increased markedly in most locations along our coasts (Nelson, Wilson, and McNeill 2014; Sweet et al. 2014). Chris Silver, Hampton, NH, fire chief, comments: "If I know there's been a high tide, I'll drive around the areas that get a lot of flooding and see if there's been damage" (Clean Air Cool Planet 2012).

High tides matter more today than in decades past because our shores are more highly developed, and because these tides are occurring on top of elevated and rising sea levels (Church and White 2011; Pielke et al. 2008).

[High tides matter more today than in decades past because our shores are more highly developed, and because these tides are occurring on top of elevated and rising sea levels.]

Around the world, sea level is rising in response to global warming, toward levels in the coming decades that have not been seen in more than 100,000 years.

Around the world, sea level is rising in response to global warming, toward levels in the coming decades that have not been seen in more than 100,000 years (Dutton and Lambeck 2012). As sea level rises, local flood conditions are reached more often, to a greater extent, and for longer time periods just from simple high tides (Ezer and Atkinson 2014; Church et al. 2013). With this trend, tidal flooding that is now considered a mere nuisance will increasingly worsen and alter the map of usable land in coastal communities, redefining how and where people in those areas live, work, play, and move through their daily lives.

Today most East and Gulf Coast communities are unprepared to deal with flooding on a daily or weekly basis. But some are making hard decisions about how to thrive in the face of this unprecedented challenge. This report explores the steep increases in tidal flooding that communities can expect over the next 15 to 30 years, based on our analysis of 52 locations along these coasts (see below). The report also shows what forward-thinking communities are doing to confront this reality, and recommends steps local, state, and federal officials can take to prepare for worsening tidal flooding—and to curb even more drastic flooding over the longer term.

SNAPSHOT

Washington, DC, Metro Area

In a region that could see almost daily tidal flooding by mid-century, the nation's capital city and nearby cities and towns are beginning to prepare.


© Katie Harbath

Today, high tides cause frequent, minor flooding along the Potomac River. Here, the Tidal Basin overflows beneath cherry blossoms in April 2010.

As they wind their way toward Chesapeake Bay, the Potomac and Anacostia Rivers define the borders of Washington, DC, and the many historic landmarks nearby, from Arlington National Cemetery to Old Town Alexandria, VA. Tides affect these rivers, and tidal flooding can produce effects ranging from patches of standing water in parks to flooded roadways.

By 2045, Washington is projected to lead the East Coast in the number of tidal floods each year: it can expect nearly 400. These chronic floods will also be more extensive than the typical tidal floods today. Leaders of the nation's capital have outfitted one of its assets—Washington Harbour—with a seawall to protect the area from flooding. Officials in nearby Alexandria are also considering options for mitigating today's flooding problems, including installing flood barriers and raising roadways (OTCA 2013; City of Alexandria 2012).

[CHAPTER 1]

Tidal Flooding: A Daily Cycle Gains Disruptive Force

The rise and fall of the tides is familiar to anyone who has spent a day at the beach. During high tide, the water comes farther onshore, and beachgoers move back to stay dry. Low tide exposes tide pools and sandbars.

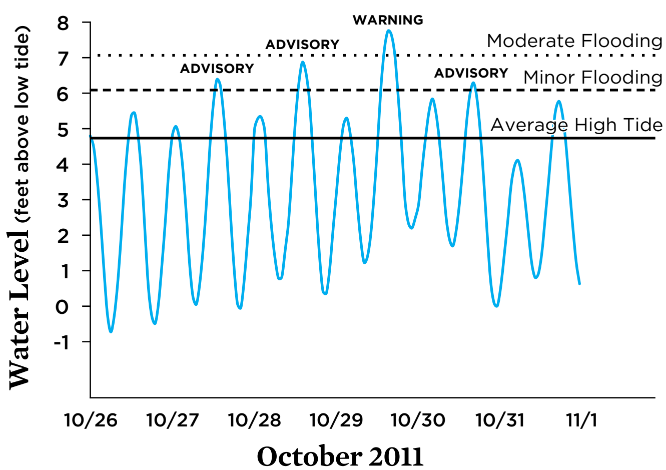
The cycle of the tides results from the rotation of Earth combined with the gravitational forces of the moon and sun. While these forces are global, wind patterns and coastal contours influence the timing and range of tides in a given location. Together these factors mean that high and low tides typically occur twice daily along the East Coast and once daily along the Gulf Coast.

Twice a month (during new and full moons), Earth, sun, and moon align. The combined gravitational pull of the sun and moon during these times exerts a greater force on Earth's oceans, and high tides become slightly higher than normal, while low tides are slightly lower. These tides are often called spring tides. Several times a year, during a new or full moon when the moon is closest to Earth, the range of the tides is even greater. These are sometimes called king tides, or perigean spring tides. In this report, we refer to spring and king tides as extreme high tides.

Coastal communities are accustomed to these rhythms: tides typically rise and fall with little impact. However, when high tides are above normal—usually by one to three feet depending on the location—the National Weather Service may issue a coastal flood advisory. Advisories can be issued on consecutive days for the time of day surrounding high tide (Figure 1).

The National Weather Service categorizes tidal flooding that is limited in extent and duration as "minor" or "nuisance" flooding. While these floods typically do not pose a direct risk to life or property, they can and do present challenges to daily life in affected areas (Figure 2). And like any nuisance—a brief power outage, heavy traffic, a loss of cell phone coverage—such floods take on a new level of gravity and significance when they become chronic. Inches—or sometimes feet—of seawater may make roadways impassable. Water may also overtop docks and boat ramps, wash high

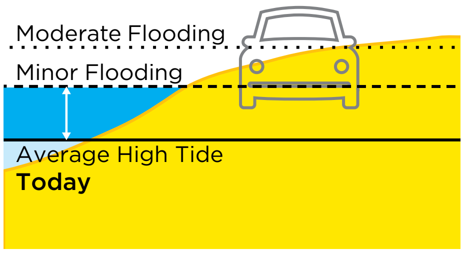
FIGURE 1. Normal Variations in the Tides



When tides are running high, such as during a new or full moon, high tides can cause flooding several days in a row. In this example from Lewes, DE, in October 2011, high tides crossed the minor flooding threshold on four consecutive days, until the pull of the new moon began to diminish.

SOURCES: IOWA ENVIRONMENTAL MESONET 2014; NOAA 2013.

FIGURE 2. Identifying Flooding Thresholds



Tidal flooding can occur when high tide exceeds the normal level by about one to three feet (white arrow), depending on the location. Minor, or nuisance, flooding, as determined by the National Weather Service, can disrupt local transportation and daily life. Moderate flooding is more extensive and can threaten life and property. This type of flooding can occur with an extreme high tide, or when high tide combines with a storm system. As sea levels continue to rise, tides will exceed these thresholds more often.

up on beaches and erode sand, back up sewers and storm drains, and fill neighborhood parks and parking areas with standing water.

Today's extreme high tides tend to cause nuisance flooding. However, if they occur with wind, rainfall, or storms, more extensive flooding can result (see Box 1). The National Weather Service categorizes this type of flooding as "moderate." Because it poses a threat to public safety and property, the National Weather Service typically issues a coastal flood warning for such an event. While moderate coastal flooding can occur during events such as tropical storms, both minor and moderate flooding are distinct from the catastrophic flooding associated with storm surge, as occurred during Hurricane Sandy.[2]

Most coastal locations have the potential to flood, but some places face tidal flooding more often than others. Communities along Chesapeake Bay, for example, where land is almost uniformly low-lying *and* sinking (subsiding), or along coastal New Jersey, where subsidence is slow but low-lying barrier islands are heavily developed, see minor floods regularly. Along the Gulf Coast, in contrast, tidal flooding is infrequent today despite exposure to storm surge from tropical storms and hurricanes.

BOX 1.

High Tides Make the Impact of Foul Weather Worse

When tidal flooding combines with heavy rain, strong wind, or storms, the result is more severe coastal impacts. Hurricane Sandy provided ample evidence of this. Its winds and storm surge battered New York and New Jersey through a high-tide cycle, leaving widespread destruction in its wake. By the time the storm reached Boston it was less intense, and the tide was also low, so damage was minimal. Communities farther south were not as lucky.

Winds below nor'easter or hurricane strength can also drive water ashore. At high tide, this effect can be amplified and lead to coastal flooding. In some coastal communities, heavy rainfall and runoff at high tide can create extensive flooding—partly because high sea levels impede gravity-driven drainage of stormwater. In places such as Charleston, SC, rainwater backs up into the streets from storm drains because high tide slows its discharge into the harbor. Many factors are at play during a wind, rain, or storm event, but the level of the tide when severe weather strikes makes an enormous difference in the damage wrought on coastal areas.

Though spring and king tides are responsible for most of today's tidal flooding, sea level rise is expected to cause flood conditions during an increasing number of normal high tides, and to make flooding during extreme high tides more extensive.

2 *While storm surge poses a critical risk to coastal communities, we do not explore it in this report. Useful sources of information on that topic include NOAA's Digital Coast website* (www.csc.noaa.gov/digitalcoast/) *and the Climate Central Surging Seas Risk Finder* (http://sealevel.climatecentral.org/).

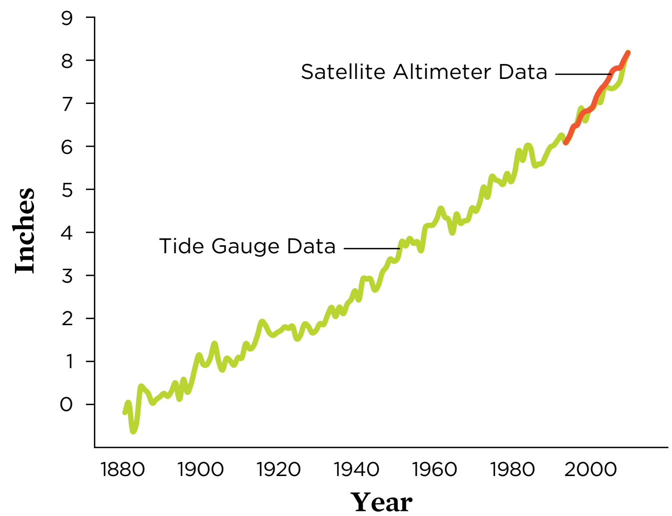
Though spring and king tides are responsible for most of today's tidal flooding, sea level rise is expected to cause flood conditions during an increasing number of normal high tides, and to make flooding during extreme high tides more extensive.

How Rising Seas Are Affecting Tidal Flooding

Global sea level rose roughly eight inches from 1880 to 2009, with global warming the main driver (Figure 3) (Church and White 2011; Church et al. 2011). The planet has warmed by about 1.5°F (0.8°C) since 1880 (Hartmann et al. 2013; Hansen et al. 2010). And as air temperature rises, so does the temperature of the oceans, which have absorbed more than 90 percent of human-caused warming since 1955 (Levitus et al. 2012). As seawater warms, it expands.

This expansion and the shrinking of mountain glaciers and polar ice sheets are the primary reasons that global sea level is rising (Cazenave and Llovel 2010; Lombard et al. 2005). And the rate of global sea level rise has nearly doubled in recent years. In the 25-year period from 1993 to 2008, the global rate of sea level rise was more than two-thirds higher than the twentieth-century average (Church and White 2011; Ablain et al. 2009; Leuliette, Nerem, and Mitchum 2004).

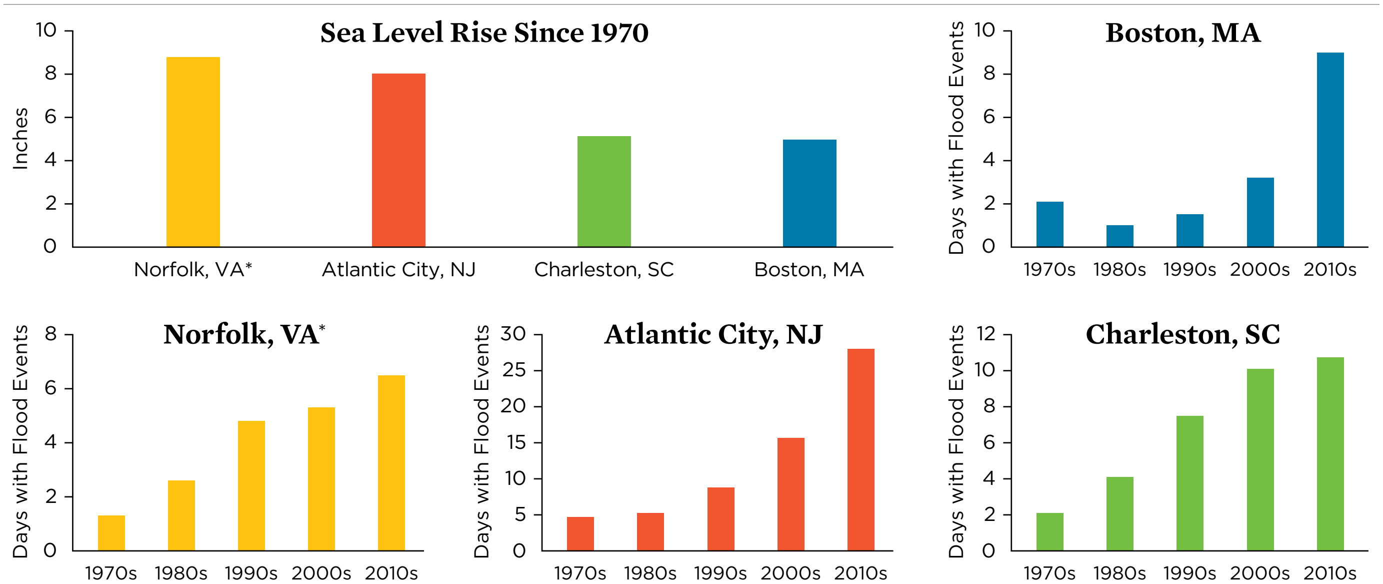
FIGURE 3. Average Global Sea Level Rise



The expansion of seawater as it warms and the melting of land-based ice have been the key drivers of an average global sea level rise of about eight inches since 1880. Tide gauges have recorded this rise (in green), and satellite observations since 1993 (in orange) have confirmed the trend. Global warming is responsible for both expanding seas and shrinking ice.

SOURCE: CHURCH AND WHITE 2011.

FIGURE 4. Local Sea Level Rise and Tidal Flooding, 1970–2012



Sea level has risen by about 3.5 inches globally—but more along the East Coast—since 1970. At Sewells Point, VA, for example, sea level has risen more than eight inches, and at Boston, about five inches. Rising seas mean that communities up and down the East and Gulf Coasts are seeing more days with tidal flooding. Charleston, SC, for example, faced just two to three days with tidal flooding a year in the 1970s. The city now averages 10 or more such days annually.

*Norfolk statistics recorded at the Sewells Point tide gauge.

SOURCES: UCS ANALYSIS; MORALES AND ALSHEIMER 2014; NOAA TIDES AND CURRENTS 2014; NOAA TIDES AND CURRENTS 2013B.

In several communities, tidal flooding has quadrupled in frequency over the past 40 years.

Local factors such as land subsidence and groundwater withdrawals, as well as changes in ocean dynamics, are contributing to even higher rates of sea level rise along parts of the East Coast. North of Cape Hatteras, NC, for example, a possible slowdown in the Gulf Stream has caused sea level to rise faster than the global average (Ezer et al. 2013; Boon 2012; Sallenger, Doran, and Howd 2012). Sea level at the Battery in New York City has risen by more than 17 inches since record-keeping began in 1856. And sea level at Baltimore has risen by more than 13 inches since 1902, and at Boston by nearly 10 inches since 1921 (NOAA Tides and Currents 2013b; Sallenger, Doran, and Howd 2012).

These increases have contributed to tidal flooding that is more frequent and longer-lasting (Ezer and Atkinson 2014; Sweet et al. 2014). Long-term trends show that nuisance flooding along the East, Gulf, and West Coasts occurred only about once every one to five years in the 1950s, but was occurring about once every three months by 2012 (Sweet et al. 2014). In several communities, tidal flooding has quadrupled in frequency over the past 40 years (UCS analysis; Ezer and Atkinson 2014; Nelson, Wilson, and McNeill 2014; Sweet et al. 2014). Atlantic City, NJ, for example, averaged five days per year with tidal flooding in the 1970s, but now averages nearly 30 days per year (Figure 4). And this trend is accelerating in many places along our coasts (Sweet et al. 2014).

Daily Impacts of Encroaching Tides

From Miami Beach, FL, to Norfolk, VA, to the coast of Maine, chronically inundated areas are becoming a feature of everyday life (Davenport 2014; Gregory 2013). In Miami Beach, traffic is rerouted around flooding and local businesses deal with lost revenue (Prothero 2013). On Tybee Island, GA, residents prepare for the temporary loss of access to the mainland (Nunley 2012). In Annapolis, MD, a coastal town with a maritime past and present, the popular City Dock is swamped on a regular basis, nearby parking lots are often submerged, and the U.S. Naval Academy reroutes traffic from flooded roadways (WBCM 2012).

In and around Atlantic City, NJ, the back-bay area floods regularly when winds and high tides combine to pile water against the shore, forcing road and bridge closures that strand

SNAPSHOT

Ocean City, MD

With no landward retreat, Maryland's most popular tourist destination is adapting to the growing threat of coastal flooding.

© John Hayden/marylandonmymind.com

A high tide combined with a nor'easter caused extensive tidal flooding in Ocean City in October 2009. With the next few decades of sea level rise, extreme tides are expected to drive more extensive flooding in many locations.

Ocean City is home to some 7,000 year-round residents, but its population swells to more than 300,000 on summer weekends as vacationers from the region flock to its boardwalk, beaches, and fishing. Leisure and hospitality have recently accounted for the most growth in private-sector jobs in Maryland, putting Ocean City in a key position in the state economy (MDLLR 2014). A recent report, however, outlines the potential for sea level rise to significantly affect jobs in the state (LNS 2014).

Because it sits on a fragile barrier island, Ocean City is highly vulnerable to flooding from storms and high tides—more so with sea level rise. While tidal flooding occurs about eight times a year today, the city is projected to face some 30 tidal floods each year by 2030, and more than 170 by 2045. These floods would be far more extensive than the limited flooding typically seen today—more along the lines of flooding associated with heavy rain or strong winds.

Sea level rise is also expected to worsen coastal erosion in coming decades, exposing Ocean City to even more flooding (Zhang, Douglas, and Leatherman 2004; Titus et al. 1985). Aware of the threat a rising sea poses to its tourism infrastructure, the town now requires developers to elevate new buildings, and the city council has drafted a policy to raise streets during periodic upgrades (Town of Ocean City 2011).

residents (Watson 2012a). And in Broad Channel in Queens, New York City, parts of some streets now flood roughly twice a month, and residents regularly move cars to higher ground to avoid saltwater damage to vehicles (Gregory 2013).

As resident Dan Mundy, Sr., says: "Fifteen years ago I didn't believe in sea level rise, but I do now. Flooding has become so common that we live by the tidal cycles in Broad Channel." Indeed, concerned that communities may become desensitized to advisories about coastal flooding, in 2012 the National Weather Service decided to raise the water level at which local offices issue advisories in several states, including New Jersey (Szatkowski 2014; Watson 2012b).

Locations vulnerable to tidal flooding include small towns, working-class communities, housing near military bases, tourist destinations, and vacation communities. The number of people and value of property exposed to flooding differ considerably from place to place, as does the ability to prepare for and withstand flooding impacts.

Entire **neighborhoods** can be affected—even isolated—when floodwaters rise. Flooding of primary access routes can cut residents off from inland facilities and services, as now occurs several times a year in places such as Tybee Island, GA (Evans 2014). With a foot of water on their streets, some residents can be effectively trapped in their homes—now a common occurrence in Jamaica Bay, NY. Tidal flooding can also damage homes and neighborhoods, causing flooded basements, backed-up sewers, and salt-poisoned yards. In places where tidal and other flooding is a regular feature, home owners must also contend with falling property values and loss of investment.[3] And as the value of these homes declines and home owners seek property tax abatements—as has occurred in Jamaica Bay, for example—a community's tax base and ability to invest for the future can similarly shrink.

Shops, restaurants, and other **businesses** are often clustered in low-lying waterfront areas and can suffer serious effects, including direct damages and lost revenues. Flooded parking lots, for example, can hobble businesses and coastal attractions until waters subside, and street parking can be impossible or inadvisable, given the risk of saltwater damage to automobiles. Notes Bobby Thakore, owner of the Taste Bakery Café on Alton Road in Miami Beach, "It [tidal flooding] has really affected our business. We are down 15 percent on revenue during flooding, and in the past year construction [to address the flooding has been] mixed with the flooding

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Today's tidal flooding might persist for a couple of hours as the tide peaks and ebbs, as it did here in Carolina Beach, NC. In the near future, as sea level rises, high tides will be able to reach farther into communities, creating flood conditions that last longer and disrupt business as usual for growing numbers of people.

3 During the twentieth century, proximity to the shore was a reliable driver of increases in real estate values. However, that same proximity now stands to undermine the value of some of those properties, as the risks and costs of coastal flooding ratchet upward (Koch 2013; Stiles and Hulst 2013; Kaufman 2010).

and has made our revenue loss worse. They say they are going to fix the flooding, but let's see."

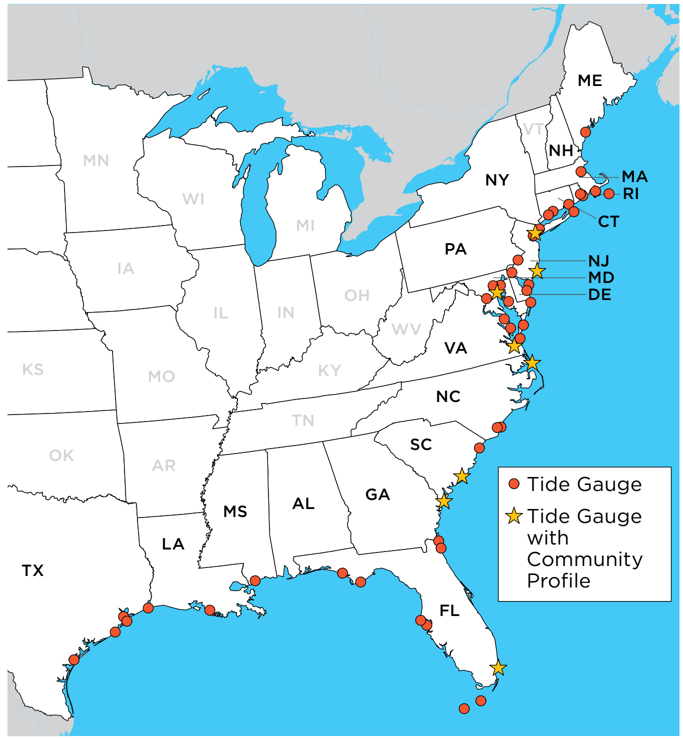
In older cities and towns such as Charleston, SC, and Savannah, GA, flooding can significantly harm both historic districts and the tourism revenue on which they rely, over both the short and long term. In communities such as Portland, ME, and Miami, FL, offices and manufacturing, shipping, and storage facilities sit along the shore. The effects of flooding on these businesses can have economic impacts beyond their walls.

Tidal flooding can also damage or destroy **infrastructure** such as pumping stations, sewage treatment facilities, and pipes for diverting stormwater. Many communities built this infrastructure more than a century ago, when sea level rise was not a consideration. Miami Beach Commissioner Jonah Wolfson reports that the city is going to "tackle the immediate problem" by allocating $400 million for projects such as adding pump stations to prevent seawater from backing up in sewers (Veiga 2014). Officials in Norfolk, VA, have identified at least $1 billion in needed infrastructural improvements to protect the city from flooding (City of Norfolk n.d.).

Flooding can make **transportation** on coastal roads risky or impossible for hours. Sometimes this is a nuisance, requiring the rerouting of traffic. Other times such flooding affects evacuation routes, as it can on the South Jersey Shore and the Bolivar Peninsula near Galveston, TX. In some coastal communities, both public safety and commerce depend on just one or two access routes, as on the Outer Banks of North Carolina. In the face of such flooding, communities and states must not only clear coastal roads but also repair damage from erosion, undermining, and over wash. As Steve Miller of the Great Bay National Estuarine Research Reserve observes, "In many cases, [cities and towns] are going to have to raise the roads on their existing path. Money is a big question" (Marshall 2012).

Salt marshes, sea grass flats, barrier beaches, oyster reefs, mangroves, swamps, and other **ecosystems** along our coasts serve as buffers against flooding (Gedan et al. 2011). Scientists credit the dune system adjacent to Seaside Park, NJ, with dampening storm surge and preventing damage to homes during Hurricane Sandy (ALS 2012). However, rising sea levels, tidal flooding, and more coastal development undermine these ecosystems. The results range from obvious beach erosion to more subtle shifts, such as the gradual drowning of coastal forests and salt marsh vegetation (Moser et al. 2014; Craft 2012; Doney et al. 2012; Saha et al. 2011; Morris et al. 2002).

FIGURE 5. East and Gulf Coast Locations in Our Analysis



We analyzed information recorded by 52 tide gauges from Portland, ME, to Freeport, TX. This report includes profiles of starred locations.

SOURCE: NOAA TIDES AND CURRENTS 2014.

How We Analyzed Tidal Flooding Today, in 15 Years, and in 30 Years

To analyze how often flooding now occurs at locations along the East and Gulf Coasts—and the frequency and extent of flooding these communities can expect, on average, 15 and 30 years from now—we relied on 52 tide gauges from Portland, ME, to Freeport, TX (Figure 5). We used two criteria to choose these gauges, maintained by NOAA.

First, the local forecast office of the National Weather Service in these areas has set thresholds for water levels that can cause tidal flooding. Second, instances when water levels actually cross these thresholds correlate well with instances when the local office issues a coastal flood advisory. This second criterion indicates that when water reaches the local threshold, a flooding event that warrants public notification often follows. Specifically, we only used tide gauges for which the National Weather Service issued coastal flood advisories or warnings to local communities at least two of every three

SNAPSHOT

Portland, ME

With a working waterfront that serves local industry as well residents and tourists, Portland is considering the costs of action and inaction in the face of sea level rise.

© Liz Bieber

Tidal flooding in Portland has spawned informal public awareness-raising events, organized around the spring and king tides. Here, an observer uses a platform to stay dry and a GPS receiver to trace the extent of flooding that occurred on July 14, 2014, on Marginal Way and Cove Street.

Situated on picturesque Casco Bay, Portland is home to many waterfront treasures. The city's bustling Old Port features a waterfront that serves fishing fleets, industry, a Coast Guard station, and tourists. Across the city, trails and parks ring the quieter Back Cove coastline.

With much of its commerce and infrastructure concentrated close to the water, the city is vulnerable to flooding during high tide, even in fair weather. When floods occur, pedestrian pathways and piers can become unusable, and businesses struggle to stay open (WCSH 2013).

Today Portland sees about a dozen tidal floods each year, but it is projected to face more than 60 annually by 2045. About eight inches of sea level rise by 2050 could increase the cost of damage to real estate from all forms of coastal flooding in the Back Cove area alone by about $90 million if no action is taken (Merrill et al. 2012). Drawing on a suite of scientific and economic simulations, the city is beginning to consider its options for adapting to rising seas, including installing surge barriers or levees (Merrill et al. 2012).

times that water levels at the tide gauge exceeded local thresholds.[4]

We used these thresholds and NOAA's online inundation analysis tool to determine the frequency of flooding in these locations today, in 2030, and in 2045 (NOAA Tides and Currents n.d.). In analyzing what these communities can expect in the future, we used projections for local sea level rise based on a mid-range scenario for future heat-trapping emissions, adjusting the threshold in the inundation analysis tool (see Box 2) (Climate Central n.d.; Tebaldi, Strauss, and Zervas 2012).[5] (For details on our projections, see the appendix.)

Collection of Gretchen Imahori, NOAA/NOS/OCS

Tide gauges such as this one at Long Island Sound, NY, record water levels every six minutes, documenting the ocean's rise and fall. Scientists rely on such gauges to monitor potential flood conditions—both when storms do and do not occur.

4 *This means that we excluded several tide gauges along the Gulf Coast because the correlation between water levels above the flooding thresholds and coastal flood advisories fell below 66 percent. NOAA also maintains fewer tide gauges along large stretches of the Texas, Louisiana, and Mississippi coastlines, so our 52 gauges include fewer in that region. Still, our analysis reflects a reasonably representative sample of communities along the East and Gulf Coasts.*

5 *For details on our projections and methods, see the appendix, and the Supporting Technical Document available at* www.ucsusa.org/encroachingtides.*)*

BOX 2.

Projecting Future Sea Level Rise

Scientists have developed a range of scenarios for future sea level rise, based on estimates of growth in heat-trapping emissions and the responses of oceans and land-based ice. The latest research—in the Third (2014) National Climate Assessment—shows with 90 percent certainty that global sea level will rise between six inches and 6.3 feet above 2012 levels by 2100 (Figure 6) (Walsh et al. 2014; Parris et al. 2012). And scientists expect sea level to continue rising well beyond the end of this century—some say for thousands of years, given the slow response of Earth's systems and recent evidence of instability in the West Antarctic Ice Sheet (Joughin, Smith, and Medley 2014; Rignot et al. 2014; Levermann et al. 2013; Jevrejeva, Moore, and Grinsted 2012).

The lowest end of this range is a simple extension of historic sea level rise. That prospect is unlikely, given the acceleration of sea level rise since the 1990s (Church and White 2011; Ablain et al. 2009; Leuliette, Nerem, and Mitchum 2004). Three other scenarios—known as intermediate-low, intermediate-high, and highest—show a more plausible range of 1.5 feet to 6.3 feet of sea level rise above 2012 levels by 2100. The rate and magnitude of the loss of land-based ice—primarily the ice sheets of Greenland and Antarctica—account for much of the difference in the projections (Walsh et al. 2014).

We used the intermediate-high scenario of the Third National Climate Assessment to project coastal flooding at 52 tide gauges.[6] This scenario projects a global sea level rise of about five inches above 2012 levels by 2030, and about 11 inches by 2045. However, local factors such as land subsidence, groundwater withdrawals, and changes in ocean circulation will continue to affect local sea level rise. For instance, the northeastern United States is projected to see above-average rates of sea level rise because of changes in the flow of the Gulf Stream in response to global warming (Ezer et al. 2013; Yin, Schlesinger, and Stouffer 2009).

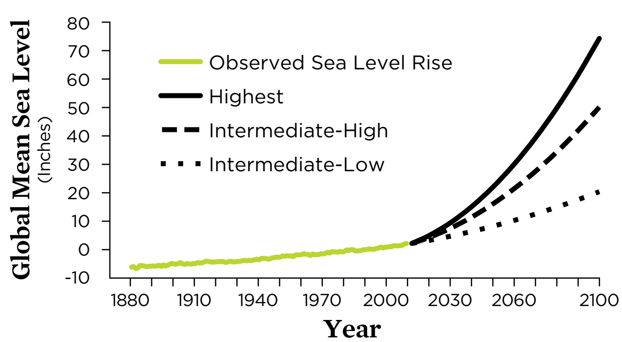
To account for local variability, we used projections for local sea level rise developed by the research organization Climate Central (Climate Central n.d.; Walsh et al. 2014; Parris et al. 2012; Tebaldi, Strauss, and Zervas 2012). Climate Central scientists developed these projections by combining the intermediate-high projection for global sea level rise with tide gauge observations from 1959 to 2008 (Tebaldi, Strauss, and Zervas 2012). This analysis reveals that the locations in our analysis are projected to see 9 to 20 inches of sea level rise by 2045. (For details, see the appendix.)

We do not have local projections for all 52 of our locations. For locations without local projections, we used the projection from the nearest tide gauge with one. In all these cases, the projection we used was within 100 miles of the tide gauge in question.

(For more information and additional results, see the Supporting Technical Document at *www.ucsusa.org/encroachingtides*.)

[The scenario we used projects a global sea level rise of about five inches above 2012 levels by 2030, and about 11 inches by 2045.]

FIGURE 6. Historical and Projected Sea Level Rise



The 2014 National Climate Assessment used several different assumptions about how oceans and land-based ice will respond to future warming to project global sea level rise. We based projections for sea level rise at our 52 locations on the assessment's intermediate-high scenario.

SOURCES: CLIMATE CENTRAL N.D.; WALSH ET AL. 2014; PARRIS ET AL. 2012.

6 While the underlying analysis looked at all three scenarios for sea level rise, our analysis is based on the mid-range intermediate-high scenario. The intermediate-low scenario allows experts and decision makers to assess the risk of sea level rise associated primarily with ocean warming. The intermediate-low scenario assumes limited loss of ice sheets. The intermediate-high scenario assumes ice sheet loss that increases over time, while the highest scenario assumes rapid loss of ice sheets. Decisions involving an especially low tolerance for risk could consider the latter scenario (Parris et al. 2012).

[CHAPTER 2]

Tidal Flooding in 2030: From Occasional to Chronic in 15 Years

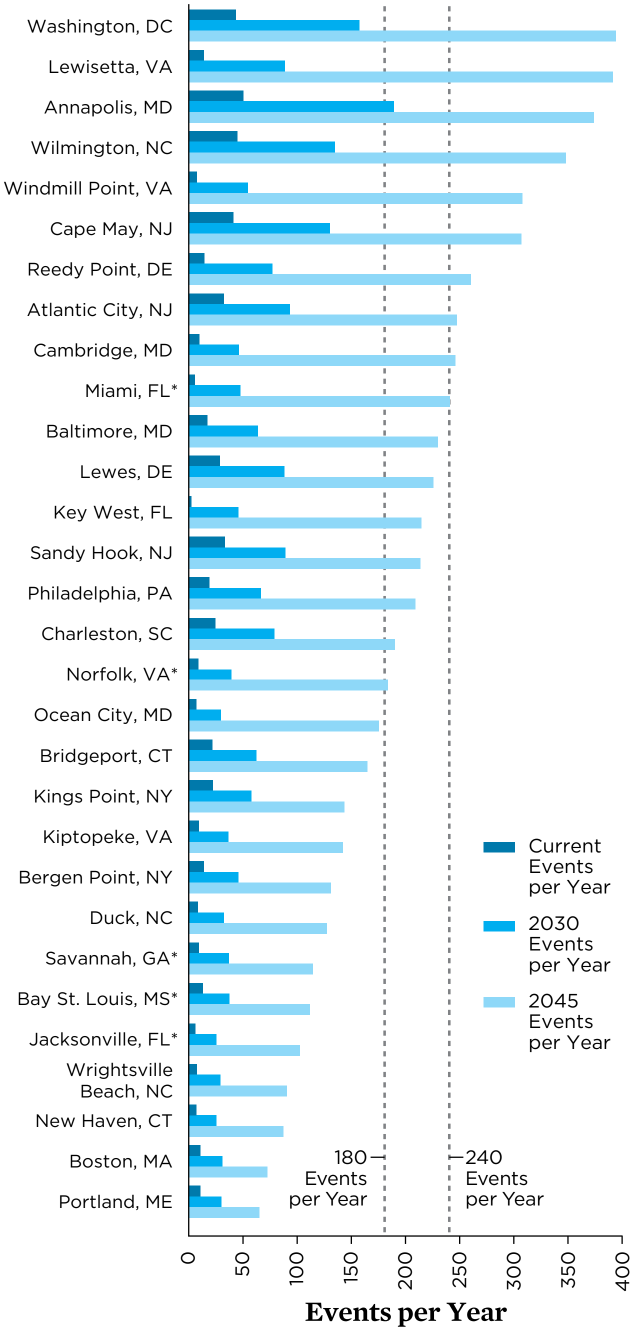
Eight of the 52 communities we analyzed already see more than two dozen tidal floods per year. By 2030, given projected sea level rise, 30 of these communities—more than half—can expect to face tidal flooding at least that often (Figure 7). That represents an extremely steep increase in flooding for many of these places. About two-thirds of those 30 communities can expect to see the yearly number of high-tide floods triple in just 15 years. Because many of these communities already face frequent tidal flooding, a tripling or more has the potential to make flooding a more-than-weekly occurrence. Disruptions from traffic detours, business closures, flooded neighborhood streets, and the inability to walk, drive, and park in flooded areas will vary from one location to the next, with one constant: water where it isn't wanted.

Some of the greatest increases in flooding frequency will occur in communities along the mid-Atlantic coast. By 2030, several New Jersey locations can expect to average 80 to 130 tidal floods a year. And places such as Annapolis, MD, and Washington, DC, can expect to average 150 to 200 tidal floods each year.

© Sean Bath

With near-term sea level rise, tidal flooding like that shown here in Charleston, SC, in September 2014 is expected to become an all-too-regular occurrence in many coastal communities.

FIGURE 7. Tidal Flooding Today, in 2030, and in 2045



Of the 52 locations we examined, 30 (shown here) can expect at least two dozen tidal floods per year, on average, by 2030. (Note that some communities, such as Broad Channel in Jamaica Bay, NY, see roughly this much flooding today*; however, this flooding is not captured by the closest tide gauge.) And tidal flooding will occur even more often in many locations. By 2045, one-third of the locations we analyzed can expect 180 or more tidal floods per year. And nine locations could average 240 or more tidal floods a year by 2045.*

*Data for these locations are represented by nearby tide gauges; see the appendix for tide gauge locations.

SNAPSHOT

Lewes, DE

With their sense of community tied to the sea, many Lewes residents recognize the need to build the city's resilience to coastal flooding.

© Bob Mical

Lewes, DE, is one of the mid-Atlantic region's quintessential coastal towns.

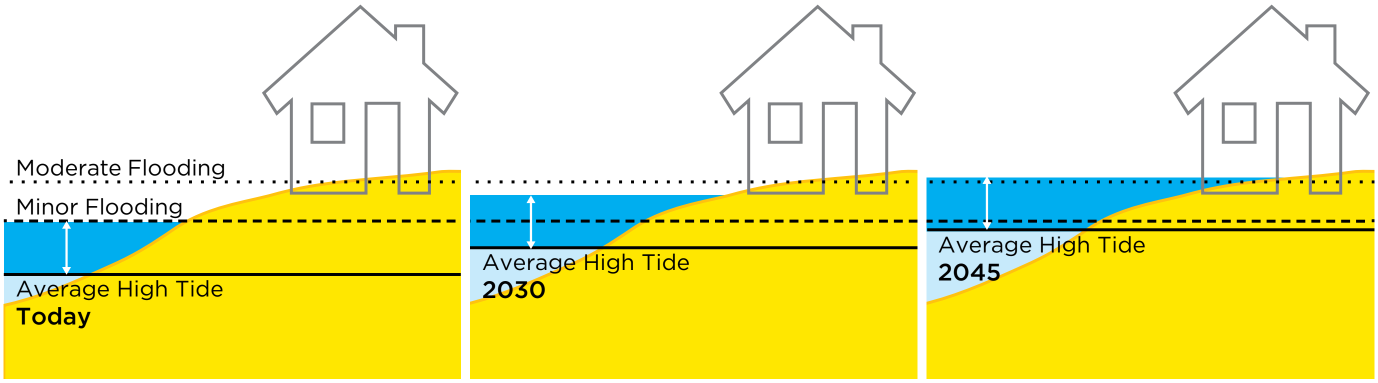
Lewes is a small town that prides itself on its strong relationship with the sea. With its walkable downtown, active recreational fishing industry, and five-mile-long beachfront, Lewes offers visitors and year-round residents alike an intimate seaside experience (City of Lewes 2011).

Owing to its mid-Atlantic location, however, Lewes sees flooding during both nor'easters and tropical storms. Extra-high tides occurring even without storms can also affect roadways and cause erosion in downtown Lewes and nearby beach communities (AHPS 2014).

Because of sea level rise, Lewes is projected to face almost 90 tidal floods a year in 15 years. By 2045, the city could see more than 200 tidal floods annually—nearly 30 of them more extensive than those of today.

By developing the first-ever community action plan that integrates hazard mitigation and adaptation to climate change, Lewes has been a small-town leader in the mid-Atlantic region in planning for sea level rise (City of Lewes 2011; NOAA Coastal Services Center 2011). The University of Delaware and the Delaware Geological Survey also recently completed a Coastal Flood Monitoring System, which will communicate information in real time to residents, emergency managers and first responders, and others so they can prepare for flood events (DCFMS 2014).

FIGURE 8. The Growing Reach of Tidal Flooding as Thresholds Are Exceeded More Often



A tide that causes a minor flood today is a nuisance (white arrow). *In the future, higher sea levels will allow high tides to push water deeper into coastal communities, affecting more homes, businesses, and infrastructure. Extensive moderate flooding—now usually associated with storms and high winds—is expected to become more common, simply from high tides.*

Tidal Floods Become More Extensive

Because of rising seas, tidal flooding will not only occur more often, but also reach farther inland and have more serious impacts than most tidal floods today (Figure 8). Except for a few locations, such as Norfolk and Miami, tidal flooding now tends to affect limited—if important—geographic areas. And extensive tidal flooding typically occurs only when onshore wind and heavy rain compound high tides. But that is changing. Tybee Island, near Savannah, GA, for example, has recently seen extensive flooding from tides alone. In November 2012, tides more than two feet above the typical high-water mark flooded significant areas of the island (Haywood 2012).[7]

By 2030, tides that cause nuisance flooding today are expected to cause extensive flooding in some locations. At Lewisetta, VA, for example, only six inches now separate a tide that causes so-called minor flooding from one that causes moderate, or more extensive, flooding. That means tides alone could cause extensive flooding when sea level rises by just six inches—as expected within 15 years—threatening nearby historic and tourism destinations such as Reedville, VA.

Seven other communities among our 52—Cambridge, MD; Charleston, SC; Duck, NC; Kiptopeke, VA; Savannah, GA (at Fort Pulaski); Vaca Key, FL; and Windmill Point, VA—are also expected to face extensive flooding from tides alone by about 2030, because of sea level rise. In places such as Charleston, where residents are already familiar with frequent coastal flooding and the occasional extensive flood during heavy rains and storms, less than half a foot of sea level rise will mean that high tides alone could flood substantial areas up to two dozen times per year, on average, by about 2030.

© Tim Greenway/Portland Press Herald

Extensive flooding, like that seen here in downtown Portland, ME, will become more common with the tides. Though the winds from a nor'easter are responsible for the flooding shown here, storms will not be required for extensive flooding to occur in the next several decades.

7 *Here we use "high-water mark" to refer to MHHW levels (see footnote 1). During this event, the tide ran 0.48 foot higher than the threshold for minor flooding, equating to 2.2 feet above MHHW levels.*

[CHAPTER 3]

Tidal Flooding in 2045: From Chronic to Incessant

Many coastal communities can expect about a one-foot increase in sea level by 2045, and with that increase, many can also expect highly regular tidal flooding (see the appendix). Riding on ever-higher seas, these tides will be able to reach farther into communities, creating flood conditions that can last longer and disrupt life for growing numbers of people.

By 2045, within the lifetime of a typical home mortgage, more than half of our 52 communities could see a 10-fold or

In the next 30 years, the frequency, reach, and duration of high-tide floods could reshape daily life in affected areas like this frequently flooded Norfolk neighborhood.

©Terry Dickson/*Florida Times-Union*

As tidal flooding increases, officials will need to take measures to protect areas that already flood during extreme tides, like this stretch of U.S. Highway 17 in Brunswick, GA.

greater increase in the frequency of tidal floods. And one-third of the 52 could average more than 180 tidal floods per year. In affected locations, efforts to conduct daily life would become, at best, unreliable and, at worst, dangerous.

Vulnerable coastal land areas may not be permanently inundated—that is, submerged during all high tides—until late this century or beyond. However, nine of the 52 locations we studied—almost one-fifth—would face an average of 240 or more tidal floods a year. That means some areas in those locations could be effectively inundated in just the next few decades, by virtue of being so often underwater (Figure 7).

Tidal Floods Grow More Severe

Tidal floods will also be more severe in both duration and extent by 2045. Today tidal floods typically last a few hours or less. And only two of our locations—Annapolis, MD, and Washington, DC—now see flood conditions for more than 85 hours each year, or more than 1 percent of the time.

By 2045, more than one-third of our 52 locations—including Ocean City, MD, a fragile barrier island, and Wilmington, NC—can expect flood-prone areas to spend more than 345 hours per year underwater, or more than 5 percent of the time. And five locations in the Chesapeake Bay area, including Baltimore and its flood-prone Inner Harbor, are projected to be underwater for more than 875 hours a year—10 percent of the time—by 2045.

Tidal floods will also reach still farther inland as sea level rises (Figure 9). By 2045, nearly half of our 52 communities can expect normal tidal fluctuations to bring extensive flooding (Figure 10, p. 22). The coastal areas of Delaware, Long Island, and Maryland, for example, will face extensive flooding from tides alone. The combination of more frequent and more severe floods will affect many locations, including Philadelphia, PA, which is expected to see extensive tidal flooding nearly 20 times per year, on average, by 2045.

Water, Water Everywhere: The Spread of Tidal Flooding

Our analysis shows that increases in tidal flooding will be substantial and nearly universal in our 52 locations (Figure 11, p. 23). That means the steady creep of sea level rise will force many communities largely unfamiliar with tidal floods today to grapple with chronic flooding in the next 15 to 30 years.

For some of these locations, the changes in flood frequency in the next three decades could be steep. In New London, CT, for example, even minor tidal floods now occur just twice per

continued on p. 24

FIGURE 9. Expanding Reach of Tidal Flooding: Atlantic City Area and Miami

The top maps show the extent of tidal flooding today (turquoise) *just south of Atlantic City* (left) *and in Miami* (right). *The bottom maps show the extent of flooding that would be possible from that same high tide in 2045, with a higher sea level. By then, these cities can expect to average 240 and 230 minor floods, respectively, each year.*

Note: These maps are for discussion and research purposes only. They are not appropriate for detailed analysis.

SOURCES: OUR ANALYSIS; MAP BASED ON DATA FROM NOAA DIGITAL COAST 2014; OPENSTREETMAP 2014; U.S. CENSUS BUREAU 2013.

SNAPSHOT

Portsmouth, NH

A small, thriving city facing big problems from sea level rise, Portsmouth is working to understand and manage its risks.

© Tim Hayes/Puddleduck Photo

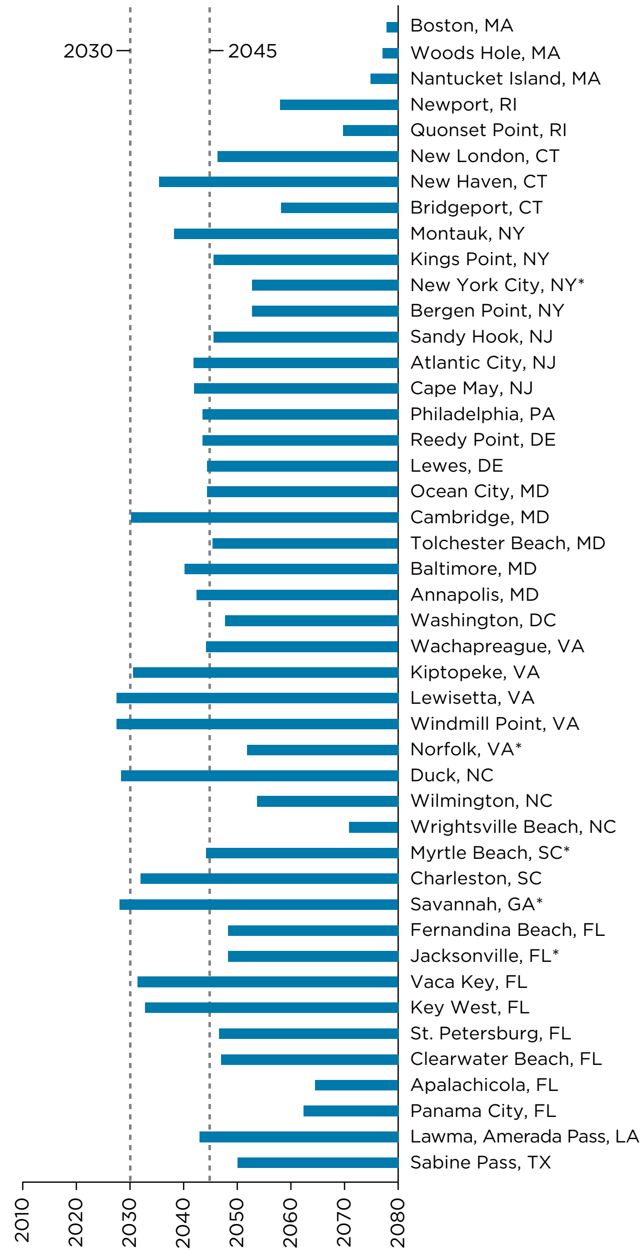
Neighborhoods closest to the shore have historically been some of the most desirable places to live. In communities like Portsmouth, tidal flooding may upend that thinking.

One of the nation's oldest cities, Portsmouth built much of its housing and infrastructure on low-lying ground to allow easy access to the water. But that water has now become all too accessible. Roadways, parking lots, and stormwater management systems along the state's short but treasured seacoast, which runs from Portsmouth south to Seabrook, flood during seasonal high tides even without storms.

During several recent extra-high tides, for example, the narrow causeway connecting Portsmouth to the island of New Castle was nearly submerged (Marshall 2012). City officials recently offered a walking tour of the historic South End to point out areas at risk of flooding from storm surge and sea level rise, and to highlight the city's Coastal Resilience Initiative (City of Portsmouth 2013).

Portsmouth is part of a pilot program funded by NOAA and the Gulf of Maine Council to recommend measures to protect the city from future sea level rise and storm surge. With those recommendations in hand, city officials are updating their 10-year master plan to make Portsmouth a more flood-resilient community (Clow 2013).

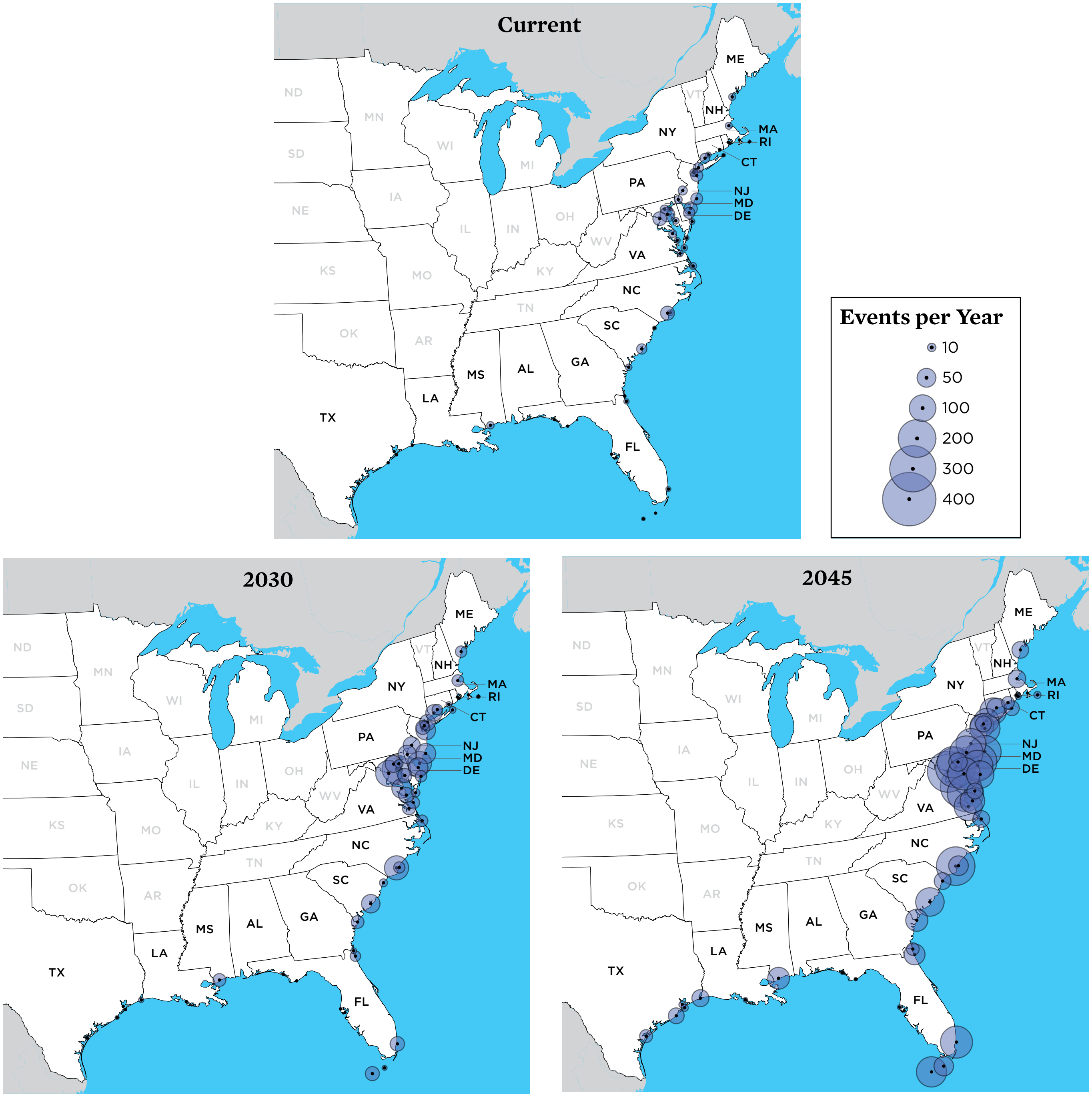
FIGURE 10. **Year When Nuisance Floods Become Extensive**



Tides that cause minor, or nuisance, flooding today will be rolling in on higher seas in the future. The year when those tides begin to cause moderate, or more extensive, flooding, varies with the location. The time frame reflects the difference between today's minor and moderate flooding thresholds in each location, as determined by the National Weather Service, and the projected pace at which local sea level rise will close the gap between the two. (Some locations included in our analysis, like Miami, do not have a defined threshold for moderate flooding. Locations are shown from north to south by state, wrapping around Florida to the Gulf Coast.)

* Data for these locations are represented by nearby tide gauges; see the appendix for tide gauge locations.

FIGURE 11. The Growing Frequency and Spread of Tidal Flooding



Relatively few of the 52 locations we analyzed on the East and Gulf Coasts now face minor or moderate tidal flooding on a regular basis (top; circle size represents the number of flood events). *But by 2045, sea level rise will bring more tidal floods to nearly every location. Nearly 70 percent of these communities can expect tidal floods to at least triple in frequency by 2030* (bottom left). *Charleston, SC, Reedy Point, DE, and Sandy Hook, NJ, could average more than 75 tidal floods per year by 2030, while Cape May, NJ, Wilmington, NC, and Annapolis, MD, could average more than 120.*

By 2045, many communities can expect a 10-fold increase in the frequency of tidal floods (bottom right). *Cambridge, MD, Atlantic City, NJ, and Washington, DC, could average more than 240 per year by 2045. Only five of our locations would average fewer than five a year: Woods Hole, MA, Quonset Point, RI, and Panama City, Apalachicola, and St. Petersburg, FL.*

continued from p. 20

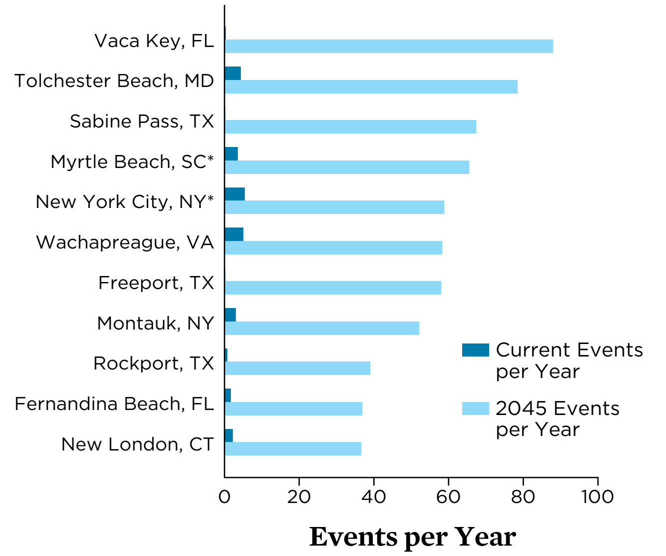
year, on average. By 2045, however, high tides riding on the back of higher sea levels could bring more than 35 tidal floods to the city every year, on average. Other locations that have fewer than five tidal floods per year today—including several on the Gulf Coast—could see a 10-fold or greater increase in the frequency of floods by 2045 (Figure 12).

The Gulf Coast, in particular, can expect to see many new areas exposed to tidal flooding (Box 3). Several Gulf Coast locations that now see little to no tidal flooding, including Freeport, Rockport, and Sabine Pass, TX, could face 35 to 70 tidal floods per year by 2045.

The nearly ubiquitous rise in flood frequency in the 52 locations studied suggests that communities not covered by our analysis can expect to see changes on a similar scale, depending on their local topography, natural and physical defenses, measures to accommodate the changes, and other preparatory steps. Tidal flooding will be on the rise all along the East and Gulf Coasts, with safe havens few and far between.

Other locations that have fewer than five tidal floods per year today—including several on the Gulf Coast—could see a 10-fold or greater increase in the frequency of floods by 2045.

FIGURE 12. New Locations Join the Front Line of Tidal Flooding



Sea level rise will bring regular tidal flooding to many communities where it is rare today, especially along the Gulf Coast. Communities listed here now average fewer than five tidal floods per year. However, they can expect to average 24 or more by 2045, and all face more than a 10-fold increase in the average number each year. (Note that some communities in Jamaica Bay, which is represented by the New York City, NY, tide gauge, currently flood far more frequently than shown here.) Tides that cause so-called nuisance flooding today are expected to cause extensive flooding by 2045 in five of these communities: Vaca Key, Tolchester Beach, Myrtle Beach, Wachapreague, and Montauk.

* Data for these locations are represented by nearby tide gauges; see the appendix for tide gauge locations.

© Peter Mahon/West 12th Road Block Association

© Peter Mahon/West 12th Road Block Association

The actual impact on a community facing steep increases in tidal flood events is difficult to predict. Floods will vary in magnitude, and some communities will be better prepared than others. However, the large number of such events and their growing duration and extent has the potential to cause deep disruption, as is already the case here in Broad Channel in Jamaica Bay, NY.

BOX 3.

The Gulf Coast: Sinking Shores Meet Rising Seas

The Gulf Coast faces rates of sea level rise that are among the highest in the world—in some places more than three times the global average—partly because land in the region is sinking (NOAA Tides and Currents 2013b; Milliken et al. 2008). Subsidence affects large swaths from Mississippi to Texas. Louisiana has lost 1,900 square miles of land since the 1930s, for example. And parts of the Houston area have sunk by more than seven feet in 100 years (Climate.gov 2013; Kasmarek, Gabrysch, and Johnson 2009).[8]

Subsidence rates vary widely along the Gulf Coast because sediments are compacting and people are extracting groundwater, oil, and gas to different extents along the coast (Kolker, Allison, and Hameed 2011). The composition of the underlying land also plays a role. The Pensacola region, for example, is composed of limestone and sand—both stronger materials than the sediment underlying places such as Grand Isle, LA—making subsidence less of a concern. In all locations, though, sea level is rising.

Vulnerability to Storms

The Gulf Coast's location, low-lying topography, and large population render it highly vulnerable to storm surge during hurricanes and tropical storms. Hurricane Katrina alone took nearly 2,000 lives, forced about a quarter of New Orleans residents to leave the city permanently, and caused roughly $125 billion in damage (Plyer 2013). More than a quarter of the major roads in the Gulf Coast region are on land less than four feet in elevation, which places critical transportation infrastructure well within striking range of sea level rise, storm surge, and tidal flooding (USCCSP 2008).

Wetlands and barrier islands that line the Gulf Coast have historically provided a natural line of defense against storms and coastal floods. However, these fragile systems are themselves subject to the forces of nature—including subsidence, storms, erosion, and sea level rise—and human development. As these natural defenses change, so does their

© Jonathan Henderson/Gulf Restoration Network/Flight provided by *Southwings.org*

A glimpse of Gulf Coast topography, crisscrossed with canals.

8 The causes of subsidence on the Gulf Coast are complex. Over the last century, the amount of sediment flowing down the Mississippi River to the coast has dropped by half, largely because of damming upstream and other human activities (Blum and Roberts 2009; Syvitski et al. 2009). Lacking replenishment, the coastal delta is sinking, while sediments underlying the land are compacting (Törnqvist et al. 2008). The pumping of groundwater and extraction of hydrocarbons worsen these problems (Konikow 2011; Morton, Bernier, and Barras 2006).

The Gulf Coast: Sinking Shores Meet Rising Seas *(continued)*

ability to protect the coastline from some floods (Moser et al. 2014; NRC 2012).

Tidal Flooding Today

Because of its exposure to hurricanes and tropical storms, the Gulf Coast is no stranger to major coastal flooding. Still, as noted, the region rarely sees coastal flooding except for that driven by winds or storms. Only one of the 10 Gulf Coast sites we examined—Bay Waveland Yacht Club, MS—experiences tidal flooding more than once a year.

Natural and human-induced processes play roles in this gap. Gravitational forces, combined with the shape of the Gulf of Mexico and its limited connection to the open Atlantic Ocean, mean that many places along the Gulf Coast see just one high tide and one low tide per day, rather than the two that are common along most of the East and West Coasts. That means they are exposed to potential tidal flooding just once daily. And the difference between high and low tide is usually smaller on the Gulf Coast than along much of the East Coast (Flick, Murray, and Ewing 1999).

Low-lying topography and exposure to tropical storms have prompted states and communities to build hard defenses along stretches of Gulf coastlines, which help limit flooding, including tidal flooding. A levee along the coast of Jefferson County, TX, for example, protects the Port Arthur area from storms, and a 10-mile-long seawall protects the coast near Galveston, TX (Rappleye 2008).

While tidal flooding is now relatively rare along the Gulf Coast, it can have a significant impact when it does occur. Along the upper Texas coast, tides running 1.5 to 2 feet above normal have caused waterfront roads and highways to close, particularly on the Bolivar Peninsula, shutting off access (Reilly and Kyle 2014). And on South Padre Island in southern Texas, minor coastal flooding prevents access to beaches and can damage cars parked near beach access points (Goldsmith 2014).

The future risks of tidal flooding along the Gulf Coast will vary, because local rates of sea level rise differ substantially between the Gulf's eastern and western halves. Local sea level has risen much more quickly along the western half of the Gulf than the eastern half, because land in the west is sinking faster.

That means sea levels may rise 15 to 19 inches along Louisiana and parts of Texas by 2045—versus 9 to 11 inches

Caitlyn Kennedy/NOAA *Climate.gov*

The Gulf region is home to important ports such as the Port of South Louisiana. Fuel production and shipping, which require safe highways, are also major industries in the region. Rising seas and coastal floods that push farther inland are putting critical infrastructure that serves both the region and the nation—such as Highway 1 in Louisiana—at risk.

along the Gulf Coast of Florida and Mississippi (Climate Central n.d.; Parris et al. 2012; Tebaldi, Strauss, and Zervas 2012). St. Petersburg and Clearwater Beach, FL, are projected to face just under one foot of sea level rise by 2045—on par with what is expected globally (Climate Central n.d.; Tebaldi et al. 2012).

Because the western half of the Gulf is projected to see a substantial rise in sea level in the next 30 years, communities there—such as Freeport, Rockport, and Port Arthur, TX (at Sabine Pass)—are expected to face dramatic increases in the frequency of tidal flooding. These changes could impact the economic boom now under way in Sabine Pass and nearby Port Arthur, where companies are building large-scale energy processing facilities (Kozelichki 2012).

Texas is largely unprepared for these challenges (Texas Sea Grant 2013). Other Gulf Coast states and their local partners have made some effort to plan for sea level rise—mainly in response to Hurricane Katrina, and to reduce risks to the energy industry.[9] Although much of this work focuses on minimizing the impact of storm surge, communities such as Biloxi, MS, now require developers to construct new buildings at least one foot above the base flood elevation (City of Biloxi 2014). More stakeholders in the Gulf region, especially the western half, need to plan for the lower-risk, high-probability tidal flooding that may chronically affect their communities in the next 30 years.

9 A recent study commissioned by Entergy, an energy company that serves 2.8 million customers, and America's Wetlands Foundation developed a framework for quantifying the risks climate change poses to the Gulf Coast, as a starting point for making the energy sector more resilient (Entergy and America's Wetland Foundation 2010). A comprehensive study of transportation infrastructure in the Gulf region similarly identified vulnerabilities to sea level rise, and suggested integrating climate change into transportation planning (USCCSP 2008).

On the Front Line of Tidal Flooding

Annapolis, MD

Home of the U.S. Naval Academy, Annapolis is coping with seas that are rising faster than the global average.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

The low-lying city of Annapolis is well-acquainted with coastal flooding, as it faces regular disruptions to downtown streets and parking. A more than fourfold increase in tidal flooding since 1970 has made Annapolis among today's most frequently flooded East Coast cities.

With a population of 40,000, this picturesque city lies on Chesapeake Bay, at the mouth of the Severn River, and is part of the Baltimore-Washington metropolitan area. This historic state capital was briefly the nation's capital after the American Revolution. Many preindustrial colonial buildings still stand, harkening back to the days when the city was a hub for the transport of tobacco, iron, and grain.

Today the popular City Dock—a central meeting place along the waterfront—sees flooding around 50 times a year during high tides. During such flood events, seawater can move into downtown areas and surrounding neighborhoods, and push water out of storm drains and onto surrounding streets, even on fine sunny days with no wind or storms.

During "spring tides"—the highest tides of the month, when the influence of the moon and sun is greatest—areas around the U.S. Naval Academy, the Market House, Compromise Street, and the Eastport neighborhood can become awash with seawater. In December 2012, for example, an extreme high tide combined with a southeasterly wind that prevented the bay from draining left residents knee-high in water (Prudente 2013). Streets were closed, as was the Eastport Bridge, and businesses on Dock Street were inundated. Parking lots were submerged and restaurant and store owners were forced to close their premises. Flip Walters, the city's director of public works, said the flooding was more substantial than during Hurricane Sandy, and advised drivers against forcing their way through floodwaters and spraying their brakes with highly corrosive saltwater (Staver 2012).

Sea level at Annapolis has risen by more than a foot over the last century—more than twice the global average (NOAA 2012a). Just since 1990, sea level has risen by three inches, and the number of minor floods has more than doubled (Nelson, Wilson, and McNeill 2014; Sweet et al. 2014). Flooding from high tides has become so common that residents of some neighborhoods feel anxious about flooding, even when the weather is fine (Skaggs 2014).

Annapolis is also familiar with severe flooding associated with major storms. In 2006, for example, a five-foot storm surge from tropical storm Ernesto inundated downtown, affecting the ground floors of many buildings, including the Maritime Museum (Birch 2006; WMO 2006). And buildings at the U.S. Naval Academy flooded during Hurricane Isabel in 2003, incurring extensive damage.

In 2030, just 15 years from now, projections show that Annapolis may see another half-foot of sea level rise, and a tripling of flood events to around 180 a year. By 2045, projections of sea level rise of around a foot mean that Annapolis would face more than 360 flood events a year—about 50 of them extensive. If the city does not pursue substantial measures to defend against rising seas or retreat from the sea, parts of Annapolis would essentially never be dry again.

TAKING ACTION

To stem the damage wrought by a steadily encroaching waterfront, Annapolis is beginning to plan for a wetter future. Officials from the city and Anne Arundel County used funding from NOAA and the Maryland Coastal Zone Management Program to assess the area's vulnerability to sea level rise. City officials are now using funding and expertise from the Federal Emergency Management Agency (FEMA), the Army Corps of Engineers, and the Maryland Historical Trust to study almost 200 structures at risk from rising seas. The result will be suggestions for how to mitigate future flooding, and an online database that allows first responders to survey potential damage immediately after a disaster.

© Mary F. Calvert/Reuters

Tidal flooding has become much more frequent in Annapolis. And in the near term, extensive flooding—the kind that completely inundates the boardwalk at the City Dock—is expected to occur more frequently, simply from tidal activity.

Through a partnership with NOAA, the state also runs the CoastSmart Communities Program, which provides tools and resources, financial assistance, and training for local officials on coastal flooding. As part of a public education strategy, city officials are asking residents to take pictures of flooding from tidal inundation, storms, wind, and rain (MDNR 2014; MKTI 2014).

During ongoing public hearings on long-term development plans for downtown, officials also solicit suggestions for dealing with flooding. Suggestions have included an extension of the public boardwalk in City Dock, a contentious plan for a floodwall, and alterations to major infrastructure. The City Dock Master Plan and a recent flood mitigation report already take sea level rise into account (CDAC 2013; WBCM 2012).

The U.S. Naval Academy is also planning for sea level rise and climate change (St. John 2011). Because the academy already faces disruption from road closings, restricted access to buildings, and flooding of sports fields, leaders realize that they will need more preparedness to continue operating. Toward that end, academy leaders are partnering with city officials and the state Department of Natural Resources to coordinate efforts to prepare for sea level rise. Both the Department of Defense and the Department of the Navy consider sea level rise a national security issue, and the academy participated in a study, with Annapolis as a pilot site, that modeled flooding that could occur when storm surge combines with higher seas (USNA 2014; NRC 2011).

According to Kevin Jenkins, director of the academy's Facilities Management Division, "Each of us seemingly has a role and responsibility in sea level rise and climate change. Those roles and responsibilities are evolving rapidly. The immediate challenges are coordinating information and planning positive efforts on a local and regional level, while anticipating national and Department of Defense policies that will guide much-needed hazard mitigation actions."

Charleston, SC

A historic gem faces extensive near-term tidal flooding.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

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Downtown Charleston, no stranger to flooding, faces a wet future.

The historic city of Charleston lies on a narrow peninsula at the confluence of the Ashley and Cooper rivers. One of the oldest, most beautiful, and best-preserved cities in the South, Charleston boasts more than a thousand historic buildings—many lining downtown streets.

Charleston has a tumultuous history. During the American Revolution, it was the site of the initial naval victory against the British. It was also where the Confederates fired their first shots during the Civil War, and where millions of Africans were brought by ship and sold into slavery. Today a strong sense of southern pride permeates the city, which draws on English, French, and West African culture, and whose galleries, restaurants, and festivals attract a healthy stream of tourists.

But the grand city of Charleston is facing the slow creep of a rising sea. Tidal events alone cause about two dozen floods a year. That means regardless of the weather, tourists and locals alike frequently slosh through shin-deep water in downtown Charleston, including historic Market Street. Residents know to move their cars and vacate the area early—often using social media such as Twitter to spread the word.

Rain during these high-tide floods compounds the problems. Stormwater drains back up, and the water has nowhere to go but into surrounding neighborhoods. These areas, which have had fewer infrastructure improvement projects, bear the brunt of the impacts of repeated flooding. Mobility of pedestrians, bicyclists, and motor vehicles is disrupted, businesses close, and homes are flooded. Long-term damage to buildings, roads, and other critical infrastructure from saltwater inundation mounts.

Sea level at Charleston has risen by more than five inches over the last 40 years, and the number of tidal floods has doubled every 20 years (NOAA 2012a). In 1970 the city averaged six such floods a year. Today it averages more than two dozen.

Onshore winds, storm surge, high tides, a few inches of rain, or a combination can aggravate the impacts of tidal floods in Charleston. When the water level hits a certain point, a coastal flood advisory becomes a warning, indicating a more extensive flood. Such floods usually occur when wind or storms affect the ocean. But in a future of higher seas, extensive floods from tides alone will be common in Charleston.

TAKING ACTION

Charleston's future looks very wet. By the time today's toddlers graduate from high school just 15 years from now, and given a mid-range scenario for sea level rise, the city would face nearly 80 tidal floods a year. Because of this, South Carolina recognizes long-term sea level rise as a serious concern (SCDNR 2013).

By 2045, under the same mid-range scenario, Charleston would see more than 180 tidal floods a year. And because sea levels will be higher, flooding would be more extensive and persist for about 400 hours a year. Under rising seas, an average high tide could inundate the historic district and flood low-lying neighborhoods as often as every other day. Charleston will face a constantly inundated landscape and much more damage.

Even in the very near future, the community needs to tackle the impacts of tides on daily life. The city is already

NOAA Digital Coast

During extreme high tides, some Charleston streets tend to flood, creating hazards for pedestrians and drivers. As part of its King Tide and Storm Witness initiatives, the South Carolina Department of Health and Environmental Control encourages the public to upload photos to a database used to assess vulnerability and plan for long-term resilience.

spending hundreds of millions of dollars on a drainage improvement project for Market Street, to cope with flooding from rain during a high tide (City of Charleston 2013). Very costly pumping stations will channel excess rainwater into the ocean—although they will become less effective as tides rise higher.

The city is also installing a multimillion-dollar seawall off the tip of the peninsula (City of Charleston n.d.). However, seawalls are effective only if they prevent tides from filtering up through the ground, and can compound problems when they prevent rainwater from draining out. Ultimately, the city will need more creative solutions.

Jamaica Bay, NY

Working-class communities along an urban coast contend with the impacts of rapid increases in tidal flooding on daily life.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

Spanning the shoreline of the populous boroughs of Queens and Brooklyn in New York, Jamaica Bay's salt marshes provide habitat for fish and birdlife amid one of the world's largest cities. The narrow Rockaway Inlet, which links the bay to the Atlantic Ocean, funnels tides and storm surges into the bay with some force.

Hurricane Sandy had a devastating effect on communities along the bay, including the Rockaways, Howard Beach, Broad Channel, Sheepshead Bay, and Mill Basin, causing major flooding (City of New York 2013a; Bloch et al. 2012). Rebuilding continues, but scars on the landscape may be visible for years to come. Though a far gentler force, regular high tides also pose flooding problems for residents of these same beleaguered areas, because of their low elevation and rising seas.

Jamaica Bay is part of the Gateway National Recreation Area, a unique natural environment within a highly urbanized setting, an important waypoint for migratory birds, and a place of significant historic and cultural heritage. This is the only wildlife refuge in the country accessible by subway. But dredging, shoreline bulkheads (barriers), sea level rise, and sewage runoff have led to major erosion of the bay's marshes and islands (Swanson and Wilson 2008; CSOTP 2007; Hartig et al. 2002).

The area once had rich shellfisheries, and the Rockaways were a popular summer resort destination. Today, mostly working-class neighborhoods enjoy spectacular water views, but must contend with frequently flooded streets and sidewalks during high tides and heavy rainfall, and worse impacts during larger storms.

Because drainage infrastructure is aging, flooding today sometimes causes combined sewage and stormwater to overflow into streets. Standing water provides a breeding spot for mosquitoes, and vehicles caught in the water can be damaged. Major floods—such as those during Hurricane Irene in 2011, which coincided with a new moon—can bring several feet of inundation, cutting off entire neighborhoods, flooding basements, and damaging property.

FEMA flood-risk maps released in 2013 show that most of the Rockaways and Broad Channel neighborhoods—which have much higher poverty rates than Howard Beach—are already high-flood-risk zones (FEMA 2012). With further sea level rise, flood risks are expected to grow.

Over the last century, the water level in Jamaica Bay (as measured at the nearby Battery tide gauge) has risen nearly a foot, owing to both sea level rise and local subsidence of the land (NOAA 2012a). Minor flooding events in the Broad Channel area now occur once or twice a month, or more. And our analysis shows that continued sea level rise means that the frequency of flooding events in Jamaica Bay will triple by 2030, and increase nearly 10-fold by 2045, compared with today.

Dan Mundy, Sr., former president of the Broad Channel Civic Association and a retired captain in the New York City Fire Department, knows that flooding is becoming worse. "Every home in Broad Channel has a calendar with the lunar cycle and tide predictions clearly marked for each day of the year," he says. "We live by the tidal cycles here: flooding is becoming more common, and much more of an inconvenience than ever before." Volunteer firefighters at the Broad Channel Fire Department know which streets might need evacuation by inflatable boats.

Locals also know to keep an eye on the winds. Even a slight east or northeast wind with a high tide can cause areas in Broad Channel to flood. In Jamaica Bay, high tides during a full moon occur once a month near 8:00 a.m.—about the time families are trying to commute to work and school. In some areas residents move their cars the night before—particularly if wind is forecast—or both they and their cars can be stranded. Importantly, there is no NOAA tide gauge in Jamaica Bay itself. The nearest gauge, used as a proxy in this analysis, is located at The Battery in New York City, and sees far less flooding than communities like Broad Channel. On days like September 12, 2014, Broad Channel can experience significant tidal flooding though no coastal flood advisory for the broader area is issued.

© Peter Mahon/West 12th Road Block Association

During an extreme high tide in Broad Channel, high school student Amy Mahon wades through shin-deep water on her way to the A train station.

TAKING ACTION

The Broad Channel community is a proactive one. After more than a decade of lobbying by the Broad Channel Civic Association, the City of New York has funded and begun work on a $23 million project to enable West 11th, 12th, and 13th Streets to withstand and avoid flooding. The project entails elevating roads, installing a new sewer system and water mains, building a special drainage system to the bay, and instituting a novel shared-streets approach, wherein pedestrians and vehicles occupy a single one-lane road together—the first of its kind in the state.

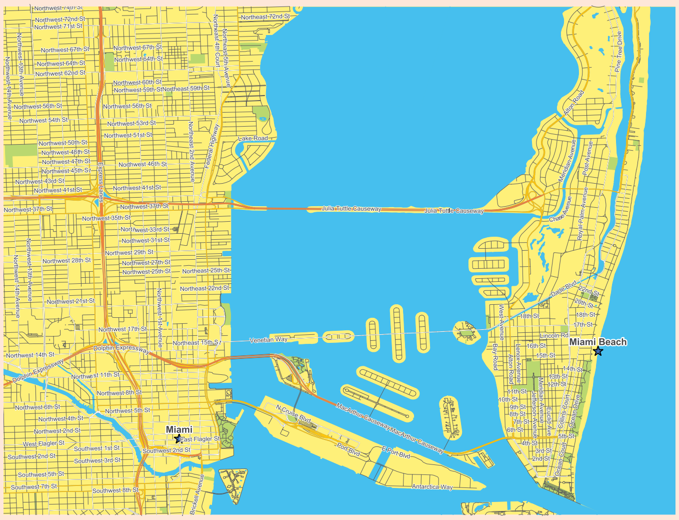
Hurricane Sandy exposed key vulnerabilities that will increase with continued sea level rise. *A Stronger, More Resilient New York*—a 2013 report spearheaded by former Mayor Michael Bloomberg—outlines plans to improve the city's ability to cope with climate change and future storms (City of New York 2013). Included are proposals for breakwaters, sand dunes, bulkheads, and tide gates, as well as efforts to preserve natural barriers such as marshes to protect vulnerable communities along Jamaica Bay (NYT 2013). Governor Mario Cuomo's 2100 Commission is also assessing emergency preparedness and infrastructure resilience, and recommends restoring wetlands in Jamaica Bay (NYS 2013).

Measures to make critical services more resilient, including the power supply, wastewater treatment, health care, and transportation, are also under development. The Army Corps of Engineers, the New York City Department of Environmental Protection, and the state Department of Environmental Conservation are pursuing marsh and island restoration projects in the bay (USACE n.d.). Community, labor, and civic groups have formed the Sandy Regional Assembly to ensure "the recovery and resiliency planning efforts address the needs of the most vulnerable communities" (NYCEJA 2013). And the Rockefeller Foundation has funded the Science and Resiliency Institute at Jamaica Bay to help communities build resilience.

The communities of Jamaica Bay—with partner agencies and organizations—are charting a path to urban coastal resilience that others around the country can build on.

Miami, FL

At "ground zero" for sea level rise and increases in tidal flooding, Miami needs major infrastructure upgrades to cope.



SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

© Joe Raedle/Getty Images North America

Several sections of Miami Beach can flood even on calm, sunny days. During tidal floods in October 2012, the city noted that such events underscore the importance of developing strategies to address and reduce coastal flooding impacts in the face of future sea level rise (Miamidade.gov 2013).

Miami's sand beaches, cultural and retail attractions, and vibrant nightlife draw people from around the nation and the world. A dense metropolis of high-value real estate and growing financial and commercial sectors, low-lying Miami is also one of the places most vulnerable to sea level rise (Nicholls et al. 2008). But the high-profile cities of Miami-Dade County—Miami and Miami Beach—are showing how major urban areas can grapple with frequent tidal flooding (Burkett and Davidson 2012).

Miami is home to some 417,000 people, while Miami Beach—on a heavily developed barrier island—has 90,000 (U.S. Census 2013a, 2013b). Nicknamed the capital of Latin America, Miami is the second-largest U.S. city with a majority Spanish-speaking population (after El Paso, TX) (Salomon 2008; Booth 2001). Tourism is the number-one industry, and wealth is on display. In 2012, Miami received $21.8 billion of the $71.8 billion spent by visitors statewide (VisitFlorida.com 2013). A 2012 study ranked Miami as the world's seventh-richest city in purchasing power, and among the world's top cities for sales of luxury property (City Mayors 2012).

Most analysis of the risks to Miami and Miami Beach from sea level rise has focused on high-end districts. Yet more than 20 percent of families with children in Miami-Dade County live below the poverty line, and neighborhoods such as Miami's low-lying, low-income Little River have received less attention (Brannigan 2014; Eisenhauer 2014). This disconnect adds to the county's adaptation challenges.

A majority of Miami's land area—and all of Miami Beach—is in a flood zone (Miami-Dade County 2010). The porous geology of Miami and all of Southeast Florida worsens exposure to sea level rise. Saltwater not only tops coastal areas but moves underground through Swiss cheese–like limestone, raising groundwater levels and causing inland flooding. An aquifer that provides fresh drinking water through wells to much of Southeast Florida also sits within the limestone. Cities in the region are already losing wells to saltwater intrusion and spending millions of dollars to relocate well fields. And because of its porous limestone, Miami cannot rely on measures used elsewhere to adapt, such as the Netherlands' extensive seawalls (Berry 2012).

Seasonal high tides are the most visible manifestation of sea level rise in Miami. Here, the highest tide of the year, often called a king tide, typically occurs in the spring or fall during a new or full moon. Because Miami built much of its infrastructure more than 50 years ago, it struggles with today's high tides, which occur on top of higher seas. And because the city is so densely populated, tidal flooding affects homes, businesses, and government offices. In Miami Beach, keeping seawater off the streets is expected to cost some $400 million over the next 20 years (Veiga 2014).

As sea level continues to rise, flooding is expected to become more common during monthly high tides. A *New York Times* article noted how business owners in Miami Beach are facing the impacts of "sunny-day flooding." According to laundromat owner Eliseo Toussaint, "This never used to happen. . . . I've owned this place eight years, and now it's all the time" (Chadwick 2013). Resident Moses Schwartz agrees: the area "gets super flooded from the tide every couple of months. It's getting worse and worse as the years go by. It'll be interesting to see what happens to Miami Beach in 10 to 20 years" (Buteau 2013).

By 2030, Miami can expect the frequency of tidal flooding to increase nearly eightfold—from about six per year today to more than 45. And by 2045, the city can expect more than 40 times as many floods as today. Booming development and growing population in Miami and Miami Beach add to the risks to public health and the local economy.

TAKING ACTION

Government agencies, academics, and nonprofits are trying to make the region more resilient in the face of rising seas. For example, Miami-Dade County has developed GreenPrint, a plan to adapt to and mitigate climate change. The plan includes projects by the U.S. Geological Survey and the South Florida Water Management District to study the impacts of sea level rise on flooding and potable water sources, which will guide investments in public infrastructure (Miami-Dade Board 2010).

In 2009, the county partnered with neighboring Broward, Palm Beach, and Monroe Counties to create the Southeast Florida Regional Climate Change Compact. Touted as a model for adapting to climate change, the counties have developed a unified projection for sea level rise for Southeast Florida, and advocated the designation of "adaptation action areas" (FL Compact 2010). The legislature has since adopted this approach for the state.

Florida International University and the University of Miami are pursuing several research projects to better understand the area's vulnerability and develop adaptive solutions in architecture, engineering, and natural resources management (FL Institute 2014). Nonprofits such as the CLEO Institute and Resilient Miami are training officials and offering certificate programs in storm preparedness, as well as hosting workshops and art projects to educate the public.

While these efforts are important steps toward living with sea level rise, the region still has room to develop more robust, long-term adaptation plans. Observes Katy Sorenson of the University of Miami's Good Government Initiative, "No one wants to pay increased taxes or fees, but if people want to live here, we have to make these investments to do [. . .] all the stuff that needs to be done so that we can stay habitable" (PBS 2014).

If leaders can create a broad vision for resilience in the face of sea level rise, the region could serve as a model—nationally and beyond.

© Gunther Hagleitner

Beauty and coastal vulnerability, both stunning, are evident in Miami and Miami Beach.

Norfolk, VA

In this frequently flooded city, ensuring public safety and supporting national security require grappling with tidal flooding.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

Norfolk, Virginia's second-largest city, is home to nearly 250,000 people as well as the world's largest naval base. One of nine cities and seven counties in the Hampton Roads metropolitan area, Norfolk sits between the Elizabeth River and Chesapeake Bay. Surrounded by water on three sides and lacking high ground, residents know what it is like to live with flooding. Some neighborhoods have permanent road signs warning of flooding. And, as in other communities along the mid-Atlantic coast, locals are starting to use social media as a flood-warning system, and to gather more information on the extent of flooding.

The city is vulnerable to flooding when tides combine with heavy rain, and when nor'easters and hurricanes bring storm surge ashore. However, Norfolk residents are increasingly grappling with floods caused by the more frequent and subtle occurrence of high tides combined with a slowly rising sea (VIMS 2013).

Sea level has been rising along the mid-Atlantic coast at about three times the global pace. At places along the Hampton Roads coastline, it has risen by more than a foot over the past 80 years (VIMS 2013; Sallenger, Doran, and Howd 2012). As the sea encroaches on Norfolk, the city's experience paints an informative picture of what is in store for many other East Coast cities.

Diligent residents track the tides and move their cars to higher ground during full moons—sometimes streets away from where they live—and many sidestep salty puddles to get to their homes and businesses (Kaufman 2010). When tides are at their most extreme, some streets become impassable from floodwater (Brangham 2012a). And waterfront parks are becoming too soggy and salty for grass to grow (Applegate 2014).

To address chronic flooding, the city is restoring wetlands, essentially allowing the sea to reclaim these areas (Applegate 2014). Richmond Crescent—waterfront parkland north of downtown—has become a wetland, and the city has built pools to absorb both tidal flooding and stormwater runoff.

Today an extensive road and tunnel network linking the city to the surrounding area usually closes only during heavy rain events and other storms. However, few alternate routes are available, requiring lengthy detours. Flooding of tunnels and approaches to bridges hinders safe evacuation and emergency services, and shelter options in such a low-lying area are limited. Continued sea level rise will only compound these problems. As James Redick, director of the city's Department of Emergency Preparedness and Response, says: "As sea levels rise, the areas that need to be evacuated increase, and the space for sheltering shrinks."

The number of flooding events in Norfolk each year has tripled since the 1970s, and tidal flooding now occurs about once a month. Sea level at Norfolk is projected to rise at least six inches by 2030. By then the city could see almost 40 tidal flooding events per year—about a quadrupling compared with today. Facing such frequent flooding, the city would likely continue to lose coastal parks to wetlands or otherwise cede them to the sea.

What that would mean for flood-prone neighborhoods depends on residents' tolerance for repeated disruption and on the policies put in place to assist them. Tidal flooding has already made it more difficult for some residents to sell their homes and driven declining home values in neighborhoods key to the city's tax revenues (Brangham 2012b; Fears 2012).

© Bill Tiernan/Virginian-Pilot

Some coastal parks in Norfolk, such as Myrtle Park at Richmond Crescent, pictured in February 2014, face such frequent tidal flooding that the city is turning them back into wetlands.

© Kirsten Howard and Allie Goldstein/*adaptationstories.com*

While some residents in Norfolk's frequently flooded Larchmont neighborhood are elevating their homes to avoid flood damage and to lower insurance rates, others either choose not to or cannot afford to.

In 30 years' time—the duration of a typical mortgage—the city could see 180 floods a year from regular high tides. Higher seas would also allow high tides to penetrate farther inland, affecting many more people and places in the metropolitan area, home to 1.5 million people.

TAKING ACTION

One of the first U.S. cities to plan for sea level rise, Norfolk is considering large-scale, citywide measures to protect residents and critical infrastructure. The city already requires developers to raise new buildings three feet above the 100-year flood level. And Fugro Atlantic, a Dutch energy infrastructure firm, has recommended a suite of options such as floodwalls, tide gates, elevated roads, and pumping stations, at a cost of at least $1 billion (Redick 2014; CBP 2013; Koch 2013; Fears 2012; Fugro 2012).

With almost 30,000 workers employed at the naval shipyard, access is crucial if the naval station is to continue to operate, and its leaders are working with the community to cope with future sea level rise (Norfolk Naval Shipyard n.d.). For example, the station is replacing some of its 14 piers—at a cost of $60 million each—to make them less vulnerable to tidal and storm-induced flooding (Fears 2011; Springston 2010).

Like other places in Virginia, Norfolk has received limited guidance from the state, which only recently set up a Climate Change Commission. But as the Department of Defense (DOD), a major source of funding in Virginia, and other federal agencies begin to view sea level rise as a security risk, there are signs of change at the state level. The governor has created a Task Force on Climate Resilience, a Recurrent Coastal Flooding Subpanel, and a pilot project to coordinate efforts between the DOD and local, state, other federal, and industry officials (MARI 2014; McAuliffe 2014; Virginia.gov 2013).

Norfolk Mayor Paul Fraim reports that flooding now occurs monthly, and the city has joined the Rockefeller 100 Resilient Cities Challenge, a program that encourages cities around the world to become more resilient in the face of physical, social, and economic challenges this century (100 Resilient Cities 2014). But despite Norfolk's efforts to tackle the impacts of sea level rise, the mayor has acknowledged that residents might need to eventually retreat from areas that flood repeatedly owing to both tides and rain (Brangham 2012a; Fears 2012).

As more and more U.S. cities face regular tidal flooding, they will be looking to Norfolk as a community seasoned in the hard work of persisting amid encroaching seas.

Outer Banks, NC

These barrier islands—with tenacious residents, rich natural resources, and vacation destinations—face fast-rising seas.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

© Dan Waters Photography/www.DLwaters.com

Projections show that sea level on the Outer Banks will rise steeply by 2045. To prepare for the future, communities there and on the mainland need to apply good science to long-term decisions.

The North Carolina coastline stretches some 325 miles along the mid-Atlantic and boasts dozens of barrier islands large and small. These include the Outer Banks—a thin chain that includes Cape Hatteras National Seashore and the Pea Island National Wildlife Refuge, along with eight villages that are popular vacation destinations.

As in many coastal communities worldwide, residents of low-lying islands along the North Carolina coast struggle to maintain a robust infrastructure in the face of a rising sea. And sea level is rising faster here than the global average, partly because the land is also subsiding (NOAA Tides and Currents 2013b).

NOAA's tide gauge at Duck, NC, records around eight tidal flood events a year, mostly during full and new moons. Along the mainland-facing side of the Outer Banks, wind-driven tides from Pamlico Sound can also bring flooding, particularly in fall, winter, and spring (Riggs 2014).

Highway 12, a National Scenic Byway, links the Currituck, Dare, and Carteret peninsulas with Roanoke Island and the Outer Banks. Over time, storm surge from nor'easters, tropical storms, and hurricanes—including Isabel, Ida, Irene, and Sandy—has damaged or washed away miles of this highway (Riggs et al. 2011). Costly efforts to keep it open are an example of the challenge of maintaining infrastructure on a barrier island in the face of frequent storms and rising seas (Riggs et al. 2011; Pilkey et al. 1998).

Says Carol Dillon Dawson, a motel owner and sixth-generation native: "Sea level rise makes storms worse for us, and the lack of access because of bridge and road closures puts our communities at risk, with no emergency services able to reach us."

The rate of sea level rise along this part of the East Coast is increasing (Ezer et al. 2013; Boon 2012; Sallenger, Doran, and Howd 2012). By 2030, just 15 years from now, projections show that Duck will face a tripling of flooding events—to more than 30 per year. By 2045, sea level may be more than a foot higher, threatening more property and posing greater risks to residents.

North Carolina communities are already taking steps to build resilience to storms, such as by nourishing beaches, building dikes, raising houses, and relocating roads, and many of those measures will also help with sea level rise and tidal flooding. Coastal erosion and sea level rise prompted the National Park Service (NPS) to take action in 1999 to save the Cape Hatteras Lighthouse by moving it inland. However, communities will need to pursue other measures to protect infrastructure, housing, and wildlife habitat over the longer term.

In May 2014, the North Carolina Coastal Resources Commission asked the state Science Panel on Coastal Hazards to produce a report on sea level rise based on 30-year projections (NCDENR 2014a, 2014b).[10] That report will help North Carolina join other coastal states in tackling this immense challenge. Communities on the Outer Banks and elsewhere will need the best available information and a willingness to work with nature's power, not against it, in dealing with the pace of sea level rise.

10 This contrasts with a 2012 state law banning the use of projections of sea level rise in the state's coastal zone management program.

Savannah and Tybee Island, GA

These historic coastal communities are taking steps to tackle tidal disruption.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

Savannah is a major port city that also boasts one of the nation's most extensive National Historic Landmark Districts. The waterfront is in many ways the engine behind the city's past and present prosperity. Founded as a major cotton export town, Savannah's picturesque cobbled streets and old warehouses draw millions of visitors each year and provide a popular hub for recreational fishing. However, the city is entering a new era as riverfront buildings increasingly flood at high tide.

Neighboring Tybee Island, at the mouth of the Savannah River, was once known as Savannah's beach. The island has a permanent population of around 3,000, which swells to 30,000 during the summer. Georgia's most densely developed barrier island and a tourist destination, Tybee Island has a colorful past as the haunt of the notorious pirate Blackbeard.

Like Savannah, this vacation town knows that it sits on the front line of sea level rise and is already taking steps to adapt. These efforts include raising the elevation of electronic controls for city wells, placing tide gates on storm-sewer outflows, raising roads, and nourishing eroding beaches.

Floods in the Savannah area, including Tybee Island, now occur about 10 times a year—up from an average of just five or fewer some 40 years ago (Sweet et al. 2014). The island is served by a single highway, Highway 80, which has become particularly prone to tidal flooding during a full or new moon. When water floods this and other roads, residents often contend with standing water, and downtown parking lots become inaccessible. Conditions are worse during higher spring tides, which occur twice a month when sun, moon, and Earth align. At these times, flooding can affect many sections of downtown, as well as stretches of the railway to the Port of Savannah.

Onshore winds and low-pressure systems off the coast often aggravate flooding by pushing water against the shore and allowing successive tides to build up. On those occasions, sewer pipes on parts of Tybee Island fill with seawater and cannot drain into the ocean, so backflow occurs. Such events leave cars stuck and properties flooded.

Projections show that by 2030, just 15 years from now, Savannah could see more than 30 tidal floods a year—a threefold increase compared with today. And sea level rise of almost half a foot will transform today's nuisance tidal floods into more dangerous and damaging ones, with conditions that now occur only during the worst tidal floods.

Projections for 2045 are stark: Savannah could see a foot of sea level rise and a 10-fold increase in tidal flood events—to more than 100 annually. Each year, about 10 of those floods would fall into the extensive category, affecting highways, houses, businesses, infrastructure, and parks, across an expanded area of the city and region.

According to Jason Evans of the Carl Vinson Institute at the University of Georgia, "With a foot of sea level rise, you'd expect to see tidal flooding on the order of 100 days a year, rather than just four to five times a year as we do now." Observes Paul Wolff, Tybee Island's longest-sitting city council member, "Now is the time to plan and budget for infrastructure that we'll need 20, 50, and 100 years from now to deal with the impacts of sea level rise."

The cost of flood insurance for residents of Tybee Island is set to increase, partly because of the growing flood risk to their homes from sea level rise (Wolff 2014). FEMA plans to redraw flood maps in 2016, putting even more pressure on residents—more than a third of whom own vacation rentals that bring summer income.

© Jason Evans/Georgia Sea Grant

Flooding on Tybee Island, associated with extreme tides, affects a neighborhood for hours on a November 2012 day.

TAKING ACTION

Dealing with sea level rise is a steep challenge for historic coastal cities and low-lying barrier islands, but one that both Savannah and Tybee Island are trying to tackle. In southwest Tybee Island, which has seen chronic flooding, large-diameter pipes with tide gates—a multimillion-dollar project—now prevent seawater from flowing into the sewer system. These pipes can also store rainwater to limit flooding when heavy rains occur with high tides. Other neighborhoods have retrofitted storm sewers, and the island has built five canal pumping stations to deal with the highest tides (Curl 2012).

More projects to increase resilience in the face of flooding are in the works. The Chatham County–Savannah Metropolitan Planning Commission has suggested that Savannah retrofit bridges with deeper foundations and increase the capacity of culverts to cope with both rainfall and seawater (CCSMPC 2013). In the longer term, the region plans to elevate new bridges and dig deeper foundations to enable infrastructure and buildings to withstand continued flooding (O'Har and Meyer 2013). Other ideas include raising roads, building dunes, and even moving vulnerable facilities and infrastructure (Curl 2012).

Building coastal resilience needs to be a national imperative, but many places will face limits both on their ability to adapt and on available funding. Stakeholders must eventually make difficult decisions about retreating from areas constantly inundated by tides. Meanwhile state and local planners need to fully account for sea level changes in store. Organizations in Georgia that are collaborating on solutions, such as the Carl Vinson Institute, Georgia Sea Grant, and the state's Coastal Management Program, can provide leadership and vision for other such efforts nationwide.

© Dean Hardy

A tidally flooded road on Tybee Island, July 2013.

South Jersey Shore, NJ

The low-lying South Jersey Shore is highly exposed to the sea, but some locations are more vulnerable to tidal flooding than others.

SOURCES: MAP BASED ON DATA FROM OPENSTREETMAP 2014; USGS 2014; U.S. CENSUS BUREAU 2013.

On the South Jersey Shore, Atlantic City and neighboring coastal and island towns such as Ventnor, Brigantine, and Ocean City are not only rebuilding after Hurricane Sandy but also grappling with how to prepare for rising seas. The region—a low-lying chain of barrier islands and back-bay estuaries—is vulnerable. Atlantic City, a major resort renowned for its boardwalk, beaches, and casinos, has put revitalizing the arts and city parks high on its agenda, while other less-resourced areas struggle just to recover from the 2012 storm.

With some of the highest unemployment and poverty rates in the region, segments of the Atlantic City community are particularly vulnerable to the impacts of coastal inundation. Some older neighborhoods that are home to the most socially vulnerable residents flood regularly during a full or new moon, or if winds and high tides combine to push water against the shore. When the wind blows onshore during storms, water does not drain out of the bays, raising water levels even higher during high tide and complicating daily life.

Tidal flooding now occurs 30 times a year in the region, on average. Such floods typically make the news when a nor'easter bottles up the water in the back bays, but more isolated flooding occurs far more often. In barrier island towns from Ventnor to Beach Haven, and on the mainland from Egg Harbor Township to Little Egg Harbor Township, road closures complicate commutes to work and school. When a high tide is predicted, residents may move their cars to avoid corrosion and the need to wade.

Bridges and causeways—crucial links from the coast to inland areas—are especially vulnerable to closure. The

Blackhorse Pike, linking West Atlantic City to the mainland—closes about once a month. After a strong nor’easter in early January 2014, for example, the most flood-prone areas were under more than a foot and a half of water, and many roads closed for several hours (*Shore News Today* 2014; Watson 2014). Tidal flooding can also lead to backflow from the stormwater system in many towns, because water cannot drain to the sea.

Since the 1970s, the frequency of tidal floods in Atlantic City has grown fivefold. Sea level along the mid-Atlantic coast is now rising at more than three times the global pace—partly because the land is sinking. Over the last 100 years, sea level has risen more than 15 inches at Atlantic City, contributing to the area’s flooding problems (Strauss, Tebaldi, and Ziemlinski 2012).

In Atlantic City, flooding is becoming so common that the National Weather Service raised the water level at which it issues coastal flood advisories by more than three inches, to avoid causing public fatigue with such alerts (Watson 2012b). That means that even as tidal flooding occurs more often, the public will receive fewer advisories.

If the closures of roads and bridges are now a periodic annoyance, they are expected to be a regular occurrence in just 15 years’ time. As sea level rises, the frequency of tidal floods could more than triple in the Atlantic City area—occurring 90 times a year. This means that, on average, tidal flood conditions would beset communities twice each month over a roughly four-day period. Flooded communities would face constant road and bridge closures and saltwater damage to property, without substantial changes to infrastructure. And when high tide coincides with wind or rain, weather systems far less powerful than Hurricane Sandy could cause substantial damage.

© Michael Ein/Press of Atlantic City

In October 2011, the combination of onshore wind and an extra-high tide brought extensive flooding to parts of the Black Horse Pike in Atlantic City. In many communities, volunteers are collecting photos like this of the impacts of high tides to help decision makers plan for the future.

© Frank Galipo

The Mud City section of Stafford Township on the Jersey Shore, shown here in December 2009, floods with certain high tides.

The picture for 2045 is even more serious. Based on a mid-range estimate of slightly more than a foot of sea level rise by 2045, the Atlantic City area can expect more than 240 floods annually. And because sea level will be higher, more floods will be extensive, posing greater risks to people and property. Such unrelenting disruption could radically change the South Jersey Shore as a place to live and play.

TAKING ACTION

After Hurricane Sandy, Atlantic City received federal funding to build a several-mile-long seawall to protect parts of the city from severe flooding and storm surge (Bogdan 2013; Atlantic City and CRDA 2012). The state is also beginning to act. New Jersey’s new Hazard Management Plan suggests how to minimize risk to both natural and built systems (Sturm 2013). And Governor Christie’s administration is helping 14 counties update their hazard mitigation plans with $3 million in aid (NJDCA n.d.; NJDEP 2013; OOG 2013). Communities are also beginning to recognize sea level rise as a growing problem. Ocean County, for example, has produced New Jersey’s first county hazard mitigation plan that highlights sea level rise (Ocean County 2014).

Many flood-prone areas of the South Jersey Shore are heavily developed. In the near term, houses and roads may need to be elevated to be kept safe and usable, and in the long term even relocated. Communities faced with incessant tidal flooding may eventually need to draw back from parts of the shore. Sea level is rising, and this low-lying area is highly vulnerable. Residents and leaders have hard work ahead to build the resilience of the South Jersey Shore.

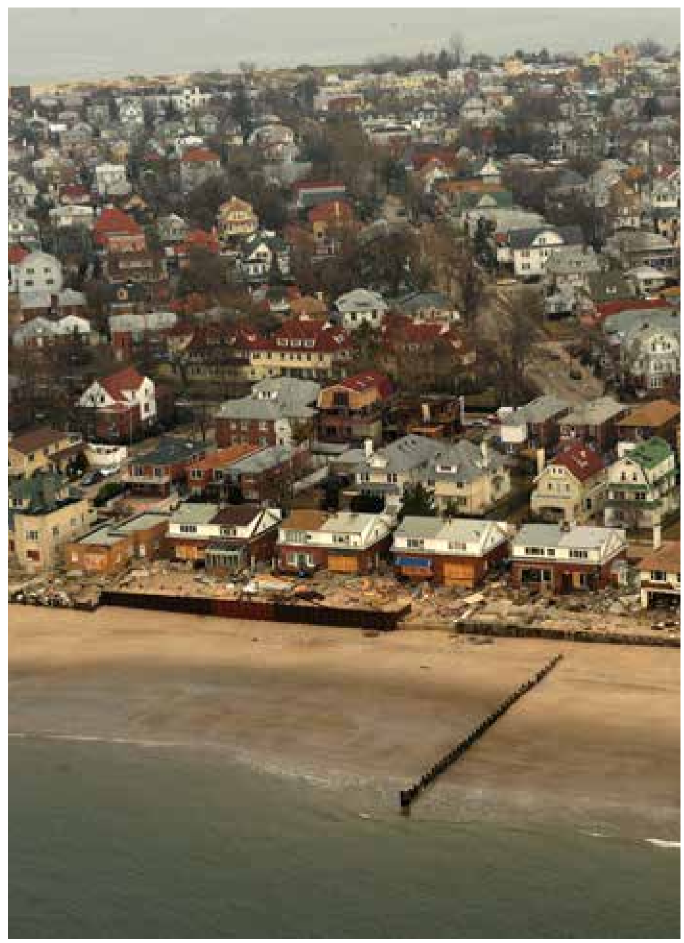
[CHAPTER 4]

Sensible Steps and Forward-Looking Policies for Resilient Communities

The nation needs to prepare for near-term changes in tidal flooding while working hard to both adapt to and limit longer-term flooding and sea level rise. The magnitude of sea level rise over the next several decades will depend largely on how the world's land-based ice masses respond to the warming that our past and present carbon emissions have set in motion. As our analysis shows, even within that time frame, many coastal communities can expect to see much more flooding from tides alone, and must prepare for those changes.

Many coastal communities recognize the tidal flooding challenge, their vulnerability to major storms, or both, and some are taking steps to achieve a new balance between public safety, environmental protection, and growth that strengthens local resilience.[11] Those communities are doing so amid a range of challenges, but some are making real progress. Residents have begun the hard work of figuring out how to live with and even thrive on the front line of sea level rise, breaking ground for others.

Most coastal communities engaged in building resilience are responding to the rising risks of storm surge.[12] This vital work can also strengthen resilience to tidal flooding, and vice versa. But measures that help slow erosion and dampen



Jocelyn Augustino/FEMA

With roughly a third of the U.S. population living in coastal counties (U.S. Census Bureau 2010), we are in many ways a coastal nation, as this view of the New York coastline illustrates. There is much that localities, states, and the country as a whole can do to ensure enduring coastal communities. One sensible step is to design and build for greater resilience, especially in the wake of disasters, as the state of New York is working to do in the aftermath of Hurricane Sandy.

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11 Local and state decision makers usually try to ensure public safety and environmental protection along with economic development. However, growth has tended to take precedence along our coasts (Burkett and Davidson 2012). As a result, many people and assets now occupy coastal locations at risk of flooding, while protective wetlands have greatly shrunk (Pielke et al. 2008; Crossett et al. 2004). Rising seas make coastal decision makers' efforts to balance and even achieve any one of these tasks increasingly difficult.

12 See, for example, StormSmart Coasts (http://stormsmartcoasts.org/) *and NRC 2014.*

storm surge, such as dune restoration or construction of a new seawall, will not always help a community withstand an inexorably rising sea and tidal flooding, as water can work its way under or around some of these structures (NRC 1990). Building resilient coasts requires focused attention on tidal flooding—its dynamics, projections, and best responses—as well as storm surge.

Coastal communities such as those on the Outer Banks and Chesapeake Bay have lived with a dynamic shoreline and slowly rising sea for decades and more. But the accelerating rate of sea level rise—and the number of people and extent of development it now threatens—require us to face that challenge as a nation, with good scientific information, adequate funding, and political will.

Adapting to sea level rise at the needed pace and scale is an unprecedented challenge, and preparing to live with higher tides will take time. Though many communities will not join the ranks of the regularly flooded for decades, they would be well advised to use this time wisely, and state and federal decision makers must support them in doing so. Equally urgent, governments and stakeholders at all levels must recognize that expanding population and development along our coasts only increases the risks and costs of tidal flooding (Moser et al. 2014).

Though increases in near-term tidal flooding are unavoidable, changes in store later this century and beyond are not yet fixed.[13] Our other near-term imperative, then, is to do everything we can to slow the rate at which sea level rise accelerates. To limit long-term sea level rise and give ourselves time to adapt, we must swiftly and deeply reduce our heat-trapping emissions.

Coastal Adaptation: The Big Three

The solutions that can help protect individual communities from tidal flooding vary widely. However, these measures fall into three categories: *defending* against the sea, *accommodating* rising water, and *retreating* from the immediate shoreline (Moser, Williams, and Boesch 2012). In practice, many communities will combine these approaches to build resilience.

13 This is partly due to uncertainty around how land-based ice will respond over that longer time frame, but also to uncertainty about our emissions choices. Covering more than 70 percent of the world's surface, oceans are slow to change. Indeed, the ocean's ability to absorb excess heat over the past century has greatly limited increases in average global air temperatures (Levitus et al. 2012). That inertia means that changes in the ocean are slow to take hold but then hard to stop. Even if we eliminated all heat-trapping emissions today, sea level would continue rising for centuries (Jevrejeva et al. 2012; Vermeer and Rahmstorf 2009; Rahmstorf 2007). Recent studies of West Antarctica, for example, suggest that the loss of major segments of its ice sheet is unstoppable now (Joughin et al. 2014; Rignot et al. 2014).

SNAPSHOT

Baltimore, MD

Recognizing the risk sea level rise poses to its historic and other landmarks, the city is developing a preparedness system.

© Flickr/A. Currell

High tide combined with onshore winds caused significant flooding along Baltimore's Inner Harbor on September 30, 2010.

Like many major U.S. cities, Baltimore is culturally and socioeconomically diverse. The city encompasses low-income neighborhoods and national landmarks, such as the popular Inner Harbor—a key economic asset. It is also home to the Fell's Point district, where some of the first U.S. naval ships were built and many eighteenth-century homes still stand.

Baltimore's coastal assets are prone to flooding during particularly high tides as well as storms. When combined with strong winds, high tides can limit pedestrian access to parts of the Inner Harbor, potentially affecting business revenues.

By 2045, Baltimore is projected to face more than a 10-fold increase in the number of tidal floods it sees each year—to more than 225—because of sea level rise alone (compared with today's average). The city has already started work to protect its historic assets and prepare its economically vulnerable areas, such as Cherry Hill and Southeast Baltimore, where median family incomes are roughly one-third those in the Inner Harbor neighborhood (BOS 2014; U.S. Census 2012). These measures include the creation of a Flood Resilience Area, which allows the city to apply flood-ready design standards within the 500-year floodplain.

Baltimore has also taken a forward-thinking approach to the hazard mitigation planning process. Instead of a routine update to its hazard mitigation plan, the city has integrated hazard mitigation and climate adaption into one comprehensive plan. The Disaster Preparedness and Planning Project (DP3) aims to create a risk-preparedness system, based on input from residents, that is storm-ready today and flexible enough to cope with future impacts of rising seas (BOS 2014).

SNAPSHOT

Bridgeport, CT

A city struggling with high poverty rates seeks to strengthen its resilience in the wake of Hurricane Sandy.

© WB Unabridged with Yale ARCADIS Team

As rising seas arrive on the doorstep of many communities, stakeholders in places such as Bridgeport are making hard decisions about how to thrive in the face of the challenge.

Both the recent recession and Hurricane Sandy hit Bridgeport residents hard. Those challenges have only added to the decades of economic decline that have left a staggering 40 percent of the city's children living below the poverty line (Cuda 2012). Many low-income communities are in Bridgeport's South End—close to the coast and vulnerable to flooding.

While these communities sustained heavy damage from Hurricane Sandy's storm surge, seasonal high tides also flood roads and basements regularly. By 2045, the city is projected to see more than 150 tidal floods a year, or 12 each month, on average.

As part of Rebuild by Design—an initiative of the Hurricane Sandy Rebuilding Task Force—designers and builders have been working with residents, neighborhood trusts, and other stakeholders to develop a citywide resilience framework that includes protecting the South End from future flooding. A core goal is to enable the city's vulnerable communities to help shape the sea level rise solutions that they will ultimately live with (NOAA Coastal Services Center 2014; Rebuild by Design 2014).

Most defensive measures are meant to help minimize wave action, reduce erosion, and protect against storm surge—up to a certain level (NRC 2014). Many communities along the East and Gulf Coasts have employed armoring or "grey" infrastructure measures, such as seawalls, tide gates, and levees. Some have used ecosystem-based, or "green," infrastructure measures, such as beach nourishment, salt-marsh restoration, and the creation of new offshore reefs (Jones, Hole, and Zavaleta 2012; Colls, Ash, and Ikkala 2009; EPA 2009).

However, in the face of rising seas, hard structures can actually aggravate coastal erosion and beach loss, diminishing both the protective function of natural shorelines and the beaches we treasure (Berry, Fahey, and Meyers 2014; NRC 2014; Kittinger and Ayers 2010; Zhang, Douglas, and Leatherman 2004; NRC 1990). Nor do such structures typically protect against infiltration of saltwater from below (Mazi et al. 2013; Barlow and Reichard 2010). To defend communities against worsening tidal flooding, seawalls and floodwalls would need to extend along large stretches of shoreline and avoid channeling incoming seas toward other exposed areas (NRC 2014).[14] Along our densely developed coasts, those are tricky propositions. Legal, financial, physical, and ecological factors can make it challenging to justify, finance, and engineer certain large-scale projects, such as continuous hard shoreline protection (see below; Moser 2014).

Some communities already practice accommodation: managing floodwater by making space for it and living flexibly with a shifting shoreline. The basic idea is to maintain current land uses but adjust or build in ways that acknowledge that a dynamic shoreline will bring flooding and occasional hazardous events (Moser et al. 2014). Homes and vital infrastructure can be elevated, built to withstand flooding, or otherwise retrofitted to accommodate regular tidal and storm-driven inundation.

States and localities may increasingly transition areas not suited for these options to open buffer space, as communities gradually shift inland, away from places too risky or costly to maintain (Kousky 2014; Agyeman, Devine-Wright, and Prange 2009). Economic and behavioral incentives to locate away or retreat from the shore can assist in this transition.

Not all adaptation measures work everywhere, many are costly to sustain, and rising seas may simply foreclose some options (Moser, Williams, and Bosch 2012). In choosing the most feasible way forward, communities will need to weigh difficult trade-offs, their tolerance for risk, and resource constraints.

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14 Such channeling of ocean water away from protected areas occurred during Hurricane Sandy (e.g., flooding the back-bay area of Atlantic City).

U.S. Army Corps of Engineers

This 2.2-mile-long seawall in New Jersey is part of a project by the U.S. Army Corps of Engineers to protect the shoreline. The project also entails creating 4.3 miles of beach that is 150 feet wide, and replenishing the sand every three years. Whether such projects are sustainable or widely replicable is unclear.

Local Challenges and Opportunities

In applying these strategies, efforts to build local resilience can face a host of obstacles (Bierbaum et al. 2014; Moser et al. 2014). These include:

Legal barriers. Property rights can complicate coastal adaptation measures, as they pit property owners—public or private—against each other (Thomas and Medlock 2008; Kusler and Thomas 2007). For example, legal battles can ensue when hard defenses protect some property from flooding while worsening erosion of a neighboring shore (Seiders 2013; Shaw 2008; NRC 2007).

Regulatory barriers. Home owners seeking to elevate their property to offset tidal flooding may face local zoning barriers or rules set by home owners' associations (Hendrickson 2014). Efforts by communities to implement adaptation measures may run afoul of state and federal regulations (e.g., those protecting wetlands and species) (Bierbaum et al. 2014).

Political and institutional barriers. Despite robust research showing that flooding disasters and post-disaster recovery are 4 to 10 times more costly than efforts to mitigate such hazards before they occur, elected officials tend to have limited incentives and opportunities to build long-term resilience (Moser, Williams, and Boesch 2012; Neumann et al. 2011). Leaders may need to spend significant political capital to mobilize efforts to stem tidal flooding, especially if the threat will not fully materialize for a decade or more.

Financial barriers. Coastal adaptation will require new revenue. And though it is a sound investment,[15] raising local taxes for costly projects is difficult. As one official who chose to remain anonymous put it, doing so requires "getting people to spend money they don't have, on things they don't want, to prevent something they think will never happen." State and federal agencies have also shifted away from supporting large-scale, capital-intensive projects (Moser et al. 2014).

Information barriers. Local officials, home owners, business leaders, and other stakeholders often lack the information they need to clearly understand the risks of tidal flooding—handicapping even the most forward-looking communities. Inadequate disclosure of flood risks also prevents people

15 Robust research suggests that the costs of hazard mitigation are one-tenth to one-quarter the costs of disaster losses and post-disaster recovery (Neumann et al. 2010).

SNAPSHOT

Boston, MA

With its low-lying, historic, and highly developed waterfront periodically flooded, the city is actively preparing for more sea level rise.

© Matt Conti

Tidal flooding in the wake of a nor'easter left public walkways and parking lots along Boston's North End waterfront underwater in January 2014.

Founded where several rivers meet the sea, the port city of Boston grew by filling in marshy areas and mudflats. Today the Boston waterfront hosts some of the city's most popular tourist destinations, from museums and restaurants to public parks and historic sites, such as Faneuil Hall and parts of the Freedom Trail.

These public places are vulnerable to sea level rise and coastal flooding. In January 2014, for example, in the wake of a nor'easter, high tides in Boston Harbor exceeded those seen during Hurricane Sandy. Parking lots and public walkways in the city's North End were heavily flooded, limiting access to popular destinations.

Flooding also occurs here during seasonal high tides. The number of days with tidal flooding has more than quadrupled since 1970—to roughly nine events per year. And as sea level continues to rise, Boston is projected to see more than 70 tidal floods annually by 2045.

As one of the most climate-aware cities in the nation, Boston is actively working to build resilience to sea level rise. City officials are tackling risks to sewers, transit, and other infrastructure, and pursuing environmental restoration projects (Brady-Myerov 2012). Some of the city's major property owners, including those along the popular but flood-prone Central and Long Wharves, are participating in the Green Ribbon Commission, which is working to build the resilience of waterfront buildings and support the city's Climate Action Plan (BGRC 2014; City of Boston 2014).

from making informed choices about which homes to buy. And federally subsidized flood insurance rates have provided home owners with a poor indication of the real risks of living by the sea (Cleetus 2013).

Barriers like these are daunting, but they can be changed with political will and public support (Adger et al. 2009; Adger, Lorenzoni, and O'Brien 2009; Moser and Ekstrom 2010).

Despite such barriers, communities can apply several principles to become more resilient in the face of tidal flooding, as well as storm surge and other coastal risks:

Upgrade built systems that are in harm's way. With help, communities can prioritize and incentivize flood-proofing of homes, neighborhoods, and key infrastructure such as sewer and stormwater systems. Adding and restoring natural buffers such as oyster reefs, dunes, and seagrass beds can protect these resources (NRC 2007). Embedding sea level rise and changing flood risks in local master and hazard mitigation plans, waterfront redevelopment, and infrastructure upgrades can help codify resilience (NOAA 2010).

Avoid putting anything new in harm's way. Communities can curtail new development in coastal locations subject to tidal flooding now and in the future (USACE 2013; ASFPM 2008). Regulatory tools for doing so include coastal setbacks, rolling easements, armoring permits, and rebuilding standards.[16] Maps that include projections for sea level rise are essential in adopting and applying such measures (Seiders 2013; Grannis 2011).

Consider the risks and benefits of adaptation measures. Some measures to limit tidal flooding, such as natural buffers, can provide multiple benefits, including protection from storm surge, treatment for runoff, and habitat for fish and waterfowl (USACE 2013; Jones, Hole, and Zavaleta 2012). Other measures, as noted, such as seawalls and other coastal armoring, can alter shoreline dynamics and neighboring areas and ecosystems (BNRC 2007). Decision makers will need to work to ensure that a rush to protect coastal communities builds broad resilience rather than protected pockets next to areas of risk.

Develop a long-term vision. Communities that develop a vision for near-term protection and long-term resilience in the face of sea level rise are in a stronger position to marshal funds, permits, and political will for successful rebuilding after flooding occurs (Haimes 2012; IFRC 2009; Cutter et al. 2008; Moser 2005). In the wake of disastrous flooding,

16 Such standards can require, for example, that rebuilt structures be elevated or set back from the coast.

rebuilding should aim to build better, safer, and more equitably—or even not to rebuild at all.[17]

Taking such sensible steps now buys time for communities, states, and the nation to consider more far-reaching efforts, such as constructing barriers in major harbors and rebuilding stormwater management systems, or managing retreat from coastal areas (Moser, Williams and Bosch, 2012). For better or worse, the steady uptick in tidal flooding will keep these larger questions front and center for many coastal communities.

How Coastal Communities Are Building Resilience Today

If a neighborhood floods each day, it will be considered unlivable without major investments designed to protect it. If a business district faces regular flooding, it will be considered undesirable without investments to manage the water. And if roads are inundated for parts of each day, communities will need to elevate or reroute them to ensure safe and reliable access.

Today, in places such as Norfolk, VA, and Tybee Island, GA, which face tidal flooding as a matter of course, residents and policy makers are already planning and implementing strategies to improve their community's resilience. For example, after years of sewer backups when rain and high tide occur together, Tybee Island has installed large-diameter pipes with tide gates to prevent seawater from flowing into the sewer system. Norfolk is converting some of its coastal parks to wetland, and its Department of Emergency Preparedness and Response is using Twitter to alert residents to flood conditions and road closures—part of a suite of responses to tidal floods (Redick 2014).

Jim Redick, director of emergency preparedness and response in Norfolk, puts it this way: "Transportation is a significant issue for us, from both a quality of life as well as a national security standpoint. Not only is it necessary at times to reroute vehicles, but those who live in areas most vulnerable to flooding must consider where to park their cars during high tide. The soldiers and sailors who live in our community must be able to report to their installations when needed, which could also be impeded during flood events. In Norfolk, we're working to figure this out today. Other cities, as they start to see more flooding of roadways, will need to take a hard look at their transportation planning options."

The Southeast Florida Regional Climate Change Compact is a leading example of local and regional planning to adapt to a changing climate. Four counties—Broward, Miami-Dade, Palm Beach, and Monroe—are using building codes to make new construction more resilient. They are also using regulations to discourage building and post-disaster rebuilding in areas of substantial flood risk (FL Compact 2012).

Most communities along New Hampshire's short but vulnerable coastline are also planning for rising seas. For example, the 10-year master plan of Portsmouth, the state's largest city, calls for elevating pump stations to protect them from flooding (City of Portsmouth et al. 2013). Boston officials are similarly working with major property owners and developers on a strong new building code that will require them to site boilers, generators, and other critical utilities above the first floor (Newman et al. 2013).

Philadelphia has adopted a master plan that includes the creation of wetlands to help protect the city from rising seas. And managers at the U.S. Naval Academy in Annapolis, MD, are using quickly deployable "door dams" to protect the entrances of academic buildings and other important facilities from minor flooding.

Critical Help from State and Federal Partners

Although coastal communities from southeast Florida to coastal Maine are beginning to take steps to grapple with sea level rise, communities cannot be left to cope in patchy, uncoordinated, underresourced efforts. The technical and legal complexities are too great, the costs too steep, the trade-offs too difficult, and the number of people too large for these communities to go it alone.

Partnerships with state and federal governments will be essential in building coastal resilience (Moser, Williams, and Boesch 2012). With roughly a third of the U.S. population living in coastal counties, we are in many ways a coastal nation, and must meet this challenge as a nation (U.S. Census Bureau 2010). Fortunately, awareness of sea level rise and growing risks to coastal communities is already spurring state and federal action. For example:

Direction from the top. The president's Climate Action Plan, most known for the centerpiece policy regulating carbon emissions from power plants, also calls for creating a task force on climate preparedness, a $1 billion resilience fund, a $1 billion resilience competition, and a host of new information and planning resources to support state and local action (EOP 2013; The White House 2014).

17 For example, after Hurricane Sandy, the state of New York established a program in which the state would buy out home owners in a heavily affected Staten Island neighborhood as an alternative to rebuilding damaged homes (New York Rising 2014).

New initiatives. In response to the president's Executive Order 13514 in 2009, most federal agencies have made strong strides in integrating coastal risks and resilience-building into their policies and activities (Bierbaum et al. 2014). On top of this, a host of new initiatives is taking shape across a range of agencies.[18]

Information sharing. The Third National Climate Assessment outlines coastal risks and adaptation options, and efforts by communities, tribes, states, and federal agencies to prepare for climate change (Moser et al. 2014). States and coastal communities can use this information to collaborate on measures to adapt to higher seas and more tidal flooding.[19]

Still, despite growing federal recognition of the need to make homes, infrastructure, and whole cities more resilient to climate change, few federal policies require that approach, and some can actually stymie it (Georgetown Climate Center 2014b). For example, the agencies overseeing federal funds for highway construction and urban development do not yet require adaptive planning for sea level rise and coastal flooding. And given the nation's deteriorated infrastructure and competing needs, securing federal funds for projects designed to build long-term resilience is a challenge.

Nor are all states firmly on board. Some, such as California, require local regulatory and permitting authorities to consider historical and projected sea level rise (California Coastal Commission 2013), while others, such as North Carolina, have discouraged such consideration (General Assembly of North Carolina 2011). And misalignment between federal, state, and local policies and priorities can stymie adaptation efforts (Bierbaum et al. 2014).[20]

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Federal and state officials announce funding for the Connecticut cities of Norwalk and Bridgeport to build coastal resilience, some of which is slated for redevelopment of aging housing projects.

ESSENTIAL STEPS

Although state and federal officials are beginning to respond to sea level rise and coastal flooding, they must mobilize on a scale commensurate with the challenge. Fortunately, when we resolve to direct resources to a crisis, we can respond quickly and effectively. Sensible steps include:

Build and maintain a monitoring and data-sharing system equal to the threat. Because coastal communities have limited information on historic and projected sea level rise, maintaining adequate budgets for NOAA's tide gauges and satellite measurements is critical. Combining such monitoring with higher-resolution methods for completing topographic coastline surveys will help communities make well-informed decisions.

Encourage or mandate the use of good scientific information. Requiring communities and other applicants for federal funds to consider sea level rise in planning, designing, and permitting new development and post-disaster redevelopment can ensure that they can withstand tidal flooding and storm surge. Federal agencies can also require applicants to show what measures they will take to cope with future sea level rise.

Support planning. Though planning resources exist, local stakeholders may lack the tools they need to plan adaptive

18 For example, FEMA is updating flood risk maps for communities around the country. The Department of Housing and Urban Development has developed a post-Sandy rebuilding strategy that treats improved resilience in the face of future events as a core goal of the rebuilding process. And the Army Corps of Engineers has launched a North Atlantic Comprehensive Study to outline steps to strengthen the resilience of coastal communities (Bierbaum et al. 2014). Many states are also assessing their vulnerability to rising seas and coastal flooding, updating hazard mitigation plans, and planning adaptation measures (Bierbaum et al. 2014; Georgetown Climate Center 2014a).

19 See, for example, NOAA Coastal Services Center n.d. and The White House 2014.

20 For example, local stakeholders—home owners, developers, insurers, and elected officials—may oppose new federal policies perceived to restrict their rights, options, and profits. And local adaptation plans could run afoul of, for example, state coastal management and federal wetlands regulations.

measures and learn from the efforts of others.[21] Federal support for state and local planning and collaboration could accelerate efforts to build coastal resilience.

Mobilize funding. Communities will need substantial and sustained federal and state funding to prepare for sea level rise. The Obama administration's 2015 budget proposal included $1 billion to establish the president's proposed resilience fund, and funding for Hurricane Sandy relief will support the $1 billion local resilience competition. These steps are a down payment on the major investment that adapting to sea level rise will require.

Improve risk management. Property values and the price of flood insurance today do not reflect the true risks of living and running a business along our coasts (Kunreuther 1996). The National Flood Insurance Program (NFIP), the only insurer in most coastal areas, has for years been providing flood insurance at rates that some studies suggest are roughly half the true risk-based cost (PCI 2011), resulting in roughly $24 billion in NFIP debt in 2013 (GAO 2013). Changing this—such as through increases in the cost of federal flood insurance—will be hard for many coastal property owners. But without reforms, the risks and costs can become unmanageable, and the system insolvent (Michel-Kerjan and Kunreuther 2011). In the near term, federal incentives and mandates to reduce communities' flood risks, such as incentives for home owners to invest in flood-proofing upgrades, can aid the transition (Cleetus 2013). Projections for more tidal flooding make this effort urgent.

Ensure equitable investments. Regular flooding in low-income neighborhoods will hit vulnerable home owners especially hard (Moser et al. 2014). Chronic tidal flooding may turn some home owners into repetitive claimants, increasing the cost of their flood insurance while driving down the value of their property. And communities differ in the financial resources at their disposal, exposing important equity challenges. Federal investments in coastal resilience should prioritize households and communities with the greatest need.

Reduce carbon emissions. Near-term sea level rise and increases in tidal flooding may be locked in, but changes later this century and beyond are not. To slow the rate of sea level rise—and enable our coasts to adapt in affordable and manageable ways—we must reduce our heat-trapping emissions.

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21 For example, ProVIA offers comprehensive guidance to the international community (www.unep.org/provia/)*; EcoAdapt offers a U.S.-focused climate adaptation "starter kit"* (http://ecoadapt.org/programs/awareness-to-action/climate-starter-kit). *See also resources from the Climate Adaptation Knowledge Exchange* (www.cakex.org/)*, the Urban Sustainability Directors Network* (http://usdn.org/)*, Georgetown Climate Center* (www.georgetownclimate.org/)*, and the American Society of Adaptation Professionals* (https://adaptation professionals.org).

SNAPSHOT

Key West, FL

With fewer options than most cities for holding back the sea, Key West considers how to cope with frequent flooding.

© Key West Citizen

A new moon and extreme tides drove flooding in portions of Key West over several days in September 2009.

Tourists, sailors, artists, nature lovers, and fishing enthusiasts come together in Key West—the southernmost city in the continental United States. With little elevation, Key West is easily overwhelmed by storm surge during hurricanes, as it was during Wilma in 2005.

But the sight of seawater coming up through storm drains and sloshing over historic Duval Street no longer occurs only during storms (Carter 2014; Neugent and Bergh 2010). With sea level on the rise, the city now increasingly floods at high tide when the moon is either full or new (Allen 2013). By 2045, it could face on the order of 200 tidal floods a year.

Built on porous limestone, which allows seawater to easily percolate up through it, the city has limited options for containing the sea (Zhang et al. 2011). The Southeast Florida Regional Climate Change Compact is developing a regional response to the threats of climate change and sea level rise. But recognition is growing among residents of famously laid-back Key West that, without concerted action, parts of the city could eventually become unlivable (Kay 2013).

SNAPSHOT

Philadelphia, PA

The city is redeveloping its waterfront with future flooding in mind.

© Lauren Michell Rabaino

On Philadelphia's waterfront, efforts are being made to enable parks to serve as buffers against flooding.

For decades, planners and residents in Philadelphia—the East Coast's second most populous city and a historic treasure—have been considering how to expand public access to waterfront parks now cut off by Interstate 95 (DRWC 2014a). But in fulfilling a master plan for redeveloping the Delaware River waterfront, the city must contend with the surprising challenge of tidal flooding.

Although Philadelphia is not directly on the coast, it is vulnerable to coastal flooding because tides affect the Delaware and Schuylkill Rivers, which surround the city. During the full moon in June 2012, for example, high tides caused widespread flooding along the Delaware (NWS 2012).

By 2045, Philadelphia is projected to face more than 200 tidal floods a year—nearly 20 of them more extensive than the tidal flooding typically seen today. With officials aware of the threats of sea level rise and coastal flooding, the city's master plan for the waterfront includes the creation of wetlands to help protect Philadelphia from the encroaching sea (DRWC 2014b).

The Hard Truth: Fundamental Limits to Coastal Adaptation

As sea levels continue to rise, even our best efforts to adapt will not suffice in some areas under pressure from the resulting tides, waves, and storm surges (Dow et al. 2013; Moser, Williams, and Boesch 2012).

In certain places, shoreline dynamics will make it impossible to build a particular defensive structure. Adaptive measures may threaten certain ecosystems and the essential services they provide. At the household scale, a saltwater-corroded septic tank or lack of road access, for example, can compromise even flood-proofed homes. Residents, business owners, communities, and ultimately the nation may reach their capacity to fund costly measures. People may also simply reach the limit of how many flood-related disruptions they are willing to live with.

These and other physical, economic, and social tolerance thresholds are de facto limits to coastal adaptation, and when they are reached, communities face the prospect of retreating from the shore. If we plan well, though, before flooding becomes too disruptive, we can pull back from the most affected areas while sustaining our communities. This, too, is adaptation—although not adapting in place. Of course, retreat can occur through an unmanaged process (Kousky 2014). But if a community exhausts all other options and finds itself forced to withdraw from certain areas amid daily high-tide flooding, an unplanned process of retreat could strain the community further. In either case, the sea slowly claims flooded areas.

In one of the most poignant and striking early cases of large-scale, coordinated retreat, the Pacific island nation of the Maldives is working to relocate its entire population of 350,000 citizens, potentially to Australia (Boyle 2012). The population of the Carteret Islands, part of Papua New Guinea, also began relocating in 2009. Scientists say the islands will be uninhabitable by 2015 (Edwards 2013).

In the United States, these limits will be reached sooner in those areas exposed to greater risks, those near more fragile ecosystems and with limited natural buffers, and those with fewer resources (Martinich et al. 2012). Retreat will also happen sooner if we allow climate change and sea level rise to grow into an even greater crisis.

Curbing Carbon Emissions to Limit Future Sea Level Rise

Global heat-trapping emissions are rising rapidly, and are on a trajectory to push average global surface temperatures more than 2°C above the preindustrial average—the threshold beyond which dangerous climate change is likely, scientists and governments alike agree (IPCC 2014a; UNEP 2010; Smith et al. 2009). We are creating and leaving our children and grandchildren an altered and more dangerous planet. And the warmer and more disruptive our climate becomes, the less feasible and effective—and more stark, disruptive, and costly—our efforts to adapt will be (IPCC 2014b).

To stay below this temperature threshold—and slow the rate of sea level rise later this century and beyond—nations would need to cut global carbon dioxide (CO_2) emissions 50 percent or more below 1990 levels by 2050. Ensuring that outcome would likely also require actively removing CO_2 from the atmosphere in the second half of this century (IPCC 2014a; UNEP 2010).

We are late in taking serious steps to meet this critical goal. However, it is within reach if global emissions begin to decline by 2020, and emissions drop steadily from then until 2050 (IPCC 2014a; Peters et al. 2013; UNEP 2010). The Intergovernmental Panel on Climate Change (IPCC) has made clear in its latest report, though, that only an intensive push over the next 15 years to bring emissions under control can get us there (IPCC 2014a). "We cannot afford to lose another decade," said Ottmar Edenhofer, a German economist and co-chair of the committee that wrote the report. "If we lose another decade, it becomes extremely costly to achieve climate stabilization" (Gillis 2014).

Some 195 nations are now negotiating commitments to reduce emissions in the 2020–2030 time frame, under the United Nations Framework Convention on Climate Change. The strength of the resulting agreement—scheduled for completion in December 2016—will be a major factor in determining the world's prospects for ensuring that global warming does not exceed 2°C (Rogelj et al. 2012).

In 2009, the United States pledged to reduce its emissions 17 percent below 2005 levels by 2020 (EOP 2013). And in 2014, the U.S. Environmental Protection Agency (EPA) announced the nation's first-ever regulations of carbon emissions from power plants—the largest source. The resulting

An extreme high tide in Hampton, NH, swamps a backyard.

© Flickr/Chesapeake Bay Program

Flooding in Annapolis, MD, driven by rain, wind, and tides suggests the scale of flooding that certain tides alone could bring—absent proactive measures—over the next several decades.

cuts in emissions—coupled with limits on those from the transportation sector—could put the United States on track to meet its goal. However, UCS analysis suggests that the EPA regulations could be made much stronger. If we ramp up the production of renewable energy, the nation could reduce emissions from the power sector alone 50 percent by 2030 (UCS 2014). As the United States makes its post-2020 pledge, it should confidently commit to reducing its emissions more than one-third by 2025.

Meanwhile the sea is rising and our only responsible choice is to plan for it. Leaders at all levels of government need to take seriously the risks facing people living along our coasts and the urgent need for action. Communities faced with tidal flooding need to hold their local, state, and national leaders accountable for taking strong action to both adapt to rising seas and limit global warming. Silence will slow efforts on both fronts during this critical window.

The challenge of sea level rise and encroaching tides cuts straight to our national identity and vision for the future. In the near term, coastal America faces a slow-moving but unstoppable and transformative force. We can respond by digging in for a long and bruising century of worsening coastal impacts: we can wait until tides that never recede force our hand. We can then abandon some of the places we love in an unmanaged manner.

Instead, as a nation, we should commit to the challenge today, treating the resilience of our coasts as a century-long project—one that requires a concerted early push, one to which we commit for the long haul, and one that enables communities to thrive even in the face of encroaching tides.

[Communities faced with tidal flooding need to hold their local, state, and national leaders accountable for taking strong action to both adapt to rising seas and limit global warming.]

[KEY TERMS]

Adaptation: The process of adjusting to actual or expected climate change. In human systems, adaptation seeks to moderate harm or exploit opportunities. In natural systems, human intervention may facilitate adjustments to expected climate change and its effects (IPCC 2014b).

Climate change: Major changes in temperature, precipitation, or wind patterns, among other phenomena, over several decades or longer (NCA 2014; EPA 2013).

Coastal flooding: When water inundates normally dry land. This flooding can be caused by extreme high tides (sometimes referred to as shallow coastal flooding), storms and the resulting storm surge, rainfall and runoff that empties into coastal areas, or a combination. The National Weather Service categorizes coastal flooding as "minor," "moderate," or "major" when issuing public alerts (NWS n.d.). Extreme high tides typically result in minor and sometimes moderate coastal flooding, whereas storms can create major coastal flooding.

Extreme high tide: Twice a month (during new and full moons), Earth, sun, and moon align, and the combined gravitational pull of the sun and moon exerts greater force on Earth's oceans. As a result, high tides become slightly higher than normal, while low tides become slightly lower. These tides are often called spring tides. Several times a year, when a new or full moon occurs when the moon is at its closest point to Earth, the range of the tides is even larger. These are called perigean spring tides, or king tides. In this report, extreme high tides include both spring and king tides—both of which can result in coastal flooding.

Global warming: The recent and continuing increase in average global temperature near the earth's surface (Walsh et al. 2014).

Minor or "nuisance" flooding: Flooding that exceeds the minor flooding threshold as determined by the National Weather Service (NWS) for a given location. Floods categorized as minor—associated with NWS coastal flood advisories—are not expected to pose a risk to life or property (NWS n.d.). Because the NWS defines the flooding threshold locally, the level of flooding during a minor event will vary from one place to another. Impacts can be as isolated as standing water in parking lots, or as disruptive as flooded, impassable streets.

Moderate flooding: Flooding that exceeds the NWS moderate flooding threshold. Moderate floods—associated with NWS coastal flood warnings—typically affect substantial local areas and can pose a risk to life and property (NWS n.d.). Because the NWS also defines this flooding threshold locally, the level of flooding during a moderate flood event will vary from one place to another.

Mitigation: A human intervention to reduce heat-trapping emissions or remove carbon already in the atmosphere (IPCC 2014b). This is not to be confused with mitigating the risks of disasters, including those that are human-induced, by reducing hazards, vulnerability, and exposure (IPCC 2014b).

Resilience: The capacity to cope with a hazardous event or disturbance. Building resilience entails responding or reorganizing in ways that maintain a community's essential identity, structure, and function while sustaining its capacity for adaptation, learning, and transformation (IPCC 2014b; Arctic Council 2013).

Risk: The potential for consequences when something of human value, including people's lives, is at stake and the outcome is uncertain (IPCC 2014b).

Sea level rise:

- **Global sea level rise:** An increase in the average height of Earth's oceans, observed globally since the late nineteenth century (Church and White 2011). This trend is primarily attributed to expansion of the oceans as they absorb heat from a warming atmosphere, and shrinking land ice—both resulting from global warming (NOAA Tides and Currents 2013a).
- **Local sea level rise:** The combination of global sea level rise and local factors, such as subsidence (sinking) of land and changes in ocean dynamics, measured at a specific point on the coast. Because local factors can be significant, local trends in sea level can differ greatly from average global sea level rise (NOAA Tides and Currents 2013a).

Tidal flooding: Varying degrees of flooding (sometimes referred to as shallow coastal flooding) that occur along the coast during extreme high tides.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change. Vulnerability is a function of the character, magnitude, and rate of variations to which a system is exposed, its sensitivity, and its adaptive capacity (Walsh et al. 2014).

Projections for Flooding Frequency in 52 Communities

State	Tide Gauge	Gauge #	SLR (inches)	SLR (inches)	Events per Year			Nearest Sea Level Rise (SLR) Projection	Miles to Nearest Proj.
			2030	2045	Today	2030	2045		
CT	Bridgeport	8467150	5.1	11.3	22	62	162		
CT	New Haven	8465705	5.1	11.3	7	25	86	Bridgeport	27
CT	New London	8461490	5.2	11.4	2	7	37		
DC	Washington, DC	8594900	5.4	11.9	43	155	388		
DE	Lewes	8557380	5.7	12.4	28	87	223		
DE	Reedy Point	8551910	5.9	12.8	15	76	257		
FL	Apalachicola	8728690	4.3	9.7	1	1	3		
FL	Clearwater Beach	8726724	5.0	11.1	0	1	5		
FL	Fernandina Beach	8720030	4.7	10.5	2	8	37		
FL	Key West	8724580	5.0	11.0	3	45	212		
FL	Mayport (Jacksonville)	8720218	4.7	10.5	7	25	101	Fernandina Beach	19
FL	Panama City	8729108	4.3	9.7	0	0	3	Apalachicola	51
FL	St. Petersburg	8726520	5.1	11.2	0	1	1		
FL	Vaca Key	8723970	5.4	11.8	0	6	88		
FL	Virginia Key (Miami)	8723214	5.4	11.8	6	48	237	Vaca Key	92
GA	Fort Pulaski (Savannah)	8670870	5.4	11.9	10	37	113		
LA	Lawma, Amerada Pass	8764227	9.6	19.4	0	0	5	Grand Isle	84
MA	Boston	8443970	5.0	11.1	11	31	72		
MA	Nantucket Island	8449130	5.6	12.2	1	3	12		
MA	Woods Hole	8447930	5.2	11.4	0	0	0		
MD	Annapolis	8575512	5.5	12.0	50	187	368		
MD	Baltimore	8574680	5.4	11.8	17	63	227		
MD	Cambridge	8571892	5.9	12.7	10	46	242		

State	Tide Gauge	Gauge #	SLR (inches)	SLR (inches)	Events per Year			Nearest Sea Level Rise (SLR) Projection	Miles to Nearest Proj.
			2030	2045	Today	2030	2045		
MD	Ocean City	8570283	5.7	12.4	8	30	173	Lewes	31
MD	Tolchester Beach	8573364	5.4	11.8	4	16	78	Baltimore	45
ME	Portland	8418150	4.2	9.6	11	30	65		
MS	Bay Waveland Yacht Club (Bay St. Louis)	8747437	4.7	10.5	13	37	110	Pensacola	83
NC	Duck	8651370	6.7	14.1	8	32	126	Sewells Point	62
NC	Wilmington	8658120	4.6	10.4	44	133	343		
NC	Wrightsville Beach	8658163	4.6	10.4	8	29	90	Wilmington	10
NJ	Atlantic City	8534720	6.4	13.7	32	92	244		
NJ	Cape May	8536110	6.4	13.6	41	128	302		
NJ	Sandy Hook	8531680	5.4	11.7	33	88	211	The Battery	16
NY	The Battery (New York City)	8518750	5.4	11.7	5	16	59		
NY	Bergen Point	8519483	5.4	11.7	14	45	130	The Battery	8
NY	Kings Point	8516945	5.4	11.7	22	57	142	The Battery	15
NY	Montauk	8510560	5.6	12.2	3	10	52		
PA	Philadelphia	8545240	5.9	12.8	19	66	206	Reedy Point	35
RI	Newport	8452660	5.2	11.4	0	1	8		
RI	Quonset Point	8454049	4.9	10.8	0	0	3	Newport	7
SC	Charleston	8665530	5.2	11.5	24	78	187		
SC	Springmaid Pier (Myrtle Beach)	8661070	5.8	12.4	4	15	66		
TX	Eagle Point	8771013	7.7	16.0	0	1	11	Galveston Pier 21	14
TX	Galveston Pier 21	8771450	7.7	16.0	0	1	12		
TX	Rockport	8774770	7.6	15.8	1	3	39		
TX	Sabine Pass	8770570	7.1	14.9	0	7	67		
TX	USCG Freeport	8772447	9.1	18.7	0	4	58	Freeport	1
VA	Kiptopeke	8632200	5.7	12.4	10	36	140		
VA	Lewisetta	8635750	7.1	14.9	14	88	386		
VA	Sewells Point (Norfolk)	8638610	6.7	14.1	9	39	182		
VA	Wachapreague	8631044	5.7	12.4	5	16	58	Kiptopeke	35
VA	Windmill Point	8636580	7.1	14.9	8	54	304	Lewisetta	28

Note: Events per year today represent the number of times that tide heights, as measured at the nearest NOAA tide gauge, exceed local water level thresholds that have been established (by the Weather Forecast Offices of the National Weather Service) as triggering local flood conditions. These figures are an annual average, based on the 5-year period from 2009 to 2013. The number of events per year, in each of the three time frames, is an indicator of localized flooding, from the most minor to the more extensive. This analysis does not assign a specific flood type or location to these flood events. For more information, see the Supporting Technical Document online at: *www.ucsusa.org/encroachingtides*.

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Encroaching Tides

How Sea Level Rise and Tidal Flooding Threaten U.S. East and Gulf Coast Communities over the Next 30 Years

By 2045, within the lifetime of a typical home mortgage, more than half of the 52 communities in our analysis could see a 10-fold or greater increase in the frequency of tidal floods, and one-third of them could average more than 180 tidal floods per year.

Today scores of coastal communities in the United States are seeing more frequent tidal flooding. And as global warming drives sea levels higher over the next 15 to 30 years, flooding from high tides is expected to occur even more often and cause more disruption, particularly on the East Coast and, increasingly, on the Gulf Coast. This flooding will redefine how and where people in affected areas live, work, play, and otherwise go about their daily lives. Coastal communities, and the nation as a whole, need to start planning today to cope with sea level rise and unprecedented tidal flooding, and to take swift and decisive action to limit longer-term damage to our coasts.

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NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
Phone: (617) 547-5552
Fax: (617) 864-9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Suite 800
Washington, DC 20006-1232
Phone: (202) 223-6133
Fax: (202) 223-6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
Phone: (510) 843-1872
Fax: (510) 843-3785

MIDWEST OFFICE
One N. LaSalle St., Suite 1904
Chicago, IL 60602-4064
Phone: (312) 578-1750
Fax: (312) 578-1751

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