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

A US CLIVAR Workshop
April 23-25, 2019
Norfolk, Virginia

SEA LEVEL HOTSPOTS FROM FLORIDA TO MAINE: DRIVERS, IMPACTS, AND ADAPTATION

Workshop Report

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FRONT COVER IMAGE

Tidal flooding in Annapolis, Maryland (Credit: Amy McGovern, University of Oklahoma)

BACK COVER IMAGE

Group photo of workshop participants (Credit: Jennie Zhu)

Table of Contents

1 EXECUTIVE SUMMARY

The US CLIVAR Workshop "Sea Level Hotspots from Florida to Maine: Drivers, Impacts, and Adaptation" took place in Norfolk, Virginia from April 23 to 25, 2019, with the main goal of bringing together the scientific community, decision makers, coastal stakeholders, and practitioners to share state-of-the-art of 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 overall coastal resilience?
2. Where are we with science, and what do we know about the drivers, the 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 gaps that need to be addressed?

The workshop sessions provided a comprehensive overview of recent progress and current needs concerning sea level science and adaptation efforts. There is currently a growing and diverse number of adaptation efforts led by local municipalities, cities, and states to implement policy and/or design and build protection infra-structure to improve coastal resilience. Some of these efforts are organized in regional networks with participation from city managers, scientists, and representatives from boundary organizations, which are helping to define a coherent set of guidelines.

Recent research progress illustrated improved understanding of (i) plausible scenarios for future sea level rise as well as (ii) regional differences throughout the US East Coast with the associated regional drivers. The understanding of and capabilities to model changes in the coastal landscape has improved. New computational tools and frameworks help improve uncertainty quantification necessary for optimized solutions within complex decision-making circumstances. Several web-based tools have recently been developed such as the NOAA Sea Level Rise Viewer, the NASA Sea Level Portal, USGS's Coastal Change Hazards Portal, and the US Army Corps of Engineers' Sea Level Tracker, which are being used by planners and practitioners to carry out adaptation efforts. Observational assets such as satellite observations, tide gauges, meteorological stations, and custom water level sensors also provide an important resource for monitoring changes. Open data and citizen scientists applications are being implemented to gather information from users concerning local flooding conditions, which can later be used to validate simple models as well as high-resolution modelling systems.

Focused discussions during the workshop identified key recommended actions to guide development of future information resources, to focus scientific research for informing such resources, and to implement best practices linking science and adaptation decision support.

Key Information Needs

- Develop additional educational resources aimed at informing decision makers on how to interpret and use the diverse and divergent sea level rise projections, scenarios, and its associated uncertainties.
- Improve storm frequency and surge projections to support long-term planning of infrastructure.
- Establish a coherent set of standards, guidance, and best practices for engineers to work with sea level rise projections.
- Update the NOAA Atlas 14 database to include improved and up-to-date rainfall estimates.
- Improve coverage and availability of coastal sea level (e.g., tide gauges, low-cost sea level sensors) and hydrologic data (e.g., rain gauges).
- Improve subseasonal to interannual sea level (King Tides) forecasts and implement a centralized nuisance flooding and King Tides information tool.

Key Research Needs

- Further explore the role of integrated model approaches in reducing uncertainty in long-term sea level rise projections.
- Formalize and foster advances to the field of decision science and advance the field of climate adaptation.
- Improve uncertainty quantification of observational and modeling efforts to better support decision-making needs.
- Improve understanding of drivers of sea level variability across timescales from subseasonal to interannual to decadal (e.g., storminess, ocean dynamics, natural climate variation).
- Improve understanding of the relationship between tidal range, sea level rise, groundwater, and coastal erosion processes.
- Improve understanding on compound flooding probabilities (e.g., intense rain, coastal surge).
- Assess the long-term performance and reliability of natural and nature based infrastructure such as living shorelines in coastal risk reduction to changing water levels associated with sea level rise and storm surge.
- Improve understanding of feedback between ecosystem health and sea level rise.

Recommendations to Link Science and Decision Support

- Foster sustained opportunities for sea level information exchange across communities as was enabled by this workshop.
- Maintain current network of sea level observations and implement new observations of coupled natural and human systems in support of long-term records.
- Carry out a comprehensive inventory of current adaptation efforts in place along the US East Coast.
- Nurture the establishment of an institutionalized framework to move science information into actionable decision making support tools, i.e., through research grants tailored to encouraging co-production, and to identifying and rewarding talent among adaptation professionals.
- Foster the integration of end-user perspectives and needs within efforts to develop fit-for-purpose tools scaled to the range of needs and resources available.
- Foster opportunities for public engagement for informing communities and helping drive political will towards adaptation efforts and addressing community needs.
- Assess the design and impacts of hazard information through use-focused experiments.
- Catalog and improve understanding of the mapping of preferences (e.g., risk tolerance) to hazard characterization and communication.
- Establish regional networks for adaptation efforts, bringing together sea level experts, boundary organizations, and sea level practitioners.
- Establish an institutionalized network for the exchange of sea level information and science knowledge within the US that includes scientists, engineers, and stakeholders.

This workshop provided a very unique opportunity to gather those working at the forefront of the sea-level science and adaptation efforts, enabling a much needed exchange of multi-disciplinary information related to sea level rise and changes. Such interactions will become increasingly more important in the future as the impacts of sea level rise amplify.

2 INTRODUCTION

2.1 Background

The United States East Coast is a global "hot spot" for regional sea level changes with densely populated and highly developed areas that are exposed to observed sea level rise. Observations show that several areas along the US East Coast are experiencing sea level rise rates higher than the global average of approximately 3 mm year-1 (Figure 1a), and the frequency of nuisance flooding events in this region is increasing (Figure 1b) and further projected to intensify (e.g., for Norfolk, Virginia, Figure 1c, Sweet et al. 2018). According to NOAA's long-term intermediate scenario projections for example, Norfolk is expected to experience nuisance flooding conditions nearly every other day (~180 days per year) considering current flooding threshold values (Sweet et al. 2017). Similar conditions are also expected for most locations along the US East Coast, including other densely populated areas such as Miami, Florida.

The ability to quantify and project exposure to changing sea levels and other changes in tides, surge, and waves is key to understanding the vulnerability of these locations, and in turn how and when to adapt to these changes. We consider exposure, sensitivity, and adaptive capacity to be the primary components of vulnerability. Exposure may not be an issue for areas with low or no sensitivity (as discussed later for parts of the US Northeast). In these cases, adaptation is generally not a key priority. Where there is exposure and sensitivity, one must assess adaptive capacity – the financial, technical, and social capabilities of the community to adapt to the disruptions caused by or exacerbated by changing sea levels. In sensitive areas with high adaptive capacity, the planning and implementation process as well as the suite of potential adaptation measures may be different than areas where there is low adaptive capacity (e.g., constrained financial or technical resources). The most vulnerable locations will be those that are exposed to the changes now or in the near future, sensitive to these changes, and with low adaptive capacity.

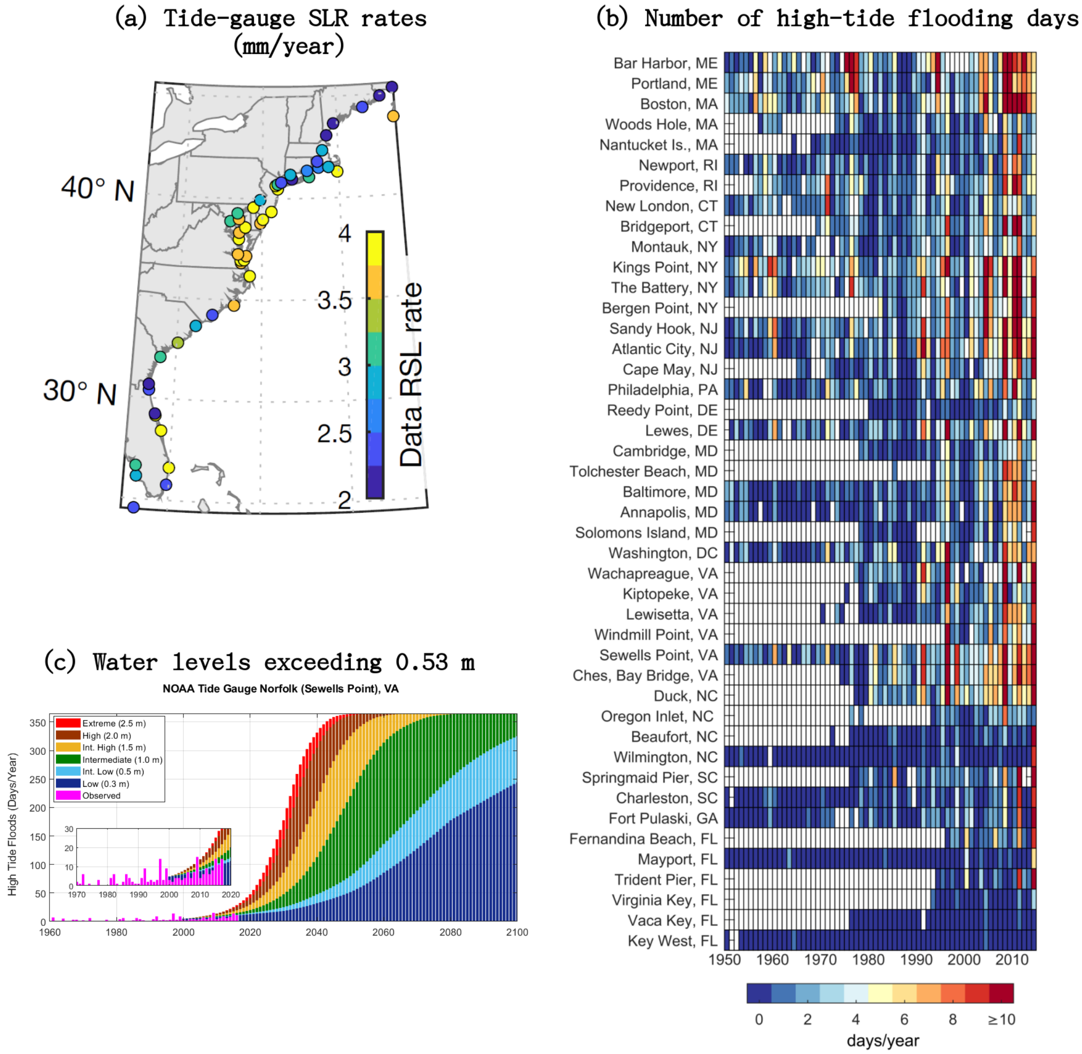

Figure 1. (a) Rates of sea level rise observed by 43 tide gauges along the US East Coast (reproduced from Piecuch et al. 2017). (b) Yearly number of high-tide flooding days estimated at 43 tide gauges for water levels exceeding a local threshold. (c) Projected number of high-tide flooding days for Norfolk, VA according to NOAA's sea level rise scenarios and assuming an unchanged flooding threshold value of 0.53 m (MHHW). Panels (c) and (d) are adapted from Sweet et al. (2018).

Many cities along the US East Coast experiencing larger sea level rise rates than the global average are beginning to plan and implement adaptation efforts to mitigate the effects of sea level rise and improve coastal resilience. The New York City Panel on Climate Change (NPCC) gathers expert information to provide regional guidance on sea level rise for coastal planners in the region. Extensive and high-budget resilience projects are currently underway in New York City and its surrounding metropolitan area, including projects being implemented by the Port Authority of New York and New Jersey. Similarly, the Southeast Florida Regional Climate Change Compact was jointly established in 2010 by Broward, Miami-Dade, Monroe, and Palm Beach Counties to coordinate mitigation and adaptation activities and strategies across county lines. These activities and strategies involved coordinating with the local scientific community to adopt a unified sea level projection for the region. Another international effort to help cities engage and implement resiliency practices for physical, social, and economic challenges including sea level rise and floods was established in 2013 with the Rockefeller Foundation's 100 Resilient Cities. In addition to Miami and New York City, other US East Coast cities within this program include Boston, Norfolk, and Washington DC.

In light of the many locations along the US East Coast vulnerable to the effects of sea level rise and of ongoing adaptation efforts already in place, the need for a workshop focused on the US East Coast sea level science and decision making was identified. In addition, the workshop provided an opportunity for much needed interaction and exchange of information/knowledge between the scientific community and stakeholders, planners, and managers. Therefore, the main workshop goal was to **bring together the scientific community, engineers, economists, decision makers, coastal stakeholders and practitioners to discuss the state-of-the-art of knowledge about sea level changes from Florida to Maine.**

The workshop was centered around four key questions:

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

The workshop expanded upon recent research programs, conferences, and national efforts within the US aimed at identifying critical resources and science information to help plan for the effects of sea level rise. These efforts include the World Climate Research Programme (WCRP) Sea Level Grand Challenge that hosted a number of core projects and working groups specifically focused on sea level rise and regional impacts. The 2017 WCRP Regional Sea Level Change and Coastal Impacts Conference provided an opportunity for the global community to discuss and provide an assessment of the state-of-the-art knowledge on regional sea level changes. The US Global Change Research Program and the National Ocean Council organized the Sea Level Rise and Coastal Flood Hazard Interagency Task Force where one of the main outcomes was a set of plausible regional sea level rise scenarios aiming to aid in decision making and local adaptation strategies (see Sweet et al. 2017). NASA has established a Sea Level Science Team, whose primary objectives include gathering a network of sea level scientists and experts to improve and make sea level science available for users. NOAA's Regional Integrated Sciences and Assessments (RISA) program supports research teams to help expand and build the nation's capacity to prepare for and adapt to climate variability and change, within which sea level rise is a critical component.

Norfolk was selected as the host city for being a location on the US East Coast that shows considerable vulnerability to sea level rise. Norfolk is already being affected by recurrent flooding conditions with several days of flooding annually over the past few years (Figure 1c), and projections further indicating that such events are expected to intensify over this century, possibly reaching 180 days of flooding per year by 2050 (Figure 1b,c). As Norfolk Councilwoman Andrea Mclellan pointed out during the workshop opening remarks, Norfolk is the second most vulnerable city in terms of flooding risk in the entire continental US coastline (after New Orleans) due to its exposure, sensitivity to changing sea level, and varying adaptive capacity across the area. For those reasons, which additionally served to illustrate current impacts and ongoing projects and for being centrally located along the US East Coast, Norfolk provided an excellent location for the workshop.

This report presents a summary of the main outcomes from the workshop, highlighting key findings and recommendations discussed. The report is organized as follows: section 2 provides an overview of the number, background, and affiliation of participants; section 3 summarizes the main points presented and discussed during the three workshop sessions; section 4 describes the challenges, needs, and gaps identified by the breakout group discussions, which were organized by regions along the East Coast; and section 5 concludes with final remarks and presents the main lists of needed improvements, research needs, and recommendations identified during the workshop.

2.2 Workshop by the numbers

A key objective of the workshop was to provide an opportunity for coastal managers, stakeholders, and sea level practitioners to meet and exchange information with scientists and researchers working at the forefront of sea level changes along the US East Coast. The characteristics of the participants reflected this design objective. There were 62 attendees (group picture, back cover) representing a diverse sample of sectors (Figure 2). Participant makeup included 41% of participants from universities, 26% from federal agencies, 18% from sea level practitioners, 11% from private companies, and 4% from nonprofit organizations.

The workshop agenda was designed to take advantage of the diverse background of participants and ensure maximum time allotted for discussions. Included were 14 plenary speakers who provided overview presentations covering the different aspects associated with sea level changes and its drivers, impacts, and adaptation efforts (see slides via online agenda). Another 28 participants presented posters on their work, with 13 shared online (see poster gallery).

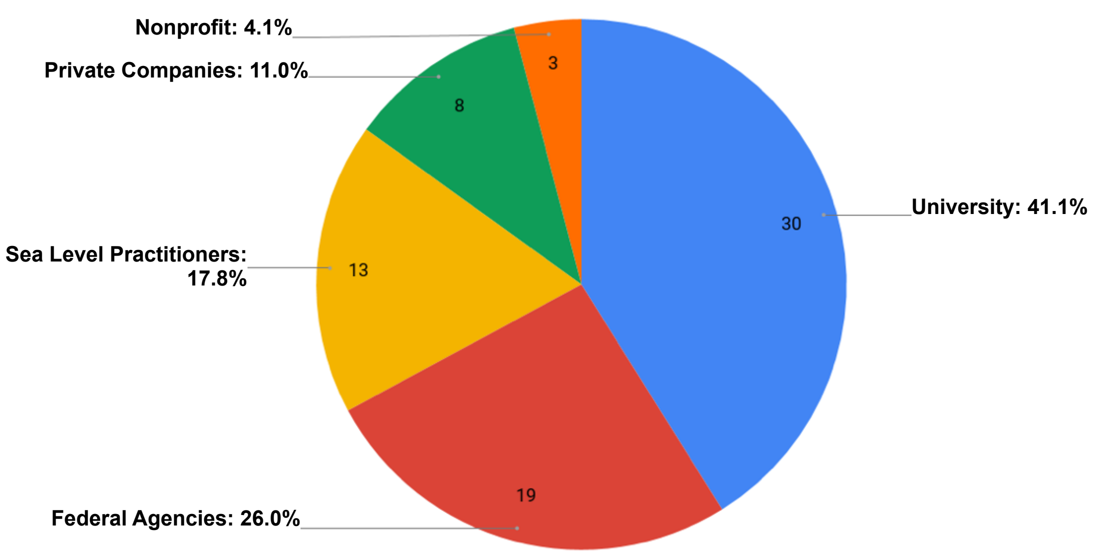

Figure 2. Workshop participants affiliations.

3 WORKSHOP SESSSIONS

3.1 Session 1: Current efforts and plans to improve coastal sea level resilience

Session 1 provided an initial overview of some of the current efforts in place aimed at improving coastal resilience. Presenters shared information on the data, tools, and other resources they are currently using for planning, identifying the most critical time-horizons, and the main challenges for implementation. Speakers in this session included:

- Kyle Spencer – City of Norfolk Office of Resilience
- Katie Hagemann – Miami Dade County Office of Resilience
- Brian Batten – Dewberry
- Susie Arnold – Maine's Island Institute
- Debra Knopman – RAND Corporation
- RDML Ann Phillips – Commonwealth of Virginia, Coastal Adaptation & Protection

The invited presentations and following discussion allowed workshop participants to identify some of the ongoing impacts of sea level rise along the US East Coast. Sea level rise largely increases exposure to persistent elevated tidal events throughout the coast. Many locations are sensitive to this exposure, and such events are already inundating the natural and managed landscape and the built environment, impacting beaches, estuaries, and wetlands, parks and wildlife sanctuaries, agricultural land, water management infrastructure (runoff drainage, water treatment), transportation infrastructure (e.g., ports, roads, railways, bridges), and public/private real estate and structures (e.g., homes, buildings, utilities, government facilities). Low-lying and reclaimed/filled land areas are among the most sensitive locations, where flooding conditions are usually first observed. For example, Miami has extensive areas built on fill over wetlands, and currently has approximately $21 billion in assets exposed to floods.

Part of the impacts from sea level rise that are being observed arise from the fact that drainage, septic, and drinking water systems were initially not designed considering sea level rise. In many exposed communities, flooding thresholds (water levels above which flooding is observed) have already been crossed. As a result, undertreated wastewater is impacting other water sources. Saltwater intrusion into drinking water sources poses a severe threat associated with sea level rise, and is already occurring in some exposed locations in South Florida and Maine.

On the other hand, property value has not yet been substantially impacted by sea level rise in Miami, indicating that in some areas, sensitivity is lower than others. For example, over $280 billion dollars in new development projects are currently underway in some of the most highly developed areas near the waterfront. However, some appraisers expect impacts in the near future.

Ongoing adaptation efforts to improve coastal resilience consists of three pillars: policy, design, and risk reduction. While policy and design are important components that involve updating building requirements/codes, land zoning, and to assess the most cost-effective adaptation solutions for each location, implementation of risk reduction infrastructure is often the main focus of actions. Formerly, the term "protection" was used for these infrastructure measures. However, clear risk communication requires that these measures be described explicitly as providing risk reduction for the design level of forcing. As sea level rises, the residual risk (i.e., the amount of risk not controlled by adaptation measures) also increases.

Most cities are evaluating scenarios within the 30-50 years time frame, which is the typical lifetime for utilities. Homeowners often require shorter time frames and some projects for critical infrastructure require longer-range outlooks, such as the expansion of the Hampton Roads bridge tunnel. Scenarios for 2100 cover the planning time-scales for most of these types of projects.

Adaptation also requires detailed local assessment and involves conducting scenario and cost analyses for a number of possible adaptation options and implementation pathways. Often, consideration of hyper-local effects, such as those associated with compounding risks from multiple drivers and the non-linearity of responses at the local level, is required for effective planning. For example, the Jamaica Bay, New York planning process allowed for identifying three specific goals for adaptation projects: reduce flood risk, improve habitat ecosystem function, and improve water quality (Fischbach et al. 2018). The sea level rise scenario adopted for planning consisted of employing the NPCC 90th percentile high projections of approximately 30 in of sea level rise by 2050 (Gornitz et al. 2019). Modeled response for two adaptation concepts were evaluated under a $3 billion dollars constraint: build storm surge barrier or restore wetlands. Model-based assessments were quantified in terms of land restoration and both concepts illustrated potential improvements in ecosystems and water quality. Planners are also developing and making use of different tools to map and examine the impact on waste water treatment plants, septic systems, transportation, and county infrastructure (e.g., fire, police rescue operations). For example, the Norfolk STORM and TITAN web applications were developed for helping track storm and tidal inundations, respectively.

A key challenge associated with the implementation of adaptation efforts is the cost for implementing new and updated risk reduction infrastructure. The cost is often two-to-three orders of magnitude larger than the cost of planning and carrying out assessments for solutions. Funding to support studies and risks assessments is usually available, but there is a lack of sustained and integrated funding from federal, state, and local governments for implementation of identified adaptation solutions.

Local physical characteristics pose additional challenges for adaptation options. Specific solutions often have to be tailored to the local conditions. For example, because of the porous bedrock in Miami, walls and dikes represent inefficient solutions for long-term sea level rise. Detailed local assessments are required to address questions such as how ground water will change with sea level rise, how compound events (e.g., extreme precipitation during high tide) will behave within specific geographic settings, and how non-linearity will affect responses.

Understanding how to use the multiple sea level rise scenarios to inform planning decisions presents yet another challenge (Hall et al. 2016; Sweet et al. 2017; Boon et al. 2018; Ruckert et al. 2019). Overall, multiple scenarios are found useful, with probabilistic information also corresponding to a valuable resource for communicating with stakeholders, who often express the desire for a "single number" to target their efforts. However, it is sometimes challenging to motivate communities to make decisions when they have to plan for multiple sea level rise scenarios. In general, multiple scenarios and uncertainties are considered during initial stages of planning. At more advanced stages of planning, the multiple scenarios are then streamlined to fewer alternatives, with considerations to the specific circumstances of each project, such as project life-cycle and criticality. During the implementation stage, many decision makers select one sea level rise curve or projection and assign different levels of risks for such choice (see, for example, Sriver et al. 2018 for a different perspective). Still, some organizations, such as the Port Authority of New York/New Jersey, have simplified scenarios that are tailored to their specific need in order to effectively implement resilient design standards within their organization. The US Army Corps of Engineers advocates a "when, not if" approach in which triggers and thresholds related to performance and reliability (e.g., critical infrastructure) are identified, with the scenarios providing a range of time over which exposure may occur.

Engineers and local decision makers need specific guidance on how to make choices for different sea level rise scenarios and for correctly assessing the levels of risk associated. In addition, educational resources and improved communications are likely needed to improve awareness and recognition among stakeholders for impacts of sea level rise. Often, stakeholders do not distinguish between sea level rise and other reasons for coastal flooding (e.g., precipitation, development, stormwater capacity). Involvement of informed constituents corresponds to an important driver for implementation.

The establishment of coordinated regional efforts is also highlighted for its benefits towards planning and implementation of adaptation measures. An organized process to develop consensus among municipalities towards identifying optimized implementation pathways and overall guidance is a fundamental component for successful regional efforts. Successful examples of such networks include the Southeast Florida Regional Climate Change Compact and the NPCC; both of which synthesize input from city officials, planners, engineers, the local scientific community, and federal agencies to provide unified guidance on sea level rise. In the absence of well-defined coordinated regional efforts, a culture of stovepipes and redundancy often occurs.

In Virginia, the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project attempted to coordinate resilience projects among different municipalities. However, different priorities by each community prevented the establishment of a common set of scenarios to follow. Absent cohesive policies at the state level extending to localities contributed to the little coordination with and between the different municipalities within the Hampton Roads. Later, a resolution for common planning of sea level rise scenarios was adopted by the

Hampton Roads Planning District Commission communities. With the passage of Virginia House Bill 345, which creates the position of Special Assistant to the Governor for Coastal Adaptation and Protection, Virginia is now more closely working with local communities to foster coordination. The new position is to lead in developing and providing direction for a statewide coastal flooding adaptation strategy. As another example, specific sea level rise scenarios in Maine have not been endorsed by the state. Different approaches are being adopted by each municipality. One of the main motivations for the establishment of regional networks is that the effects of regional sea level changes will affect neighboring localities similarly. Decisions made in one municipality are not necessarily independent of the surrounding municipalities, and may trigger impacts in surrounding locations. For example, the inclusion of water barriers in a location may amplify the compound flooding response in another. The establishment of such regional networks also usually enables the development of a set of tools (e.g., sensors networks, warning systems) to serve the region and may potentially benefit exposed municipalities with limited financial and technical resources available to carry out studies and implement their specific set of solutions. Therefore, coordination is likely essential for successful projects.

3.2 Session 2: What can the natural sciences provide? What are open research questions?

The objective for this session was to provide participants with a broad overview of the latest scientific knowledge and information products available for estimating current sea level and future changes intended to inform adaptation planning along the US East Coast. Presentations addressed the following key questions:

- What are the main processes driving relevant sea level changes from Florida to Maine? What are their dominant timescale, magnitude and predictability?
- How are geomorphological coastline changes from Florida to Maine being affected due to long-term sea level rise and extreme sea level events?
- What are the available flood hazard projections and their underlying uncertainties and challenges?
- What are the optimal strategies for dealing with non-stationarity in flood hazard and risk projections?

The session included invited talks from:

- Christopher Piecuch - Woods Hole Oceanographic Institution
- Erika Lentz - United States Geological Survey
- Nathan Urban - Los Alamos National Laboratory

Several different mechanisms cause sea level rise to exhibit regional differences throughout the US East Coast. Observations from tide gauges show that long-term sea level rise varies regionally along the coast, with the greatest rates of rise in the Mid-Atlantic Coast, reaching 4mm/year and lowest south (Key West, Florida) and north (Portland, Maine). Local sea level changes are linked with multiple forcing mechanisms, some of which have a global footprint while others have more regional and local characteristics. Global sources include ocean warming (Domingues et al. 2008), changes in mass associated with melting ice sheets (Kopp et al. 2017; Wong and Keller, 2017; Wong et al. 2017), and land water storage (Llovel et al. 2010). From a regional perspective, changes in ocean circulation (Ezer et al. 2013), ocean heat content (Domingues et al. 2018; Volkov et al. 2019), atmospheric conditions (Piecuch et al. 2016), and vertical land motion (Peltier et al. 2015) play an important role. Key physical causes of long-term regional sea level rise differences along the US East Coast include the fingerprint of glacial isostatic adjustment. These contribute to larger rates of sea level rise due to land-subsidence north of Cape Hatteras (see. Peltier et al. 2015); the gravitational force fingerprint from changes in the Greenland Ice Sheet, which causes lower sea level rise rates over the Northeast coast (see Hay et al. 2015); and changes in overturning circulation (Griffies et al. 2011). Piecuch et al. (2018) addresses some of these regional differences in greater detail.

Sea level rise along the US East Coast caused by these global and regional/local factors is already linked with observed changes in the coastal landscape. This is because the increasing baseline sea level is associated with changes in the coastal dynamics through erosion, altered sediment redistribution, tidal wave propagation, and wave energy as shown through satellite observations over the past two decades (Figures 3 and 4). Projecting such changes throughout the coast presents a challenge for long-term planning, given that specific coastal dynamics responses and sediment transport changes need to be accurately represented. Approaches based on Bayesian Networks (Wilson et al. 2015) are helping to model and project these changes to the coastal landscape. USGS provides a portal that assists planners in identifying and understanding some potential risks to the landscape of their local area associated with the different future scenarios.

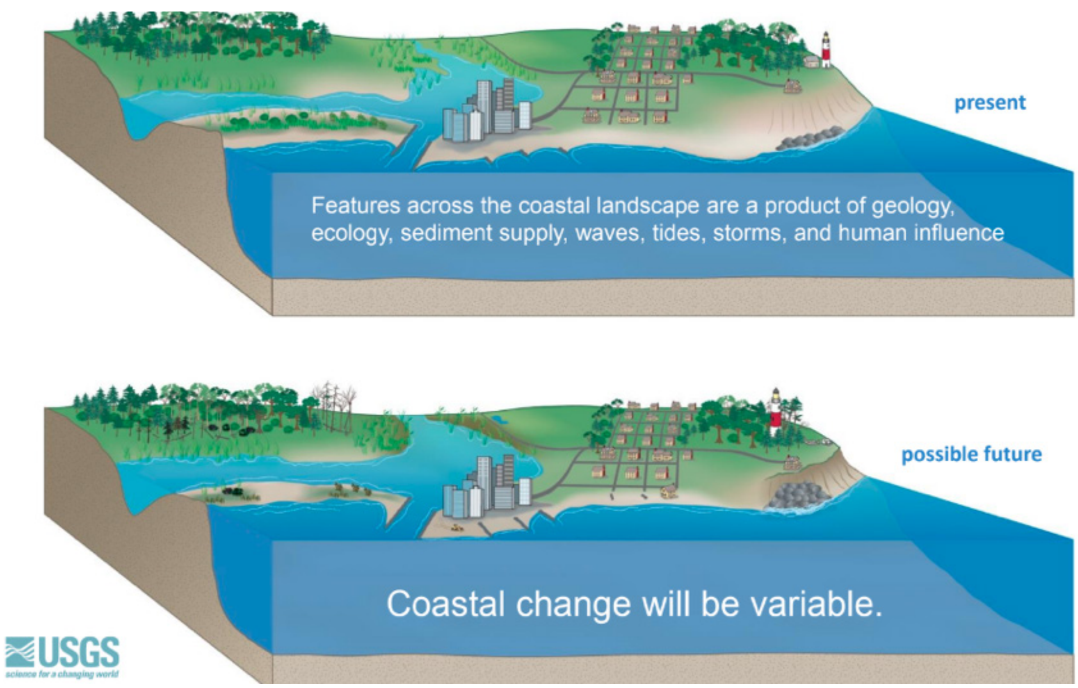

Figure 3. Schematic diagram illustrating potential changes in the coastal landscape associated with increasing sea level through coastal dynamics changes (source: USGS).

Figure 4. Geomorphological changes in the coastline of Cobb Island, VA, due to sea level rise. Figure courtesy of Erika Lentz, USGS.

Accurate projections of future scenarios also require correct representation of global and regional/local processes. As indicated above, reported sea level changes from Florida to Maine may be associated with multiple timescales and forcing mechanisms. While some mechanisms are more directly linked with long-term changes at almost linear rates on human timescales, others can be non-linear and governed by complex dynamics. For example, the glacial isostatic adjustment observed along the US East Coast is associated with long-term timescales (decades to centuries), linear trends, and largely predictable changes for the foreseeable future (Peltier et al. 2015; Piecuch et al. 2018). On the other hand, sea level rise associated with changes in melting ice sheets and ocean dynamics have an elevated level of complexity since they are inherently nonlinear phenomena and may reach tipping points, from which rapid changes can be triggered after crossing a specific threshold. One of the challenges concerning constraining ice sheet projections relates to properly identifying and simulating where and by how much the ice sheets are melting. Recent observational efforts, such as those led by NASA's Gravity Recovery and Climate Experiment (GRACE), have documented increasing contributions to sea level rise from the melting of Greenland and Antarctic Ice Sheets (Harig et al. 2015; Chen et al. 2017), and have improved the ability to close the global sea level budget (Cazenave et al. 2009). For coastal areas from Florida to Maine, the impact of potential long-term changes in ocean circulation and redistribution of heat associated with the Gulf Stream and Meridional Overturning Circulation are still an ongoing debate (Little et al. 2019). In practice, changes forced by these more complex mechanisms imply in a greater range of likely scenarios for future sea level change (Kopp et al. 2017; Sweet et al. 2017). However, during the next 30-50 year time period, the various scenarios of likely sea level rise for locations along the US East Coast are usually well constrained.

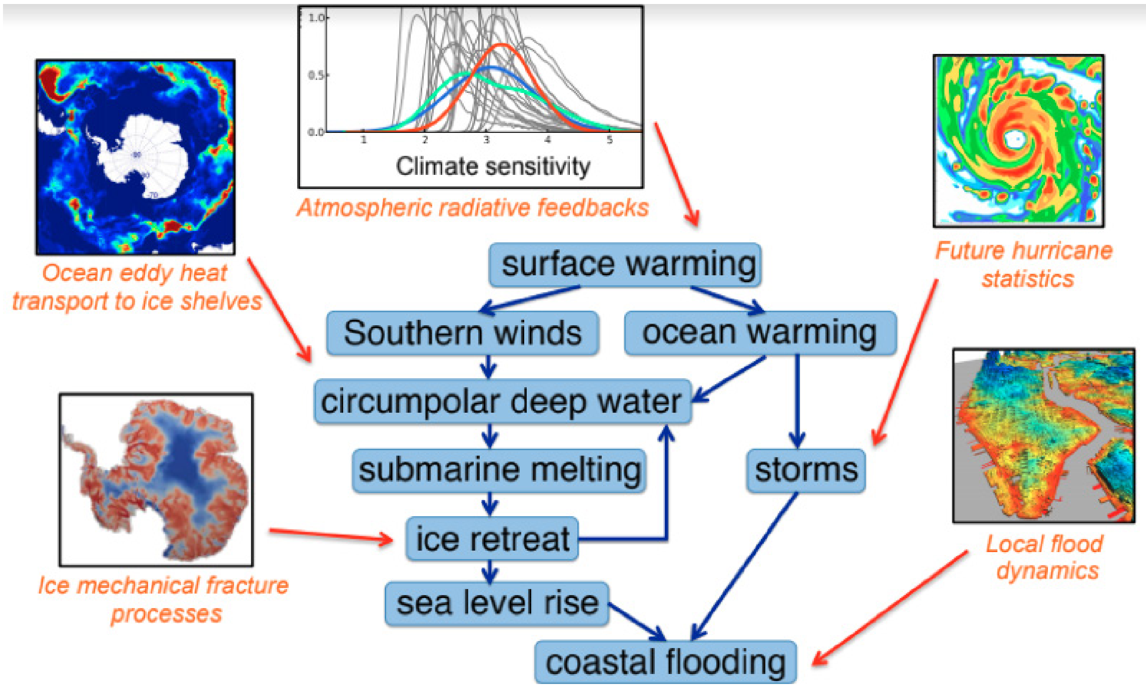

Figure 5. Example of integrated modeling framework linking regional process studies, high-resolution applications, and future hurricane statistics with potential future effects for local flooding. Figure courtesy of Nathan Urban, Los Alamos National Laboratory.

Scenario-based analyses are likely to benefit from recent trends of transitioning synthesis reports into synthesis products. Upcoming products may explore more extensively integrated modeling networks (Figure 5). These networks can allow for specific process studies, such as those based on localized high-resolution simulations, to be included in a broader scale simulation used for long-term sea level projections. The expanding field of uncertainty quantification is helping to downscale, assess bias corrections, skill weighting, and evaluate extreme statistics more carefully, all of which will help in determining future risks for each scenario (Wahl. et al. 2017, Wong et al. 2018). In addition, computational tools are being utilized to aid decision making associated with complex adaptive systems, which inherently involve multiple sectors (e.g., waste water, energy, traffic management) and planning agencies (e.g., local, state, and federal), comprising an interconnected web of decision where impacts often cascade down. Computational tools are already being employed (Figure 6), and are expected to be expanded in the near future to search through the complex web of decisions for optimal adaptive solutions.

Although the tendency is to build more complex computational modeling techniques, there is value in recognizing that problems, their consequences, and the resources available to adapt are scalable. Thus, transparent tools with easily accessible information and that are scalable to the financial and technical constraints of the user communities are also needed. The tradeoff between precision and accuracy in modeling should be part of the decision making along with the cost and time of the modeling.

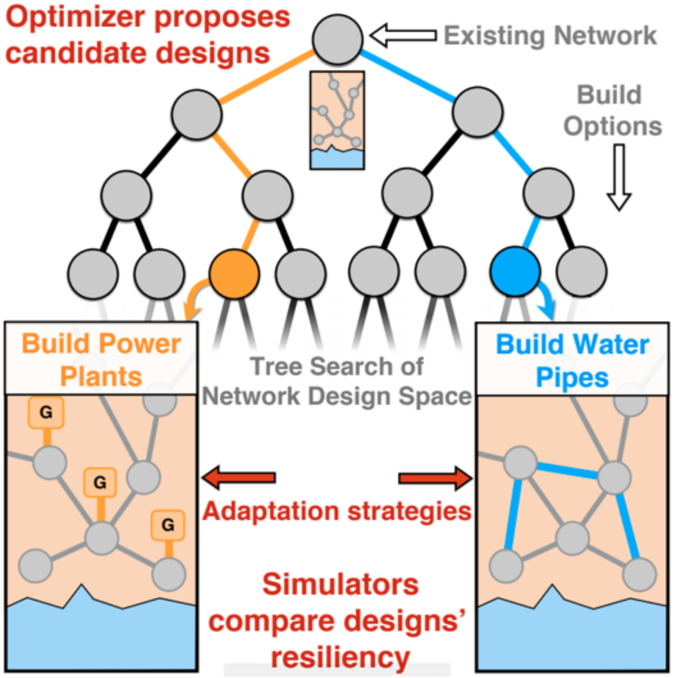

Figure 6. Schematic example for optimized decision making framework for interconnected web of decisions. Figure courtesy of Nathan Urban, Los Alamos National Laboratory.

Discussion conveyed during this session acknowledged the challenge coastal planners and sea level practitioners face while dealing with multiple scenarios. While probabilistic information is generally easier to use, especially for communicating with stakeholders, such information is often input by engineers into cost-benefit ratios and risk curves, which aid the decision makers in identifying the return on investment of alternative adaptation measures compared to the cost of doing nothing. The drawback of the probabilistic information is that it may not support a robust assessment of the performance and reliability of the measures under the range of future scenarios expected (i.e., higher precision at the cost of lower accuracy). Implementation based on a specific choice of sea level rise scenario will depend on the level of risk the project requires and on the lifespan for the planned infrastructure. Differences in scenario selection will have little impact on short-term infrastructure projects (20-30 years) given that scenarios are well constrained in this time frame. For mid- to long-term projects (50-100 years), the scenarios begin to diverge. An approach in which the sensitivity of the alternative adaptation measures is assessed against the various scenarios may help decision makers to identify the alternatives that best match their risk profiles. Again, users could select a scenario or they could assess the performance of the alternatives against the time horizon of the occurrence of the different scenarios. Typical questions to guide the assessment process include: Which measures perform well in all cases? Which perform well under a limited set of future conditions? Are there differences in the consequences (i.e., sensitivity)? To support such decisions, a two-way information flow from the state-of-the-art science knowledge to sea level practitioners and coastal planners, and vice-versa, is critical. Efficient information flow will often require the involvement of boundary organizations. For public policy decision makers, it is important to convey the trend to inform action, but a distinction is required among the different decision-making audiences or between those decision makers compelled to use cost-benefit analyses (e.g., many federal agencies) and those free to incorporate other assessment methods (e.g., private sector).

3.3 Session 3: What are the tools currently available? What are the needed innovations, and observations?

The third workshop session addressed some of the tools that are currently available to aid decision-making. A broad definition of tools was deliberately adopted to cover different assets associated with (i) sea level and related observing sensors/platforms; (ii) web-based tools and products; and (iii) science-based statistical and/or empirical decision-making support tools. The session included four invited talks:

- Carmen Boening - NASA Jet Propulsion Laboratory
- William Sweet - NOAA National Ocean Service
- Jayantha Obeysekera - Sea Level Solutions Center, Florida International University
- Nick Deffley - Office of Sustainability, City of Savannah and Kim Cobb - Georgia Institute of Technology

One of the key resources in terms of sea level observations for monitoring and planning is made available by several tide gauges strategically positioned along the coast. The NOAA National Ocean Service maintains a network of over 60 tide gauges stations from the Florida Panhandle to Eastport, Maine[1]. In addition to providing real-time water level monitoring, tide gauge sea level observations are used for tracking changes in threshold exceedance and high tide flood frequencies. These observations are used at the local level for short- and long-term planning. Tide gauges are often also equipped with meteorological sensors including rain gauges, which also provide key measurements used to understand and model compound flooding events originating from elevated sea levels and high rainfall. Rain gauges also comprise an important resource for the characterization of modes of variability used for interannual prediction and long-term planning.

In addition to tide gauge observations, networks of water level and other sensors are now more commonly employed at the local level. For example, specialized sensors are often installed by city utility engineers to privately monitor ground-water levels and wastewater. Newly developed sensors are being incrementally installed at exposed or sensitive locations. In Savannah, a partnership between the city and the Georgia Institute of Technology has been established in the SMART Sea Level Sensors Project. This initiative works on the development and installation of a portable and low-cost (~$300 in parts) sensor that can measure water level and air temperature at 12 locations in the tidally influenced region. The goal is to expand the array to 50 sensors. Water level information collected in this project is made available to communities through a web dashboard and application programming interfaces. The collected information is also being used by the scientific community to develop and validade high-resolution modelling solutions.

Satellite observations comprise an important resource that complements the in situ observations. They are more accessible to engineers and sea level practitioners thanks to user-friendly web-based tools. One of these tools is the NASA Sea Level Portal, which was started by the NASA Sea Level Change Science Team to foster interdisciplinary research and provide a resource for translating remote sensing information about the ocean, ice sheets, solid earth, land, and atmosphere to stakeholders. The portal provides near-real time information on global sea level changes in terms of total rise as well as individual contributions from changes in ocean density (temperature and salinity) and mass added from polar ice sheets. In addition, the ancillary Data Analysis Tool, available in the portal, also enables quickly analyzing satellite-based observations at custom locations for research, regional assessments, or teaching purposes. The NASA Sea Level Change Team is currently working with outreach experts to translate information for the general public which will include a set of indicators and estimates for uncertainty.

The NOAA National Ocean Service provides screening tools that are being actively used by sea level practitioners and engineers to visualize the potential effects of sea level rise and plan accordingly to their specific location. One of these tools is the Sea Level Rise Viewer, which is a GIS-based interactive tool that allows users to visualize vulnerable areas that are/will be impacted with different magnitudes of sea level rise and to identify areas that are currently prone to high-tide flooding. The tool also provides an annual recap of the number of high-tide flooding days. The NOAA Sea Level Rise Viewer allows users to overlay other socio-economic vulnerability indicators on the map and to quickly access the different NOAA sea level rise scenarios downscaled for their specific location (Sweet et al. 2017). The current plans expect to incorporate:

- An annual outlook for potential high-tide flooding;
- Projections of local decadal changes in high-tide flooding for the different scenarios; and
- A feature to map the land exposed to different high-tide flooding frequencies under different sea level rise projections.

The US Army Corps of Engineers frequently suggests the use of the Sea Level Rise viewer and ingests NOAA data into its own publicly available tools. For example, their Sea Level Tracker allows users to visualize changes in mean sea level and other tidal statistics at long-term NOAA tide gauges in comparison to sea level rise scenarios.

Computational tools such as those based on modeling approaches are increasingly being adopted and incorporated within adaptation efforts. Some examples include employing:

- Synthetic event modeling to develop joint probabilities for compound flooding;
- Regional predictors combined with interannual variability to establish a set of boundary conditions for modeling water levels at coastlines;
- Empirical simulations for infrastructure;
- Machine learning techniques for deriving probabilistic information; and
- Dynamic adaptive pathways for evaluating potential outcomes from different decisions.

More specific modeling tools, such as the USGS groundwater model, are being used to assess potential impacts to the local water table from different sea level rise scenarios.

One of the key points discussed during this session addressed the need of engaging stakeholders, sea level practitioners, and other potential users when developing fit-for-purpose tools aimed at helping with adaptation efforts. User engagement is critical to ensure that developed tools are effective and have a ready audience. In addition, the engagement of stakeholders is important to help inform communities about potential adaptation measures, which is key to drive action towards implementation. Also of importance is the coordination of the various efforts among different cities/regions. Oftentimes, efforts being developed locally will present a large overlap of interests and techniques being employed. Establishing a network for coordinating regional efforts will likely be beneficial and help with implementation by fostering exchanges of information, collaboration, and coordinated regional guidance. The discussion also touched on the group's perspective on the role played by the federal, state, and local governments compared with the role of the private sector. In general, participants indicated that while government resources may not always be available to fund the development of new applications and tools by the private sector, expertise and data from the government should be made available to inform and power private sector applications.

4 BREAKOUT GROUPS

The second day of the workshop took advantage of the content presented during the first three sessions and had participants engage more closely via breakout group discussions. The key accomplishment envisioned was to address the fourth workshop question: What are the best practices for linking scientific information with decision-making support tools? And what are the gaps that need to be addressed?

In order to accomplish this, the organizing committee had the participants divide into smaller breakout working groups of 15-20 people focused around one of the regions on the US East Coast (Figure 7): the Southeast group including areas from Florida to South Carolina; the Mid-Atlantic group with areas from North-Carolina to Delaware; and the Northeast breakout group with areas from New Jersey to Maine. Key points raised by each group are summarized, and some takeaway points identified during the plenary discussion are presented.

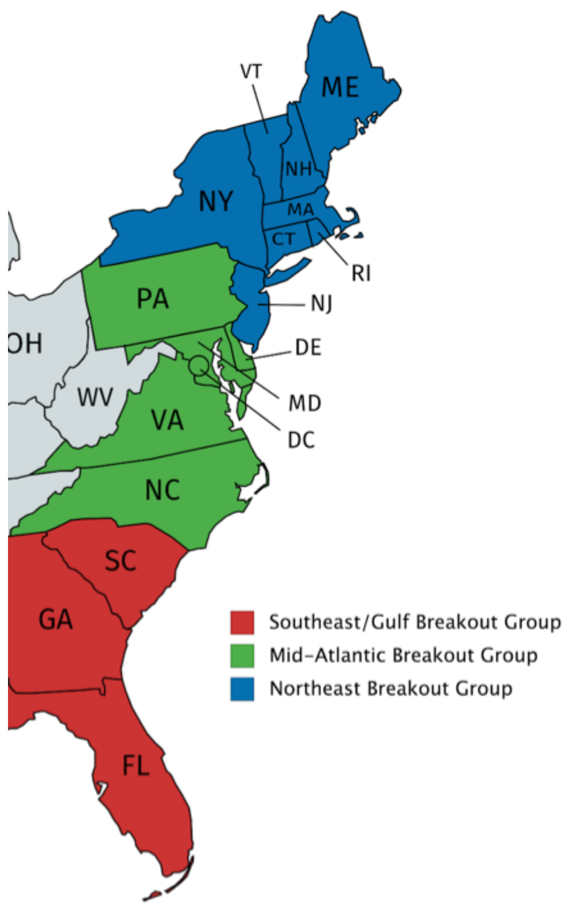

Figure 7. Suggested breakout groups division by regions.

4.1 Southeast

The Southeast Coast presents some of the key challenges and hotspots for recent accelerated sea level changes (e.g., Valle-Levinson et al. 2017; Domingues et al. 2018). Within the Southeast Coast, Florida is known for developing tools and policies as well as overcoming challenges geared towards adaptation, given its exposure to long-term sea level rise due to its low-lying topography, long-shore lines, dense coastal population, vulnerability to hurricanes, and leadership in adaptation efforts. In Miami, for example, sea level rise is a bipartisan issue recognized by constituents, which generally represents the main driver of political will towards implementation. One of the most important characteristics of Florida is its geological structure consisting of porous bedrock. Under such conditions, typical solutions for reducing the risk of sea water intrusion such as dikes and seawalls will generally not be applicable as a long-term solutions against sea level rise, since water may intrude through the bedrock. The bedrock also presents challenges for managing the groundwater response and protecting drinking water supplies. The relatively small tidal range throughout the Southeast Coast also help make it more exposed because it supported previous infrastructure to be implemented closer to the water. On the other hand, land-subsidence is generally small throughout the region (e.g., Piecuch et al. 2018).

Efforts carried out in Florida are also in the process of establishing regional networks of experts, who can generally help with exchanges of information, leveraging funding opportunities, and helping define a coherent set of standards. For example, the Southeast Florida Climate Compact includes scientists, engineers, and city officials who work towards developing and updating a unified regional sea level scenario and set of guidance for Miami-Dade, Broward, Monroe, and Palm Beach counties. The Compact meets every few years to update its set of guidance that provides sustained interaction opportunities between scientists, practitioners, and facilitators.

Along the Georgia coast in the city of Savannah, regional networks of scientists, engineers, city officials, emergency planners, and planning directors are coming together to develop a high density, city-scale, sea sensor network to allow monitoring, forecasting, and planning against sea level extremes. The combination of high resolution sea level data with forecast models allows local stakeholders to engage citizen groups and local communities in the planning processes for improving coastal resilience and awareness.

Key challenges to adaptation identified by participants include:

- Differences in political interests at the state and local level, especially relating to establishing longevity of adaptation efforts beyond the state and local election cycles. One of the most important factors driving political will, however, is constituent involvement, as illustrated in the South Florida and Georgia cases.
- Geographic characteristics consisting of long-coastlines combined with socioeconomic conditions that include low-income populations sensitive to disruptions and with concomitant low adaptive capacity throughout these areas also presents key challenges. These challenges are generally exacerbated when combined with accelerated population growth, which has been observed.
- Sand shortage for beach restoration projects that can provide important buffer zones for storm surge and other impacts associated with sea level rise.
- Managing and balancing water needs for the population. Elevated levels are generally needed for wetland restoration projects, but there can be an impact to adjacent western suburbs as water table rises.
- Impacts of strong or slow-moving tropical storms, with storm surge compounded by coastal and inland precipitation needing to be considered by efforts aiming to improve coastal resilience.

Participants of the Southeast breakout group indicate that continued efforts towards building intuition on sea level rise and tidal flooding is still a very important need. Constituent involvement can be one of the main drivers for implementation of adaptation efforts. Additional resources are therefore needed to inform stakeholders, for example, on (i) why predicted tides sometimes differ from observed tides; (ii) the factors (e.g., winds, ocean dynamics, ocean heat content) contributing to variations in the king tides amplitude and reach from one year to the next; and (iii) the dynamical coupling between the coastline response and sea level rise.

4.2 Mid-Atlantic

Areas along the Mid-Atlantic Coast include some of the main hotspots for accelerated sea level rise within the US East Coast (e.g., Sallenger et al. 2012, Figure 1a) linked with local effects of Glacial Isostatic Adjustments and changes in gravitational fields (e.g., Piecuch et al. 2018). The Mid-Atlantic Coast also includes areas exposed to coastal erosion associated with long-term sea level rise (see USGS Coastal Change Hazards Portal), including large urban areas (e.g., District of Columbia) and extensive rural areas. These areas incorporate sensitivity to the exposer and varying adaptive capacity, resulting in differing vulnerability across the region.

Ongoing adaptation in the Mid-Atlantic Coast includes efforts along the lower Maryland coast where there is currently reliance on FEMA flood mapping. Recently however, NOAA mapping tools have been used more commonly to assess flood frequency at one, five, and ten-year events. Although areas are generally focusing more on the use of sea level projection scenarios, a survey of 70 county staffers in the Hampton Roads, Virginia, region indicated that many did not use any scenarios due to the lack of education on how to incorporate them. Additional surveys carried out throughout the Mid-Atlantic suggest that there are a large number of scenarios provided by many different agencies and a lack of local knowledge on how to use them effectively. These findings point to the need for centralized provision of long-term projections by a trusted source and contextualizing the information for effective uptake by local users for adaptation planning. A set of state-endorsed centralized guidance across the coast could be a suitable approach to address this need.

A key challenge to adaptation in this region is the effective communication between the different disciplines involved, i.e., scientists, economists, engineers, and social scientists. As most decisions associated with adaptation efforts occur at the local level, the science community should learn from local users how information is applicable, or could be applicable. Initiating those dialogues is often challenging and requires tailoring the message depending on the audience. For example, addressing climate change, sea level rise, or wetland change can be challenging within communities with reservations on those topics. Framing conversations in terms of well recognized impacts such as coastal erosion, flooding, and road closures helps put the problem in the context of common experience that collectively can be addressed, which can lead to increased traction for initiating dialogues about actionable solutions. Messaging should be tailored to the audience, where the specific scale and type of decision making involved shape how information is provided.

Stakeholder awareness development through educational resources is key to overcoming some of these communication challenges. For instance, educational resources aimed at informing stakeholders on how to visualize and understand tide gauge observations can help develop intuition about sea level rise and a sense of ownership for those observations, all of which may help with implementation of adaptation efforts. Visual references can also prove an excellent resource for educating stakeholders, serving as evidence of change from familiar places. For example, a picture of a lighthouse once surrounded by a farm but now surrounded by water conveys the change over a span of time comparable to a human lifetime. NOAA is currently moving in this direction, with recently developed tools providing a clear visual reference on a web-based map of how and where flooding conditions may occur with different sea level rise scenarios. NASA is also targeting support of outreach activities aimed at educating stakeholders.

While educating stakeholders is an important need for successful implementation, structured data on how information is being assimilated by stakeholders can provide metrics for identifying more effective communication strategies on how science information is translated. Engagement of social scientists is important to help assess these needs through surveys or other evaluation instruments. Establishing specific metrics for monitoring impacts on human experiences (e.g., road closures), changes in stakeholder perception, and following the aftermath of an event (e.g., storm surge, nuisance flooding) would be useful for both practitioners and academics. Local indicators are important but often challenging to collect. Another avenue for identifying best practices is to catalog how and where adaptation is being implemented so that successful examples can serve as models for other areas. Within the Hampton Roads region, for instance, different ongoing resilience projects are being cataloged to foster synergistic efforts.

Finally, assessing the effectiveness of adaptation strategies through structured experiments is an important need moving forward in the field. For example, while green infrastructure is well-known in the context of stormwater management, it is unclear how effective natural or nature-based infrastructure may help reduce coastal flood risks over the range of forcing events. However, these initiatives could improve local ecosystems and help the local economy. In Oyster, Virginia, a 30-year program to monitor the landscape and sediment dynamics is currently underway, and yet parallel monitoring of the living shoreline placed in the region is not being addressed. Having specific and quantitative assessments of the performance and reliability of these structures in reducing coastal flood risks will become increasingly important moving forward.

4.3 Northeast

Areas along the Northeast Coast are generally associated with lower rates of background mean sea level rise (Figure 1) and are mostly characterized by a unique seascape with longer stretches of steep and rocky shoreline. Tidal ranges are especially large along the Northeast Coast, which is prone to wintertime extratropical storms (Grayson 2018). The region includes mostly small communities and towns, with fewer big cities, and a relatively high density of working waterfronts (e.g., ferry terminals, lobster wharfs, fishing infrastructure) that have distinct concerns relative to homeowners. For those reasons, exposure to increasing coastal water levels is not necessarily a primary component of vulnerability. In fact, the USGS identifies the Northeast Coast as one of the areas with the lowest risks to the effects of sea level rise (Figure 8). Southeast Maine’s sensitivity to coastal events is more related to topography than water level, where erosion generally tends to follow episodic storm surges rather than long term trends in sea level. Despite that, areas along the Northeast Coast currently experience salt water intrusion, sunny day flooding, and erosion of coastal habitat.

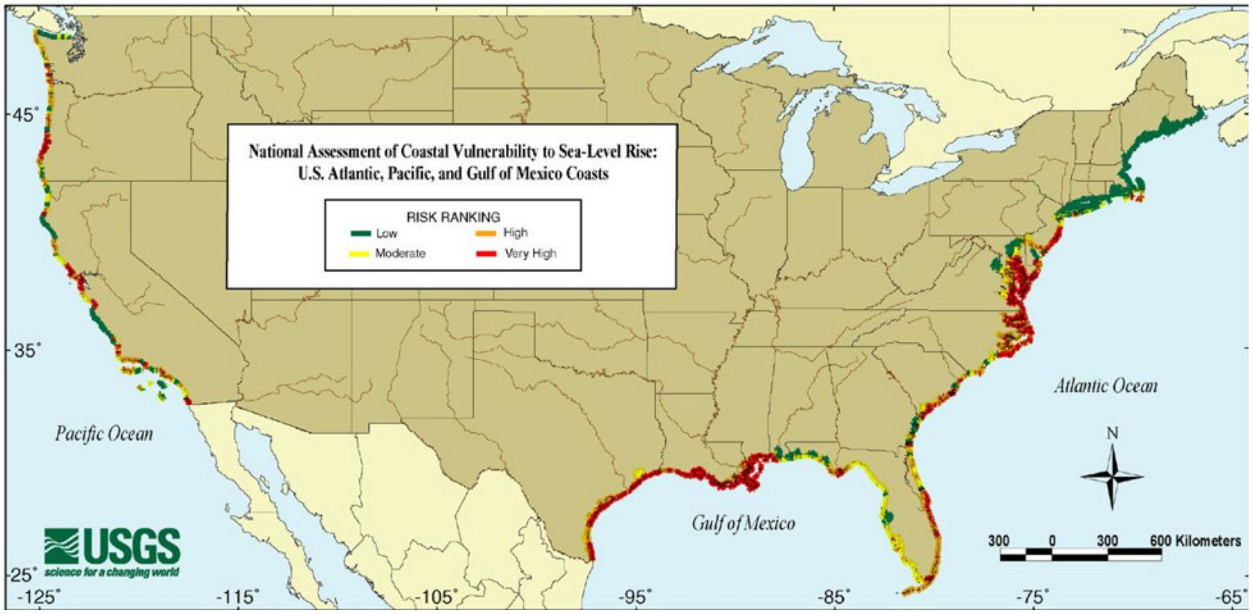

Figure 8. United States Geological Survey National Assessment of Coastal Vulnerability to Sea Level Rise for the continental United States.

Specific densely populated coastal areas, such as metropolitan New York City, include extensive and ongoing adaptation programs (e.g., the NPCC). Some of these locations take advantage of flexible decision-making approaches, which implies adopting solutions that can be later on adapted or improved through learning scenarios (e.g., Hinkel et al. 2019). One example of such an approach is being carried out at the Woods Hole Oceanographic Institution downtown dock, where current projects are aiming for an increase of two feet in elevation, but with a foundation that can be further elevated in the future if required.

Communication and sustaining community dialogues and engagement are additional challenges for implementation of adaptation efforts along the Northeast Coast. Experience shows that conversations on the need for improved risk reduction infrastructure will develop following an extreme event, such as those that occurred after the extratropical storm Grayson from January 2018. However, sustaining dialogues beyond a few weeks after the event is challenging but required for driving political will into action. Community engagement initiatives such as the ones led by SMART Sea Level Sensors in Savannah may offer a potential pathway to be carried out and help establish sustained involvement from stakeholders. There is also a need for sustained information exchanges with representatives that carry out successful adaptation efforts elsewhere, since examples within the US are still limited and often involve major adaptation measures beyond the capacity of smaller communities. Such exchanges could provide useful demonstrations for proof of concept and help in building community trust. Another key challenge suppressing planning and implementation of adaptation efforts concerns the lack of transparency in terms of quantifiable societal impacts. This is important to assess and address first in locations most sensitive to exposure and with the least adaptive capacity. For example, Maine's private utilities will generally not share information among themselves or with planners due to security or other considerations. Having access to such information about current societal impacts can be paramount to initiate and sustain efforts aimed at improving coastal and community resilience relying on uninterrupted or utilities or a rapid recovery plan.

Outstanding science questions remain regarding drivers of subseasonal to interannual and long-term sea level changes along the Northeast Coast. While drivers of interannual variability are generally well understood in this region (e.g. Goddard et al. 2015; Piecuch and Ponte 2015; Little et al. 2017; Piecuch et al. 2019), year-to-year changes in storminess, circulation, and compound flooding probabilities, and how those patterns will be influenced by changing climate are still unclear. Effects of global climate changes on regional sea level changes linked to ocean circulation and melting land ice still represent the largest source of uncertainty among the long-term scenarios. While such processes can play a dominant role on regional scales, their representation within climate models is still very limited, leading to underestimated uncertainties on decadal-to-multidecadal timescales (e.g., Kopp et al. 2017). Concerning more specific processes, there is still limited understanding on whether the large tidal range of the region can confer improved predictive skill, and how it interacts and amplifies with coastal erosion processes. Detailed research on how coastal ecosystems will respond to sea level changes is also lacking for the Northeast Coast.

4.4 Discussion

Specific characteristics of each region play a role in defining how, where, and when adaptation projects aiming to improve coastal resilience are to be carried out. Despite these regional differences, the breakout group discussions allowed for identifying overlapping needs that will likely benefit efforts across the entire US East Coast. Some of the most critical needs relate to:

1. Sustained funding for adaptation responses;
2. Implementing better communication and end-user engagement practices; and
3. Establishing a coherent set of standards and guidance for planners and engineers.

Streamlining scientific interaction with stakeholders on what is needed will constitute an important feedback for driving future US sea level science. However, an institutionalized framework to sustain interaction among scientists and stakeholders is still missing. Regional Expertise Networks for exchange of information, such as the ones currently in place at Southeast Florida and New York City, are likely to help with providing sustained opportunities of exchanges between scientists, facilitators, stakeholders, and coastal managers, and also with defining clear and coherent set of standards and guidance for engineers in charge of adaptation infrastructure projects. Another critical need is to catalogue the adaptation projects being carried out across the US East Coast, which will allow for identifying the current adaptation strategies being used and best practices.

Observational resources were also raised by participants as some of the key needs across the different regions along the US East Coast. For instance, tide gauges are sparsely placed along some sections of the coast. Increasing the density of the sea level observation network will benefit both local stakeholders and the scientific community. New and more affordable observational technologies such as the ones being implemented in Savannah (see SMART sea-level Sensors Project) are likely to help fill some of these observational gaps, though maintaining tide gauges with long-term records is crucial to set a context for these additional sea level measurements from other platforms. Additional rain gauges were also noted as an important observational requirement to help assess current and future compound flooding probabilities. A centralized tool enlisting observational resources could provide an excellent resource for stakeholders and practitioners. Finally, a new King Tide/Nuisance flooding tool could potentially benefit the three different East Coast sub-regions by providing a subseasonal-to-seasonal King Tides regional outlooks and real-time attributions component enlisting the contribution from the different physical factors driving observed changes in high-tide from one year to the next. Such tools could provide a valuable information resource and help build intuition among users and stakeholders.

5 RECOMMENDATIONS

The US CLIVAR Workshop "Sea Level Hot Spots from Florida to Maine" provided a unique opportunity for the scientific community to meet and exchange knowledge with sea level practitioners, stakeholders, and decision makers. Invited keynote presentations provided a high-level summary of the current scientific understanding and of ongoing adaptation projects along the US East Coast aimed at improving coastal resilience. Oral presentations were complemented by 28 poster presentations that also highlighted some of the latest sea level science being carried out for this region. The extensive discussions identified the following specific, recommended actions to guide development of future information resources, to focus scientific research for informing such resources, and to implement best practices linking science and adaptation decision support.

Information resource needs

- Develop additional educational resources aimed at informing decision makers on how to interpret and use the diverse and divergent sea level rise projections, scenarios, and its associated uncertainties.
- Improve storm frequency and surge projections to support long-term planning of infrastructure.
- Establish a coherent set of standards, guidance, and best practices for engineers to work with sea level rise projections.
- Update the NOAA Atlas 14 database to include improved and up-to-date rainfall estimates.
- Improve coverage and availability of coastal sea level (e.g., tide gauges, low-cost sea level sensors) and hydrologic data (e.g., rain gauges).
- Improve subseasonal to interannual sea level (King Tides) forecasts.
- Implement a centralized nuisance flooding and King Tides information tool.

Research needs

- Further explore the role of integrated model approaches in reducing uncertainty in long-term sea level rise projections.
- Formalize and foster advances to the field of decision science and advance the field of climate adaptation.
- Improve uncertainty quantification of observational and modeling efforts to better support decision-making needs.

- Improve understanding of drivers of sea level variability across timescales from subseasonal to interannual to decadal (e.g., storminess, ocean dynamics, natural climate variation).
- Improve understanding of the relationship between tidal range, sea level rise, groundwater, and coastal erosion processes.
- Improve understanding on compound flooding probabilities (e.g., intense rain, coastal surge).
- Assess the long-term performance and reliability of natural and nature based infrastructure such as living shorelines in coastal risk reduction to changing water levels associated with sea level rise and storm surge.
- Improve understanding of feedback between ecosystem health and sea level rise.

Integrating science and decision support

- **Foster sustained opportunities for sea level information exchange across communities.** The workshop proved to be an excellent opportunity for exchange of information among the scientific community and adaptation professionals, for the identification of key challenges and recommendations, and for the development of new collaborations. Carrying out similar and periodic events in the future would likely help foster collaboration and improve overall adaptation efforts aimed at improving coastal resilience.
- **Maintain current network of sea level observations and implement new observations of coupled natural and human systems in support of long-term records.** Sea-level and other ocean observations are recognized as a valuable resource for understanding the mechanisms and characteristics of sea level changes in support of planning efforts. Additional observations of the natural systems (e.g., high-resolution rainfall and streamflow) and of human dimensions (e.g., socioeconomic indicators) provide important resources and should be expanded.
- **Carry out an inventory of ongoing adaptation research projects and implementation efforts.** Detailed understanding of ongoing research and adaptation efforts aimed at improving coastal resilience to sea level changes is a critical need in supporting informed decision making, engaging communities, identifying best practices, and helping tailor solutions that can work across county/state borders.
- **Foster the establishment of an institutionalized framework to move science information into actionable decision making support tools.** Several successful examples discussed during the workshop illustrate that there can be benefits from engaging the science community with adaptation professionals. Funding is available (e.g., NOAA Sea Grant funding opportunities) for development of these collaboration efforts, however in a largely insufficient amount. The following recommendations were identified to help with this:
    - Implement sustainable funding opportunities for adaptation science and efforts.
    - Explore additional opportunities for making research funds available at the local level.
    - Implement research grants tailored to identifying and rewarding talent among adaptation professionals.

- **Foster end-user driven tool development.** There is no "one-size-fits-all" for implementing adaptation efforts. To overcome this, end-user engagement was identified as critical for the development of fit-for-purpose tools and resources aimed at supporting the development and implementation of such efforts.
- **Foster opportunities for public engagement.** Public engagement, including citizen science, is demonstrated to be a valuable resource for informing communities and helping drive political will towards adaptation efforts and addressing community needs. One successful example presented at the workshop was the development and implementation of a water level sensor network in Savannah involving direct participation of citizens within the local communities.
- **Assess the design and impacts of hazard information through use-focused experiments (e.g., Judgement, Decision Making type).** Such experiments can evaluate how information is displayed to improve decision making.
- **Catalog and improve understanding of the mapping of preferences (e.g., risk tolerance) to hazard characterization and communication.** This includes determining what specific aspects of hazards are important for which decision makers, and if those aspects are provided by the scientific community.
- **Establish regional networks for adaptation efforts (see Figure 9).** Implementation of adaptation efforts require detailed information and planning at the local level. Regional networks can help by: (i) enabling the analysis of hyper local issues inherent to particular locations, such as ground-water modeling, compound flooding assessments, and storm surge vulnerabilities; (ii) facilitating the adoption of regional standards for adaptation to sea level rise; and (iii) supporting municipalities with low adaptive capacity (e.g., limited resources and low availability with technical capacity). One proposed mechanism to foster the establishment of such networks is to position proposal calls that require a joint co-production proposal development process including members of three groups: regional network of sea level experts, boundary organizations, and sea level practitioners.

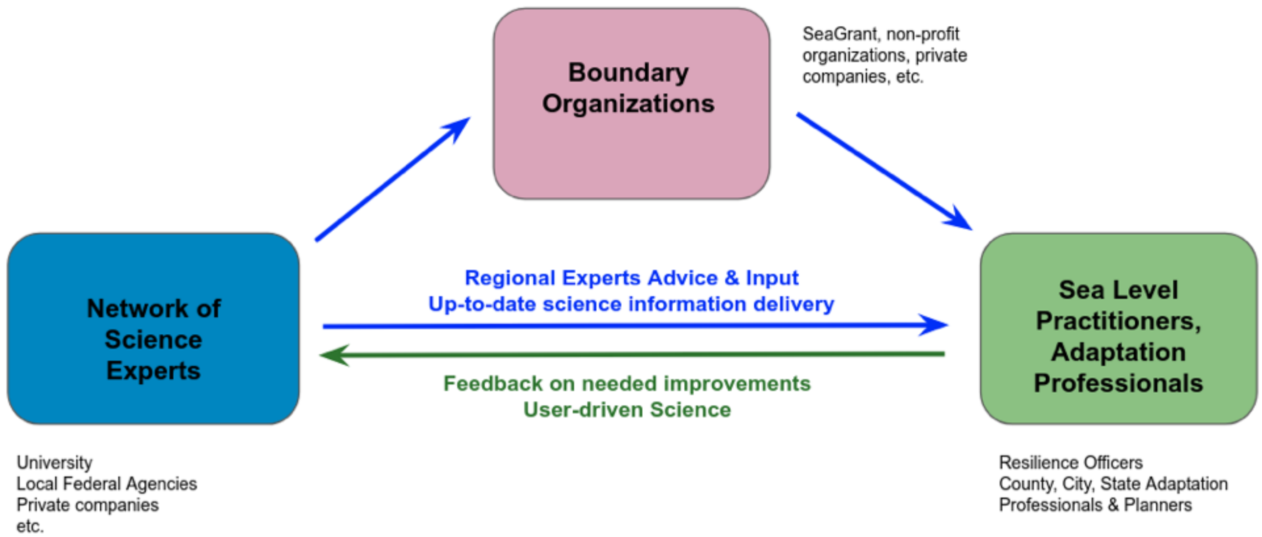

Figure 9. Regional framework for facilitating exchange of sea level science, knowledge, and adaptation strategies, and also to support the establishment of coherent set of guidance across the region.

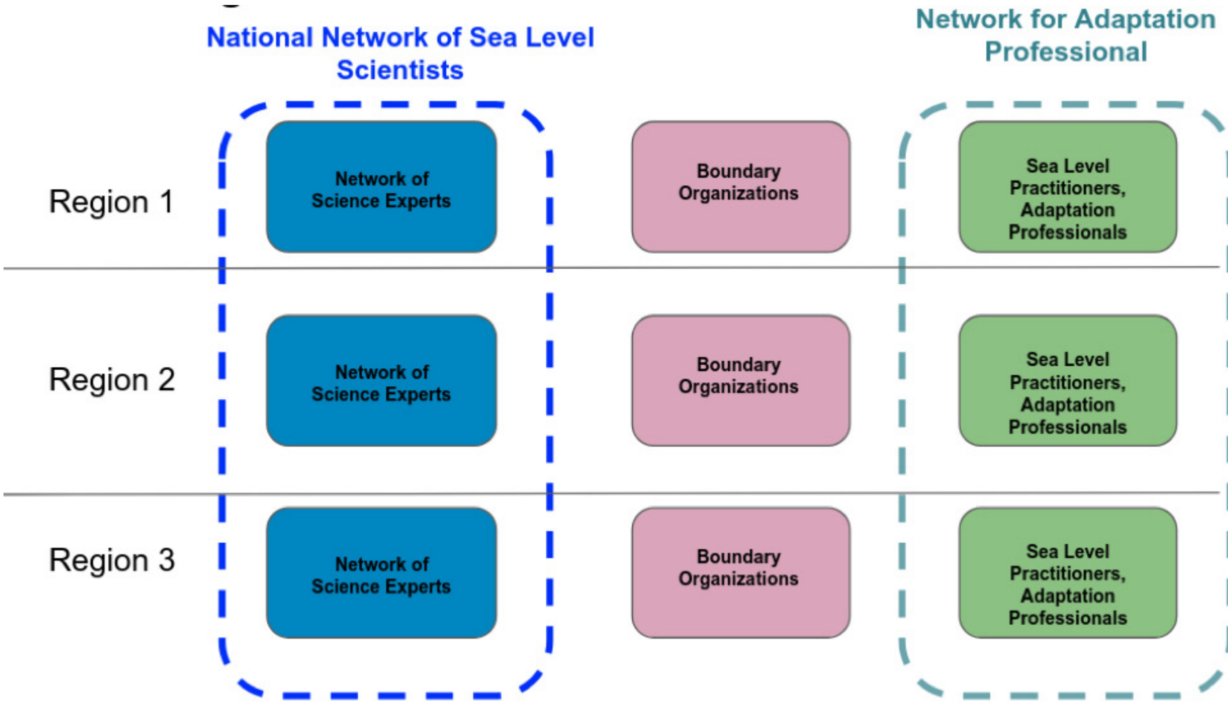

Figure 10. National framework for exchange of sea level science information, and best practices for adaptation efforts.

- **Establish an institutionalized network for the exchange of sea level information and science knowledge within the US (see Figure 10).** Researchers from various institutions within the US currently lead state-of-the-art research on different disciplines related to sea level changes. The establishment of a network including engineers, economists, and stakeholders, would benefit by favoring the exchange of science information and enhance networking, coproduction, and collaborations. Expanded use of boundary organizations (e.g., Sea Grant, IOOS regional associations, RISAs) should be promoted to facilitate the translation of science-based information to specific decision maker applications.

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Appendix A: Organizers

Scientific Organizing Committee

Ricardo Domingues (Co-Chair), University of Miami/NOAA AOML
Klaus Keller (Co-Chair), Penn State University
Krisa Arzayus, NOAA US IOOS
Larry Atkinson, Old Dominion University
Carmen Boening, NASA JPL
Emanuele Di Lorenzo, Georgia Institute of Technology
Gary Mitchum, University of South Florida
William Sweet, NOAA NOS
Phil Thompson, University of Hawaii
Kathleen White, US Army Corps of Engineers

Program Organizing Committee

Mike Patterson, US CLIVAR
Jeff Becker, US CLIVAR
Jennie Zhu, US CLIVAR

Appendix B: Participants

Thomas Allen	Old Dominion University
Susie Arnold	Island Institute
Jeff Arnold	US Army Corps of Engineers
Krisa Arzayus	NOAA US IOOS
Larry Atkinson	Old Dominion University
Molly Baringer	NOAA AOML
Brian Batten	Dewberry
Jeff Becker	US CLIVAR
Joshua Behr	Old Dominion University
Carmen Boening	NASA JPL/Caltech
Pamela Braff	Penn State University
Brett Buzzanga	Old Dominion University
Madison Clapsaddle	Ecology and Environment
Kim Cobb	Georgia Institute of Technology
Nick Deffley	City of Savannah
Emanuele Di Lorenzo	Georgia Institute of Technology
Ricardo Domingues	University of Miami/NOAA AOML
Tal Ezer	Old Dominion University
Joseph Fehrer	The Nature Conservancy
Mary Ford	MARACOOS
Cyril Germineaud	University of Miami/NOAA AOML
Marlos Goes	University of Miami/NOAA AOML
Gustavo Goni	NOAA AOML
Katherine Hagemann	Miami-Dade County

Benjamin Hamlington	NASA JPL
Klaus Keller	Penn State University
Debra Knopman	Rand Corporation
Ian Kraucunas	Pacific Northwest National Laboratory
Glenn Landers	US Army Corps of Engineers
Eric Larour	NASA JPL/Caltech
Erika Lentz	US Geological Survey
Ming Li	University of Maryland Center for Environmental Science
Christopher Little	Atmospheric and Environmental Research
Trevor Meckley	NOAA NCCOS
Amanda Medley	City of Virginia Beach
Molly Mitchell	VIMS
Gary Mitchum	University of South Florida
Robert Nicholas	Penn State University
Jayantha Obeysekera	Florida International University
Mike Patterson	US CLIVAR
Ann Philips	Commonwealth of Virginia/The Center for Climate & Security Board
Christopher Piecuch	Woods Hole Oceanographic Institution
Kelsey Ruckert	Penn State University
Emily Smith	UCAR/NOAA
Kyle Spencer	City of Norfolk
Vivek Srikrishnan	Penn State University
Ryan Sriver	University of Illinois
William Stiles	Wetlands Watch
Hilary Stockdon	US Geological Survey
Michael Sukop	Florida International University
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Philip Thompson	University of Hawaii
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Steve Woll	Open Water Innovations
Anthony Wong	Rochester Institute of Technology
Joshua Woodbury	Neuberger Berman
Robert Young	Program for the Study of Developed Shorelines
Jian Zhao	University of Maryland Center for Environmental Science
Jennie Zhu	US CLIVAR

Appendix C: Agenda

Tuesday, April 23, 2019

07:30	Registration & Light Breakfast	
08:30	Opening Remarks and Workshop Objectives	Ricardo Domingues & Klaus Keller
08:45	Welcome from Norfolk	Councilwoman Andria McClellan, City of Norwalk
09:00	Session 1: Current Efforts and Plans to Improve Coastal Sea Level Resilience (Framing the Challenges and Needs)	
09:00	Resilient Norfolk: Designing the Coastal Community of the Future (Norfolk Case Study)	Kyle Spencer, City of Norfolk
09:20	Adapting to Sea Level Rise in Miami-Dade County (Miami Case Study)	Katie Hagemann, Miami Dade County Office of Resilence
09:40	Virginia Beach Case Study	Brian Batten, Dewberry
10:00	Break	
10:30	Maine Case Study	Susie Arnold, Island Institute
10:50	Building Resilience in an Urban Coastal Environment: Technical Analysis Is the Easy Part	Debra Knopman, RAND Corporation
11:10	Coastal Adaptation and Prediction in Virginia	RDML Ann Phillips, Commonwealth of Virginia / Coastal Adaptation & Protection - The Center for Climate & Security Board
11:30	Questions/Discussion	Facilitators: Larry Atkinson & Klaus Keller
12:00	Lunch	
13:00	Session 2: What can the natural sciences provide? What are open research questions?	
13:00	Mechanisms of Sea-Level Change from Florida to Maine and Their Predictability	Christopher Piecuch, Woods Hole Oceanographic Institution
13:20	Coastal Change Hazards: Understanding What's at Stake and Planning for the Future	Erika Lentz, USGS
13:40	Synthesizing Climate Uncertainties and Decision Making in Complex Interdependent Coastal Systems	Nathan Urban, Los Alamos National Laboratory
14:00	Q&A with Panel of Speakers	
14:30	Break	

15:00	Questions/Discussion	Facilitators: Gary Mitchum & Phil Thompson
15:30	NASA Presentation	Benjamin Hamlington, NASA JPL
15:50	Lightning presentations for evening poster session	
17:00	Poster Session & Networking Event	
18:30	End of Day 1	

Wednesday, April 24, 2019

07:30	Light Breakfast	
08:30	Goals for the day & changes to the breakout groups	
08:45	Breakouts by Region: NE, Mid-Atlantic, SE/Gulf of Mexico	
10:00	Break	
10:30	Session 3: What are the tools currently available? What are the needed innovations, and observations?	
10:30	NASA & NOAA Tools Overview	Carmen Boening and Bill Sweet
11:00	Tools and Resources Currently in Place and in Development to Help Planning Adaptation to Sea Level Rise in South Florida	Jayantha Obeysekera, Florida International University
11:30	Engaging and Activating the Local Community on Sea Level Topics	Nicholas Deffley & Kim Cobb, City of Savannah & Georgia Tech
12:00	Questions/Discussion	
12:30	Lunch	
13:30	Breakouts by Region (continued)	
15:00	Break	
15:30	Breakouts by targeted topics determined from discussions	
17:00	End of Day 2	

Thursday, April 25, 2019

07:30	Light Breakfast	
08:30	Summary of key findings and recommendations	Ricardo Domingues
08:45	Discussion of findings and recommendations Agency manager feedback Closing Comments	
10:30	Adjourn Workshop	

Appendix D: Web-Based Tools, Resources, and Phone Apps

Tool	Description
USGS Coastal Change Hazards Portal	Provides interactive access to coastal change science and data for the US coasts.
USGS Coastal/Marine Hazards and Resources	Provides interactive access to various analysis, resources, and datasets associated with coastal change science and observations.
NOAA Sea Level Rise Viewer	Allows visualization of community-level impacts from coastal flooding or sea level rise (up to 10 feet above average high tides). Also provides data related to water depth, connectivity, flood frequency, socio-economic vulnerability, wetland loss and migration, and mapping confidence.
NOAA Tides & Currents Portal	Provides access to real-time water-level and current measurements based on a network of tide gauges and stations distributed along the coast, as well as to tidal predictions.
US Army Corps of Engineers' Sea Level Tracker	Allows the user to compare actual mean sea level (MSL) values and trends for specific NOAA NWLON tide gauges with the USACE sea level change scenarios as described in ER 1100-2-8162, "Incorporating Sea Level Change in Civil Works Programs."
NASA Sea Level Portal	Provides accessible information about how NASA satellite observations help in the understanding of sea level changes and access to user-friendly data analysis tools that can be used by planners, engineers, and stakeholders to quickly visualize changes and trends on sea level data.
Flood IQ Portal	Provides a web based GIS-type application that allows to visualize the risk of sea level rise flooding today and up to 15 years in the future for specific addresses from users along the coast.

Wetlands Watch Resources and Phone App	Provides access to various planning and educational resources on adaptation to sea level rise. Available for download is also a phone application that crowdsources information about flooding along the East Coast.
Adapt VA	Provides a gateway to information for individuals, local programs, and agencies engaged in climate adaptation within Virginia, including access to legal and policy resources, stories that explain adoption through maps and pictures, a searchable web catalogue, and mapping tools that address short and long-term predictions for rising water levels.
SMART Sea Level Sensors	Accesses a network of internet-enabled sea level sensors across Chatham County, Virginia, providing real-time data on coastal flooding for emergency planning and response.
VIMS Sea Level Report Cards	Provides access to annually-updated sea level trends and projected sea level height to the year 2050 for 32 localities along the US East, Gulf, and West Coasts.
The Nature Conservancy Coastal Resilience Program	Gathers key information on coastal resilience and adaptation and provides access to planning and educational resources, web-based tools, and phone applications to aid in implementation.

usclivar.org/meetings/sea-level-hotspots-florida-maine

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