Project Summary

Project Title: Modeling, Visualizing and Communicating Nor'easter and Hurricane Threats with Sea-level Rise to Support Coastal Management within New England (LOI#21-CR59)
NOAA Program name and focus area: Effects of Sea-Level Rise 2021 Coastal Resilience
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Coastal communities and critical habitats are at increased risk due to sea-level rise (SLR). Adapting to SLR and extreme weather conditions in our changing climate is a growing concern. In New England, extratropical storm events with strong winds and heavy precipitation (commonly called nor'easters) are the most common coast-shaping storms, followed by hurricanes. There is limited information on how the impact of both types of storms may be amplified under a changing climate and SLR. This information gap inhibits our ability to properly plan for the future and is likely to lead to under-informed and ineffective adaptation measures. The overarching goal of this four-year project is to inform and improve resource management and resilience in New England coastal areas covering five National Park Service (NPS) units, two National Wildlife Refuge (NWR) sites and many adjacent communities. The project will provide high-resolution model outputs of the impact of future storm/SLR scenarios, in terms of quantified vulnerability of ecosystems and infrastructure, and accompanying compelling visualizations for target areas of interest. A specific challenge of existing SLR tools (e.g., NOAA SLR Viewer) is the static treatment of the shoreline condition, and this is especially a concern for barrier-bay systems where changes are inevitable. For two dynamic systems in RI and MA, scenarios will be simulated without and with site-specific Natural and Nature Based Feature (NNBF) mitigation strategies, defined interactively and iteratively with stakeholders to assess system-wide vulnerability. The project will employ a three-tiered stakeholder-driven process to facilitate and enhance science-end user collaboration and relationships, as well as increase capacity and awareness of NPS, NWR and community managers, planners and other stakeholders to incorporate project outputs in decision-making. The approach will be tailored to 1) integrate study areas that are diverse in geomorphology, natural processes, and human influence (sandy to rocky, urban to pristine); and 2) address a variety of management issues (societal to environmental) that require critical decisions to be made, such as resource protection, emergency preparedness, and safe public access. Leveraging NOAA, NPS, NWR, Department of Homeland Security (DHS), and other federal investments, this project will build on existing knowledge and dynamic model frameworks of the impact of extreme storm events and evaluate SLR ramifications. An online portal will be developed to share model output visualization, synthesize project deliverables, and communicate with stakeholders and public audiences. The project will engage parks, refuges, local and state governments, and non-profits in a collaborative and iterative process to ensure, models, results, vulnerability assessments, and accompanying 3D visualizations support specific stakeholder management concerns and affect decision making today and in the future. The place-based information and critical insights provided from this project will promote the wise expenditure of resources to improve coastal resilience and protect communities (people/infrastructure) and their ecosystems (habitats, resources, services).

Project Description

a. Proposed Research

This proposal addresses how parks, refuges and surrounding communities can use dynamic models to adapt to storm/Sea Level Rise (SLR) impacts within the *Coastal Resilience focus area*.

i) *Goal* The overarching goal of this project is to enhance science-stakeholder dialog and inform/ improve resource management and resilience to future extreme storms, combined with SLR, in New England coastal areas covering five NPS units, two National Wildlife Refuge (NWR) sites, and many adjacent communities (Fig. 1, inset top right) (all referred to hereafter as *sites*). This will be achieved by predicting the inundation, geomorphic changes, and selected ecosystem responses induced in these beach-barrier/coast/lagoon systems and, if applicable, hydrodynamic loads on structures, for a variety of storm/SLR scenarios. To this effect, a series of integrated models, leveraged from earlier and existing projects, will simulate both long-term and event-timescale evolutions, at regional to local (high-resolution) spatial scales. Scenarios will combine the dominant coast-shaping storms in the region, nor'easters and hurricanes, with measured or modeled geomorphic/ecosystem changes (e.g., dune, marsh loss) and various SLR assumptions. At each site, model results will be expressed in terms of vulnerability to storm/SLR scenarios for ecosystems, communities and infrastructures, quantified with multiple metrics (Bridges et al., 2015). Identical scenarios will be simulated both without and with human responses, implemented in terms of site-specific Natural and Nature-based Features (NNBFs) and adaptation of existing grey infrastructure. These mitigation measures will be iteratively and interactively defined, in consultation with a diverse range of stakeholders, and guided by initial model results. Quantified differences in vulnerability for selected NNBF management strategies will allow evaluation of human and habitat concerns (e.g., piping plover (*Charadrius melodus*) habitat loss) and management options. Advanced 3D visualizations and webtools will be used to facilitate stakeholder discussions and communicate project results. This project will produce critical information across New England sites co-developed with and provided to a broad range of stakeholder groups for use in management and planning decisions. The place-based information will promote a fully informed and wise expenditure of resources to improve coastal resilience and protect communities (people, infrastructure) and their ecosystems (habitats, resources, services).

ii.1) *Scientific objectives*

1. Simulate impacts of future extreme nor'easters/hurricanes combined with SLR scenarios for five NPS and two NWR sites and adjacent communities using advanced integrated models and coastal data, e.g., topography, hydrodynamic and ecosystem information.
2. For two sites with dynamic systems, determine likely geomorphic/ecosystem changes from measurements and models, and then hydrodynamically model, assess, and visualize hazard impacts for scenarios without and with site specific NNBF strategies identified by end users, and provide stakeholders with quantitative information on long-term coastal and community vulnerability.
3. Promote scientist-stakeholder dialog and enhance/expand model results available to end-users, to build their awareness and capacity for making informed resource management decisions.
4. Use data analysis and advanced 3D visualizations of inundation and erosion modeling to support planning for adaptation scenarios related to emergency response, public access, ecosystem restoration, infrastructure planning, and stakeholder education.

ii.2) *Background - study sites and management challenges presented by climate change*

Coastal communities and critical habitats are at increased risk due SLR. Adapting to SLR and extreme weather conditions in our changing climate is a growing concern. In New England, extra-

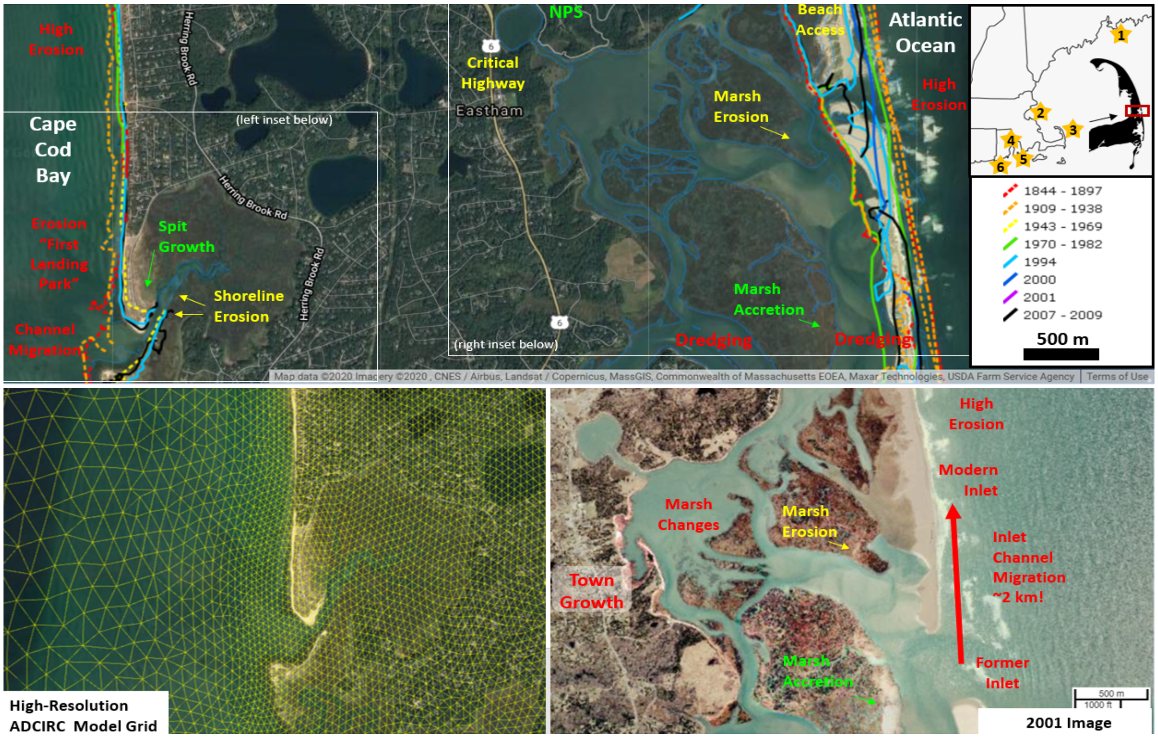

Fig. 1: (Upper 1/2) Eastham, MA (partial) and Cape Cod (CACO) National Seashore (eastern side) with historical shorelines and coastal changes indicated; inset shows location of six study sites. (Lower-left) example of ADCIRC model grid. (Lower right) Inlet movement and marsh changes are highlighted. Note, repeat shoreline mapping does not currently extend into embayments, a focus of this study.

tropical storm events with strong winds and heavy precipitation (commonly called nor'easters) are the most common coast-shaping storms, followed by hurricanes. There is limited information on how the impact of both types of storms may be amplified (in frequency and intensity) under a changing climate and SLR. This information gap inhibits our ability to properly plan for the future and is likely to lead to under-informed and ineffective adaptation measures. These changing conditions will exacerbate inundation, erosion, wind, and precipitation impacts, adding further complexity for effective management of the coastal environment and communities. Management challenges resulting from these storms range from ecological to coastal defense to societal, and include shoreline erosion, dune migration, breaching, and alterations of ecosystem services; damage to cultural resources, including historic structures and archeological sites; emergency access and other maintenance needs from flood-water inundation; and damage to infrastructure including roads, bridges, seawalls, and parking lots. Providing improved, locally explicit projections of storm impacts in terms of quantified vulnerability metrics, in different management scenarios (do nothing versus selected NNBF mitigations) will be invaluable for developing efficient adaptation strategies into planning processes. Pre-storm event planning can provide opportunities to increase the shared understanding of the best available science among all partners, which will help management teams respond to and adapt after storms in ways that protect resources and will leave communities less vulnerable to repeated impacts. Understanding the range of coastal vulnerability associated with future storm events, without/with the implementation of mitigation strategies, will provide actionable information to managers and the public about the role and long-term ramifications of coastal mitigation efforts.

While there are many SLR tools, most have shortcomings in their treatment of complex hydrodynamic processes, such as assuming a static "bathtub" flooding. While the latter may be useful for large-scale assessment, it is potentially misleading for local decision-making. The physics-based models proposed for use in this study include dynamic processes affecting coastal water levels, such as tides, waves, winds, storm surge, SLR, and wave-induced forces, and at some of the sites, account for shoreline/barrier and back-barrier morphologic evolution, at a fine enough resolution to identify site-specific locations that may require adaptation measures. Specifically, as part of ongoing projects funded by the DHS and NPS, the University of Rhode Island (URI) team has adopted NOAA's operational Extratropical Surge and Tide Operational Forecast System (ESTOFS, 2020) based on the coupled ADCIRC-SWAN coastal circulation and wave model (Westerlink et al., 1994; Booj et al., 1999; Luettich and Westerink 2004, Dietrich et al., 2012), with high-resolution bathymetry/topography across New England. The unstructured mesh size has a 10 to 90 m resolution, as a function of distance to shore and water depth (e.g., Fig. 1, lower left). In addition, the URI team has implemented the coupling framework based on the Earth System Modeling Framework (ESMF) and the National Unified Operational Prediction Capability (NUOPC) technologies under the NOAA Environmental Modeling System (NEMS) developed for the ADCIRC-WAVEWATCH III system (Moghimi et al. 2020). The proposed study will leverage this modeling system to simulate coastal flooding at the proposed sites from extreme nor'easters and hurricanes combined with SLR. For two dynamic sedimentary sites, along with these simulations, shoreline/barrier and back-barrier evolution will be predicted for a series of SLR scenarios, using the community models ShorelineS (Roelvink et al., 2020) and Delft3D (Lesser et al., 2004). At the timescale of each extreme storm, coastal erosion/ breaching/geomorphic changes will be simulated with the standard model XBeach (Roelvink et al., 2009), on high-resolution local grids, forced along its offshore boundary by ADCIRC-SWAN/WAVEWATCH results. Additionally, wherever relevant, wave-induced forces on critical infrastructure and built-up communities will be simulated using the phase-resolving model FUNWAVE (Wei et al., 1995; Shi et al., 2012). XBeach has been used at URI as part of NOAA, HUD and Sea Grant-funded projects (Schambach et al., 2018). FUNWAVE, an open-source model, was co-developed and applied at URI to similar problems (Grilli et al., 2020) and its latest developments were funded by the USACE, which selected it as their phase-resolving coastal wave model. FUNWAVE is also the main model used at URI for conducting tsunami inundation mapping work for NOAA-NTHMP (Schambach et al., 2019). Finally, in the selected dynamic areas, marsh evolution modeling will be applied along with historical measurement of estuarine topography, to allow the most realistic future modeling.

The coastal areas to be examined in this study (Fig. 1, inset top right) are diverse in their geomorphology, natural processes, and human influence, ranging from dynamic, sedimentary systems with superimposed communities (southern RI and Cape Cod, MA) to more geologically stout coastal areas with adjacent population centers (Acadia, ME and Boston Harbor Islands, MA) to sites within well-developed, well-populated urban centers (Providence, RI and New Bedford, MA). While all sites have critical risk today and increasing concern for the future, each location has different management needs, data availability, and existing planning efforts. The project will be tailored to meet the specific needs of each study site, as determined through close and continued interactions with key stakeholders. The sites are described below.

Cape Cod, Massachusetts. The Cape (#3 in Fig. 1 inset) is a sedimentary system being constantly reshaped through storms and other coastal change processes (Giese et al. 2015). The area is characterized by eroding bay and ocean shorelines and evolving marsh-lined embayments. A USGS coastal vulnerability assessment highlights many areas of concern along the Cape (Hammar-Klose et al., 2003). This project will engage Cape Cod National Seashore (CACO) and a management partnership that includes the towns of Eastham, Provincetown, Truro, and Wellfleet.

The project will focus on two areas of particular management concern, the eastern coast from Race Point to Nauset Bay, and the bayside shoreline. This proposed study will build on the current nor'easter inundation modeling study in CACO led by the PI Ginis and other research by adding targeted ocean and bay coastal change measurements, modeling, directly engaging with the four-town partnership to tailor research and visualizations to meet their needs, and leveraging CACO's communication expertise and relationships with other stakeholder groups. Specific management needs this project aims to support include planning for inundation of emergency access routes, the local airport, vulnerable historic structures, planned salt marsh restoration, and upcoming Conservation Commission revisions for resiliency. An oceanfront focal area, in the vicinity of Coast Guard Beach (CGB), will model how storm/SLR scenarios may impact Nauset Bay and the adjacent community of Eastham. This area is identified as vulnerable by USGS assessment and the Eastham Hazard Mitigation Plan (Eastham, 2020). Safe public access for park visitors is also a key NPS management need for CGB, an area that has experienced significant erosion, necessitating changes to access routes. The park already has adaptation strategies that include retreat and is considering the need to plan for further retreat over time, and this proposed project can provide valuable information to guide that conversation.

Washington County, RI. Extending from the eastern edge of Long Island Sound to Point Judith, the south-western RI coast consists of a series of barrier beaches and headlands with Atlantic Ocean exposure and several protected coastal lagoons or "salt ponds". Humans have played a recent role in altering the system through development, shoreline hardening, and management efforts (#6 in Fig. 1 inset, Fig. 2). This study will focus on the central portion of this coast where two National Wildlife Refuges - Ninigret and Trustom Pond (NITR) - are located within the adjacent municipalities of Charlestown and South Kingstown. Overwash, erosion, and breaches during extreme storms are part of the natural processes that influence the lagoon system, yielding episodic flushing, changes in salinity, and alterations to the shoreline and sediment budget. Human alterations have also occurred, e.g., dredging, hardening. Long-term changes in the dynamics due to storm events and SLR are concerning for important estuarine habitats (submerged aquatic vegetation, marsh), and oyster aquaculture, a growing part of the RI blue economy. Based on studies performed in the context of the Beach Special Area Management Plan (SAMP) (RI CRMC, 2018), the lagoon system and adjacent communities are identified as highly vulnerable, however with high adaptive capacity (Grilli et al., 2017). The area was used for several previous hazard and risk assessment studies (e.g., Schambach et al., 2018). The proposed study will build on the Beach SAMP effort and focus on the adaptive capacity of the site by exploring anticipated geomorphic and ecosystem changes and relevant management scenarios and mitigation strategies (e.g., nourishment, marsh restoration, breach response) to support coastal resilience planning/management decisions.

Fig. 2: Map of NITR study area. Note the NWR sites and towns. Change concerns are noted.

Stakeholder engagement will build upon both the longtime collaboration between NITR and their host communities, as well as URI's extension initiatives involving community/governmental/ private stakeholders.

Acadia, Maine. Acadia National Park (ACAD; #1 in Fig. 1 inset) conserves the ecological integrity, cultural history, and scientific values of its rocky headland islands and the Schoodic Peninsula. ACAD identified the need for research on nor'easters and climate change through a 2015 scenario planning workshop. In response, ACAD is participating in the current nor'easter inundation modeling study led by PI Ginis. This proposed study will build on existing efforts by directly engaging with key partners including Friends of Acadia, A Climate to Thrive, municipalities, and the Maine Department of Transportation. Stakeholder engagement will be facilitated by Schoodic Institute, and involve the park and surrounding communities. Specific management needs this project aims to support include roads, access, and emergency preparedness at vulnerable locations (Schoodic Point, Trenton Bridge (Fig. 3), Seawall), as well as park management decisions about visitor infrastructure (Sand Beach) and ongoing salt marsh restoration (Bass Harbor).

Boston Harbor, Massachusetts. Boston Harbor Islands National Recreation Area (BOHA; #2 in Fig. 1 inset) is a partnership park that plays a coordinating role for a range of partners and has been involved with a variety of Boston area SLR planning efforts. BOHA has been part of a current nor'easter inundation modeling study led by the PI Ginis. This project will include modeling and visualizations for gateway communities and leverage the Park's relationships to engage stakeholder groups to understand their concerns and communicate project results and products. Anticipated partners include the Boston Harbor Now and Stone Living Laboratory. Coordination with Boston National Historical Park, including Charlestown Navy Yard and the Long Wharf ferry station are additional opportunities for education and outreach.

Providence, Rhode Island and New Bedford, Massachusetts. Roger Williams National Memorial (ROWI) and New Bedford Whaling National Historical Park (NEBE) are historical sites in urban settings (#4, #5 in Fig. 1 inset). Both parks are located upland of protective hurricane barriers, influencing the dynamics of coastal flooding from storms and SLR within these areas. The proposed study will build on previous URI modeling of the Providence area (Ullman et al., 2019) to perform modeling and visualizations for target areas of interest in both parks and in Providence and New Bedford, and implement an outreach and education plan to communicate project results and products. The project will support ecosystem restoration efforts, such as those underway by the Buzzards Bay Coalition and the Narragansett Bay Estuary Program, as well as infrastructure management that is reliant on a partnership with neighboring organizations, including city and state agencies. This project will inform the parks, cities and property owners, including the New Bedford Whaling Museum and other historical societies, of vulnerabilities, management possibilities, and planning decisions. NEBE and ROWI have strong cultural and historical ties to their respective communities, and they will engage less-represented communities. As part of sharing whaling history at NEBE and RI's early development at ROWI, these park units have built relationships with diverse communities, including immigrants, people of color, LGBTQ, and regional tribal nations.

ii.3) *Scientific activities of value to the program goals*

Overview. In recognition of the varied needs across parks, refuges and communities, this project will implement a three-tiered stakeholder-driven approach to research, outreach, and engagement. The process will: 1) facilitate and enhance science-end user collaboration and relationships; 2) increase capacity and awareness of NPS, NWR and community managers, planners and other stakeholders of current and future storm/SLR impacts; and 3) promote the incorporation of project outputs in decision-making processes (e.g., implementation of NNBF mitigation measures). An issue of many SLR tools (e.g., the NOAA Viewer) is unrealistic boundary conditions for future-focused hydrodynamic models. Hence, for all sites, regional scale hydrodynamic modeling will be performed for selected storm/SLR scenarios, along with GIS analyses and 3D visualizations. Activities specific to each tier are as follows; Table 1):

1) *Tier 1* (CACO, NITR). For these two sites, where significant changes in coastal morphology are anticipated over the next half century, shoreline evolution will be simulated and local-scale hydrodynamic/geomorphic modeling will be done and combined with data collection and analysis, incorporating existing marsh evolution modeling, to perform more realistic storm/SLR scenario modeling. In addition, in developed areas of adjacent communities, forces on structures and infrastructures will be modeled. Hazard impacts will be quantified at high-resolution (1 to 5 m), without/with proposed NNBF mitigation strategies, both using standard metrics, e.g., inundation (Base Flood Elevation, total water depth), maximum wind speed and total precipitation, flooding time; and in terms of ecosystem/infrastructure vulnerability metrics (Bridges et al., 2015): e.g., changes in beach and dune system and breach occurrences, land and habitat loss due to SLR. All results will be delivered as maps and 3D visualizations, emphasizing changes in vulnerability and coastal hazard impacts without/with NNBF scenarios. In these top tier sites, there will be sustained interactive involvement with end-users, with research and engagement efforts directed at specific management actions that will affect modeling and guide associated coastal change measurements/visualizations. Data compilation, collection, modeling, visualizations, and webtools will be interactively and iteratively informed by end-users and refined as needed.

2) *Tier 2* (ACAD). Research and engagement efforts will be directed at specific management action(s) that guide associated storm/SLR modeling and visualizations. The engagement process will be interactive and iterative, with models, visualizations and webtools informed by end-users and adapted or refined as needed.

3) *Tier 3* (ROWI, NEBE, BOHA). Research and engagement efforts will be informed by specific management needs that guide associated storm/SLR modeling, visualizations, and webtools. The primary goal for these sites is education and outreach. As such, the engagement process will involve intermittent interaction with end-users, most heavily focused at the project beginning (to understand stakeholder concerns and management needs) and end of the project (to understand how to apply products to decision making).

Data compilation, collection, and analysis

An important first step for any new research is learning from past efforts including that of academic, government or private researchers. The team has already reached out to NPS, NWR, USGS, state and local entities. A comprehensive literature review and compilation of topographic, bathymetry, shoreline, habitat, and sediment data will be compiled and incorporated into analysis efforts and the online portal (described below). To understand recent and potential future ecological change in Tier 1 areas, this study will not conduct new ecological modeling but rather build off extensive past/ongoing research. Specifically, the Sea Level Affecting Marshes Model (SLAMM) has recently been used to assess future habitat change for both areas (RI CRMC, 2015; MA OCZM, 2016), and another update is underway in RI. Also, the Spatial Marsh Equilibrium Model has been used in CACO (Morris and Renken, 2019). This work uses available spatial (elevation, habitat) and process data (e.g., localized accretion rates from Surface Elevation Tables; Raposa et al., 2016; Morris and Renken, 2019). However, there are limitations to this modeling, for example, commonly observed variable lateral erosion or complex deposition are not usually incorporated. Also, earlier SLAMM studies have employed state-wide, but now a decade old, habitat data. Rather than repeat this modeling with its well-recognized limitations, Tier 1 analysis of coastal subaerial/subaqueous geomorphic and ecosystem change will be completed with emphasis focusing on estuarine habitat (e.g., marsh) and dune transformations, including human manipulations over the last two decades. For example, in both areas overwash and channel migration have yielded appreciable marsh and dune impacts from recent storms (Figs. 1, 2; Smith et al., 2017). Time-changes in key morphological features (e.g., shoreline, dune, vegetation) and parameters will be determined from aerial photograph or LiDAR measurements to quantify of coastal dynamics. Barrier-bay systems often show coupled ocean-estuarine-human responses (e.g., back-barrier deposition/ erosion; Conery et al., 2018) that need to be understood for vulnerability assessment.

New shorezone mapping will be conducted in estuarine areas for three time steps (at a minimum): historical (possibly 1950s, depending on image availability/quality), ~2000 and recent (e.g., Cowart et al., 2010; 2011; Eulie et al., 2013; 2017). This may require scanning and georectification of images. We will aim to complete estuarine shoreline mapping during timesteps when ocean shorelines have already been digitized and will follow the protocol established by the NC Division of Coastal Management (2012; created by Walsh and colleagues). While much past research has focused on map-view changes (e.g., ocean shoreline movement), 3D subaerial/subaqueous topographic dynamics will need to be examined to accomplish realistic modeling of these dynamic human-impacted systems. Subtle topography can have important influences on water and sedimentation (e.g., Lagomasino et al., 2013; Conery et al., 2018; Brodie et al., 2019), and future conditions may be best predicted from past changes. Given the size of the study areas, complete remapping of topobathy cannot be completed, but where remotely sensed data indicates marked changes and stakeholders recognize need, field measurements of marsh erosion and dune migration will be made. New elevation data collection will be made with RTK, single-/multi-beam data collection, and sedimentation/habitat assessment (e.g., quadrat biomass) will add to existing data. URI has the necessary equipment and broad experience to do so. Where feasible aerial (e.g., drone) or ground-based LiDAR mapping will be used. Given the constraints, bathymetric data will only be collected where significant seabed movement has occurred. As mapping is time consuming, and before any field efforts, dialog will occur with other researchers so synergies can be leveraged.

Sediment sampling will be conducted to measure grain-size distributions, organic matter content and potentially sediment accumulation rates (^{210}Pb) in marshes to complement published or otherwise available data as needed (e.g., Corbett and Walsh, 2015). These data coupled with 3D surface changes and bulk density estimates will be used to establish sediment budget data for discrete areas identified by stakeholder needs (e.g., Eulie et al., 2018). Sediment grain-size and manning roughness (based on sediment and vegetation) are also important for the modeling efforts.

Hydrodynamic modeling (all sites). Historical nor'easters will be simulated in each site region, such as the 1991 Halloween Nor'easter and the 2013 Nor'easter (a.k.a., Storm Nemo). Decisions on specific storms to model will be based on discussions with park managers and surrounding communities. To study the cumulative effects of repeat impacts, one of the historical simulations will include the case of a series of storms in succession, such as the March 1-3, March 6-8, and March 12-14, 2018 nor'easters. Atmospheric forcing for the nor'easter simulations will be based on the ECMWF ERA-5 reanalysis dataset at a 30 km grid resolution available from 1950 to present. Hurricane simulations will include historic high impact storms in New England - the 1938 New England Hurricane, Hurricane Carol 1954, Hurricane Sandy 2012, and hypothetical extreme hurricane scenarios with higher storm intensity and reduced translation speeds, such as described in Ullman et al. (2019). Atmospheric forcing for the hurricane simulations will be based on the combination of the high-resolution hurricane boundary layer model (Gao and Ginis, 2016; Ullman et al. 2019) and the ECMWF ERA-5 reanalysis. Selected historical and hypothetical high impact storm events combined with varying SLR rise rates, and targeted time frames will result in at least 12 scenarios at each site; additional scenarios will be developed where geomorphic change forecasts (based on modeling and historical data) and management scenarios are being evaluated.

Morphodynamic and high-resolution hydrodynamic modeling (Tier 1 sites). Long-term ocean shoreline changes will be modeled for each SLR scenario with the long-term geomorphic model ShorelineS. The predicted new shoreline will be combined with marsh modeling (SLAMM) and historical measurements of estuarine shoreline and topographic changes to create future topographic and land cover conditions, to be used as initial condition for the high-resolution modeling of future storm events, i.e.: 1) changes in morpho-dynamics with XBeach/Delft3D; 2) forces on structures with FUNWAVE, at highly vulnerable sections of the sites identified in regional modeling and/or prioritized in discussion with stakeholders.

Mitigation strategies implementation (Tier 1 sites). In light of regional/local modeling without mitigation, to support site-specific concerns raised by stakeholders, various mitigation strategies will be evaluated to improve site coastal resilience to future extreme storm/SLR scenarios. Where relevant, mitigation strategies may include NNBF as well as grey scenarios, consistent with park/refuge policy, such as: vegetation enhancement to increase flow energy dissipation in overwash and inundation events; filling dune breaches after storm events; increasing sand reservoir through beach nourishment; implementing an artificial reef designed to dampen nearshore wave energy; dune reinforcing with Geotextile Sand-filled Containers (GSC; e.g., Al Naser et al., 2018); elevating structures, and retreat; etc.

Hazard impact and coastal vulnerability assessment (Tier 1 sites). Visual impact and quantitative metrics (Bridges et al., 2015) addressing long-term changes in coastal vulnerability and community exposure will be developed, without/with selected mitigation strategies. These will provide tools for assessing the strategies' efficiency for the site targeted value functions (stakeholders-defined). Relevant maps and metrics will include: 1) coastal hazard exposure parameters such as inundation, momentum forces from flow-plus-waves, including breaking on structures, and loss of habitat for piping plover (*Charadrius melodus*); 2) sensitivity metrics (e.g., dune reservoir or breaching); and 3) adaptive capacity metrics assessed by comparing the impact over time of different storm/SLR and mitigation scenarios. These metrics will be used to compare the efficiency of the mitigation scenarios designed to increase the shoreline resilience.

Development of 3D visualization tools. Realistic visualizations make modeled outputs immediately relatable, local, and tangible to stakeholders, thus enhancing risk perception and promoting engagement (Sheppard, 2015; Stempel and Becker, 2019). Visualization frameworks developed by Co-PI Stempel that couple ADCIRC to realistic 3D visualizations will be applied to serve an essential bridging function between model outputs and local stakeholder concerns (Stempel et. al., 2018). Priorities of stakeholders and pathways to adaptation often involve cultural concerns and meanings ascribed to place operating at different scales (e.g., home, neighborhood, city) and different time frames (e.g., O'Neill and Graham, 2016). Development of visualizations employs iterative practices maximizing the ability of stakeholders to shape visualization priorities (Stempel, 2019). Significant existing 3D infrastructure has already been created for NITR (Charlestown), CACO (Eastham, Provincetown), BOHA (Georges Is.), ACAD (Trenton Bridge, Sand Beach), and ROWI (Providence), including nearly 100,000 3D models of specific structures/vegetation making up extensive "virtual" sites that can be re-positioned and reused to support changing visualization foci and model outputs. This will be expanded to include additional sites, new infrastructure for NEBE, and new 3D proxy objects (e.g., local vegetation species, structures, and landforms) as necessitated by the stakeholder directed processes. Work in Tier 1 sites will also include transformations of landforms and vegetation based on model outputs and measured changes to represent landscape change. Number of visualized locations in the sites will be determined by stakeholders.

ii.4) ***Methods***

Overview. This project includes a complementary combination of stakeholder engagement, modeling, data collection and analysis, and product development for communication and to support management efforts. While there are several planned thrusts for scientific studies outlined below, stakeholder needs will drive the science questions and products. Co-development of the research through interactive and sustained stakeholder engagement will allow more robust, relevant research -- the essence of transdisciplinary science. As model results are produced, we will continually engage NPS, NWR and key community stakeholder groups at each study site to tailor the project (in particular select mitigation measures to be simulated and target areas for visualizations) based on site-specific circumstances and needs. We will establish a Management Transition Advisory Group (MTAG) composed of NPS, NWR, and community end-users from all sites that will convene once or twice per year throughout the duration of the project. The purpose of the MTAG is to ensure, the study accomplishes objectives relevant to management, provides synergistic opportunities for discussion and collaboration, and fosters relationships that facilitate sharing of knowledge and lessons learned during and beyond the project period.

The time frames and SLR scenarios simulated with various models (site dependent) will be adjusted to inform management application, but a general approach consistent across sites will be to use three time frames (current, 2050, 2075) and two SLR rates (TBD). This approach will be confirmed with the MTAG at the start of the project. Each SLR scenario will be combined with simulated extreme nor'easter and hurricane events. Following NPS experience with scenario planning, the employed SLR rates will span a plausible range for those time frames, from a least change to a most change prediction, that for NITR and CACO will be paired with a range of other scenario factors to account for high uncertainty in accompanying geomorphic change. Hydro-dynamic conditions (i.e., waves and currents) generated for all cases will be used to evaluate new equilibrium stresses or future events to assess shoreline and habitat response (e.g., Eulie et al., 2017). For example, deposition from a new breach may alter back-barrier current flow enhancing marsh erosion or promoting marsh expansion.

Hydrodynamic Modeling (I. Ginis, A.,S. Grilli)- To address current/future human and habitat risk. This project will employ a high-resolution version of NOAA's operational Extratropical Surge and Tide Operational Forecast System, developed for New England based on the ADCIRC-SWAN coupled storm surge-wave model. In addition, in collaboration with NOAA (see attached letter from NOAA/NCEP), we will use the recently developed coupling framework developed for the unstructured ADCIRC-WAVEWATCH III surge/wave prediction models (Tolman, 2009; Moghimi et al. 2020) based on the Earth System Modeling Framework (ESMF) and the National Unified Operational Prediction Capability (NUOPC) technologies. As part of an ongoing DHS funded project PI Ginis implemented an improved method for coupling storm surge and wave models that accounts for wave-current interactions and sea-state dependent atmospheric forcing in deep (Reichl et al. 2014, 2016; Soloviev et al., 2017) and shallow coastal waters (Chen et al. 2020).

Additionally, for selected locations within Tier 1 sites, the wave-resolving Boussinesq model FUNWAVE (Shi et al., 2012) will be applied at a higher-resolution of 2-4 m, over the built-up DEM, in order to more accurately assess storm hazard from wave runup and swash oscillations, as well as momentum forces on and current between structures (Grilli et al., 2020), in particular when the impact of specific mitigation strategies will be assessed. Offshore boundary conditions will be obtained from the regional scale ADCIRC – SWAN/WAVEWATCH simulations.

Geomorphic Modeling -- To understand future conditions and storm-driven dynamics (A. and S. Grilli). For the Tier 1 sites, changes in coastal morphology associated with storm/SLR events will be modeled using physics-based morpho-dynamics models. At the scale of years to decades, shoreline changes resulting from selected SLR scenarios will be simulated with the 1D ShorelineS model. At the scale of specific storms (a few days to weeks for repeated storms), morpho-dynamics changes will be simulated with the 2D models XBeach and Delft3D, at high spatial resolution (2-15 m). ShorelineS simulates ocean shoreline changes, including barrier beaches, islands, lagoons, bays, as a series of evolving segments, under the effects of longshore sediment transport due to the wave climate combined with SLR (Hurst et al., 2015). While USGS uses a similar model including additionally cross-shore transport (Vitousek et al., 2017), this process can be neglected for assessing long term shoreline changes, as evidenced by case studies (Quetzalcóatl et al., 2019; Roelvink et al., 2020). XBeach has been successful in simulating beach-dune erosion/accretion, overwash, and barrier breaching during extreme storms, in comparison to field data, at many North Atlantic US East Coast sites, including the NITR site (Schambach et al., 2018; de Vet et al., 2015). XBeach can been combined with Delft3D to accurately model the storm-induced changes in the lagoon and back-barrier/bay (van Ormondt et al., 2020). Delft3D is typically run in 2D to simulate the depth-integrated circulation and sediment processes (Eulie et al., 2017; Liu et al., 2018).

Vulnerability Assessment -- To quantify storm/SLR impacts (A. Grilli). We will assess vulnerability to storm/SLR scenarios, at CACO and NITR (Tier 1 sites), which feature beach-barriers, as defined by the USACE (Bridges et al., 2015): “Vulnerability is the degree to which a system’s attributes of concern are susceptible to, and unable to cope with, the adverse effects of hazards over a period of time or temporal reference”. We will include the three components of vulnerability as defined by Ramieri et al., (2011): 1) exposure (magnitude of the hazard); 2) sensitivity (potential for the system functions to be affected by the hazard); and 3) adaptive capacity (the system’s ability to evolve, naturally or through engineered activities, to preserve or enhance its functions). We will use standard metrics to quantify the vulnerability for each scenario, primarily in terms of the “coastal storm damage reduction” functions provided by the barrier-beach systems, e.g., water level, runup, wave characteristics, storm duration (exposure); dune elevation, dune volume, berm width, vegetation type (sensitivity); long-term shoreline change, dune volume, longshore transport processes (adaptive capacity). Additional functions identified by stakeholders will be included (e.g., piping plover habitat, or aquaculture with specific metrics). The modeling of multiple storms will provide a range for these metrics, providing robust new indicators. The modeling of different SLR scenarios occurring over a period of time will show the potential for the system to naturally adapt with time. The simulation of a range of mitigation scenarios (natural, nature-based, or traditional structures/infrastructures - with the choices driven by stakeholders) will assess and quantify the adaptive capacity of the system and inform management decisions.

Geomorphic, geologic and ecosystem-change investigations (J.P. Walsh). Critical to understanding coastal hazards, and ultimately to modeling and communicating their ramifications, is the measurement of important characteristics and processes to identify temporal and spatial relationships (e.g., topographic variability, vegetation, sediments and sedimentary processes). Know-ledge of how the coast, habitats and ecosystem services have changed over the past half century, and will evolve from SLR, subsequent storms, and over seasons, is key to informed management in the next century (Donnelly and Bertness, 2001; Kirwan et al., 2010; Watson et al., 2017). Updating of data layers is needed to conduct realistic modeling, especially where erosion, deposition and human activities are altering the coast (e.g., Bertness et al., 2002; Grilli et al., 2017). Focused analyses and assessments of the system are required to identify potentially effective mitigation measures. The investigations planned for this study will be designed to complement and directly contribute to the geomorphic modeling research being performed in the CACO and NITR study sites. Co-PI Walsh, in partnership with other team members, a student, managers, community officials, and federal and university researchers will conduct targeted investigations in two topical areas: 1) estuarine shorezone change (subaerial or subaqueous) related to human and environmental processes, and 2) ocean barrier dynamics with potential estuarine impacts, e.g., dune loss causing overwash/breaching. Both of these require knowledge of environmental- and human-processes that vary spatially/temporally and affect storm surge (Chaumillon et al., 2017).

In the MA Shoreline Change Project of the Coastal Erosion Commission (MA-CEC, 2015), the CACO towns of Eastham, Provincetown, Truro and Wellfleet are identified as having ocean and bay erosion among the highest for the State. As shown in Fig. 1, this area has ocean and bay shoreline information but most change mapping does not extend into embayments with marshes. The USGS and other entities continue to add important new information. Research by NPS has shown, marshes have complex shifting zonation patterns, are low in the tidal frame, and at risk to sea-level rise (Smith, 2015a,b; 2017). For example, in Nauset Bay low marsh loss (13%) was attributed to overwash and inlet-related impacts. Marsh modeling by Morris and Renken (2019) suggests only under extreme SLR lead to substantial loss in CACO by 2074. Lateral erosion, excluded from this model, will be an emphasis of the proposed study. Many concerns exist about how fundamental coastal changes, including dune and marsh loss, may lead to broader ecological and societal effects. From the 2015 MA-CEC report, two relevant findings include: 1-A: Increase observational capabilities for waves, water levels, and coastal response, and 1-B: Advance sediment transport mapping and modeling to develop regional sediment budgets. This project will help with these and other priorities. The four towns noted above have formed an Intermunicipal Shoreline Management Framework and are working to address concerns on Cape Cod Bay in partnership with the MA Coastal Zone Management and the Center for Coastal Studies. This study will further inform this work, including attention on Nauset Bay, located on the east side of Eastham (Fig. 1).

Similarly, in RI, data is available on ocean shoreline changes along with fundamental information on coastal processes, and much of this work is reviewed and available as a result of the NOAA funded Beach SAMP (2018) and associated tools (Spaulding et al., 2017a,b, 2020a,b,c). The PIs and colleagues were involved in this and other related coastal research at URI and have worked closely with the RI Coastal Resources Management Council and other RI entities on the analyses, tools, and governing policy. In RI, there is a long history of oceanfront beach profiling and shoreline analysis (Boothroyd et al., 2016), as well as some recent geomorphic modeling efforts (Schambach et al., 2018). As noted above, marsh evolution modeling has been completed for NITR using SLAMM model, results indicate extensive back-barrier marshes losses with only three feet of rise (RI CRMC, 2015). This significant body of work along with modeling (described above) have identified many vulnerable areas and provided initial insights for communities in Washington County and elsewhere in RI. But, to aid local decision making and modeling, detailed mapping and analyses of estuarine shoreline and habitat changes will be needed, especially as these areas are anticipated to transform as a result of SLR and storms.

Collection, analysis, and distribution of geospatial data. As RI's center of technical expertise in GIS and host for the statewide geospatial data and image repository, the URI Environmental Data Center (EDC; R. Duhaime, C. Damon) will leverage its experience in ecological mapping and data integration for environmental applications. While EDC efforts will be integrated throughout all aspects of the project, three broad areas of focus will be: 1) data development and manipulation; 2) data translation; and 3) interactive visualizations and data distribution. Being able to accurately model geomorphological change requires that current conditions and historical trends of coastal changes are incorporated into the process. Co-PI Walsh will guide this process for the study sites, building on available work by NPS, USGS and others. Data development and manipulation activities will concentrate on providing the modeling team with "best available" environmental and physical data for input to the analyses (e.g., from USGS, NPS, NOAA, OCM), such as combined topographic/bathymetric surfaces, with built-up infrastructure, land cover, wetlands, seagrass beds, and historic shoreline positions. Shorelines, topography and sediments will be mapped where needed, and change rates and model parameters quantified. Model results for storm/SLR scenarios will populate GIS layers, accessible by stakeholders via an online portal, integrated with management and planning activities, that will: 1) visualize model outputs, 2) quantify differences between mitigation strategies, and 3) synthesize project deliverables. EDC will perform the data-model results/GIS layer translation work and support additional related overlay analyses, visualization, and community outreach activities. Refer to the Data Management Plan section for detail on data, storage platforms, formats, and documentation.

Allowing full transparency to stakeholders and the interested public, early posted information will include project goals, relevant research, activity timeline, and sections tailored specifically to management concerns and challenges for each site. As work continues the portal will grow, based on stakeholder needs, to include: interactive maps for visualizing model output; operational dashboards to quantify impacts of mitigation strategies and evaluate the effectiveness of management decisions; the ability to download derived datasets; and tools or training materials developed as part of the stakeholder engagement process.

<u>3D visualization framework (P. Stempel)</u>. The 3D Visualization framework creates a numeric coupling between model outputs and visualization applications. Libraries of 3D proxy objects representing vegetation and structures are indexed to, and controlled by model outputs, including assessment of consequences qualitatively derived from stakeholder input (Stempel et al. 2018). Once developed for a site this infrastructure supports dynamically updatable visualizations that reflect changing model outputs and stakeholder input. The current version of this software is being operationalized and integrated with the ADCIRC Prediction System in a pilot project as part of ongoing work for DHS led by PI Ginis (Becker et. al., 2020). Proxy object libraries have been recently expanded, under NPS funding, and utilized to represent changes to natural features such as vegetation and coastlines (Fig. 3). Versions of these tools have been previously employed in work for FEMA (w/Co-PIs Ginis and Rubinoff) (Stempel et. al. 2018). Changing shoreline morphology will be represented using updated versions of algorithms to represent beach recession in Charlestown (NITR) as part of CERI. These algorithms create visually credible representations of shoreline change by transforming LiDAR derived point clouds based on projected shoreline position. These methods have been developed and employed in the currently funded DHS and NPS projects.

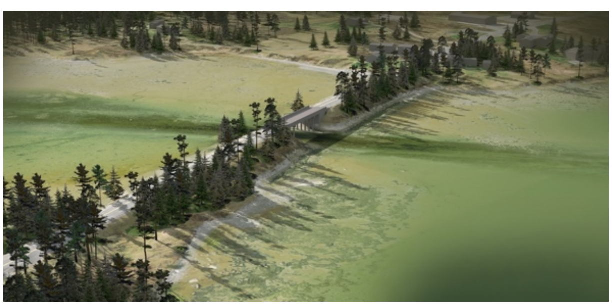

Fig. 3: 3D visualization of Trenton Bridge, ACAD. Proxy tree objects refined to be more representative

b. Application to Management

i) *Coordination and end-users* Extension and outreach will be led by the URI Coastal Resources Center (CRC)/RI Sea Grant (P. Rubinoff), recognized for its neutral facilitation and expertise in translating science to a broad range of stakeholders (government, non-government, tribal nations, industry, public). URI, with the assistance of NPS national-level staff (A. Babson and M. LaFrance Bartley) will partner with the parks and refuges to engage key local community stakeholders to ensure the science outcomes are directly relevant to end-user needs. Commitments are in place to leverage the established relationships each park or refuge has with local partners. We received Letters of Commitment and agreements to be MTAG members from each park and refuge, as well as the following local partners: Friends of Acadia, ME; the Town of Eastham representing an inter-municipal shoreline management partnership of the Towns of Eastham, Wellfleet, Truro, and Provincetown in Cape Cod, MA; Buzzards Bay Coalition, MA; Narragansett Bay Estuary Program, RI; the Town of Charlestown, RI. Additionally, the team will leverage NOAA Sea Grant resources and/or ongoing local activities as appropriate to advance community resilience and invite staff to participate as appropriate.

ii) *Significance to management priorities* The project will follow a robust interdisciplinary outre-ach and communication strategy using techniques proven effective for engaging stakeholders with a range of interests in projects where applied research is linked directly to management applica-tions such as: interviews, scoping sessions, and site visits; facilitating interactive discussions, meetings and workshops; developing a dashboard, web content, and written materials; and sharing project information, visualizations, and other products in a way that can be easily interpreted and utilized by end-users during the project and for transition to continued use after project completion. The intent is to bring the best science and provide stakeholders with the information needed to become active and engaged participants in the problem-solving process, on issues related to storm and SLR impacts. Decision makers clearly need to participate in this process, but community members and other end-users are also critical to enhance buy-in and opportunities to work together.

The process will inform planning efforts on adaptation over a range of management needs and concerns (societal to environmental) that require critical decisions to be made (e.g., resource protection, restoration, mitigation, relocation, retreat). Societally, key management topics include emergency preparedness; infrastructure and facilities planning, including historic structures and local airports; and maintaining safe public access routes and sites. Environmentally, key management topics focus on shoreline erosion, dune changes, and salt marsh impacts and associated restoration efforts, in the context of NNBF mitigation measures. More broadly, this project will help end-users better understand combined storm/SLR impacts, and provide new and complementary information to guide coastal adaptation efforts. Acknowledging that the parks, refuges, and adjacent communities are in varying stages of vulnerability assessment and adaptation, the team will tailor the extension and outreach of this project's enhanced modeling and visualization tools to most effectively complement and build upon ongoing efforts.

The Project Team will engage with NPS and NWR staff and community partners from each study site focused on obtaining input for the project (e.g. specific management needs, how needs can be supported by project, mitigation measures to be simulated, target locations for modeling and visualizations); reviewing modeling, geospatial datasets, visual interpretive products, and dashboard to guide revisions; and building end-user capacity for utilizing the results and products effectively in decision making and management applications. In recognition of the varied needs across parks, refuges and communities, this project will implement the three-tiered approach to out-reach, engagement and research detailed in section ii.3 and summarized in Table 1. Engagement will be staggered and start sooner in sites where there are modeling results from

ACTIVITIES	Sites/ Tiers for Engagement & Research					
	CACO Tier 1	NITR Tier 1	ACAD Tier 2	BOHA Tier 3	ROWI Tier 3	NEBE Tier 3
Outreach & Engagement						
- MTAG Regional Meetings	Y1 - Y4					
- Kickoff workshops; site visit/scoping	Y1	Y1	Y1	Y2	Y2	Y2
- Validate models; review mgmt application	Y1-Y3	Y1-Y3	Y1-Y3	Y2-Y4	Y2-Y4	Y2-Y4
- Transition to end-users	Y4					
Hydrodynamic Modeling						
- Storm surge and waves /SLR scenarios	E, Y1, Y2	E, Y1, Y2	E, Y1, Y2	E, Y1, Y2	Y1, Y2	Y1, Y2
- Mitigation scenario modeling	Y3, Y4	Y3, Y4				
Geomorphic Dynamic Modeling/Analysis						
- Long-term & event-based modeling	Y1-Y4	E, Y1-Y4				
- Mitigation scenario modeling	Y3, Y4	E, Y3-Y4				
- Geodata analysis barrier & estuarine	E, Y1-Y4	E, Y1-Y4				
- Focused field study barrier & estuarine	E, Y1-Y4	E, Y1-Y4				
Vulnerability Assessment						
- Exposure	E,Y1-Y4	E, Y1-Y4	E, Y1, Y2	E, Y1, Y2	Y1, Y2	Y1, Y2
- Sensitivity	Y2, Y4	E, Y2-Y4				
- Adaptive Capacity	Y3-Y4	E, Y3-Y4				
Visualizations						
- Assets and inundation	E, Y1-Y4	E, Y1-Y4	E, Y1-Y4	E, Y1-Y4	E, Y1-Y4	Y2-Y4
- Landform change	Y2-Y4	Y2-Y4				
- Waves impact	Y2-Y4	Y2-Y4				
User Interface						
- Data/map portal WWW	Y1 - Y4					

Table 1: List and timeline of activities. E: expand on existing.

earlier work (CACO, NITR, ACAD, BOHA). Engagement timing and approaches will mirror the research effort. This staggered three-tiered approach will also demonstrate how a range of approaches can be effective for engaging end-users at varied stages of adaptation planning for future expansion of this project to other sites within New England and other regions. Schoodic Institute will lead the science communication component for all locations, incorporating lessons learned into a Coastal Climate Change Communication guidance document currently in development.

The MTAG will provide synergistic opportunities for the Project Team and local partners across New England to: 1) engage in discussion about resour-ce management needs and concerns; 2) better understand storm and SLR impacts across sites characterized by various geomorphic settings, ecological systems, and levels of human interaction and development; 3) share ideas for incorporating project results into decision making processes; 4) provide input and feedback on key project elements such as selecting modeling scenarios, utility of different visualizations, and design of the data dashboard; and 5) share lessons learned among sites. Moreover, the MTAG will foster relationships among members that facilitate communication and knowledge sharing beyond the project period. For example, NPS park units within the northeast region currently do not have a well-defined mechanism to learn from and exchange ideas with one another; this MTAG could evolve into such a mechanism and be expanded to include other parks in the region.

iii) *Activities -- Transitioning results to management applications*

iii.1) *Park, Refuge and Community Engagement Actions* [Communication will enable constant collaboration between our team and local partners and ensure the science fulfills end-user needs]:

● <u>*Project Launch (virtual meetings):*</u> Separate meeting for Tier 1 sites (CACO, NITR) and Tier 2 and 3 sites (ACAD, BOHA, NEBE, ROWI). Objectives: 1) Introduce Project Team and local partners; 2) Provide overview of project goals, activities, expectations for engagement, and timeline; 3) Receive input from local partners on priority needs and issues on resource management; 4) Introduce modeling results and visualizations from currently funded NPS project as examples, and dashboard prototype; and 5) Confirm target sites for producing visualizations and modeling potential mitigation actions. Outcomes: 1) better understanding sites, management issues, and effective ways to refine and direct the project to suit end-user needs; and 2) Local partners understand the project and have the opportunity to share concerns and ideas.

- *Site Visit and Scoping Sessions (in-person workshops):* 1-2 days at each site. Involves a meeting to engage with a broad range of local partners, and smaller more focused conversations. Objectives: 1) Project Team gains experience and captures local knowledge to better understand systems and associated influential processes; 2) Participants enhance collaboration by interacting and discussing common concerns, issues, and ideas. Outcomes: 1) Increased understanding and foundation of knowledge; 2) Project Team and local partners have common knowledge and ideas to shape the research process and ensure meaningful end-user results; and 3) Scenarios and locations defined/confirmed/prioritized for erosion modeling (Tier 1) and visualizations (all sites).
- *Review of Preliminary Modeling and Initial Visualizations (virtual meetings):* Separate meetings for each site. Objectives: 1) Presenting preliminary model information and initial visualizations; 2) Review and feedback by local partners; and 3) Continue to discuss management needs and adapt modeling to support those. Outcomes: 1) Local partners become familiar with modeling results for storm/SLR impacts; 2) Feedback received will help adapt/refine modeling to ensure results accurately reflect current site conditions and can be used to plan for future conditions; and 3) Participants confirm model applicability in supporting their management needs.
- *Validate modeling and Define Options for Management Application (in-person and/or virtual workshops):* Separate workshops for each Tier 1, 2 sites. Objectives: 1) Local partners validate revised modeling results; 2) Review findings on geomorphic research, data gaps, and relevance to management needs (Tier 1 sites); 3) Confirm and prioritize (if needed) modeling/ visualizations needed to support management options; and 4) Participants review how the modeling information can be considered in management decisions. Outcomes: 1) Confirm modeling is accurate and appropriate for end-user needs, or make further revisions; 2) Provide input on details (e.g. features and views of interest) for visualizations; and 3) Local partners continue to collaborate with Project Team to shape project and understand results and applications for management. At Tier 3 sites, this process will be led by the parks, with the Project Team available to answer questions.
- *Management of Resources (in-person workshop):* Separate workshops for each Tier 1, 2 site. Objectives are the Project Team and local partners review: 1) The resulting model and visualization products; 2) Management applications, including those that have been modeled; and 3) Potential management actions to consider based on projected future scenarios. Outcomes: 1) Modeling and visualization products shared with local partners; 2) Local partners gain experience using and linking products to management needs; 3) Local partners actively discuss and consider specific management actions to potentially implement as a result of the knowledge gained from the project.
- *Transition to End Users (virtual meetings):* Separate meetings for each site. Objectives: 1) Project Team follows up on the previous workshop to confirm modeling and visualizations can support local partner needs; and 2) Local partners practice using the dashboard and linking project products to management needs. Outcomes: 1) Local partners are confident in their understanding of project results and in utilizing products (e.g., visualizations, dashboard) to support decisions.
- *Follow-up (virtual meetings):* Separate meetings for each site. Project Team meets with local partners as needed to support their use of the modeling products and dashboard tools.

iii.2) *MTAG Engagement Actions* The MTAG convenes once/twice per year during project. Meeting timing coincides with key input/feedback needed for overarching elements. Key engagement actions described above will also take place for the MTAG, having similar objectives and anticipated outcomes, but with a regional exchange/learning focus. Interim communication also occurs as needed as project progresses (unevenly) following the three-tier approach.

c. Data management plan

The collaborative team's data management plan complies with NOAA proposal guidance. It leverages existing federal and regional non-federal data assembly and archive centers infrastructure in order to access and archive data and information products that will be generated by this study.

Types of Data: The project will incorporate new data through scientific modeling and stakeholder engagement, as well as existing environmental, social, economic, and ecological data that describe the characteristics for each study area. Examples include land use/cover, salt marsh migration, historic shoreline positions, LiDAR-derived topographic/bathymetric data, hydrographic surveys, water level, meteorological datasets, and all model results generated in the project (raw/processed).

The investigators interact routinely with the existing federal data assembly centers (DACs) including the National Data Buoy Center (NDBC), Office for Coastal Management (OCM), National Ocean Service (NOS), Center for Operational Ocean Products and Services (CO-OPS), National Geophysical Data Center (NGDC), and National Climate Data Center (NCDC) that provide access to data necessary for the project and National Oceanographic Data Center for archival of project data. They also routinely interact with the Rhode Island Geographic Information System (RIGIS), and other State GIS agencies in the northeast, that provide access to ample full coverage location-based data.

Rather than expending resources on applications requiring custom programming and ongoing maintenance, commercial off-the-shelf (COTS) applications and Geographic Information Systems (GIS) software developed by Esri® (Redlands, CA) will form the framework for the projects information and outreach portal hosted on existing URI IT infrastructure that is both secure and redundant. Designed specifically for community/stakeholder engagement and quantitative assessment, ArcGIS Hub and ArcGIS Dashboards will form the core of the project's online information gateway. The communication Hub will reside on URI IT infrastructure, will be operational within weeks of the project's start and will actively evolve as work progresses.

More specifically, regarding topobathy of great use in this project, existing resources within the USGS Coastal National Elevation Database (https://www.usgs.gov/core-science-systems/eros/coned) and NPS geospatial archives will be used when available, and if needed, supplemented with updated terrestrial and bathymetric LiDAR points distributed through online portals such as the Digital Coast (NOAA, OCM) (https://coast.noaa.gov/digitalcoast/). Geospatial data will be stored in a common coordinate system and will be documented according to Federal Geographic Data Committee (FGDC) standards (https://www.fgdc.gov/metadata/geospatial-metadata-standards). All maps and final data products will be freely downloadable through the project's online communication hub and will use standard geospatial data formats that can be read and exported using Esri® software.

Data technologies: Novel data for this project will be generated by several means including computer simulations, direct field collection, quantitative overlay analyses and hands-on workshops with community planners and advocates. Postprocessing of computer simulation results will rely on standard packages such as MATLAB® (MathWorks, Natic, MA), while geospatial data will be managed using the suite of ArcGIS® (Esri, Redlands, CA) Desktop/Pro and Enterprise Server technologies. As described in the "Data storage" section, project data will be systematically archived and retained beyond the life of the project.

Data storage: The URI EDC will manage the data archival system for the project and will work directly with PIs to consolidate raw and processed model outputs into a single location. The EDC utilizes distributed technology to ensure backups of project files are efficient and secure. Project records (reports, spreadsheets, etc.) are captured using Backup Exec v20. Full backups of project documents are performed weekly, with differential backups occurring nightly. Geospatial source data, intermediate, and final project data are stored locally on workstation SSD drives and archived on both removable mechanical SATA hard drives and 2, 4 terabyte RAID 5 network attached storage units. Long-term archiving will utilize the URI Information Technology (IT) storage area networks and Google Drive Cloud shares. All data will be retained throughout the course of the project and for many years following it, until all results are properly published and disseminated.

Metadata: GIS data developed through this work will adhere to the geospatial metadata standards described by the Federal Geographic Data Committee (FGDC) (https://www.fgdc.gov/standards). Documentation will be provided for all produced data, including source information for each digital layer (i.e., scale and accuracy, map projection, coordinate system, etc.) and a description of the processing methods, data limitations, geographic extent, file format, date of creation, staff contact, and a description and definition of data fields and their contents. Easily readable metadata will be provided with the data and will also be exported to ISO formatted XML files.

Data sharing: All derived data and map products will be freely shared with stakeholders and the public and accessible through a web-based interface. Shared data will meet NOAA's Information Quality Act standards. by being approved for dissemination to the public, or providing an appropriate disclaimer. Expected repositories for these data include the project's online information portal, NPS data centers (individual park and/or national archive), and individual internal data systems for stakeholder communities. As is common with the transfer of geospatial data, metadata is an integral part of the data file and will be included with each download.

Final products/Portal: An information portal residing on existing URI IT infrastructure will be developed using the ArcGIS Hub application to serve as a single point of entry to all of the projects activities and deliverables, and for users to discover information and analyses of relevance to their respective needs. ArcGIS Hub is designed specifically as a transparent community engagement platform that organizes people, data, and tools through information-driven initiatives. The portal dashboards will be used to visualize and communicate model results. ArcGIS Dashboards are highly flexible and customizable interactive tools that allow comprehensive visualizations of both geospatial and tabular data in an intuitive interface (e.g., Fig. 3). These focused applications will provide a means of presenting model results and quantitatively comparing the range of mitigation options modeled for an area. All internet distributed products will continue to be supported beyond the life of the project and will meet 508 accessibility requirements.

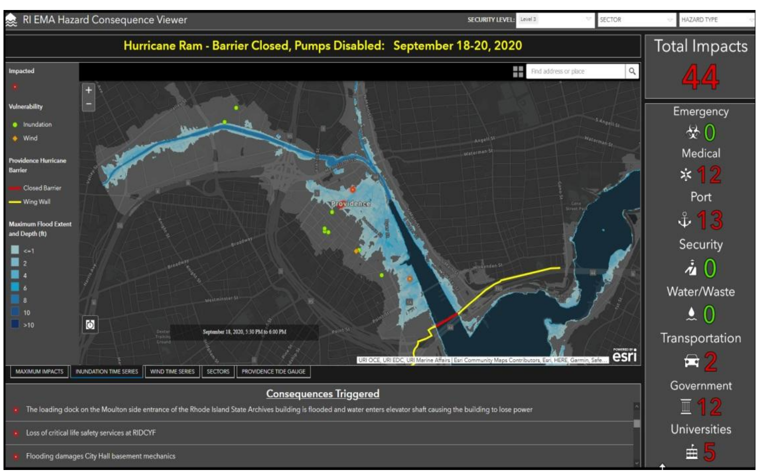

Fig. 4: Dashboard for the URI DHS Consequence Threshold project, coupling projected inundation with the number of assets impacted and specific consequences at each location.

References Cited

1. Adger, W. N., Barnett, J., Brown, K., Marshall, N. and O'Brien, K. 2013. Cultural dimensions of climate change impacts and adaptation. Nature Climate Change, 3(2), 112-117. doi:10.1038/nclimate1666
2. Al Naser N., Grilli A.R., Grilli S.T., Baxter C., Bradshaw A. and B. Maggi 2018. Land use and mitigation effects on barrier beach erosion in storms case study in RI. In Proc. 36th Intl. Conf. on Coastal Engng. (ICCE18; Baltimore, Jul 30 - Aug 3), ASCE, 1(36), 40, doi.org/10.9753/icce.v36.papers.108.
3. Becker, A., Rubinoff, P., Stempel, P., Ginis, I., Adams, S., Hallisey, N., and E. Kalaidjian, E., 2020. Hazard Consequence Threshold Models for Emergency Management and Response Decision Making, in Natural Hazards Center Researchers Meeting., Natural Hazards Center: Boulder, CO. July 15-16.
4. Bertness, M.D., P. Ewanchuk, and B.R. Silliman. 2002. Anthropogenic modification of New England salt marsh landscapes. Proceedings of the National Academy of Science 99 (3): 1395-1398.
5. Booij, N.R., Ris, R.C. and Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions: 1. Model description and validation. Journal of geophysical research: Oceans, 104(C4), 7649-7666.
6. Boothroyd, J.C., Hollis, R.J., Oakley, B.A., and Henderson, R.E. 2016. Shoreline change maps of the Rhode Island south shore, scale 1:2,000.
7. Bridges, T.S., Burks-Copes, K.A., Bates, M.E., Collier, Z.A., Fischenich, J.C., Piercy, C.D., Russo, E.J., Shafer, D.J., Suedel, B.C., Gailani, J.Z. and Rosati, J.D., 2015. Use of natural and nature-based features (NNBF) for coastal resilience. US Army Engineer Research and Development Center, Environmental Laboratory, Coastal and Hydraulics Laboratory.
8. Brodie, K., Conery, I., Cohn, N., Spore, N. and Palmsten, M., 2019. Spatial variability of coastal foredune evolution, part a: Timescales of months to years. Journal of Marine Science and Engineering, 7(5), 124.
9. Chaumillon, E., Bertin, X., Fortunato, A., Bajo, M., Schneider, J.-L., Dezileau, L., Michelot, A., Chauveau, E., Créach, A., Hénaff, A., Walsh, J.P., Sauzeau, T., Waeles, B., Gervais, B., Jan, G., Baumann, J., Breil, J.-F., and Pedreros, R., 2017. Storm-induced marine flooding: lessons from a multidisciplinary approach. Earth-Science Reviews, 165, 151-184.
10. Chen, X., Hara, T. and Ginis, I., 2020. Impact of Shoaling Ocean Surface Waves on Wind Stress and Drag Coefficient in Coastal Waters: 1. Uniform Wind. Journal of Geophysical Research: Oceans, 125(7), p.e2020JC016222.
11. Conery, I., Walsh, J.P. and Corbett, D.R., 2018. Hurricane overwash and decadal-scale evolution of a narrowing barrier island, Ocracoke Island, NC. Estuaries and coasts, 41(6), 1626-1642.
12. Conery, I., Walsh, J.P., Mallinson, D., and D.R. Corbett, submitted. Marine geology and sand resources of the southern North Carolina inner shelf: insights from a sediment-starved continental margin. Marine Georesources.
13. Corbett, D.R. and J.P. Walsh. 2015. ^{210}Lead and ^{137}Cesium – Establishing a Chronology for the Last Century. In: Handbook of Sea-Level Research, eds. Editors: I. Shennan, A. Long and B. Horton. John Wiley & Sons. West Sussex, UK. pgs. 361-372.
14. Cowart, L., J.P. Walsh, and D.R. Corbett. 2010. Analyzing estuarine shoreline change: a case study of Cedar Island, North Carolina. Journal of Coastal Research, 26, 817–830.

15. Cowart, L., D.R. Corbett, and J.P. Walsh. 2011. Shoreline change along sheltered coastlines: insights from the Neuse River estuary, NC, USA. Journal of Remote Sensing, 3, 1516–1534.
16. de Vet, P.L.M., 2014. Modelling Sediment Transport and Morphology during Overwash and Breaching Events. MSc thesis. Delft University of Technology, Delft.
17. de Vet, P. and M. Lodewij 2015. Modelling dune erosion, overwash and breaching at Fire island (NY) during hurricane sandy. In: Proc. Coast. Sediment Conf. (San Diego, CA).
18. Dietrich, J.C., Tanaka, S., Westerink, J.J., Dawson, C.N., Luettich, R.A., Zijlema, M., Holthuijsen, L.H., Smith, J.M., Westerink, L.G. and Westerink, H.J., 2012. Performance of the unstructured-mesh, SWAN+ ADCIRC model in computing hurricane waves and surge. Journal of Scientific Computing, 52(2), 468-497.
19. Dubosq, N., Schmidt, S., Walsh, J.P., Grémarea, A., Gilleta, H., Lebleua, P., Poiriera, D., Perelloa, M.-C., and Deflandrea, B., Submitted. A first assessment of organic carbon burial in the West Gironde Mud Patch (Bay of Biscay).
20. Eastham, 2020, Hazard Mitigation Plan: https://www.eastham-ma.gov/sites/g/files/vyhlif4371/f/uploads/eastham_hazard_mitigation_plan_2020_fema_approved.pdf
21. Eulie, D., Walsh, J.P. and D.R. Corbett. 2013. High-Resolution Measurements of Shoreline Change and Application of Balloon-Aerial Photography, Albemarle-Pamlico Estuarine System, North Carolina, USA. Limnology and Oceanography: Methods, 11, 151-160.
22. Eulie, D., Walsh, J.P., Corbett, D.R. and R. Mulligan. 2017. Temporal and spatial dynamics of estuarine shoreline change in the Albemarle-Pamlico estuarine system, North Carolina, USA. Estuaries and Coasts, 40(3), 741–757.
23. Eulie, D., Corbett, D. R., and J.P. Walsh. 2018. Shoreline erosion and decadal sediment accumulation in the Tar-Pamlico Estuary, North Carolina, USA: A source-to-sink analysis. Estuarine, Coastal and Shelf Science, 202, 246-258.
24. ESTOFS 2021. ocean.weather.gov/estofs/estofs_surge_twlev.php, accessed 01/02/21.
25. Fan, Y., Ginis, I. and Hara, T., 2010. Momentum flux budget across the air–sea interface under uniform and tropical cyclone winds. Journal of physical oceanography, 40(10), 2221-2242.
26. Gao, K. and I. Ginis 2016: On the Equilibrium-State Roll Vortices and Their Effects in the Hurricane Boundary Layer. J. Atmos. Sci., 73, 1205-1221.
27. Giese, G.S., Williams, S.J., and Adams, Mark, 2015, Coastal landforms and processes at the Cape Cod National Seashore, Massachusetts—A primer: U.S. Geological Survey Circular 1417, 86 p., http://dx.doi.org/10.3133/cir1417.
28. Grilli A.R, Spaulding, M.L., Oakley, B.A. and C. Damon 2017. Mapping the coastal risk for the next century, including sea level rise and changes in the coastline. Nat. Hazards, 88, 389-414.
29. Grilli A.R., Westcott G., Grilli S., Spaulding M.L., Shi F. and J.T. Kirby 2020. Assessing coastal risk from extreme storms with a phase resolving wave model: Case Study of Narragansett, RI, USA. Coastal Engineering, 160, 103735.
30. Hammar-Klose E.S., Pendleton, E.A., Thieler, E.R, Williams, SJ., 2003. Coastal Vulnerability Assessment of Cape Cod National Seashore (CACO) to Sea-Level Rise. U.S. Geological Survey, Open file Report 02-233 http://pubs.usgs.gov/of/2002/of02-233/.
31. Hurst, M.D., Barkwith, A., Ellis, M.A., Thomas, C.W. and A.B., Murray 2015. Exploring the sensitivities of crenulate bay shorelines to wave climates using a new vector-based one-line model. Journal of Geophysical Research: Earth Surface, 120(12), 2586-2608.

32. Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophysical Research Letters, 37, L23401.
33. Lagomasino, D., D.R. Corbett, J.P. Walsh. 2013. Influence of Wind-Driven Inundation and Coastal Geomorphology on Sedimentation in Two Microtidal Marshes, Pamlico River Estuary, NC. Estuarine, Coastal, Shelf Science, 36(6), 1165-1180, doi:10.1007/s12237-013-9625-0.
34. Lesser, G., Roelvink, J.A., van Kester, J.A.T.M. and G.S. Stelling 2004. Development and validation of a three-dimensional morphological model. Coastal Eng., 51, 883–915.
35. Liu, K., Chen, Q., Hu, K., Xu, K. and R.R., Twilley 2018. Modeling hurricane-induced wetland-bay and bay-shelf sediment fluxes. Coastal Eng., 135, 77-90.
36. Luettich, R. A., and J. J. Westerink 2004. Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44.XX. http://adcirc.org/
37. MA-CEC (Coastal Erosion Commission) 2015. Report of the Massachusetts Coastal Erosion Commission Volume 1: Findings and Recommendations. https://www.eastham-ma.gov/sites/g/files/vyhlif4371/f/uploads/eastham_hazard_mitigation_plan_2020_fema_approved.pdf
38. MA OCZM (Office of Coastal Zone Management), 2016. Modeling the Effects of Sea Lever Rise on Coastal Wetlands. https://www.mass.gov/files/documents/2018/12/07/czm-slamm-report-nov2016.pdf
39. Moghimi et al. 2020. Development of an ESMF Based Flexible Coupling Application of ADCIRC and WAVEWATCH III for High Fidelity Coastal Inundation Studies. J. Mar. Sci. Eng., 8(5), 308; https://doi.org/10.3390/jmse8050308.
40. Morris, J. T., and K. A. Renken. 2019. The impact of sea-level rise on saltmarsh condition and resiliency: Assateague Island National Seashore, Cape Cod National Seashore, Fire Island National Seashore, and Gateway National Recreation Area. Natural Resource Report NPS/NCBN/NRR— 2019/1974. National Park Service, Fort Collins, Colorado.
41. NC Division of Coastal Management. 2012. North Carolina Estuarine Shoreline Mapping Project. https://deq.nc.gov/about/divisions/coastal-management/.
42. O'Neill, S. J. and Graham, S. 2016. Envisioning place-based adaptation to sea-level rise. Geo: Geography and Environment, 3(2), e00028, doi:10.1002/geo2.28.
43. Paris, P., Corbett, D.R., Walsh, J.P., Leach, A., and Wilkinson, J.S., Submitted. Beach nourishment and the ecosystem response. Shore & Beach.
44. Quetzalcóatl, O., González, M., Cánovas, V., Medina, R., Espejo, A., Klein, A., Tessler, M.G., Almeida, L.R., Jaramillo, C., Garnier, R. and N., Kakeh 2019. SMCε, a coastal modeling system for assessing beach processes and coastal interventions: Application to the Brazilian coast. Environmental Modelling and Software, 116, 131-152.
45. Rabe, T.J., Kukulka, T., Ginis, I., Hara, T., Reichl, B.G., D'Asaro, E.A., Harcourt, R.R. and Sullivan, P.P., 2015. Langmuir turbulence under hurricane Gustav (2008). Journal of Physical Oceanography, 45(3), 657-677.
46. Ramieri, E., Hartley, A., Barbanti, A., Santos, F.D., Gomes, A., Hilden, M., Laihonen, P., Marinova, N. and Santini, M., 2011. Methods for assessing coastal vulnerability to climate change. ETC CCA Technical Paper, 1, pp.1-93.
47. Raposa, K. B., Wasson, K., Smith, E., Crooks, J. A., Delgado, P., Fernald, S. H., et al. (2016). Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. Biol. Conserv., 204, 263–275, doi: 10.1016/j. biocon.2016.10.015.

48. Reichl, B.G., Hara, T. and Ginis, I., 2014. Sea state dependence of the wind stress over the ocean under hurricane winds. Journal of Geophysical Research: Oceans, 119(1), 30-51.
49. Reichl, B.G., Wang, D., Hara, T., Ginis, I. and Kukulka, T., 2016. Langmuir turbulence parameterization in tropical cyclone conditions. J. Physical Oceanography, 46(3), 863-886.
50. RI CRMC (Coastal Resources Management Council), 2015. The Rhode Island Sea Level Affecting Marshes Model (SLAMM) project: Summary report. p 25
51. RI CRMC (Coastal Resources Management Council), 2018. The Shoreline Change (Beach) Special Area Management Plan (SAMP), http://www.crmc.ri.gov/samp_beach.html
52. Riou, B., Chaumillon, E., Chagué, C., Sabatier, P., Schneider, J.-L., Walsh, J.-P., Zawadzki, A., and Fierro, D., 2020. Backwash sediment record of the 2009 South Pacific Tsunami and 1960 Great Chilean Earthquake Tsunami. Scientific Reports, 10, 1–13, Doi:10.1038/s41598-020-60746-4.
53. Roelvink, J.A., Reniers, A.J.H.M., van Dongeren, A.R., van Thiel de Vries, J.S.M., McCall, R.T.and , J., Lescinski 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coastal Eng., 56(11–12), 1133–1152.
54. Roelvink, D., Huisman, B., Elghandour, A., Ghonim, M. and J., Reyns 2020. Efficient modeling of complex sandy coastal evolution at monthly to century time scales. Frontiers in Marine Science, 7, 535.
55. Schambach, L., Grilli, A.R., Grilli, S.T., Hashemi, M.R., and J. King 2018. Assessing the impact of extreme storms on barrier beaches along the Atlantic coastline : Application to the southern Rhode Island coast. Coastal Eng., 133, 26-42.
56. Sheppard, S.R., Shaw, A., Flanders, D., Burch, S., Wiek, A., Carmichael, J., Robinson, J. and Cohen, S. 2011. Future visioning of local climate change: a framework for community engagement and planning with scenarios and visualization. Futures, 43, 400-412, doi: 10.1016/j.futures.2011.01.009.
57. Sheppard, S. R. 2015. Making climate change visible: A critical role for landscape professionals. Landscape and Urban Planning, 142, 95-105. doi:10.1016/j.landurbplan.2015.07.006
58. Schambach L., Grilli S.T., Kirby J.T. and F. Shi 2019. Landslide tsunami hazard along the upper US East Coast: effects of slide rheology, bottom friction, and frequency dispersion. Pure and Applied Geophys., 176(7), 3,059-3,098, doi.org/10.1007/s00024-018-1978-7
59. Shi, F., J.T. Kirby, J.C. Harris, J.D. Geiman and S.T. Grilli 2012. A High-Order Adaptive Time-Stepping TVD Solver for Boussinesq Modeling of Breaking Waves and Coastal Inundation. Ocean Modeling, 43-44, 36-51.
60. Smith, S.M., 2015a. Vegetation change in salt marshes of Cape Cod National Seashore (Massachusetts, USA) between 1984 and 2013. Wetlands, 35(1), 127-136.
61. Smith, S.M., 2015b. Salt Marsh Vegetation Monitoring Report, Cape Cod National Seashore: A Summary of Monitoring Data from 2003, 2008, and 2013. Fort Collins, Colorado: National Park Service, Technical Report NPS / CACO /NRR-2015/ 920.
62. Smith, S.M., Tyrrell, M., Medeiros, K., Bayley, H.; Fox, S., Adams, M., Mejia, C., Dijkstra, A., Janson, S. and Tanis, M., 2017. Hypsometry of Cape Cod salt marshes (Massachusetts, U.S.A.) and predictions of marsh vegetation responses to sea-level rise. Journal of Coastal Research, 33(3), 537–547.
63. Soloviev, A.V., Lukas, R., Donelan, M.A., Haus, B.K. and Ginis, I., 2017. Is the state of the air-sea interface a factor in rapid intensification and rapid decline of tropical cyclones?. Journal of Geophysical Research: Oceans, 122(12), 10174-10183.

64. Spaulding, M.L., Grilli, A., Damon, C., Crean, T., Fugate, G., Oakley, B.A. and Stempel, P., 2016. STORMTOOLS: coastal environmental risk index (CERI). Journal of Marine Science and Engineering, 4(3), 54.
65. Spaulding, M.L., Grilli, A., Damon, C., Fugate, G., Oakley, B.A., Isaji, T., Schambach, L., 2017a. Application of state of art modeling techniques to predict flooding and waves for an exposed coastal area. J. Marine Sc. Engng., 5(1), 10, doi:10.3390/jmse5010010.
66. Spaulding, M.L., Grilli, A., Damon, C., Fugate, G., Isaji, T., Schambach, L., 2017b. Application of State of the Art Modeling Techniques to Predict Flooding and Waves for a Coastal Area within a Protected Bay. J. Marine Sc. Engng., 5(1), 14.
67. Spaulding M.L., Grilli A.R., Damon, C., Hashemi, R., Kouhi, S., and G. Fugate 2020a. STORMTOOLS Design Elevation Maps: Including impact of sea level rise. J. Marine Sc. Eng., 8(4), 292.
68. Spaulding M.L., Grilli, A.R., Damon, C., McKenna, B., Christensen, M., Vinhateiro, N., Boyd, J. and G. Fugate 2020b. STORMTOOLS, Coastal Environmental Risk Index Risk and Damage Assessment App. J. Marine Sc. Eng., 8(2),129.
69. Spaulding Grilli, A., Damon, C., Crean, T. and G. Fugate 2020c. Application of STORMTOOLS Coastal Environmental Risk Index to Inform State and Local Planning and Decision Making along the Southern RI Shoreline. J. Marine Sc. Eng., 8(4), 295.
70. Stempel, P., Ginis, I., Ullman, D., Becker, A. and Witkop, R., 2018. Real-Time Chronological Hazard Impact Modeling. Journal of Marine Science and Engineering, 6(4), 134, doi:10.3390/jmse6040134.
71. Stempel, P. and Becker, A. 2019. Visualizations Out of Context: Addressing Pitfalls of Real-Time Realistic Hazard Visualizations. ISPRS International Journal of Geo-Information, 8(8), 318, doi:10.3390/ijgi8080318.
72. Tolman, H.L., 2009. User manual and system documentation of WAVEWATCH III TM version 3.14. Technical note, MMAB Contribution, 276, p.220.
73. Ullman D.S., I. Ginis, W.Huang, C. Nowakowski, X. Chen, and P. Stempel, 2019. Assessing the Multiple Impacts of Extreme Hurricanes in Southern New England, USA, Geosciences, 9(6), 265, https://doi.org/10.3390/geosciences9060265.
74. van Ormondt, M., Nelson, T.R., Hapke, C.J. and Roelvink, D., 2020. Morphodynamic modelling of the wilderness breach, Fire Island, New York. Part I: Model set-up and validation. Coastal Eng., 157, 103621.
75. Vitousek, S., Barnard, P.L., Limber, P., Erikson, L. and B., Cole 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. Journal of geophysical research: earth surface, 122(4), 782-806.
76. Watson, E.B., C. Wigand, E.W. Davey, H.M. Andrews, J. Bishop, and K.B. Raposa. 2017. Wetland loss patterns and inundation-productivity relations prognosticate widespread salt marsh loss for southern New England. Estuaries and Coasts, 40, 662-681.
77. Wei, G., Kirby, J.T., Grilli, S.T. and Subramanya, R., 1995. A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves. Journal of Fluid Mechanics, 294, 71-92.
78. Westerink, J.J., Luettich, R.A., Blain, C.A. and Scheffner, N.W., 1994. ADCIRC: an advanced three-dimensional circulation model for shelves, coasts, and estuaries. Coastal Eng. Res. Cent., Vicksburg, Report, 2.