VARIATIONS

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## US East Coast Sea Level Changes and Impacts

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The Fourth National Climate Assessment has acknowledged that the United States trillion-dollar coastal property market and infrastructure are already threatened by the effects of sea level rise. In several communities, including densely populated urban centers along the US East Coast such as New York City, Norfolk, and Miami, recurring "sunny-day" flooding events are already causing disruptions and economic losses. Future projections further indicate that such impacts will severely increase and amplify by the end of the century, even under the lower emissions scenarios. Therefore, mitigation of these currently observed and anticipated future impacts to society requires robust science-based and multidisciplinary planning to aid in adaptation efforts. To enable this, significant

# How are decision-science methods helping design and implement coastal sea-level adaptation projects?

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Low-lying coastal communities around the globe are facing evolving risks of physical, social, and economic impacts of sea level rise (Oppenheimer 2019). Often, implications of rising seas are compounded by other stressors such as increasing intensity of rainfall and, in some cases, rising groundwater levels in coastal communities (Jane et al. 2020). Tide gage data around the world show that the Global Mean Sea Level (GMSL) from 1900 to 1990 has been in the range of 1-2 mm/year, but the more recent data supplemented by the satellite altimetry show that this rate has increased to about 3 mm/year for 1993 to 2017 (Gornitz et al. 2019). Regional and local rates of sea level change differ from the GMSL due to a variety of factors including ocean density and currents, effects of the redistribution

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advances in sea level science, technology, and adaptation efforts have been made over the past two decades. Decision makers can now count on unprecedented levels of knowledge about the specific processes that can drive sea level change along the coasts, on science-based tools for future planning under complex and uncertain decision dimensions, and on cost-efficient observing technologies that are enabling real-time sea level monitoring with high spatial and temporal resolution. Some of these recent advances are highlighted in this edition of US CLIVAR *Variations*, which also showcases some of the forefront work that is being led by practitioners and decision makers in improving coastal resilience to sea level rise. These efforts provide excellent examples of transitions of science into decision making, which will become increasingly more important to mitigate future sea level rise.

**US CLIVAR VARIATIONS**

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of melting ice on Earth's gravitation and rotation, and vertical land movement due to lasting effects of past ice mass losses (also known as glacial isostatic adjustment, or GIA), subsidence, and compaction and uplift of the earth surface (Hall et al. 2016). In many coastal areas around the globe, the impacts of sea level rise are currently manifesting themselves in the form of frequent recurrent flooding (known commonly as "nuisance flooding" or high-tide flooding; Sweet et al. 2018), and they are already causing economic impacts (e.g., loss of tourism) and societal disruption. Such flooding may be a nuisance now for many coastal communities but will likely be chronic with rising seas in the future. The demand for adaptation strategies to address impacts of rising seas is growing, in particular because planning and implementation of adaptation can take up to decades.

### Decision Making Under Deep Uncertainty

Decision making for adaptation to sea level rise, particularly for projects with long service life and/or long-term societal impact, is challenging due to a variety of reasons (Kopp et al. 2019). First, prediction of future sea levels is one of deep uncertainty (Hallegatte et al. 2012; Kopp et. Al. 2017), attributable largely to the limitations of current models of ice sheet melting, particularly in Antarctica, and the inability to forecast future emissions accurately. As a consequence, prediction bounds of late century GMSL are broad, requiring the practitioners to adapt robust strategies for adaptation. Second, the feedback of future sea levels on the physical, social, and economic systems in coastal belts is complex and poorly understood, and as a result, the traditional analysis using costs and benefits for adaptation planning is less useful. Third, the sequential actions taken in an environment of deep uncertainty cannot be assumed to be independent; decisions taken today will influence future options as well as societal developments. Deep uncertainty due to climate change requires us to move away from "predict and act" paradigm to one of "robust decision making" characterized by continuous learning and dynamic adaptation. Recent emphasis on climate change and deep uncertainty has generated a plethora of research on the topic of Decision Making under Deep Uncertainty (DMDU). Emergence of a DMDU professional society illustrates the topic's prominence. While there are many methods of DMDU (Marchau et al. 2019), one that is becoming more attractive for planning and phased implementation of projects is the Dynamic Adaptive Policy Pathways (DAPP) approach (Haasnoot et al. 2013; 2019). In this approach, a plan includes an initial action, with emphasis on monitoring data, and a series of actions over time (pathways) depending on future scenarios that may emerge. In this paper, we briefly describe the DAPP approach and present a case study of applying it to develop adaptation strategies for mitigating future flooding in a coastal basin subject to compounding effects of climate change in Miami Dade County, Florida.

## Dynamic Adaptive Policy Pathways (DAPP)

In situations of deep uncertainty, policy makers need to make decisions for the near term while ensuring that long term options for addressing uncertain future conditions are not pre-empted because of other actions and developments of the future. The DAPP approach explicitly incorporates decisions over time with emphasis on dynamic planning in an uncertain future. It integrates the concepts of adaptive planning, adaptation pathways, and tipping points to incorporate under what conditions an action is no longer meeting a particular objective. The overall DAPP approach (Haasnoot et al. 2019) is based on the premise that a particular policy or action had a design life after which it may fail due to changing environmental conditions (e.g., sea level rise). At that "tipping" point, a different policy or action may be needed to maintain a level of resilience that is desirable. As conditions evolve, alternative policy pathways (sequences of actions) are possible over the planning horizon of a particular project. The best way to illustrate the DAPP approach is to display the policies on a pathways map (Figure 1) which shows the different choices and routes under changing conditions. A particular action may not meet the objectives after some time (tipping points illustrated as "transfer stations") at which time the current policy may need to shift to a different pathway. Clearly, the decision to transfer need to happen before the occurrence of a tipping point, allowing the policy makers to plan for it. More details of the principles of the DAPP approach and its application may be found in Haasnoot et al. (2019).

## Case Study - Adaptation to Sea Level Rise in the Little River Basin, Miami, Florida

Planning for flood protection in highly urbanized, coastal basins in Miami-Dade County, Florida (Figure 2), requires consideration of compounding effects of sea level change, rising groundwater levels, and extreme rainfall. Evolution of such future environmental stresses and shocks are highly uncertain. The applications of the DAPP approach was focused on the C-7 basin (Little River Basin)

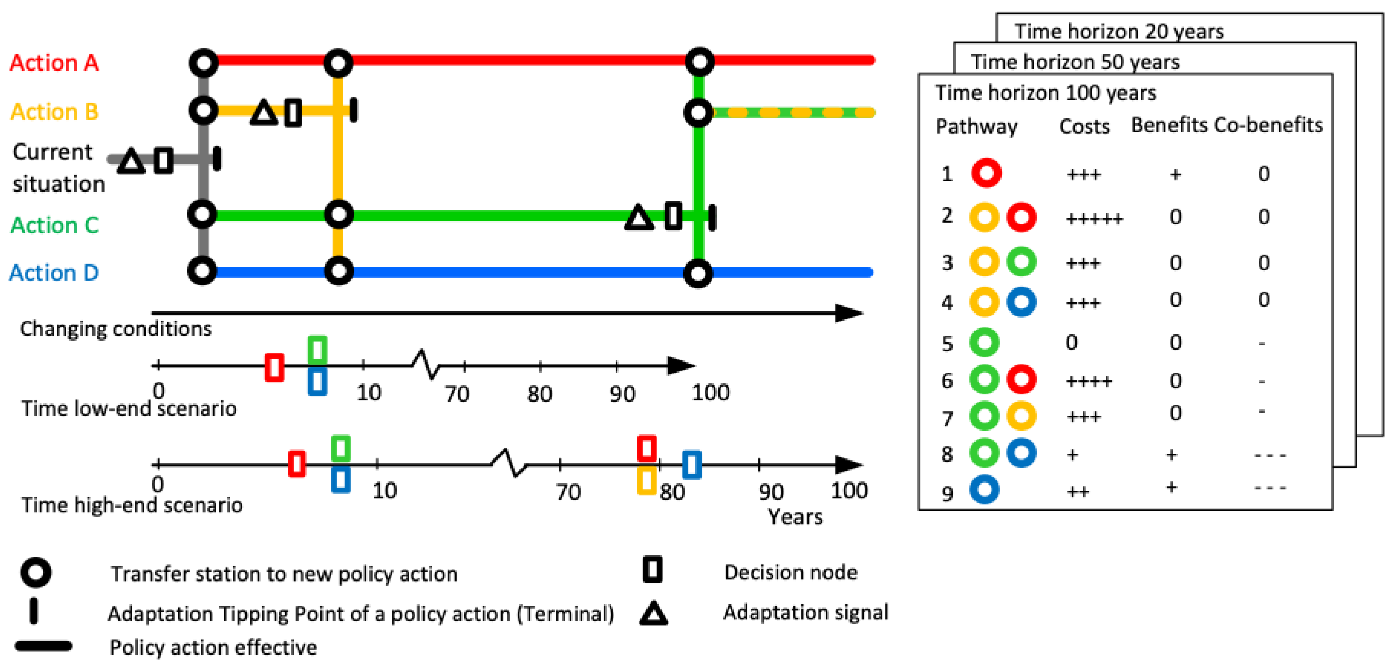


**Figure 1.** Example of a pathways map and a scorecard presenting the costs and benefits of the nine alternative pathways presented in the map. From Haasnoot et al. (2013).

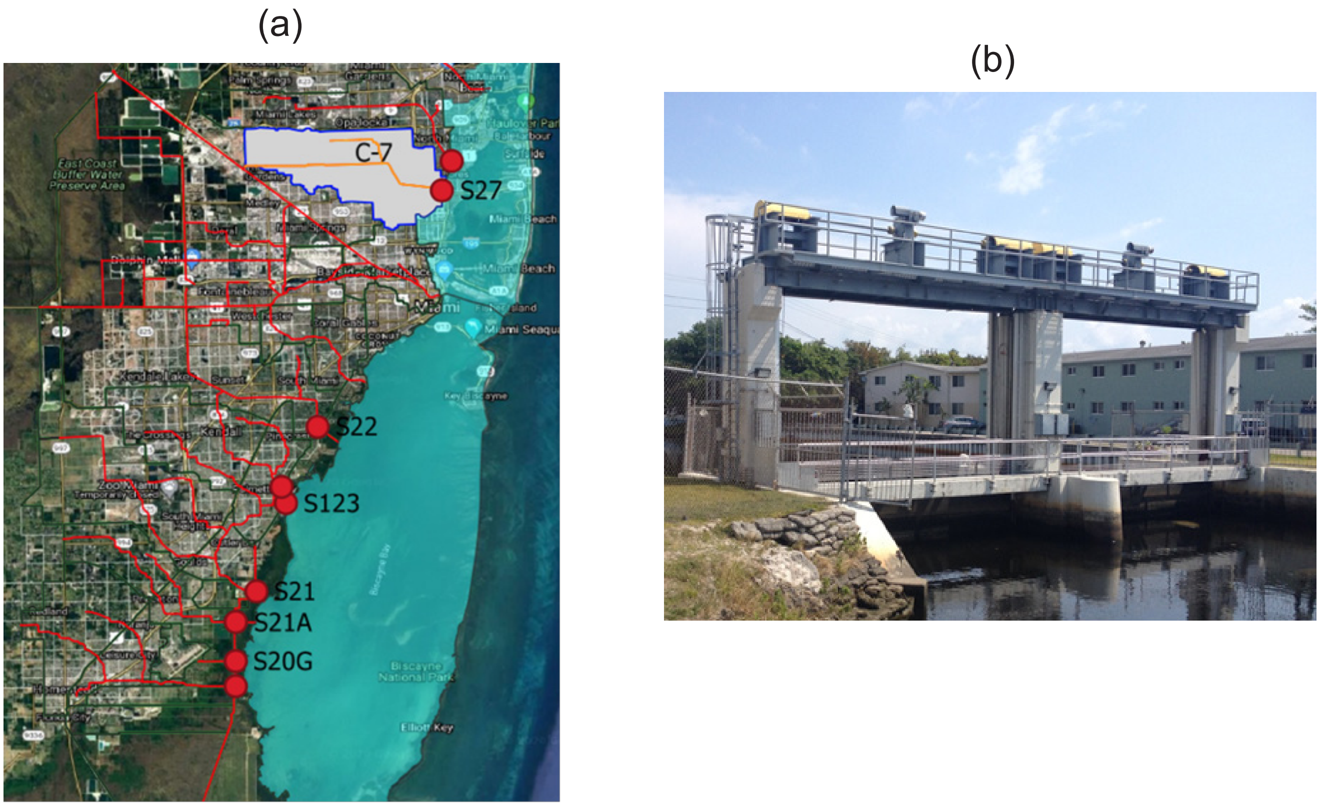


**Figure 2.** (a) Coastal basins in Miami-Dade County, Florida. The study site, C-7 (Little River Basin) is highlighted; (b) S-27 Structure at which drains the Little River Basin to Biscayne Bay.

in the northeastern Miami-Dade County (Figure 2a). The C-7 basin has an area of about 32 square miles and its primary canal, C-7 canal, provides flood protection and drainage, and maintains groundwater table elevations to mitigate saltwater intrusion. The study area comprises approximately 254,000 inhabitants in residential single family and multi-family buildings, industrial actives and public buildings. This basin is highly vulnerable to flooding, and the current repetitive property loss information shows frequent damages from flooding that are expected to exacerbate.

The C-7 canal was built as part of a large regional system known as Central and South Florida Project, and it was designed to pass the Standard Project Flood at its outlet structure, S-27 (Figure 2b), without exceeding the design headwater stage while maintaining a headwater stage to prevent saltwater intrusion. The original design of this structure, dating back to early 1960s, did not consider sea level rise as a significant factor. Since drainage of the main C-7 canal to Biscayne Bay is by gravity only, the structure S-27 is known to underperform during periods of intense rainfall and high sea levels. With rising sea levels, S-27 discharge capacity will decrease due to high downstream levels during high tide and coastal storms.

Sea level projections for South Florida region are broad, and because of low topography in many watersheds such as C-7, the potential impacts in terms of flood damage without any adaptation are likely to be extensive. The broad projection uncertainty and the varying sensitivity of impacts to sea level rise along with other uncertainties make the adaptation to a classic case of deep uncertainty.

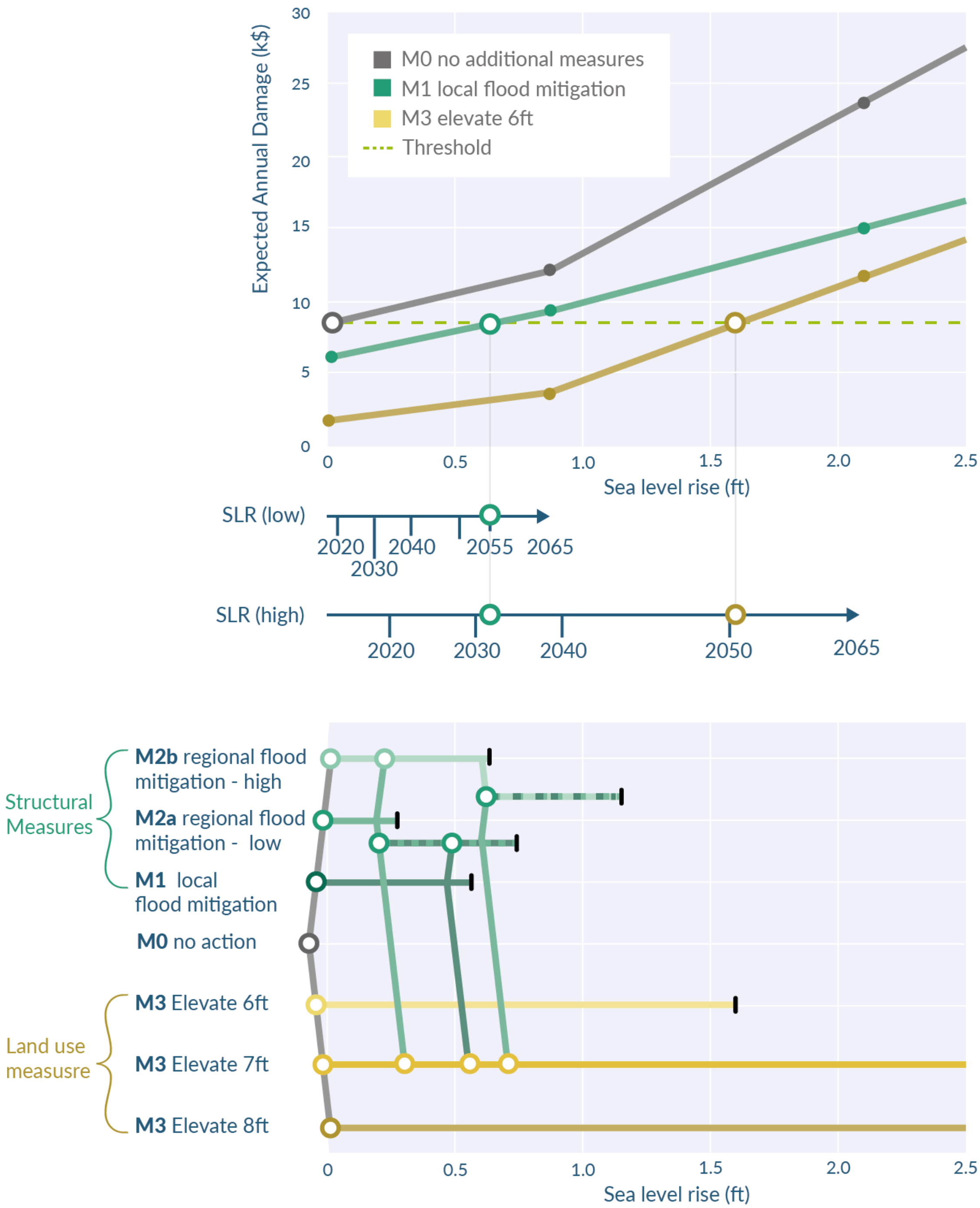


**Figure 3.** Expected annual damage (EAD) as a function of sea level rise (SLR) corresponding to M0, M1, and M3; (b) Adaptation Pathways map for the entire basin, based on the simulated expected annual damage for the current sea-level and the two possible future sea level rises.

In the case study, flood depths are carried out using the XP Storm Water Management Model for current sea level, two sea-level rise scenarios, and four rainfall return periods (5, 10, 25, and 100 years). The maximum stage water levels for each sub-basin in the study area are obtained for later use by the damage assessment model. Direct flood damages are estimated for each return period, using the Delft-Flood Impact Assessment Tool. The model adopts flood damage functions from the Federal Emergency Management Administration's Hazards U.S. (HAZUS) model for various categories of structures and calibrates the flood damage estimates from Tropical Storm Leslie that hit the area in October 2000 (Bouwer et al. 2017).

Three alternative adaptation options are assessed for effectiveness and costs:

- M1: local flood mitigation, consisting of flood walls, additional exfiltration trenches, flap gates, and local pumps;
- M2: regional flood mitigation, consisting of the installation of forward pumps at the S-27 coastal structure; and
- M3: land-use mitigation consisting of improved building codes to raise roads and buildings to a level of 6, 7, or 8 feet NGVD which correspond to flood levels under current conditions for 10-year, 25-year, and 100-year return periods respectively.
- The local and regional flood mitigation measures (M1 and M2) substantially reduce flood risk under moderate sea-level rise, by 30-50% compared to future risk without any mitigation measures, but are less effective under the high sea-level rise scenario. Local flood mitigation measures are about as effective as the regional mitigation measures. They have an especially positive effect for several downstream sub-watersheds, but cause increased stage levels and damages upstream, which offset some of the benefits. Both the local and regional flood mitigation measures studied here are not capable of keeping future risk at the current level under sea level rise. The land-use mitigation measures (raising buildings and roads) are very effective, especially when buildings and roads are raised to 8 feet. Based on the current analysis, this is the only measure found that can maintain or reduce the current flood risk under sea level rise futures.

For comparing among the adaptation options, the expected annual damage (EAD) is used as a quantitative measure (Figure 3a). The current estimate of EAD is used as a threshold. The effectiveness of future adaptation strategies (M1, M2, and M3) are assessed using their ability to keep the EAD approximately at the current level. Figure 3b shows an example of the adaptation pathways explored for the C-7 basin. The three variations of the M3 mitigation alternatives perform well up to 1.6 feet, or more than 3 feet of sea-level rise if buildings and roads are raised up to 7 or 8 feet.

Although not all combinations of measures are quantitatively assessed, the pathways analysis suggests that a combination of local or regional flood mitigation measures will be implemented consecutively. That approach can be effective as near-term risks are reduced with flood mitigation measures, while the long-term risks are mitigated by raising roads and buildings. Local and regional pumps – when implemented in the very near future – would help to maintain current levels of protection, while allowing time to implement the longer-term solution of raising building and road elevations. The pathways show that, given the high uncertainty and possible severe consequences of sea-level rise in this area, raising buildings, and transport infrastructure, including roads, is the most viable long-term option to manage future flood risk and increase flood resilience. The application of the DAPP approach suggests that a reasonable set of pathways may include (a) local and regional pumps in the near term; (b) raising properties and infrastructure for the longer term; and (c) because implementation of measures in (b) may take long time, it should be initiated now.

## Conclusions

Deep uncertainties in projections associated with climate change in general, and sea level rise in particular, require communities to consider emerging decision making methods to plan and implement coastal resiliency efforts. One such method is the Dynamic Adaptive Policy Pathways (DAPP), which integrates the concepts of adaptive planning, adaptation pathways, and tipping points to incorporate when an action is no longer meeting a particular objective. As demonstrated in this paper for a case study in Miami-Dade region of South Florida, DAPP is an effective tool for the development and phasing of adaptation projects under uncertainty.

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*References*

Bouwer, L. M., M. Haasnoot, D. Wagenaar, and K. Roscoe, 2017: Assessment of alternative flood mitigation strategies for the C-7 Basin in Miami, Florida. Report 1230718-000, 62 pp.

Gornitz, V., M. Oppenheimer, R. Kopp, P. Orton, M. Buchanan, N. Lin, R. Horton, and D. Bader, 2019: New York City Panel on Climate Change 2019 report chapter 3: Sea level rise. *Ann. N. Y. Acad. Sci.*, **1439**, 71-94, doi:10.1111/nyas.14006

Haasnoot, M., J. H. Kwakkel. W. E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: A new method for crafting robust decisions for a deeply uncertain world. *Global Environ. Change*, **23**, 485-498, doi:10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., A. Warren, and J. H. Kwakkel, 2019: Dynamic adaptive policy pathway, *Decision Making Under Deep Uncertainty*. V. Marchau, W. Walker, P. Bloemen, and S. Popper, Eds., Springer, Cham, 71-92.

Hall, J. A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional sea level scenarios for coastal risk management: Managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program. 224 pp.

Hallegatte, S., A. Shah, R. Lempert, C. Brown, and S. Gill, 2012: Investment decision making under deep uncertainty—Application to climate change. Policy Research Working Paper 6193. World Bank, Sustainable Development Network, Office of the Chief Economist, 39 pp.

Jane, R., L. Cadavid, J. Obeysekera, and T. Wahl, 2020: Multivariate statistical modelling of the drivers of compound flood events in South Florida. *Nat. Hazards Earth Syst. Sci. Discuss*., doi:10.5194/nhess-2020-82.

Kopp, R. E., and Coauthors, 2017: Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future*, **5**, 1217–1233, doi:10.1002/2017EF000663.

Kopp, R. E., E. A. Gilmore, C. M. Little, J. Lorenzo-Trueba, V. C. Ramenzoni, and W. V. Sweet, 2019: Usable science for managing the risks of sea-level rise. *Earth's Future*, **7**, 1235– 1269, doi:10.1029/2018EF001145.

Marchau, V. A. W. J, W. Walker, P. J. T. M. Bloemen, and S. W. Popper, 2019: *Decision Making under Deep Uncertainty, From Theory to Practice*. Springer International Publishing, 405 pp.

Oppenheimer, M., and Coauthors, 2019: Sea level rise and implications for low-lying islands, coasts and communities, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Sweet, W.V., G. Duseket, J. Obeysekera, and J. J. Marra, 2018: Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold. NOAA Technical Report NOS CO-OPS 086, 44 pp, doi:10.25607/OBP-128.

# Designing the resilient coastal communities of the future: A Southeast Florida case study

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In late 2009, local leaders in Broward, Miami-Dade, Monroe, and Palm Beach Counties jointly formed the Southeast Florida Regional Climate Change Compact (Figure 1) in response to the significant and shared climate change threats facing their six million residents. With foresight, these leaders recognized three important truths. One, the impact of a changing climate on their local communities is not a distant crisis to be ignored until the next political cycle; impacts are here and must be dealt with today. Two, these impacts do not recognize borders between local government authorities that divide the region into four counties and 109 municipalities. And, three, mobilizing a response at the needed scale requires local governments and other key stakeholders to coordinate, align efforts, and build capacity to respond regionally—particularly given a dearth of state and federal government action.

The establishment of the Compact addressed these interrelated challenges facing local communities and their elected leadership. More than a decade later, the Compact persists, serving as a central node through which climate action is aligned and scaled. Perhaps the best testament to this model is the formation of over 30 similar local government resilience collaboratives nationwide since the Compact's founding, with five in Florida alone.

While the impacts from a changing climate are many, Southeast Florida is frequently cited as one of the most physically vulnerable places to sea level rise (SLR) and flooding worldwide, posing tangible threat to lives, livelihoods, economies, and the environment (Nicholls et al. 2008; Obeysekera et al. 2011). The region already experiences many physical impacts: coastal inundation and erosion, increased flooding in low-lying coastal areas as well as inland areas due to impairment of the region's largely gravity-driven stormwater infrastructure, rising groundwater levels that reduce soil storage capacity, and saltwater intrusion into aquifers. The impacts of surge are exacerbated by SLR. Increased pollution and contamination from flooding also degrade natural resources critical to the region's economy. Consequences also include cascading socioeconomic impacts, such as displacement, decreases in property values and tax base, increases in insurance costs, loss of services, and impairment of critical infrastructure.

### A regional approach to shared resiliences challenges

One of the most important early innovations the Compact advanced in response to these shared challenges is a regionally Unified Sea Level Rise Projection, accounting for regional variations in SLR (see relative sea level rise near Key West, Florida, Figure 2). Developed by technical experts from the academic community, research institutions, and local, regional, and federal government, the Unified Projection was first developed in 2012, and updated in 2015 and 2019, incorporating new science. The Compact produced the Unified Sea Level Rise Projection and an accompanying guidance report to assist decision-makers in advancing science-based adaptation strategies and policies, and to ensure regional consistency across Southeast Florida. The Compact's 2019 Projection is based on SLR projections of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2014) and the National Oceanic and Atmospheric Administration (Sweet et al. 2017), reflecting regional influences of gravitational effects of ice melt, changes in ocean dynamics, vertical land movement, and thermal expansion from warming of the Florida Current (Compact 2020).

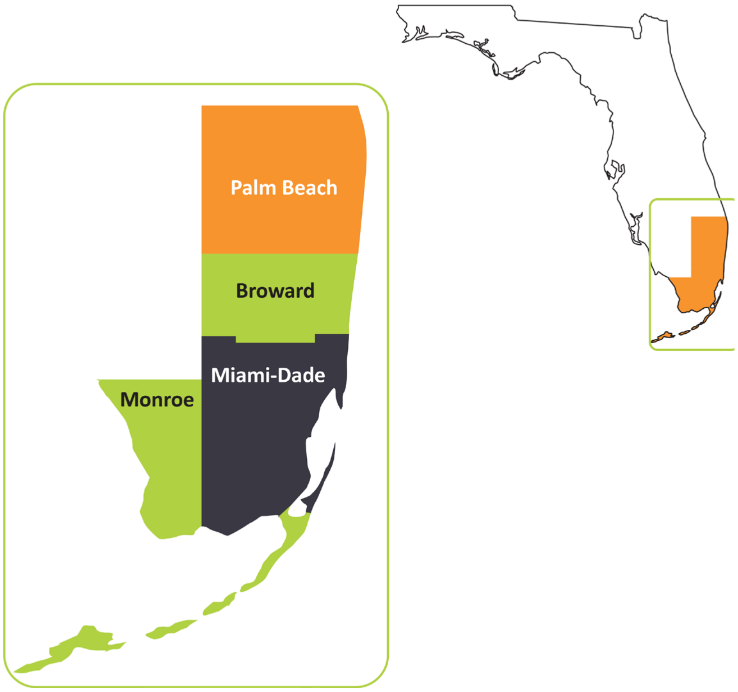


**Figure 1.** Map of the Southeast Florida Regional Climate Change Compact region, inclusive of Broward, Miami-Dade, Monroe, and Palm Beach counties.

The Compact has also produced a Regional Climate Action Plan, which is updated on a five-year cycle. This framework for regionally coordinated responses to climate change covers 12 chapters across multiple subject areas such as water, public health, natural systems, risk reduction, and emergency management. The plan's most recent edition contains 142 recommendations supporting concerted regional climate action (Southeast Florida Regional Compact Climate Change Climate Action Plan 2.0 2017).

Other major regional initiatives the Compact has advanced include the development of a regional vulnerability assessment, an analysis of health impacts related to SLR, and several guidance reports pertaining to resilience challenges—from water supply planning to climate risk and economic resilience.

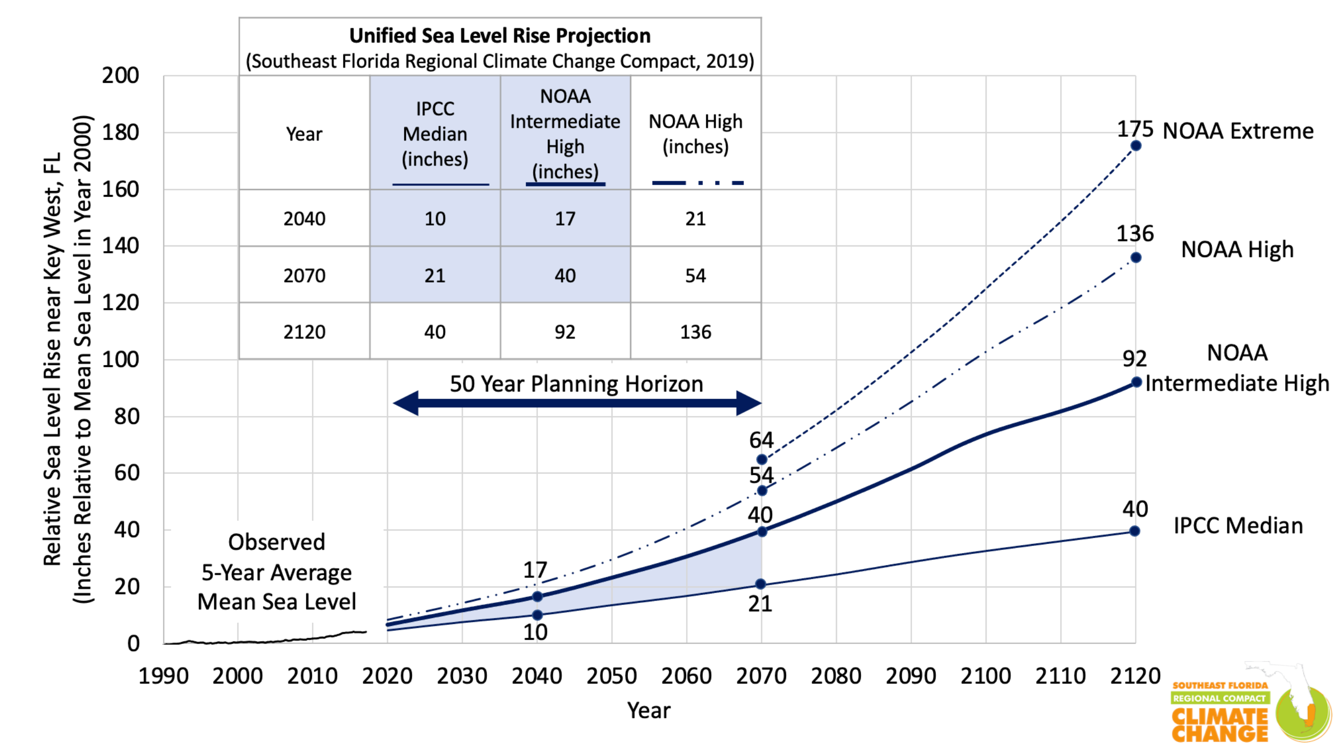


**Figure 2.** Southeast Florida Regional Climate Change Compact's 2019 Unified Sea Level Rise Projection of relative sea level rise (inches) near Key West, Florida. Observed 5-year average mean sea level for 1990-2017 is referenced to the Key West tide gauge. Projection curves from 2020 to 2120 are shown for the global median of the IPCC AR5 RCP 8.5 scenario (solid thin line) and three NOAA projections: **intermediate high** as the upper boundary for short-term use until 2070 (solid thick line), **high** as the upper boundary for medium-to-long-term use (dash dot line), and **extreme** as the upper range under an accelerated ice melt scenario (dash line; not recommended for design). The shading denotes the range recommended for design applications within a short-term (up to 50-year) planning horizon. (From Southeast Florida Regional Compact Climate Change Climate Action Plan 2.0 2017).

## Local government response to increasing climate risk

Local governments across Southeast Florida and the four Compact counties are individually advancing significant initiatives responsive to flood-related risks posed by climate change.

### *Assessing vulnerability of infrastructure and community assets*

The four counties have spent extensive resources to assess infrastructure and systems within their jurisdictions.

- *Palm Beach County* is working with seven of its municipalities to conduct a climate change vulnerability analysis and develop collaborative adaptation strategies.
- *Broward County* has analyzed the vulnerability of critical infrastructure networks and their cascading effects, including roads, airports, stormwater, wastewater, telecommunications, drinking water, electricity, and ports. Broward's investments in hydrologic models and groundwater monitoring wells serve to assess and mitigate the impacts of saltwater intrusion of wellfields. Recognizing the need for water supply diversification in the face of increasing drought and loss of coastal wells, Broward has led in the decades-long advancement of the C-51 Reservoir Project, the region's first

multi-jurisdiction alternative water supply project (construction to commence in 2021).
- *Miami-Dade County* has conducted vulnerability assessments of projects within their multi-year capital improvement plan and has assessed vulnerability of more than 1,000 County-owned assets (e.g., properties, parks, facilities, planned projects) to flood risks, evaluating these assets' criticality to departmental operations and emergency management. Multiple efforts have assessed how water and wastewater systems will be affected by SLR and storm surges, including identifying future conditions, exposure of assets, appropriate design elevations, and costs. Miami-Dade released a report outlining potential impacts to the functionality of septic systems due to groundwater elevation. In addition, ongoing studies are monitoring and modeling saltwater intrusion of the aquifer.
- *Monroe County* is updating its county-wide vulnerability analysis. The South Florida Water Management District, the region's water management agency, has initiated a program to assess the vulnerability of the region's aging flood protection infrastructure and potential retrofits.

**Box 1.** Peril of Flood language

> Section 163.7138(2)(f)1-6, Florida Statutes "Peril of Flood" Community Planning Requirements. The 2015 Florida Legislature directed jurisdictions that have a Coastal Management Element as a part of their comprehensive plan to include a redevelopment component with principles that must be used to eliminate inappropriate and unsafe development in the coastal areas when opportunities arise.

### *Developing adaptation strategies*

While working together regionally, each of the four Compact counties are likewise highly focused on developing localized adaptation strategies to meet specific priorities.
- *Broward County* is developing a countywide resilient infrastructure improvement plan based on a basin-level economic risk assessment and identification of infrastructure improvements and redevelopment strategies needed to mitigate future flood risk.
- *Miami-Dade County* will soon complete a comprehensive SLR strategy, encompassing several vulnerability assessments and research projects, proposed adaptation approaches, and capital projects.
- *Monroe County* is conducting a countywide roads and stormwater analysis to underpin a phased capital plan for associated adaptation projects, inclusive of an assessment of the current level of service, and funding options for countywide road elevation.

### *Planning and setting standards for future conditions*

Integration of the SLR projections and other future conditions modeling (e.g., groundwater elevations, rainfall) into planning and standards is critical to each of the counties' approaches to preparing for climate change. Several of the counties are updating comprehensive plans and development codes, in particular adding the Peril of Flood language (Box 1) to their Unified Land Development Code.
- *Palm Beach County* is developing a policy and procedure manual to incorporate resilience and sustainability into the planning phase of county capital construction projects, requiring considerations of SLR in planning, and documenting integration of green infrastructure and other resiliency efforts into facilities and infrastructure projects.
- *Broward County* has established a future conditions map series to formalize resilient design standards for project permitting, including a map that defines the wet season groundwater elevation based on combined surface and groundwater modeling. Revised policy requires major development/redevelopment projects to be designed in accordance with modeled

2070 conditions. Broward County is updating its 100-year flood map based on flood elevations modeled from predicted 13% increase in rainfall intensity and SLR, which informs finished floor elevations and infrastructure siting. Broward's land-use plan policy and code set minimum requirements for the top elevation of coastal infrastructure serving as a tidal flood barrier for adjacent properties, such as seawalls and berms.

- *Miami-Dade County* has enhanced the requirements for climate adaptation planning in its Comprehensive Development Master Plan.

***Investing in upgrades in resilient infrastructure***

The efforts of the Compact partners extend beyond planning into implementation as well.

- *Broward County* is partnering with municipalities and the state to inform improvements to address high-tide flooding along critical evacuation corridors and has integrated future conditions standards as part of internal asset planning.
- *Monroe and Miami-Dade Counties* have already begun to invest in projects and upgrade infrastructure to contend with flooding. *Miami-Dade* has made improvements to stormwater infrastructure, water and sewer facilities, and parks, and has begun road elevation and drainage projects in response to king tide flooding. *Monroe* is similarly embarking on a pilot Roads Elevation Project.

## Robust data is the starting point to inform resiliency planning

While more data than ever is available to local governments and regional agencies to assist in developing science-based strategies and policies, gaps remain:

- **Updated geospatial data.** Current LIDAR data and parcel elevation is foundational for linking observable and modeled parameters to inform policy and investment decisions.
- **Data related to current climate change hazards and future projections.** The Compact has invested significant effort in developing locally relevant SLR projections. A similar basis for other climate hazards, including extreme heat and precipitation, and down-scaled future projections, would be invaluable for planning. Models that integrate SLR projections with surface water, groundwater, surge, and tidal flooding are also integral to understanding comprehensive risk.
- **Frameworks for integrating climate hazards and socio-economic data to provide a comprehensive picture of climate risk.** Understanding climate risk requires assessing both the degree of exposure and sensitivity to climate impacts, as well as an individual or community's level of adaptive capacity. Improved vulnerability analysis frameworks are needed that adequately capture and integrate disaggregated socioeconomic data (race/ethnicity and indicators of wealth/income) and indicators of the adaptive capacity of people, systems, and institutions.
- **Economic and social-cost modeling.** Given scarce resources, policymakers need information on the social and economic costs and benefits of various adaptation approaches and alternatives, as well as the cost of no action.

Moreover, even where abundant data and information exist to support practitioners, several challenges inhibit its translation into action.

- **Building the right tools, translating to the right user**. Too frequently, data platforms and tools are built on the principle of "if we build it, they will come," without the end-user in mind. Without end users' collaboration, many platforms will remain unknown or unused by those who could most benefit from them. Further, there is not a single end-user. Involved disciplines each have their own "language," thus integrating climate data into project design may require engagement with multiple professional communities to reach diverse end-users—e.g., architects, engineers, planners, water and wastewater professionals—to ensure information is provided in appropriate terms. These issues point to the critical need for expanded capacity-building resources to help bridge the gap between the science community and practitioners.

- **Uncertainty—real and perceived.** Climate scientists take care to bracket projections and identify topics of uncertainty or continuing scientific inquiry. However, uncertainty can mean different things to different audiences; at times discussion of uncertainty can result in deferment or "analysis paralyses" by decision-makers, particularly when considering long-term planning horizons.
- **Internal decision support.** Locally relevant projections and climate model outputs can help to quantify exposure of assets, but susceptibility and criticality are harder to assess—and speaks to how decision-makers use data. More advanced decision-support frameworks that account for uncertainties are required to support elected officials in prioritizing implementation actions in response to the science, particularly considering regular updates that incorporate new data and models. Common challenges include timing investments that result in "no regrets" actions, which at minimum avoid maladaptive pathways, and contending with level of service versus cost tradeoffs.
- **Uncharted waters for local government and equity implications.** When climate data point to a future where neighborhoods may be underwater in the foreseeable planning horizon, local governments are in unprecedented territory. What is the local government's responsibility to build new or maintain existing infrastructure? At what cost, for how long, and for how many people? How should investments be directed equitably while also considering economic implications? Who pays for adaptation? Who benefits? These novel questions ultimately must be addressed to realize the opportunity for community transformation inherent in the upheaval presented by climate change.

For the last decade, strong collaboration between the science community, local, and regional governments and agencies has enabled the Compact to provide sound, science-based information to support climate adaptation. Regional consistency of science input has been a hallmark of this collaboration. Collaboration between the science community and practitioners must be broadened to ensure continued and accelerated progress. Our experience highlights the need for greater integration of the latest downscaled, and regionally-relevant data, and expansion of interdisciplinary research to inform the socioeconomic and political dimensions implicit in adaptive risk management and iterative decision-making.

*References*


IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 151 pp, https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact), 2020: Unified Sea Level Rise Projection: 2019 Update, 36 pp, https://southeastfloridaclimatecompact.org/wp-content/uploads/2020/04/Sea-Level-Rise-Projection-Guidance-Report_FINAL_02212020.pdf

Sweet, W.V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M Horton, E. R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical report NOS CO-OPS 083, Silver Spring, MD., 75 pp.

Nicholls, R. J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Château, and R. Muir-Wood, 2008: Ranking port cities with high exposure and vulnerability to climate extremes: Exposure estimates. OECD Environment Working Papers, doi:10.1787/011766488208.

Obeysekera, J, M. Irizarry, J. Park, J. Barnes, and T. Dessalegne, 2011: Climate change and its implication for water resources management in south Florida. *Stoch. Environ. Res. Risk Assess.*, **25**, 495-516, doi:10.1007/s00477-010-0418-8.

Southeast Florida Regional Compact Climate Change Climate Action Plan 2.0, 2017. Accessed 3 November 2020, https://southeastfloridaclimatecompact.org/about-us/what-is-the-rcap/.

# Challenges in predicting the coevolution of natural and human systems on coastal regions

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Coastal regions are thin strips around continents, which are the results of the dynamical interaction of human, terrestrial, oceanic, and atmospheric processes. Most of the largest urban centers on earth are located on the coast. In the US more than 40% of the nation's population resides in coastal counties, and its density will continue to increase. The US coastal zone is home to critical infrastructure systems (e.g., electrical power grids to support large population), ports, and military installations. The coexistence of human and natural system makes coastal zones vulnerable ecosystems to extreme weather events and long-term climatic changes such as sea level rise and drought.

Major hurricanes have caused hundreds of billions of dollars in damages to coastal population centers and billion-dollar damages to coastal military bases (Arana-Barradas 2005; Smith et al. 2013; Russo et al. 2017). The majority of historical economic damages are due to loss of electrical power and potable water services (Copeland 2006; Barnard et al. 2014) due to flooding of infrastructure facilities. Coastal regions are complex entities where the highly interconnected engineered systems sit on the top of a shifting dynamic natural systems (Figure 1). In the 21st century, sea level rise will worsen flood damage and contaminate water supplies with salt water. The timing, extent, and distribution of flooding and salt intrusion will change over time due to complex dynamics occurring within the coastal zone, such as erosion, drought, and wetland degradation.

Although there have been substantial economical investments (Public Service Electric and Gas 2017), infrastructure managers and regional decision makers are poorly prepared to adapt to increasing coastal threats. The models used by planners to predict coastal change are missing crucial land-water-vegetation feedbacks that are first-order controls on flood and salt intrusion patterns, causing decision makers to under- or over-estimate risk. Existing commercial network failure simulation tools such as PowerWorld explore how operations of infrastructure, such as the electrical power system, may be damaged by these threats, but do not specify what actions to take to mitigate risk: it is hard to convert knowledge of vulnerabilities into an actionable plan for redesigning a physical system consisting of thousands of interdependent electrical and water assets.

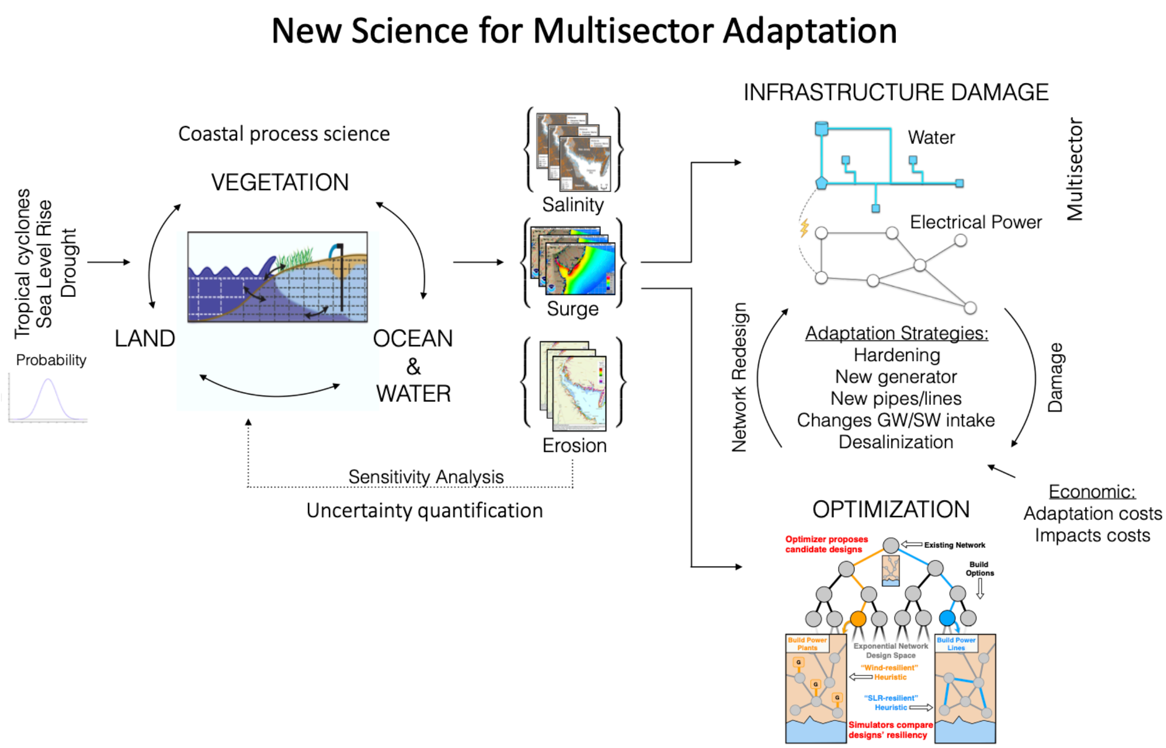


**Figure 1.** Schematic of interconnected components of coastal adaption science framework, depicting natural system stressors, their impacts, and infrastructure optimization responses. Arrows illustrate the interaction among the components.

To date, coastal disaster mitigation approaches are not capable of accurately predicting the risk of coastal critical infrastructure failure from environmental threats. Consequently, decision makers are misallocating resilience investments (e.g., protecting the wrong sites, protecting too much or little, spending too much on protecting assets and not enough on alternative resilience strategies like network expansion or redundancy). The central challenge of coastal planning is that decision makers lack the necessary predictive science needed to assess risk and decision science needed to plan for resilience. We are missing the scientific understanding of (i) how complex feedbacks within the coastal zone will affect infrastructure vulnerability, (ii) how to assess future coastal risk that accounts for the uncertainty in the underlying physical dynamics, and (iii) how to use this assessment to devise a resilient and cost-effective adaptation strategy.

## Missing coastal process science

State-of-the-art natural coastal dynamics models do not capture many processes and feedbacks necessary to predict infrastructure vulnerability and support adaptation plans. Inundation from short-term storms and long-term sea level rise is amplified by coastline erosion and the loss of protective wetlands that dampen storm surge. The dynamics of these processes are important: wetlands with plants that can migrate away from salt water regions are far less vulnerable to sea level rise (Kirwan et al. 2016). Meanwhile, erosion can alter the shoreline and, thus, affect flooding during hurricanes. Erosion and wetland loss are inextricably linked, as rooted vegetation stabilizes soil against erosion, while shoreline retreat allows for salt water to gradually encroach upon and poison vegetation. Inundated electric substations, water treatment plants, and groundwater pumps cause direct power and potable water outages: loss of power can indirectly affect potable water production. These essential feedbacks are poorly represented and only few of them have been studied in realistic model settings (Amoudry et al. 2011). Currently no coastal model exists that bridges both short- and long-time scales: models intended to evaluate infrastructure risk during storm events do not contain processes describing slow erosion, wetland change, salt intrusion (Hubbert et al. 1999; van Heerden et al. 2007; Brekke et al. 2009; Wolf 2009; Hallegatte et al. 2013; Aerts et al. 2014; Hinkel et al. 2014). Models intended to study large-scale, long-term coastal evolution do not make predictions at small scales relevant to infrastructure siting (Yin et al. 2009; Gedan et al. 2010; Marani et al. 2010; Wamsley et al. 2010; Groves and Sharon 2013; Kirwan and Megonigal 2013; Ezer and Atkinson 2014; Kirwan et al. 2016; Brown et al. 2017; Day 2007). Some of these models used for coastal planning also tend to make site-specific assumptions that do not generalize to other locations, such as hardcoding local erosion or wetland loss rates, which neglects the possibility of dynamical erosion-wetland feedbacks (Cloern et al. 2011; New Jersey Department of Environmental Protection 2011). Models used in research studies represent more feedbacks such as salt march, tidal currents, and sediment erosion, but in an approximate way that cannot be used for prediction at real locations (Mariotti and Fagherazzi 2010). A modeling approach that includes all of the major feedbacks, at small spatial scales and over short- and long-time scales, is a needed advancement of coastal science and is an essential requirement to appropriately quantify coastal infrastructure vulnerability.

### Challenges in risk assessment

Adaptation decision making requires an assessment of risk, such as the anticipated severity of a 100-year flood, which requires both predictive capability and quantification of uncertainty. The challenge to assess the risk is that it changes over time and mis-estimation of risk can have devastating consequences: Houston experienced its third "500-year" flood in three years, with many billions of dollars in damages. A single electrical utility in the Delaware Bay region has invested $2 billion to date (Public Service Electric and Gas 2017) to protect electrical power assets as a consequence of Hurricane Sandy. But its plans, like most utilities, are essentially reactive rather than anticipatory, protecting facilities that were damaged in the last large storm. They do not account for how a dynamic coastal zone changes the risk profile of the region, exposing previously safe assets to damage while reducing the vulnerability of others (e.g., if sediment is deposited in new locations along the shore). Regional planning efforts that do attempt to predict coastal evolution that do not include relevant processes, feedbacks, and scales, will not correctly assess the uncertainty in their predictions and risk to infrastructures (McNamara et al. 2015).

### Challenges in adaptation decision making

Another key gap is that planners lack a science-informed approach to develop detailed engineering-level adaptation plans for regional infrastructure networks. Computationally, the design problem is hard because complex networks are large and interdependent. The mathematics that describe the physics of infrastructure networks yield a problem formulation that is difficult to solve with existing approaches. Moreover, the impacts of design choices and failures may have far-reaching effects, for example a system failure at a coastal electrical substation may require changes at other facilities inland to rebalance power load. Detailed physics-based network analysis is needed to evaluate the effects of adaptation strategies. However, when the network is large it becomes intractable for unaided human planners to consider all relevant combinations of decisions. This leads to two simplified and largely disconnected planning approaches, neither of which solve the problem: (i) regional planners identify vulnerable locations and suggest generalized strategies like building sea walls, but do not perform network analysis or redesign infrastructures; and (ii) utility planners focus in great detail upon protecting individual facilities believed to be at risk, but do not deeply analyze how energy and water infrastructures interact, nor examine large-scale tradeoffs between protecting sites and other strategies such as e.g., adding power generation capacity to compensate for power losses, sourcing water from alternate supplies, and routing around damage (Groves and Sharon 2013; Kasprzyk et al. 2013; Kraucunas et al. 2015). A more automated approach to planning is needed that is capable of rapidly exploring a large number of facility-level design options, requiring algorithmic advances in network design methods that address the computational challenges that have hindered progress to date.

To overcome the limitations of current planning approaches, there is the need of a transformative coastal adaptation framework, a New Science for Multisector for Adaptation (NeSMA) framework (Figure 1). NeSMA needs to be able to tightly integrate coastal process science, infrastructure simulation (multisector), uncertainty quantification, and optimization. The result will be a probabilistic risk management approach to coastal adaptation science that quantifies how coastal feedback effects will alter regional vulnerabilities over decades, and recommends detailed engineering strategies to upgrade large-scale infrastructure networks for resilience with respect to this changing risk profile. It requires (i) a new coastal model that, for the first time, will simulate the land-ocean-vegetation feedbacks and is grounded in validated process science, which are necessary to predict changes in coastal vulnerabilities over decades; (ii) probabilistic risk estimates of infrastructure failure derived, for the first time, from a process-based uncertainty analysis of coastal feedbacks; and (iii) a new infrastructure network optimization algorithm that will, for the first time, redesign a large-scale regional infrastructure network with respect to uncertain predicted changes in coastal vulnerabilities.

## Infrastructure damage assessment

Figure 2 demonstrates the importance of shoreline changes on coastal infrastructure damage assessment — a feedback process neglected by many infrastructure planners (Aerts et al. 2014; Public Service Electric and Gas 2017). The shoreline of the Delaware Estuary is assumed with an artificial catastrophic wetland loss scenario and consequent massive erosion in addition of a future value of sea level. We estimate storm surge damage on electrical power substations and generators caused by a synthetic hurricane with the same characteristics of Sandy. When compared to the no-erosion case, this artificial scenario displays complex changes to flooding that are amplified

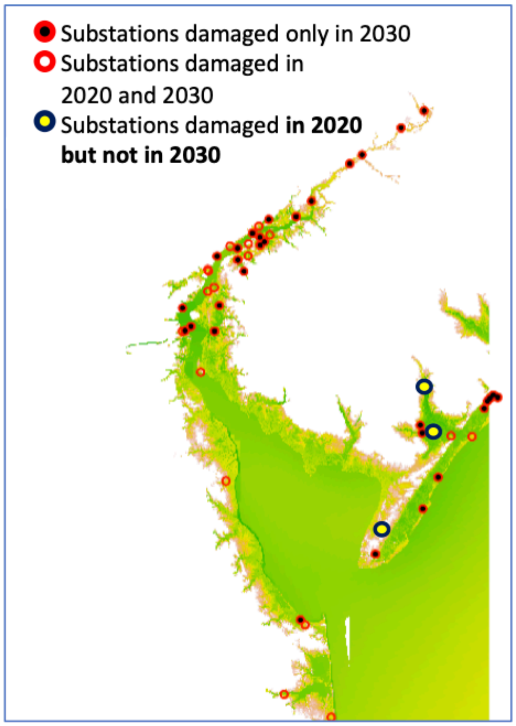


**Figure 2.** How damage of a hurricane on the electrical power system in the Delaware Bay may change due to future sea level rise and wetland loss. The map displays the locations of electrical power substations and their hurricane-related flooding damage simulated for two different shorelines scenarios. The first scenario assumes a hurricane hits the coastline with the current 2020 sea level and bathymetry; the second scenario assumes the same hurricane hitting a coastline with an artificially catastrophic wetland loss and consequent massive erosion (2 acre/year) in addition to a projected 2030 future value of sea level (RCP 8.5 estimated using R. Kopp, 2014, ). Substations are delineated by those damaged in both scenarios (red/white dots), those damaged only in the first scenario (blue/yellow), and those damaged only in the second scenario (red/black). The hurricane is a synthetic storm with the same intensity of 2012 Hurricane Sandy. Damage due to flooding is determined using the NOAA storm surge model, Sea Lake and Overland Surge from Hurricanes (SLOSH), with the standard bathymetry.

in the most densely urbanized upper Bay. Specifically, more facilities are inundated as expected with erosion (red/black dots), and unexpectedly three facilities (blue/yellow dots) that were flooded in the scenario without erosion are not flooded if we account for erosion. This artificial scenario suggests that coastal feedbacks can substantially alter infrastructure risk and, as a consequence, adaptation strategies in counterintuitive ways are not represented in existing coastal plans planners (Aerts et al. 2014; Public Service Electric and Gas 2017). Multi-billion dollar investments not based on coastal feedback science or optimization are likely being misallocated by (i) failing to protect sites that will become at risk; (ii) protecting sites that may not remain at risk; and (iii) failing to consider complex tradeoffs between flood protection and other resilience strategies.

A new approach to coastal adaptation will radically revise our understanding of future coastal risk and how to adapt infrastructure networks to mitigate this risk. Planners could then properly account for coastal feedbacks and complex design decisions, thereby improving the basis for investments in multi-billion dollar coastal resilience initiatives.

*References*


Aerts, J. C. J. H., W. J. W. Botzen, K. Emanuel, N. Lin, H. de Moel, and E. O. Michel-Kerjan, 2014: Climate adaptation. Evaluating flood resilience strategies for coastal megacities. *Science*, **344**, 473–475, doi:10.1126/science.1248222.

Amoudry, L. O., and A. J. Souza, 2011: Deterministic coastal morphological and sediment transport modeling: A review and discussion. *Rev. Geophys.*, **49**, doi:10.1029/2010RG000341.https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010RG000341.

Arana-Barradas, L, 2005: Katrina takes heavy toll at Keesler. US Air Force, Accessed 4 November 2020, https://www.af.mil/News/Article-Display/Article/133554/katrina-takes-heavy-toll-at-keesler/.

Barnard, P. L., M. van Ormondt, L. H. Erikson, J. Eshleman, C. Hapke, P. Ruggiero, P. N. Adams, and A. C. Foxgrover, 2014: Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. *Nat. Hazards*, **74**, 1095–1125, doi:10.1007/s11069-014-1236-y.

Bilinski J., G. Buchanan, D. Frizzera, R. Hazen, L R. Lippincott, N. Procopio, B. Ruppel, and T. Tucker, 2015: Damage assessment report on the effects of Hurricane Sandy on the state of New Jersey's natural resources: Final report. New Jersey Department of Environmental Protection, 62 pp, https://www.nj.gov/dep/dsr/hurricane-sandy-assessment.pdf.

Brekke, L. D., E. P. Maurer, J. D. Anderson, M. D. Dettinger, E. S. Townsley, A. Harrison, and T. Pruitt, 2009: Assessing reservoir operations risk under climate change. *Water Resour. Res.*, **45**, doi:10.1029/2008WR006941.

Brown, S., and Coauthors, 2017: 2017 coastal master plan: Appendix c: Modeling chapter 3–modeling components and overview. Coastal Protection and Restoration Authority technical report, 72 pp, http://coastal.la.gov/wp-content/uploads/2017/04/Appendix-C_chapter3_FINAL_6.19.2017.pdf.

Cloern, J. E., and Coauthors, 2011: Projected evolution of California's San Francisco Bay-Delta-river system in a century of climate change. *PLOS ONE*, **6**, 1–13, doi:10.1371/journal.pone.0024465.

Copeland, C., 2006: Hurricane-damaged drinking water and wastewater facilities: Impacts, needs, and response. CRS Report for Congress, 6 pp, https://www.everycrsreport.com/files/20060322_RS22285_b075e0c650cb9d4868f20478641ebe9835c3f299.pdf

Day, J. W, and Coauthors, 2007: Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*, **315**, 1679–1684, doi:10.1126/science.1137030.

Ezer, T., and L. P. Atkinson, 2014: Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the gulf stream, and the North Atlantic Oscillations. *Earth's Future*, **2**, 362–382, doi:10.1002/2014EF000252.

Gedan, K., M. Kirwan, E. Wolanski, E. Barbier, and B. Silliman, 2010: The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. *Climatic Change*, **106**, 7–29, doi:10.1007/s10584-010-0003-7.

Groves, D., and C. Sharon, 2013: Planning tool to support planning the future of coastal Louisiana. *J. Coastal Res.*, **67**, 147–161, doi:10.2112/SI_67_10..

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nat. Climate Change*, **3**, 802–806, doi:10.1038/nclimate1979.

Hinkel, J., and Coauthors, 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci.*, **111**, 3292–3297, doi:10.1073/pnas.1222469111.

Hubbert, G. D., and K. L. McInnes, 1999: A storm surge inundation model for coastal planning and impact studies. *J. Coastal Res.*, **15**, 168–185, http://www.jstor.org/stable/4298925.

Ingraham C., 2017: Houston is experiencing its third "500-year" flood in 3 years. How is that possible? The Washington Post, Accessed 7 November 2020, https://www.washingtonpost.com/news/wonk/wp/2017/08/29/houston-is-experiencing-its-third-500-year-flood-in-3-years-how-is-that-possible/

Kasprzyk, J., S. Nataraj, P. Reed, and R. Lempert, 2013: Many objective robust decision making for complex environmental systems undergoing change. *Environ. Modell. Software*, **42**, 55–71, doi:10.1016/j.envsoft.2012.12.007.

Kirwan, M. L., and J. P. Megonigal, 2013: Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, **504**, 53–60, doi:10.1038/nature12856.

Kirwan, M. L., D. C. Walters, W. G. Reay, and J. A. Carr, 2016: Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophys. Res. Lett.*, **43**, 4366–4373, doi:10.1002/2016GL068507.

Kirwan, M. L., S. Temmerman, E. E. Skeehan, G. R. Guntenspergen, and S. Fagherazzi, 2016: Overestimation of marsh vulnerability to sea level rise. *Nat. Climate Change*, **6**, 253–260, doi:10.1038/nclimate2909.

Kopp, R., and Coauthors, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites Climatic Change, 129, 573–588, doi:10.1002/2014EF000239.

Kraucunas, I., and Coauthors, 2015: Investigating the nexus of climate, energy, water, and land at decision-relevant scales: The Platform for Regional Integrated Modeling and Analysis (PRIMA). *Climatic Change*, **129**, 573–588, doi:10.1007/s10584-014-1064-9.

Marani, M., A. D'Alpaos, S. Lanzoni, L. Carniello, and A. Rinaldo, 2010: The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics. *J. Geophys. Res.: Earth Surf.*, **115**, doi:10.1029/2009JF001600.

Mariotti, G., and S. Fagherazzi, 2010: A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *J. Geophys Res.: Earth Surf.*, **115**, doi:10.1029/2009JF001326.

McNamara J., S. Clemmer, K. Dahl, and E. Spanger-Siegfried, 2015: Lights out? Storm surge, blackouts, and how clean energy can help. Union of Concerned Scientists Report, 40 pp, https://www.ucsusa.org/sites/default/files/attach/2015/10/lights-out-full-report.pdf.

New Jersey Department of Environmental Protection, Office of Coastal Management, 2011: New Jersey's coastal community vulnerability assessment and mapping protocol. 64 pp, http://www.nj.gov/dep/cmp/docs/ccvamp-final.pdf.

Public Service Electric and Gas, 2017: PSE&G post-Sandy investments are making New Jersey's energy grid "energy strong." Accessed 7 November 2020, https://electricenergyonline.com/article//news/energy/category/90/General/category/T&D/56/663409/PSE-G-Post-Sandy-Investments-Are-Making-New-Jersey-s-Energy-Grid-Energy-Strong-.html.

Russo E., and K. Burks-Copes, 2013: Adaptive capacity and tipping points of coastal military installation sustainability with storms and rising seas. *Coasts and Ports 2013: 21st Australasian Coastal and Ocean Engineering Conference and the 14th Australasian Port and Harbour Conference,* Sydney, Australia, 659-664, https://search.informit.com.au/documentSummary;dn=829859196475668;res=IELENG.

Smith, A. B., B. Adam, and R. W. Katz, 2013: US billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Nat. Hazards*, **67**, 387-410, doi:10.1007/s11069-013-0566-5.

van Heerden, I. L., G. Kemp, and H. Mashriqui, 2007: Use of the ADCIRC storm surge model for Hurricane Katrina surge predictions and levee forensic studies. *Embankments, Dams, Slopes*, doi:10.1061/40905(224)12.

Wamsley, T. V., M. A. Cialone, J. M. Smith, J. H. Atkinson, and J. D. Rosati, 2010: The potential of wetlands in reducing storm surge. *Ocean Eng.*, **37**, 59–68, doi:j.oceaneng.2009.07.018.

Wolf, J., 2009: Coastal flooding: Impacts of coupled wave–surge–tide models. *Nat. Hazards*, **49**, 241–260, doi:10.1007/s11069-008-9316-5.

Yin, J., M. Schlesinger, and R. Stouffer, 2009: Model projections of rapid sea-level rise on the northeast coast of the United States. *Nat. Geosci.*, **2**, 262–266, doi:10.1038/ngeo462.

# Smart Sea Level Sensors for coastal climate resilience

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Coastal flooding represents a growing threat to the City of Savannah and adjoining areas in Chatham County, Georgia, which are home to diverse communities rich with cultural heritage and thriving economies. Recent brushes with Hurricane Matthew in 2016 and Hurricane Irma in 2017 saw storm surges of 7+ feet at the county's only tide gauge at Ft. Pulaski, shutting down schools and businesses for days. During these extreme weather events, strong winds interacted with a diverse landscape of coastal rivers, tributaries, and marshlands to create a complex pattern of flooding that varied by 1-3 ft over a distance of several miles. With Ft. Pulaski and a handful of USGS water level gauges as the only official sources of real-time water level information, emergency responders couldn't determine whether localized flooding posed a hazard to critical infrastructure such as bridges. In fact, when flood levels receded, county officials were forced to visually inspect each of the county's nearly 200 bridges for signs of saltwater damage prior to fully re-opening roadways.

Flooding along the Georgia coast has become more frequent and severe over the last three decades (Figure 1), with nearly 70% of "moderate" to "major" floods occurring since 2015. In order to mitigate damages associated with increased flooding in this area, planning must incorporate the use of data and associated tools that address the compound risks of extreme rainfall, king tides, storm surge, and sea level rise, that operate on timescales of several hours to several decades. Moreover, planning tools must reflect the large uncertainties associated with sea level rise projections ranging from +3 ft to +10 ft by 2100 (NCA2018).

### The "Smart Sea Level Sensors" project

The "Smart Sea Level Sensors" project aims to provide hyper-local, real-time water level information to emergency planners and responders, decision-makers, and the general public alike, for application to emergency management and climate resilience planning efforts. The

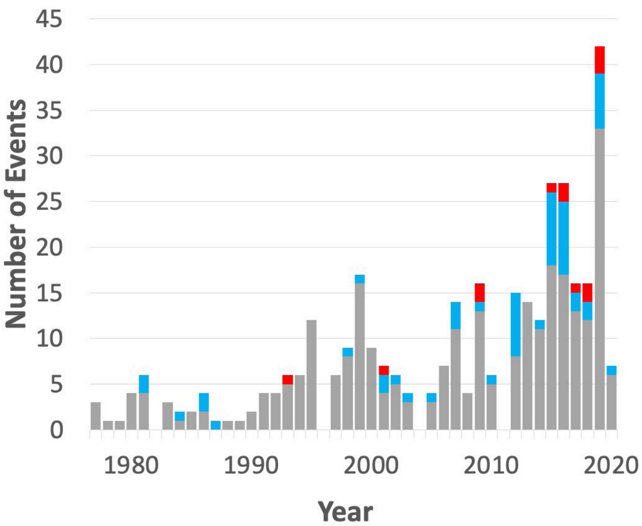


**Figure 1.** History of flooding as recorded at NOAA's Fort Pulaski tide gauge in Savannah (grey=minor flood; blue=moderate flood, red=major flood (from NWS-Charleston).

project began in May 2018 as a partnership between officials from the Chatham Emergency Management Agency, the City of Savannah, and a diverse team of scientists and engineers from Georgia Tech. The Georgia Smart Communities program provided modest seed funding for the first year of operations, including a series of meetings between researchers and municipal partners to identify high-priority community needs and sensor installation sites.

As of late 2020, the sensor network is comprised of over 50 Georgia Tech-designed sensors that relay data to 14 internet-connected gateway devices using the LoraWAN communications protocol. The sensor's components cost $250 in parts, including an ultrasonic sensor (MaxBotix 7388 HRXL), a custom-designed control board, and antenna, that are assembled and tested in Georgia Tech's Interactive Media Technology Center. The sensor is powered by four "D" batteries (or optional one watt solar panel), and is programmed to collect a burst of 10 water level measurements every six minutes, which matches the sampling interval of the NOAA tide gauge network. An on-board temperature sensor is used to correct for the effect of temperature changes on the ultrasonic-derived distance measurement. The sensors are installed on County bridges, private docks, and drainage infrastructure (Figure 2), and are surveyed by County engineers to determine their elevation with respect to NAVD88. The commercial marine-grade IP-67 rated LoRaWAN gateway devices (MultiTech MTCDTIP-L4N1-266A-915) cost $2,000 each and are installed on City and County infrastructure that have backup power and internet, with the exception of two installations on private property. Each gateway device can receive data from hundreds of sensors across a radius of 2-6 km, with higher installations and fewer tall trees affording the best data return rates. The network spans a wide range of environments, from inland to oceanfront settings, from small tributaries to large estuaries, from low- to high-density building areas.

Two Smart Sea Level Sensors co-installed at the NOAA Ft. Pulaski tide gauge since February 2019 allow for a detailed assessment of the accuracy and precision of the Georgia Tech-designed sensors across a range of environmental conditions. After removing outliers with a nearest-neighbor correction, maximum offsets of 15 cm between the NOAA and GT gauges likely reflect differences in wave height over the several-meter distance between install locations. However, the average residual between the NOAA and GT gauges is less than three cm over the duration of the co-installation, and less than one cm between the two GT gauges.

### End user application resources

Broad stakeholder engagement informed the design of visualizations and user interfaces for the sea level sensor data streams. Priority areas were identified during public workshops and briefings with city and county officials. Through this process, the team focused on the development of two distinct interfaces: i) a public dashboard for browsing individual sensor data streams and visualizing the state of water levels across the network, and ii) a portal for county emergency management officials that plots current and projected water levels

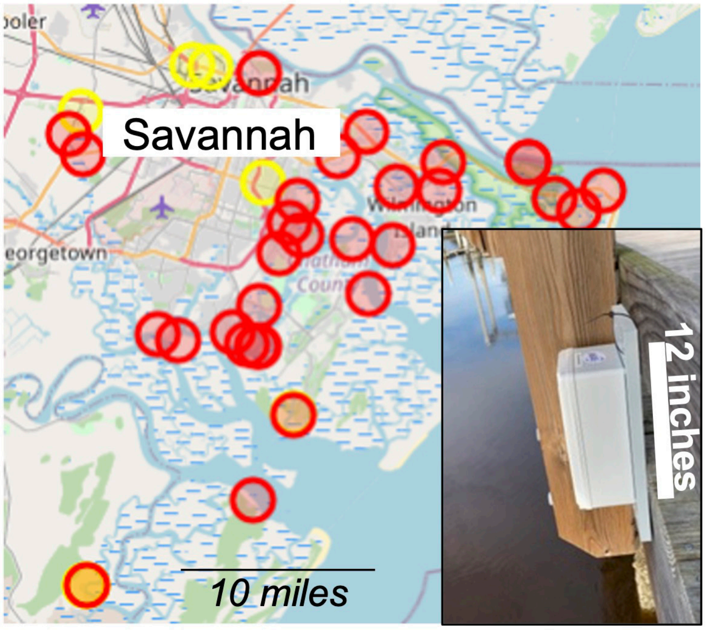


**Figure 2.** Map of 50 Smart Sea Level Sensor installed in Chatham County, based on GT-designed sensors (photo inset) that communicate 6-minute readings to 14 internet-connected gateway devices via LoRaWAN technology. Red indicates elevated water levels above 9.0 ft (relative to NAVD88) documented during the October 17, 2020 king tide. (inset) Photo of Georgia Tech-designed sea level sensor installed on a dock in Savannah.

and associated infrastructure impacts. Both portals are currently available in beta modes – as described below – with ongoing development informed through continued user feedback. A third application area of broad interest and ongoing development is dynamical forecasting of localized flooding, wherein the sensor data can provide much-needed information about the accuracy of the dynamical model.

***Public dashboard***

The status of water levels and associated sensor data streams are available to the general public via a web-based dashboard interface. Figure 2 is a snapshot of the dashboard during a king tide event that took place on October 17, 2020. Additional features include the ability to visualize individual sensor data over the previous two weeks, and access the Application Programming Interface for the sensor network, where users can acquire the full history of sensor data.

***Chatham Emergency Management Portal***

Funding from the Georgia Department of Natural Resources enabled the development of a dedicated portal for emergency planners and responders associated with the Chatham Emergency Management Agency. In this portal, users can view data from sensors installed on key bridges across the county, with color-coded flags for water levels that come within one foot of the base of the bridge, triggering an engineering inspection. Users can also visualize real-time flood layers mapped by applying optimal interpolation mapping techniques to sensor data streams.

***Public dashboard***

The sensor data collection is complemented by a suite of numerical modeling tools to inform flood risk and vulnerability. These include the S-WITCH hydrological modeling system, itself comprised of an unstructured grid 3-D coastal ocean model (SHYFEM) that ranges from 10 km to 10 m resolution from the open ocean to the city-scale (Figure 3). SHYFEM boundary conditions are provided by daily forecasts of the 1/12 degree resolution ocean reanalysis (CMEMS) and the ERA5 1/8 degree atmospheric forecasts from ECMWF. Overland, SHYFEM water flux boundary conditions are derived from a one-way coupling to the surface and groundwater model WRF-Hydro. The S-WITCH model has enabled the investigation of the relative contributions of rainfall versus wind-driven storm surge to observed flooding during Hurricanes Mathew and Dorian (Park et al. submitted). Currently, three-day forecasts are available for research purposes, and validation with sensor data is currently underway. A version of the model that incorporates land surface hydrology as well as urban drainage infrastructure in Savannah is under development, with the goal of producing dynamic maps of flood risk at the neighborhood level in Savannah.

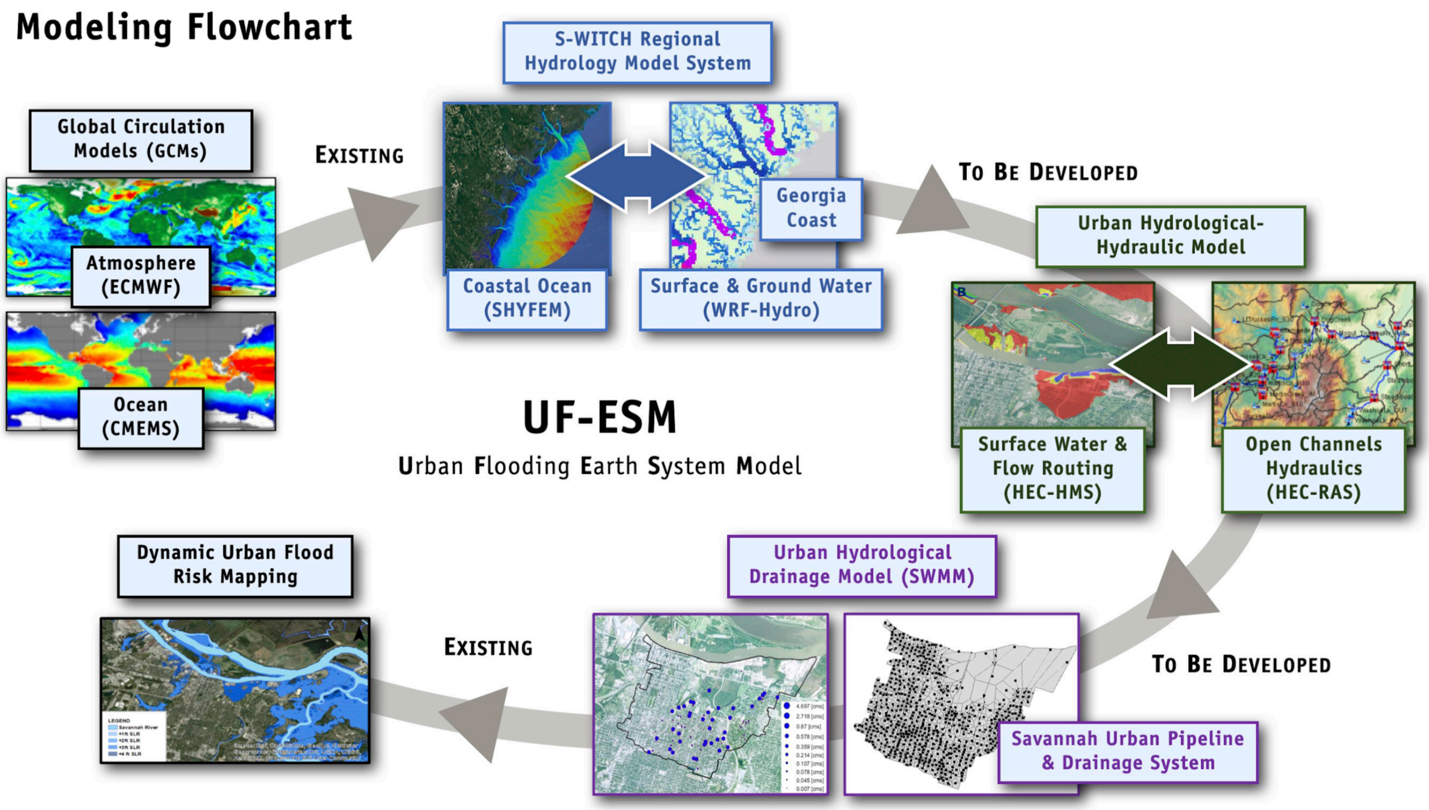


**Figure 3.** Schematic of the S-WITCH Regional Hydrology Model showing its development for applications in urban flood forecasting and risk mapping based on a variety of sea level rise scenarios (courtesy of E. Di Lorenzo, personal communication).

## Community engagement

One of the core goals of the project is to build capacity for long-term flood mitigation and adaptation planning in this flood-vulnerable region, which requires a sustained pattern of engagement with a diverse set of community stakeholders. Every two weeks, the project team holds an hour-long planning call wherein team members share key updates and near-term opportunities. Quarterly half-day workshops afford the team the opportunity to share project findings with members of the public and key stakeholders, and collect feedback. Lastly, annual executive-level briefings with the City of Savannah's Mayor, City Manager, as well as select City Councilmembers and Chatham County Commissioners ensures that the project evolves in close alignment with City and County priorities. Apart from these formal series of stakeholder engagements, the project has held briefings with National Weather Service staff, Congressman Buddy Carter (GA-1), and personnel from the King's Bay Naval Base. These exchanges help the project team identify specific gaps in the science of coastal resilience for key stakeholders. For example, while our team initially focused most of the sensor deployments on vulnerable ocean-facing sites most prone to flooding, early stakeholder engagement pointed to an acute desire to monitor water levels across the inland freshwater drainage infrastructure. As the project team continues to pursue forecasts of compound flood extremes that account for both freshwater and saltwater contributions, such data are now considered essential.

**Figure 4.** Photo of Dr. Mildred McClain, Executive Director of the Harambee House, participating in a "Map Room" exercise in Prof. Yanni Loukissas' digital media lab at Georgia Tech. (courtesy of Kim Cobb).

Given that low-income communities are the most vulnerable to any number of climate change-related stressors, including coastal flooding (Debbage 2019), direct and sustained engagement is a prerequisite for equitable climate resilience planning efforts. Towards that end the project has entered into close collaboration and partnership with The Harambee House, a Savannah-based non-governmental organization focused on environmental justice. Thus far, this partnership has focused on the co-creation of a neighborhood-level emergency planning and response plan and a community profile for Hudson Hill, a historically working class, Black community. These efforts have involved social scientists and leverage the "Map Room" as an innovative platform for the visualization of geospatial datasets (Figure 4).

## Educational partnerships

The sensors and associated data streams have inspired the creation of a Georgia standards-aligned Earth Science curriculum module for 6th grade and an engineering curriculum built around the assembly of the sensors by high schoolers (Figure 5). Teachers and students at Jenkins High School, a public high school in Savannah, have assembled over 30 sea level sensors over the last two years, in close partnership with project team researchers and educational specialists. Student testimonials speak to the enhanced learning environment that comes with contributing to the solution of a pressing community-wide challenge, with many students signing the sensor packages they constructed. However, the perceived value of these educational activities to high-level community stakeholders, including elected officials from across the political spectrum, demonstrates the universal appeal of a skills-based, solutions-oriented approach to climate change education in coastal communities.

## Hyper-local networks of sensors and people to advance climate justice

In the long term, the project aims to provide a transferable, scalable transdisciplinary research framework that advances climate justice for underserved, vulnerable communities along the coast of Georgia and beyond. In this approach, we combine sensor data streams, high-resolution models, social science datasets, and planning tools in convergent research programs that facilitate sustained community engagement on a neighborhood level. Driven by the challenge of inequity in current adaptation planning frameworks, the project draws on expertise ranging from climate scientists to sociologists to local knowledge experts. Ultimately, the project aims to deliver new tools and actionable frameworks for coastal resilience planning and solutions (e.g., land preservation, nature-based infrastructure, and community narratives) for historically marginalized, underserved coastal communities. As the number of low-cost, distributed networks of water level sensors increases (e.g., Loftis et al. 2018), they provide the opportunity to advance our understanding of the causes of consequences of flooding on the scale that people live, work, and play, and to identify the most effective set of solutions to chronic flooding.

Learn more about the community-based deployment and use of the Smart Sea Level Sensors in the City of Savannah in this AAAS video feature.

**Figure 5.** A Jenkins High School student assembling a Smart Sea Level Sensor (courtesy of Russ Clark, Georgia Tech.).

*References*


Debbage, N., 2019: Multiscalar spatial analysis of urban flood risk and environmental justice in the Charlanta megaregion, USA. *Anthropocene*, **28**, doi:10.1016/j.ancene.2019.100226.

Loftis, J. D., D. Forrest, S. Katragadda, K. Spencer, T. Organski, C. Nguyen, and S. Rhee, 2018: StormSense: A new integrated network of IoT water level sensors in the smart cities of Hampton Roads, VA. *Mar. Technol. Soc. J.*, **52**, 56-67, doi:10.4031/MTSJ.52.2.7.

Park, K., I. Federico, E. Di Lorenzo, C. G. Piecuch, T. Ezer, N. Pinardi, G. Coppini, and K .M. Cobb, 2020: Drivers of storm surge along the southeastern US coast: Comparisons between Hurricanes Matthew (2016) and Dorian (2019). *J. Geophys. Res.: Oceans*, Submitted.

# Drivers of US East Coast sea-level variability from years to decades in a changing ocean—What do we know and what do we need to know?

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Sea level varies over all time scales. At shorter periods, from minutes to months, are the familiar sea-level fluctuations due to waves, tides, storms, tsunamis, and the seasons, which have been documented by coastal populations for millennia. At longer periods, from centuries to millennia and longer, are sea-level changes tied to such global climatic and geologic phenomena as the waxing and waning of the great ice sheets, plate tectonics, and convective flow within Earth's mantle, which have been the subject of scientific inquiry for more than a century (Carlson et al. 2019; Khan et al. 2019). In between, at periods of years to decades, are more subtle sea-level variations mainly related to ocean dynamics and regional climate. Understanding sea-level variations at these intermediate time scales is informative for inferring past changes in ocean currents and anticipating future coastal hazards (Burgos et al. 2018; Piecuch 2020). Here, I review recent progress on understanding past observed sea-level variability on interannual and decadal time scales along the US East Coast—a coastline of millions of people and homes vulnerable to sea-level rise and coastal flooding (Strauss et al. 2012; Kulp and Strauss 2019). In this context, "sea level" is used to mean relative sea level, which is the height of the sea surface relative to Earth's crust, as measured by a tide gauge.

### Large-scale ocean circulation

Climate models predict that the US East Coast will experience greater-than-average sea-level rise during the next century related to changes in ocean circulation and climate (Yin et al. 2009; Landerer et al. 2007; Little et al. 2019). Over the past decade, numerous studies have used observations to test this hypothesis from models that US East Coast sea-level changes are related to changes in various components of the North Atlantic Ocean circulation, such as the Florida Current, Gulf Stream, and Atlantic meridional overturning circulation (Bingham and Hughes 2009; Boon 2012; Ezer and Corlett 2012; Sallenger et al. 2012; Ezer 2013, 2015, 2019; Ezer et al. 2013; Kopp 2013; Yin and Goddard 2013; Kenigson et al. 2014; Rossby et al. 2014; Thompson and Mitchum 2014; Woodworth et al. 2014; Goddard et al. 2015; McCarthy et al. 2015; Park and Sweet 2015; Domingues et al. 2016, 2018; Frederikse et al. 2017; Valle-Levison et al. 2017; Dong et al. 2019; Little et al. 2019; Piecuch et al. 2019a; Volkov et al. 2019; Ezer and Dangendorf 2020). A clear relation is observed between changes in the Florida Current—the Gulf Stream at Florida Strait—and coastal sea level along the South Atlantic Bight at various time scales, including interannual and decadal, such that sea level rises when the Current weakens or warms. Less clear (and more subject to debate) is the nature of any direct causal links between coastal sea level along the Mid-Atlantic Bight or Gulf of Maine and measures of the general circulation such as the latitude, width, speed, and transport of the Gulf Stream at various longitudes downstream of Cape Hatteras. To aid interpretation, analytical theories have been formulated for the connection between coastal sea level and open-ocean circulation, based on geostrophy and mass conservation in a boundary layer; these theories describe coastal sea level on a western boundary in terms of the superposition of signals propagating from upstream along coastal waveguides and along planetary potential vorticity contours, and possibly modified by friction (Thompson and Mitchum 2014; Minobe et al. 2017; Wise et al. 2018, 2020). Many questions remain regarding how sea level at the coast "feels" ongoing changes over the deep open ocean.

### Local forcing and coastal processes

One reason it has been difficult to identify the "signal" of any link between US Northeast Coast sea level and measures of large-scale general circulation is the "noise" of local forcing over the shelf near the coast (Woodworth et al. 2014; Little et al. 2019). Anomalous onshore winds can raise coastal sea level through a wind setup, whereas anomalous alongshore winds (alongshore in the counterclockwise sense of coastal-wave propagation in the Northern Hemisphere) can also increase sea level and drive an alongshore flow at the coast through frictional dynamics. According to the inverted barometer effect, lower barometric pressure forces sea level to rise isostatically (without any accompanying change in ocean circulation), while higher barometric pressure drives a corresponding sea-level fall. And it follows from Knudsen's hydrographical theorem and thermal wind balance that an increase in the volumetric rate of freshwater runoff from a river at the coast drives an increase in coastal sea level in the far field downstream of that river source, in concert with a buoyant alongshore flow. Such locally forced coastal ocean processes account for a large portion of the variability in tide-gauge sea-level records along the US East Coast north of Cape Hatteras on interannual and decadal periods (Andres et al. 2013; Li et al. 2014; Woodworth et al. 2014; Piecuch and Ponte 2015; Piecuch et al. 2016, 2018a, 2019b; Frederikse et al. 2017; Kenigson et al. 2018; Domingues et al. 2018; Chen et al. 2020). For example, Piecuch et al. (2019b) estimate that barotropic response to wind and pressure accounts for 20-50% of the interannual-to-decadal variance in US Northeast Coast tide-gauge data, but <20% of the data variance along the US Southeast Coast during the past century.

### Redistribution of ice and water

Other studies emphasize the influence of ice and water mass redistribution on US East Coast sea level. When water mass is redistributed at the surface and exchanged between the ocean and other components of the climate system, Earth's crust, gravity field, and rotation vector are perturbed, leading to spatial patterns of sea-level change (Gregory et al. 2019). Davis and Vinogradova (2017) determine that ice melt from Greenland and Antarctica accounts for most of the sea-level acceleration observed in tide-gauge records along the US Southeast Coast since the 1990s. Frederikse et al. (2017) estimate that present-day mass redistribution related to the melting of ice sheets and mountain glaciers and the building of dams explains ~30% of the acceleration observed in sea level from Virginia to Maine during 1965-2014. Karegar et al. (2016) identify the role of groundwater extraction in determining variable rates of sea-level change seen along the US Southeast Coast between South Carolina and Virginia in recent decades, revealing that rates of vertical land motion can change by ~1 mm/year on decadal time scales in response to changes in groundwater levels. These and other studies (Karegar et al. 2017; Johnson et al. 2018) demonstrate that ice and water mass redistribution, and resulting gravitational, rotational, and deformational effects, are important contributors to US East Coast sea-level changes on quasi-decadal time scales over the past century.

### Questions, challenges, and opportunities for the future

These recent studies have improved our understanding of changes in US East Coast sea level on interannual and decadal time scales. They also point to new questions, challenges, and opportunities to be addressed in the future. I briefly mention some possibilities below.

#### *How did US East Coast sea level vary during earlier time periods?*

Much of our knowledge of US East Coast sea level comes from tide-gauge records, many of which only span the past century, which is a short period relative to Earth's long climate history. To determine how representative these data are of interannual and decadal sea-level variability more generally, **future studies should interrogate US East Coast sea-level variability for earlier time periods**. Newly available instrumental and proxy data records, which extend the record of interannual and decadal sea-level variability centuries (Talke and Jay 2013; Talke et al. 2018) and millennia (Kemp et al. 2014, 2015) into the past, will be helpful to this end. A fuller portrait in space and time could be painted by applying spatiotemporal models to these new data (Cahill et al. 2015, 2016; Piecuch et al. 2017; Ashe et al. 2019; Walker et al. 2020). For example, Gehrels et al. (2020) apply probabilistic models to salt-marsh-sediment-based sea-level reconstructions, and find that there was a period of rapid multi-decadal sea-level acceleration on the US Northeast Coast in the 1700s, which was almost as rapid as accelerations observed during the twentieth century. Such studies provide a basis for evaluating whether the basic characteristics of sea-level variability will be the same or different under climate change.

***What is the spectrum of vertical land motion along the US East Coast?***

Since the advent of continuous Global Positioning System (GPS) monitoring, the community has increasingly recognized the importance of vertical land motion to coastal sea-level change (Blewitt et al. 2016; Hamlington et al. 2016; Wöppelmann and Marcos 2016; Santamaria-Gomez et al. 2017). While it has long been established that vertical land motion related to glacial isostatic adjustment (Earth's ongoing response to the last deglaciation) is a crucial large-scale, long-term control on sea-level trends (Love et al. 2016; Frederikse et al. 2017; Caron et al. 2018; Piecuch et al. 2018b), it has grown clear that high-frequency, short-scale crustal motions also contribute importantly to coastal sea-level changes (Featherstone et al. 2015; Frederikse et al. 2017; Johnson et al. 2018). It remains to fully characterize the frequency-wavenumber spectrum of vertical land motion and identify the mechanisms responsible for crustal motion at short periods and small scales along the US East Coast in the context of sea level and coastal flooding. Recent papers focusing on Norfolk, Virginia and Miami Beach, Florida use GPS records alongside remotely sensed data from interferometric synthetic aperture radar to map vertical land motion on local spatial scales (Bekaert et al. 2017; Buzzanga et al. 2020; Fiaschi and Wdowinski 2020). For example, Buzzanga et al. (2020) use Sentinel-1 data from the past five years to show that the mean rate of subsidence in Hampton Roads, Virginia is ~-4 mm/year, but that there is substantial spatial variation such that rates can vary by ~+/-3 mm/year over short spatial scales of kilometers to tens of kilometers. Such studies serve as potential templates towards more complete mapping of the drivers of coastal sea-level change and vulnerability of US East Coast communities to future flood hazards.

***How are high-frequency statistics of US East Coast sea level changing at low frequencies?***

In addition to year-to-year and decade-to-decade variations in US East Coast mean sea level, there are low-frequency modulations of high-frequency variations in tides, storms, and seasonality. The amplitude of the sea-level annual cycle on the US Southeast Coast varies on decadal time scales, reflecting a dynamic ocean response to wind forcing over the western subtropical North Atlantic (Wahl et al. 2014; Domingues et al. 2016; Calafat et al. 2018). The statistics of sea-level extremes along the US East Coast, fluctuating at decadal periods, vary in tandem with large-scale climate modes like the North Atlantic Oscillation, Arctic Oscillation, and Atlantic Multidecadal Variability (Wahl and Chambers 2015, 2016). Long tide-gauge records along the US East Coast show changes in tidal range, from more minor gradual oscillations to major abrupt changes (see recent reviews by Talke and Jay 2020; Haigh et al. 2020). **More work is needed to establish how and why such modulations and changes in tides, surges, and seasonality occur along the US East Coast, whether they are independent or covary, and the consequences for the statistics of sea-level extremes and high-tide flooding** (Ray and Foster 2016; Sweet et al. 2016; Burgos et al. 2018).

***What is the origin of the spatial covariance structure of US East Coast sea level variability?***

There is a peculiar spatial structure to sea-level variability along the US East Coast: sea levels north of Cape Hatteras vary coherently along the coast from Virginia to Maine, but are uncorrelated with sea-level variations south of Cape Hatteras from Florida to Virginia (Thompson and Mitchum 2014; Woodworth et al. 2014; McCarthy et al. 2015; Piecuch et al. 2016; Calafat et al. 2018). This "break" in covariance is surprising given a basic expectation for coastal sea level to be coherent over thousands of kilometers due to boundary waves (Hughes and Meredith 2006; Hughes et al. 2019). Hypotheses have been submitted, some having to do with ocean currents (Thompson 1986; Thompson and Mitchum 2014; McCarthy et al. 2015), others with the geometry of the coast and bathymetry (Meade and Emery 1971), but **the origin of this spatial-covariance structure in US East Coast sea level remains to be established**. Such knowledge will be important for evaluating climate models and assessing whether such covariance structure is a permanent feature of coastal sea level or if a distinct structure will emerge in the future under climate change.

***How will new altimetry data change our understanding of US East Coast sea level variability?***

Tide gauges provide long records of sea level at the coast, but these data have shortcomings. For example, they are spatially "one dimensional," in the sense that networks of tide gauges observe changes in the alongshore direction, but are "blind" to the structure of sea level offshore. Conventional satellite-altimetry data products have, in the past, not been helpful in this regard, since the quality of the data can be degraded near the coast due to errors in the instrumental measurement itself as well as uncertainties in the geophysical corrections. **Newly reprocessed, dedicated coastal altimetry products and the upcoming Surface Water and Ocean Topography wide-swath altimeter mission promise to change the game, and revolutionize our view of sea level and land-ocean interactions along the US East Coast as well as over the global coastline** (Passaro et al. 2015; Birol et al. 2017; Morrow et al. 2019).

***Are ongoing changes in the western North Atlantic Ocean affecting US East Coast sea level?***

Relationships between coastal sea level and large-scale ocean circulation remain an important topic of future investigation (Ponte et al. 2019). Noteworthy in this context are the remarkable changes ongoing in the western North Atlantic Ocean. In recent decades, the Gulf of Maine has warmed much faster than the global average (Pershing et al. 2015), marine heat waves have grown longer and more frequent (Oliver et al. 2019), the Gulf Stream has grown increasingly unstable (Andres 2016), warm core rings have been shed more often from the Gulf Stream and lived longer than previously (Gangopadhyay et al. 2019), and intrusions of warm, salty slope and Gulf Stream waters onto the continental shelf have become more frequent (Ullman et al. 2014; Zhang and Gawarkiewicz 2015; Gawarkiewicz et al. 2018). **It remains to establish if any of these regional oceanographic changes are relevant to US East Coast sea level**. The interested reader is directed to Little et al. (2019) for more general future research directions on this topic.

## Conclusion

Sea level is a "whole-Earth" process, and sea-level changes reflect myriad geologic and climatic processes acting across space and time. Here I have reviewed recent progress on understanding drivers of observed year-to-year and decade-to-decade US East Coast sea-level change. I mainly emphasize observational studies published during the past decade, and focus largely on the relevance of large-scale circulation, locally forced processes, and surface mass redistribution. I also point to some opportunities for future research, highlighting new technologies and data as well as pressing changes ongoing in the ocean. I hope this short review (see Little et al. 2019 for a more detailed treatment) motivates future research and is informative to both scientific and non-scientific audiences, serving as a jumping-off point for a deeper dive into the literature.

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*References*


Andres, M. A., 2016: On the recent destabilization of the Gulf Stream path downstream of Cape Hatteras. *Geophys.Res. Lett.*, **43**, 9834-9842, doi:10.1002/2016GL069966.

Andres, M. A., and Coauthors, 2013: Interannual sea level variability in the western North Atlantic: Regional forcing and remote response. *Geophys.Res. Lett.*, **40**, 5915-5919, doi:10.1002/2013GL058013.

Ashe, E. L., and Coauthors, 2019: Statistical modeling of rates and trends in Holocene relative sea level. *Qauat. Sci. Rev.*, **204**, 58-77, doi:10.1016/j.quascirev.2018.10.032.

Bekaert, D. P. S., B. D. Hamlington, B. Buzzanga, and C. E. Jones, 2017: Spaceborne synthetic aperture radar survey of subsidence in Hampton Roads, Virginia (USA). *Sci. Rep.*, **7**, doi:10.1038/s41598-017-15309-5.

Bingham, R. J., and C. W. Hughes, 2009: Signature of the Atlantic meridional overturning circulation in sea level along the east coast of North America. *Geophys. Res. Lett.*, **36**, doi:10.1029/2008GL036215.

Birol, F., and Coauthors, 2017: Coastal application from nadir altimetry: Example of the X-TRACK regional products. *Adv. Space Res.*, **59**, 936-953, doi:10.1016/j.asr.2016.11.005.

Blewitt, G., C. Kreemer, W. C. Hammond, and J. Gazeaux, 2016: MIDAS robust trend estimator for accurate GPS station velocities without step detection. *J. Geophys Res.*: Solid Earth, **121**, 2054-2068, doi:10.1002/2015JB012552.

Burgos, A. G., B. D. Hamlington, P. R. Thompson, and R. D. Ray, 2018: Future nuisance flooding in Norfolk, VA, from astronomical tides and annual to decadal internal climate variability. *Geophys. Res. Lett.*, **45**, 12432-12439, doi:10.1029/2018GL079572.

Buzzanga, B., D. P. S. Bekaert, B. D. Hamlington, and S. S. Sangha, 2020: Towards sustained monitoring of subsidence at the coast using InSAR and GPS: An application in Hampton Roads, Virginia. *Geophys. Res. Lett.*, **47**, doi:10.1029/2020GL090013.

Boon, J. D., 2012: Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America. *J. Coastal Res.*, **28**, 1437-1445, doi:10.2112/jcoastres-d-12-00102.1.

Cahill, N., A. C. Kemp, B. P. Horton, and A. C. Parnell, 2015: Modeling sea-level change using errors-in-variables integrated Gaussian processes. *Ann. Appl. Stat.*, **9**, 537-571, doi:10.1214/15-AOAS824.

Cahill, N., A. C. Kemp, B. P. Horton, and A. C. Parnell, 2016: A Bayesian hierarchical model for reconstructing relative sea level: From raw data to rates of change. *Climate Past*, **12**, 525-542, doi:10.5194/cp-12-525-2016.

Calafat, F. M., T. Wahl, F. Lindsten, J. Williams, and E. Frajka-Williams, 2018: Coherent modulation of the sea-level annual cycle in the United States by Atlantic Rossby waves. *Nat. Commun.*, **9**, doi:10.1038/s41467-018-04898-y.

Carlson, A. E., A. Dutton, A. J. Long, and G. A. Milne, 2019: PALeo constraints on SEA level rise (PALSEA): Ice-sheet and sea-level responses to past climate warming. *Quat. Sci. Rev.*, **212**, 28-32, doi:10.1016/j.quascirev.2019.03.032.

Caron, L., E. R. Ivins, E. Larour, S. Adhikari, J. Nilsson, and G. Blewitt, 2018: GIA model statistics for GRACE hydrology, cryosphere, and ocean science. *Geophys. Res. Lett.*, **45**, 2203-2212, doi:10.1002/2017GL076644.

Chen, NG. Han, and X.-H. Yan, 2020: Similarity and difference in interannual sea level variations between the Mid-Atlantic Bight and the Nova Scotia Coast. *J. Geophys. Res.: Oceans*, **125**, doi:10.1029/2019JC015919.

Davis, J. L., and N. T. Vinogradova, 2017: Causes of accelerating sea level on the East Coast of North America. *Geophys. Res. Lett.*, **44**, 5133-5141, doi:10.1002/2017GL072845.

Domingues, R., M. Baringer, and G. Goni, 2016: Remote sources for year-to-year changes in the seasonality of the Florida Current transport. *J. Geophys. Res.: Oceans*, **121**, 7547-7559, doi:10.1002/2016JC012070.

Domingues, R., G. Goni, M. Baringer, and D. Volkov, 2018: What caused the accelerated sea level changes along the U.S. East Coast during 2010-2015? *Geophys. Res. Lett.*, **45**, 13367-13376, doi:10.1029/2018GL081183.

Dong, S., M. O. Baringer, and G. J. Goni, 2019: Slow down of the Gulf Stream during 1993-2016. *Sci. Rep.*, **9**, doi:10.1038/s41598-019-42820-8.

Ezer, T., and W. B. Corlett, 2012: Is sea level accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data. *Geophys. Res. Lett.*, **39**, doi:10.1029/2012GL053435.

Ezer, T., and S. Dangendorf, 2020: Global sea level reconstruction for 1900-2015 reveals regional variability in ocean dynamics and an unprecedented long weakening in the Gulf Stream flow since the 1990s. *Ocean Sci.*, **16**, 997-1016, doi:10.5194/os-16-997-2020.

Ezer, T., 2013: Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophys. Res. Lett.*, **40**, 5339-5444, doi:10.1002/2013GL057952.

Ezer, T., 2015: Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009-2010 and estimated variations for 1935-2012. *Global Planet. Change*, **129**, 23-36, doi:10.1016/j.gloplacha.2015.03.002.

Ezer, T., 2019: Regional differences in sea level rise between the Mid-Atlantic Bight and the South Atlantic Bight: Is the Gulf Stream to blame? *Earth's Future*, **7**, 771-783, doi:10.1029/2019EF001174.

Ezer, T., L. P. Atkinson, W. B. Corlett, and J. L. Blanco, 2013: Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *J. Geophys Res.: Oceans*, **118**, 685-697, doi:10.1002/jgrc.20091.

Featherstone, W. E., N. T. Penna, M. S. Filmer, and S. D. P. Williams, 2015: Nonlinear subsidence at Fremantle, a long-recording tide gauge in the Southern Hemisphere. *J. Geophys. Res.: Oceans*, **120**, 7004-7014, doi:10.1002/2015JC011295.

Fiaschi, S., and S. Wdowinski, 2020: Local land subsidence in Miami Beach (FL) and Norfolk (VA) and its contribution to flooding hazard in coastal communities along the U.S. Atlantic Coast. *Ocean Coastal Manage.*, **187**, doi:10.1016/j.ocecoaman.2019.105078.

Frederikse, T., K. Simon, C. A. Katsman, and R. Riva, 2017: The sea-level budget along the Northwest Atlantic coast: GIA, mass changes, and large-scale ocean dynamics. *J. Geophys. Res.: Oceans*, **122**, 5486-5501, doi:10.1002/2017JC012699.

Gangopadhyay, A., G. Gawarkiewicz, E. Nishchitha S. Silva, M. Monim, and J. Clark, 2019: An observed regime shift in the formation of warm core rings from the Gulf Stream. *Sci. Rep.*, **9**, doi:10.1038/s41598-019-48661-9.

Gawarkiewicz, G. G., and Coauthors, 2018: The changing nature of shelf-break exchange revealed by the OOI Pioneer Array. *Oceanography*, **31**, 60-70, doi:10.5670/oceanog.2018.110.

Gehrels, W. R., S. Dangendorf, N. L. M. Barlow, M. H. Saher, A. J. Long, P. L. Woodworth, C. G. Piecuch, and K. Berk, 2020: A preindustrial sea-level rise hotspot along the Atlantic Coast of North America. *Geophys. Res. Lett.*, **47**, doi:10.1029/2019GL085814.

Goddard, P. B., J. Yin, S. M. Griffies, and S. Zhang, 2015: An extreme event of sea-level rise along the Northeast coast of North America in 2009-2010. *Nat. Commun.*, **6**, doi:10.1038/ncomms7346.

Gregory, J. M., and Coauthors, 2019: Concepts and terminology for sea level: Mean, variability, and change, both local and global. *Surv. Geophys*., **40**, 1251-1249, doi:10.1007/s10712-019-09525-z.

Haigh, I. D., and Coauthors, 2020: The tides they are a-changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms, and future implications. *Rev. Geophys*., **57**, doi:10.1029/2018RG000636.

Hamlington, B. D., P. Thompson, W. C. Hammond, G. Blewitt, and R. D. Ray, 2016: Assessing the impact of vertical land motion on twentieth century global mean sea level estimates. *J. Geophys. Res.: Oceans*, **121**, 4980-4993, doi:10.1002/2016JC011747.

Hughes, C. W., and M. P. Meredith, 2006: Coherent sea-level fluctuations along the global continental slope. *Philos. Trans. R. Soc., A*, **364**, 885-901, doi:10.1098/rsta.2006.1744.

Hughes, C. W., I. Fukumori, S. M. Griffies, J. M. Huthnance, S. Minobe, P. Spence, K. R. Thompson, and A. Wise, 2019: Sea level and the role of coastal trapped waves in mediating the Influence of the open ocean on the coast. *Surv. Geophys*., **40**, 1467-1492, doi:10.1007/s10712-019-09535-x.

Johnson, C. S., K. G. Miller, J. V. Browning, R. E. Kopp, N. S. Khan, Y. Fan, S. D. Stanford, and B. P. Horton, 2018: The role of sediment compaction and groundwater withdrawal in local sea-level rise, Sandy Hook, New Jersey, USA. *Quat. Sci. Rev*., **181**, 30-42, doi:10.1016/j.quascirev.2017.11.031.

Karegar, M. A., T. H. Dixon, and S. E. Engelhart, 2016: Subsidence along the Atlantic Coast of North America: Insights from GPS and late Holocene relative sea level data. *Geophys. Res. Lett.*, **43**, 3126-3133, doi:10.1002/2016GL068015.

Karegar, M. A., T. H. Dixon, R. Malservisi, J. Kusche, and S. E. Engelhart, 2017: Nuisance flooding and relative sea-level rise: the importance of present-day land motion. *Sci. Rep.*, **7**, doi:10.1038/s41598-017-11544-y.

Kemp, A. C., and Coauthors, 2014: Late Holocene sea- and land-level change on the U.S. southeastern Atlantic coast. *Mar. Geol*., **357**, 90-100, doi:10.1016/j.margeo.2014.07.010.

Kemp, A. C., and Coauthors, 2015: Relative sea-level change in Connecticut (USA) during the last 2200 yrs. *Earth Planet. Sci. Lett*., **428**, 217-229, doi:10.1016/j.epsl.2015.07.034.

Kenigson, J. S., and W. Han, 2014: Detecting and understanding the accelerated sea level rise along the east coast of the United States during recent decades. *J. Geophys. Res.: Oceans*, **119**, 8749-8766, doi:10.1002/2014JC010305.

Kenigson, J. S., W. Han, B. Rajagopalan, Yanto, and M. Jasinski, 2018: Decadal shift of NAO-linked interannual sea level variability along the U.S. Northeast Coast. *J. Climate*, **31**, 4981-4989, doi:10.1175/JCLI-D-17-0403.1.

Khan, N. S., and Coauthors, 2019: Inception of a global atlas of sea levels since the Last Glacial Maximum. *Quat. Sci. Rev*., **220**, 359-371, doi:10.1016/j.quascirev.2019.07.016.

Kopp, R. E., 2013: Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophys. Res. Lett.*, **40**, 3981-3985, doi:10.1002/grl.50781.

Kulp, S. A., and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat. Commun.*, **10**, doi:10.1038/s41467-019-12808-z.

Morrow, R., and Coauthors, 2019: Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) Mission. *Front. Mar. Sci*., **6**, doi:10.3389/fmars.2019.00232.

Landerer, F. W., J. H. Jungclaus, and J. Marotzke, 2007: Regional dynamic and steric sea level change in response to the IPCC-A1B scenario. *J. Phys. Oceanogr*., **37**, 296-312, doi:10.1175/JPO3013.1.

Li, Y., R. Ji, P. S. Fratantoni, C. Chen, J. A. Hare, C. S. Davis, and R. C. Beardsley, 2014: Wind-induced interannual variability of sea level slope, along-shelf flow, and surface salinity on the Northwest Atlantic shelf. *J. Geophys Res.: Oceans*, **119**, 2462-2479, doi:10.1002/2013JC009385.

Little, C. M., C. G. Piecuch, and R. M. Ponte, 2017: On the relationship between the meridional overturning circulation, alongshore wind stress, and United States East Coast sea level in the Community Earth System Model Large Ensemble. *J. Geophs Res.: Oceans*, **122**, doi:10.1002/2017JC012713.

Little, C. M., A. Hu, C. W. Hughes, G. D. McCarthy, C. G. Piecuch, R. M. Ponte, and M. D. Thomas, 2017: The relationship between U.S. East Coast sea sevel and the Atlantic Meridional Overturning Circulation: A review. *J. Geophs Res.: Oceans*, **124**, 6435-6458, doi:10.1029/2019JC015152.

Love, R., G. A. Milne, L. Tarasov, S. E. Engelhart, M. P. Hijma, K. Latychev, B. P. Horton, and T. E. Törnqvist, 2016: The contribution of glacial isostatic adjustment to projections of sea-level change along the Atlantic and Gulf coasts of North America. *Earth's Future*, **4**, 440-464, doi:10.1002/2016EF000363.

McCarthy, G. D., I. D. Haigh, J. J.-M. Hirschi, J. P. Grist, and D. A. Smeed, 2015: Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature*, **521**, 508-510, doi:10.1038/nature14491.

Meade, R. H., and K. O. Emery, 1971: Sea level as affected by river runoff, Eastern United States. *Science*, **173**, 425-428, doi:10.1126/science.173.3995.425.

Minobe, S., M. Terada, B. Qiu, and N. Schneider, 2017: Western boundary sea level: A theory, rule of thumb, and application to climate models. *J. Phys. Oceanogr.*, **47**, 957-977, doi:10.1175/JPO-D-16-0144.1.

Oliver, E. C. J., and Coauthors, 2019: Longer and more frequent marine heatwaves over the past century. *Nat. Commun.*, **9**, doi:10.1038/s41467-018-03732-9.

Park, J., and W. Sweet, 2015: Accelerated sea level rise and Florida Current transport. *Ocean Sci*., **11**, 607-615, doi:10.5194/os-11-607-2015.

Passaro, M., P. Cipollini, and J. Benveniste, 2015: Annual sea level variability of the coastal zone: The Baltic Sea-North Sea transition Zone. *J. Geophys. Res.: Oceans*, **120**, 3061-3078, doi:10.1002/2014JC010510.

Pershing, A. J., and Coauthors, 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350**, doi:10.1126/science.aac9819.

Piecuch, C. G., 2020: Likely weakening of the Florida Current during the past century revealed by sea-level observations. *Nat. Commun.*, **11**, doi:10.1038/s41467-020-17761-w.

Piecuch, C. G., and R. M. Ponte, 2015: Inverted barometer contributions to recent sea level changes along the northeast coast of North America. *Geophys. Res. Lett.*, **42**, 5918-5925, doi:10.1002/2015GL064580.

Piecuch, C. G., S. Dangendorf, R. M. Ponte, and M. Marcos, 2016: Annual sea level changes on the North American Northeast Coast: Influence of local winds and barotropic motions. *J. Climate*, **29**, 4801-4816, doi:10.1175/JCLI-D-16-0048.1.

Piecuch, C. G., P. Huybers, and M. P. Tingley, 2017: Comparison of full and empirical Bayes approaches for inferring sea-level changes from tide-gauge data. *J. Geophys. Res.: Oceans*, **122**, 2243-2258, doi:10.1002/2016JC012506.

Piecuch, C. G., K. Bittermann, A. C. Kemp, R. M. Ponte, C. M. Little, S. E. Engelhart, and S. J. Lentz, 2018a: River-discharge effects on United States Atlantic and Gulf coast sea-level changes. *Proc. Natl. Acad. Sci*., **115**, 7729-7734, doi:10.1073/pnas.1805428115.

Piecuch, C. G., P. Huybers, C. C. Hay, A. C. Kemp, C. M. Little, J. X. Mitrovica, R. M. Ponte, and M. P. Tingley, 2018b: Origin of spatial variation in US East Coast sea-level trends during 1900-2017. *Nature*, **564**, 400-404, doi:10.1038/s41586-018-0787-6.

Piecuch, C. G., S. Dangendorf, G. G. Gawarkiewicz, C. M. Little, R. M. Ponte, and J. Yang, 2019a: How is New England coastal sea level related to the Atlantic Meridional Overturning Circulation at 26N? *Geophys. Res. Lett.*, **46**, 5351-5360, doi:10.1029/2019GL083073.

Piecuch, C. G., F. M. Calafat, S. Dangendorf, and G. Jordà, 2019b: The ability of barotropic models to simulate historical mean sea level changes from coastal tide gauge data. *Surv. Geophys*., **40**, 1399-1435, doi:10.1007/s10712-019-09537-9.

Ponte, R. M., B. Meyssignac, C. M. Domingues, D. Stammer, A. Cazenave, and T. Lopez, 2019: Guest editorial: Relationships between coastal sea level and large-scale ocean circulation. *Surv. Geophys.*, **40**, 1245-1249, doi:10.1007/s10712-019-09574-4.

Ray, R. D., and G. Foster, 2016: Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future*, **4**, 578-587, doi:10.1002/2016EF000423.

Rossby, T., C. N. Flagg, K. Donohue, A. Sanchez-Franks, J. Lillibridge, 2014: On the long-term stability of Gulf Stream transport based on 20 years of direct measurements. *Geophys. Res. Lett.*, **41**, doi:10.1002/2013GL058636.

Sallenger, A. H., K. S. Doran, and P. A. Howd, 2012: Hotspot of accelerated sea-level rise on the Atlantic Coast of North America. *Nat. Climate Change*, **2**, 884-888, doi:10.1038/nclimate1597.

Santamaría-Gómez, A., M. Gravelle, S. Dangendorf, M. Marcos, G. Spada, and G. Wöppelmann, 2017: Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth Planet. Sci. Lett*., **473**, 24-32, doi:10.1016/j.epsl.2017.05.038.

Strauss, B. H., R. Ziemlinski,J. L. Weiss, and J. T. Overpeck, 2012: Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environ. Res. Lett*., **7**, doi:10.1088/1748-9326/7/1/014033.

Sweet, W. V., M. Menendez, A. Genz, J. Obeysekera, J. Park, and J. J. Marra, 2016: In tide's way: Southeast Florida's September 2015 sunny-day flood. *Bull. Amer. Meteor. Soc*., doi:10.1175/BAMS-D-16-0117.1.

Talke, S. A., and D. A. Jay, 2013: Nineteenth century North American and Pacific tidal data: Lost or just forgotten? *J. Coastal Res*., **29**, 118-127, doi:10.2112/jcoastres-d-12-00181.1.

Talke, S. A., A. C. Kemp, and J. Woodruff, 2018: Relative sea level, tides, and extreme water levels in Boston Harbor from 1825 to 2018. *J. Geophys. Res.: Oceans*, **123**, 3895-3914, doi:10.1029/2017JC013645.

Talke, S. A., and D. A. Jay, 2020: Changing tides: The role of natural and anthropogenic factors. *Annu. Rev. Mar. Sci*., **12**, doi:10.1146/annurev-marine-010419-010727.

Thompson, K. R., 1986: North Atlantic sea-level and circulation. *Geophys. J. R. Astron. Soc*., **87**, 15-32, doi:10.1111/j.1365-246X.1986.tb04543.x.

Thompson, P. R., and G. T. Mitchum, 2014: Coherent sea level variability on the North Atlantic western boundary. *J. Geophys. Res.: Oceans*, **119**, 5676-5689, doi:10.1002/2014JC009999.

Ullman, D. S., D. L. Codiga, A. Pfeiffer-Herbert, and C. R. Kincaid, 2014: An anomalous near-bottom cross-shelf intrusion of slope water on the southern New England continental shelf. *J. Geophys. Res.: Oceans*, **119**, 1739-1753, doi:10.1002/2013JC009259.

Valle-Levison, A., A. Dutton, and J. B. Martin, 2017: Spatial and temporal variability of sea level rise hot spots over the eastern United States. *Geophys. Res. Lett.*, **44**, 7876-7882, doi:10.1002/2017GL073926.

Volkov, D. L., S.-K. Lee, R. Domingues, H. Zhang, and M. Goes, 2019: Interannual sea level variability along the southeastern seaboard of the United States in relation to the gyre-scale heat divergence in the North Atlantic. *Geophys. Res. Lett.*, **46**, 7481-7490, doi:10.1029/2019GL083596.

Wahl, T., F. M. Calafat, and M. E. Luther, 2014: Rapid changes in the seasonal sea level cycle along the US Gulf coast from the late 20th century. *Geophys. Res. Lett.*, **41**, 491-498, doi:10.1002/2013GL058777.

Wahl., T., and D. P. Chambers, 2015: Evidence for multidecadal variability in US extreme sea level records. *J. Geophys. Res.: Oceans*, **120**, 1527-1544, doi:10.1002/2014JC010443.

Wahl., T., and D. P. Chambers, 2016: Climate controls multidecadal variability in U.S. extreme sea level records. *J. Geophys. Res.: Oceans*, **121**, 1274-1290, doi:10.1002/2015JC011057.

Walker, J. S., N. Cahill, N. S. Khan, T. A. Shaw, D. Barber, K. G. Miller, R. E. Kopp, and B. P. Horton, 2020: Incorporating temporal and spatial variability of salt-marsh foraminifera into sea-level reconstructions. *Mar. Geol*., **429**, doi:10.1016/j.margeo.2020.106293.

Wise, A., C. W. Hughes, and J. A. Polton, 2018: Bathymetric influence on the coastal sea level response to ocean gyres at western boundaries. *J. Phys. Oceanogr.*, **48**, 2949-2964, doi:10.1175/JPO-D-18-0007.1.

Wise, A., C. W. Hughes, J. A. Polton, and J. M. Huthnance, 2020: Leaky slope waves and sea level: Unusual consequences of the beta effect along western boundaries with bottom topography and dissipation. *J. Phys. Oceanogr.*, **50**, 217-237, doi:10.1175/JPO-D-19-0084.1.

Woodworth, P. L., M. A. Morales Maqueda, V. M. Roussenov, R. G. Williams, and C. W. Hughes, 2014: Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation. *J. Geophys. Res.: Oceans*, **119**, 8916-8935, doi:10.1002/2014JC010520.

Wöppelmann, G., and M. Marcos, 2016: Vertical land motion as a key to understanding sea level change and variability. *Rev. Geophys.*, **54**, 64-92, doi:10.1002/2015RG000502.

Yin, J., M. E. Schlesinger, and R. J. Stouffer, 2009: Model projections of rapid sea-level rise on the northeast coast of the United States. *Nat. Geosci*., **2**, 262-266, doi:10.1038/ngeo462.

Yin, J., and P. B. Goddard, 2013: Oceanic control of sea level rise patterns along the East Coast of the United States. *Geophys. Res. Lett.*, **40**, 5514-5520, doi:10.1002/2013GL057992.

Zhang, W. G., and G. G. Gawarkiewicz, 2015: Dynamics of the direct intrusion of Gulf Stream ring water onto the Mid-Atlantic Bight Shelf. *Geophys. Res. Lett.*, **42**, 7687-7695, doi:10.1002/2015GL065530.

# ANNOUNCEMENTS

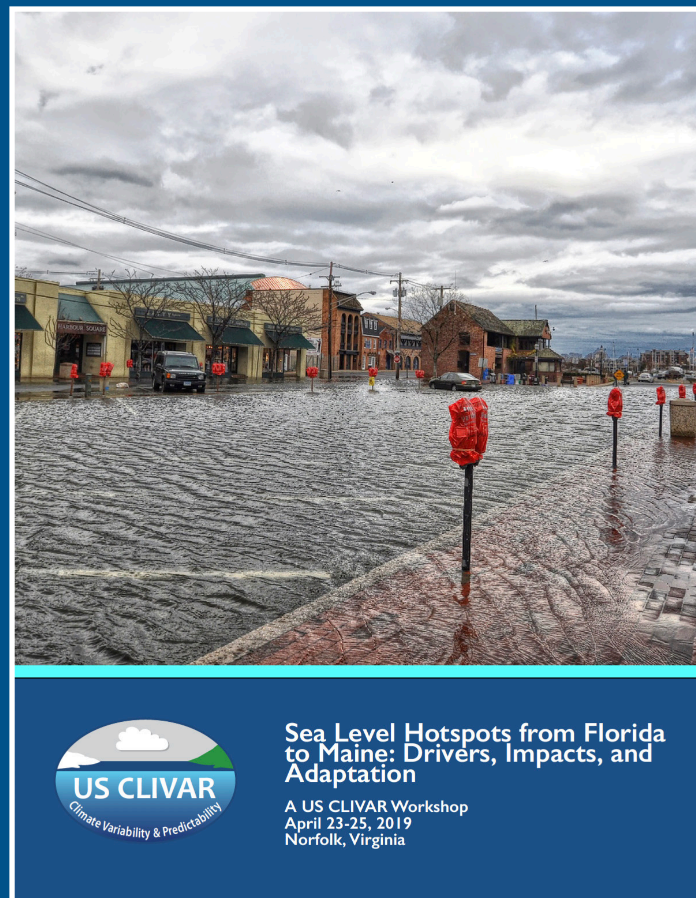
## New US CLIVAR Workshop Report!

### Sea Level Hotspots from Florida to Maine: Drivers, Impacts, and Adaptation

This US CLIVAR Workshop took place in Norfolk, Virginia from April 23-25, 2019, with the main goal of bringing together the scientific community, decision makers, coastal stakeholders, and practitioners to share state-of-the-art knowledge about sea level changes along the US East Coast. The workshop addressed four main questions:

1. What are the efforts already in place and aimed at mitigating the effects of sea level rise and improving overal coastal resilience?
2. Where are we with science, and what do we know about the drivers, uncertainty, and the future of sea level rise?
3. What are the tools and monitoring resources currently available?
4. What are best practices for linking scientific information with decision-making support tools, and what are the gapsthat need to be addressed?

Read more here

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