AGU PUBLICATIONS

Earth's Future

INTRODUCTION TO SPECIAL SECTION

10.1002/2016EF000493

Special Section:
Integrated field analysis & modeling of the coastal dynamics of sea level rise in the northern Gulf of Mexico

An *Earth's Future* Special Collection: Impacts of the coastal dynamics of sea level rise on low-gradient coastal landscapes

David M. Kidwell[1], J. Casey Dietrich[2], Scott C. Hagen[3], and Stephen C. Medeiros[4]

[1]National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, Maryland, USA, [2]Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA, [3]Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana, USA, [4]Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, USA

Key Points:
- Coastal dynamics of sea level rise
- Nonlinear effects on wetlands and hydrodynamics
- Introduction to special issue

Corresponding author:
D. M. Kidwell, David.Kidwell@noaa.gov

Citation:
Kidwell, D. M., J. C. Dietrich, S. C. Hagen, and S. C. Medeiros (2017), An *Earth's Future* Special Collection: Impacts of the coastal dynamics of sea level rise on low-gradient coastal landscapes, *Earth's Future*, *5*, 2–9, doi:10.1002/2016EF000493.

Received 3 NOV 2016
Accepted 6 DEC 2016
Accepted article online 16 DEC 2016
Published online 20 JAN 2017

Abstract Rising sea level represents a significant threat to coastal communities and ecosystems, including altered habitats and increased vulnerability to coastal storms and recurrent inundation. This threat is exemplified in the northern Gulf of Mexico, where low topography, marshes, and a prevalence of tropical storms have resulted in extensive coastal impacts. The ability to facilitate adaptation and mitigation measures relies, in part, on the development of robust predictive capabilities that incorporate complex biological processes with physical dynamics. Initiated in 2010, the 6-year Ecological Effects of Sea Level Rise—Northern Gulf of Mexico project applied a transdisciplinary science approach to develop a suite of integrated modeling platforms informed by empirical data that are capable of evaluating a range of climate change scenarios. This special issue highlights resultant integrated models focused on tidal hydrodynamics, shoreline morphology, oyster ecology, coastal wetland vulnerability, and storm surges that demonstrate the need for dynamic models to incorporate feedbacks among physical and biological processes in assessments of sea level rise effects on coastal systems. Effects are projected to be significant, spatially variable and nonlinear relative to sea level rise rates. Scenarios of higher sea level rise rates are projected to exceed thresholds of wetland sustainability, and many regions will experience enhanced storm surges. Influenced by an extensive collaborative stakeholder engagement process, these assessments on the coastal dynamics of sea level rise provide a strong foundation for resilience measures in the northern Gulf of Mexico and a transferable approach for application to other coastal regions throughout the world.

1. Introduction

One of the most prominent and measureable consequences of Earth's changing climate is that global mean sea level is rising at an accelerating rate according to long-term tide gauge records and satellite altimetry [*Church and White,* 2006, 2011; *Jevrejeva et al.,* 2006, 2008; *Nerem et al.,* 2010; *Hay et al.,* 2015]. The sea level rise (SLR) phenomenon will have effects that are observable during the lifetimes of key coastal stakeholders such as commercial, subsistence and sport fishermen, the shipping industry, resource managers, scientists, engineers and government agencies. These effects will ripple outward into the global economy, eventually reflecting back to the coastline, and then outward again as the larger system seeks an unattainable equilibrium. This distills our overarching principle when studying the effects of SLR on coastal systems: we must acknowledge the interactions and feedback between the various hydrodynamic, morphologic, biologic, and anthropogenic systems of the process. To begin, we focus our efforts on low-gradient coastal systems in the northern Gulf of Mexico (Figure 1).

The term "low gradient" generally refers to the topographic and bathymetric profile of a coastal system with relatively flat topography comprised of estuaries, marshes, shifting barrier islands, and a wide continental shelf. The low-gradient coastal systems in the northern Gulf of Mexico are also microtidal (tide range less than 1 m), exhibiting mixed diurnal and semidiurnal cycles [*Hayes,* 1979]. For a review of low-gradient coastal landscapes and past approaches to modeling them, see *Passeri et al.* [2015]. In that paper, the transition from simplistic "bathtub" SLR modeling to a dynamic approach is traced, and evidence for the value of the latter is presented in the context of past work toward that goal.

10.1002/2016EF000493

Figure 1. The low-gradient coastal land margin of the northern Gulf of Mexico including Mississippi, Alabama, and Florida and the location of the National Estuarine Research Reserve for each state.

Selection of the research setting is crucial to ensure a strong coastal stakeholder community committed to making significant contributions of resources, such as facilities, manpower and local expertise. We were extremely fortunate to find these partners through the National Estuarine Research Reserve (NERR) Program. The NERRs (Figure 1) at Grand Bay (Mississippi), Weeks Bay (Alabama), and Apalachicola (Florida) provide the perfect combination of coastal system diversity (marine, mixed, and estuarine, respectively), as well as access to personnel, stores of historic data and local knowledge, laboratory and presentation facilities, and community outreach infrastructure. Furthermore, because the NERR program is administered by the National Oceanic and Atmospheric Administration (NOAA) in conjunction with state environmental agencies, it offers a natural fit in terms of administrative expediency and synergistic objectives. The details of this symbiotic relationship, and what we achieved as a result, will be of great benefit to future studies that seek to emulate and enhance this collaborative approach [see *DeLorme et al.,* 2016].

2. Genesis

As described in *DeLorme et al.* [2016], the Ecological Effects of Sea Level Rise—Northern Gulf of Mexico (EESLR-NGOM) was initiated by NOAA in 2010 following stakeholder engagement that identified key management needs and knowledge gaps. EESLR-NGOM sought to advance SLR modeling and predictive capabilities beyond traditional bathtub approaches and toward integrated dynamic models. Focused on the effects of SLR on storm surge, coastal marshes, oysters, and submerged aquatic vegetation and incorporating routine feedback from regional stakeholders, the realization of a dynamic coastal modeling framework resulted in a paradigm shift in the methodology for examining coastal resilience and vulnerability to SLR.

The process diagram shown in Figure 2 illustrates our integrated approach to this study. Our end goal was to produce tools in the form of actionable information and applications that coastal resource managers could implement to deliver societal and ecosystem benefits. This is achieved by capturing the feedback mechanisms not only in the physical and biological processes, but also those resulting from the relationship between humans and the coastal environment.

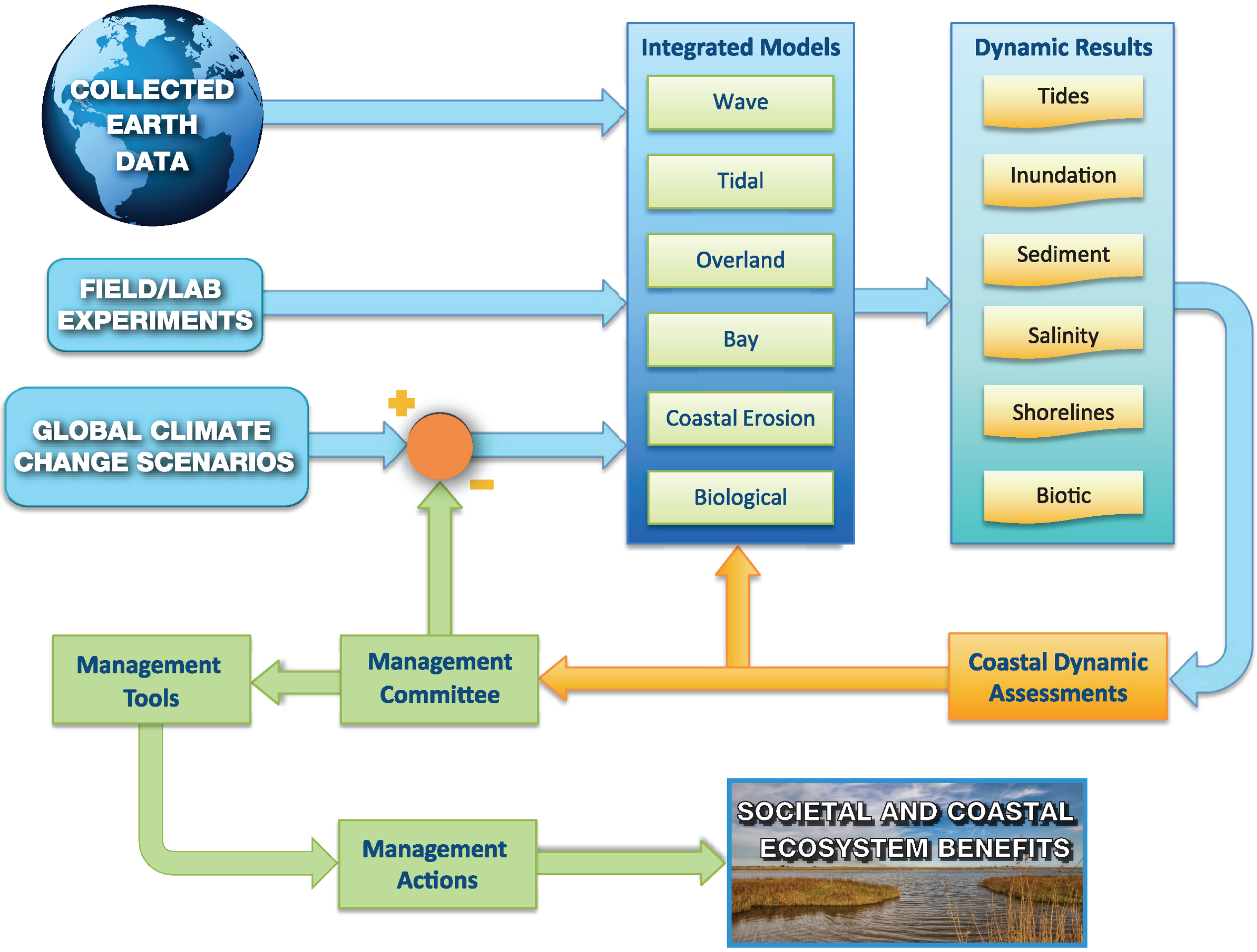

Figure 2. A process diagram for the coastal dynamics of sea level rise.

The paradigm shift in modeling the coastal dynamics of SLR begins with an understanding that carbon emission scenarios influence climate responses, such as a rise in atmospheric temperature that results in sea level change. This phenomenon further stimulates changes to coastal-related processes such as shoreline morphology, barrier islands, coastal dune systems, salt marsh productivity and migration; and influences patterns in land use/land cover (LULC) change. Our efforts during the EESLR-NGOM project encompassed the development and modification of climate change scenario-driven dynamic models.

3. Collected Data

A suite of physical and biological models were employed to simulate the behavior of the various processes that affect the response of the coastal systems to SLR. As an interdisciplinary effort, each model was overseen by an expert, or, in some cases, the original developer. The key objective for this integrated modeling approach is to capture the feedbacks among physical and biological responses to SLR through an investigation into the initial conditions for each model. Accurate initial conditions that represent the state of the system at a given time are essential to this modeling approach. These initial conditions were comprised of collected earth data (e.g., lidar-derived topography, surface roughness, tidal constituents), field and lab experiments (e.g., marsh bioassays, accretion rates), and global climate change scenarios (e.g., SLR rates, future precipitation estimates). Data collection and bioassays were completed at the three NERRs in the northern Gulf of Mexico.

For wetlands, location within an estuary or shoreline shifts in response to changes in sea level and dynamics of the intertidal zone. These changes, particularly those associated with rises in sea level, are a function of

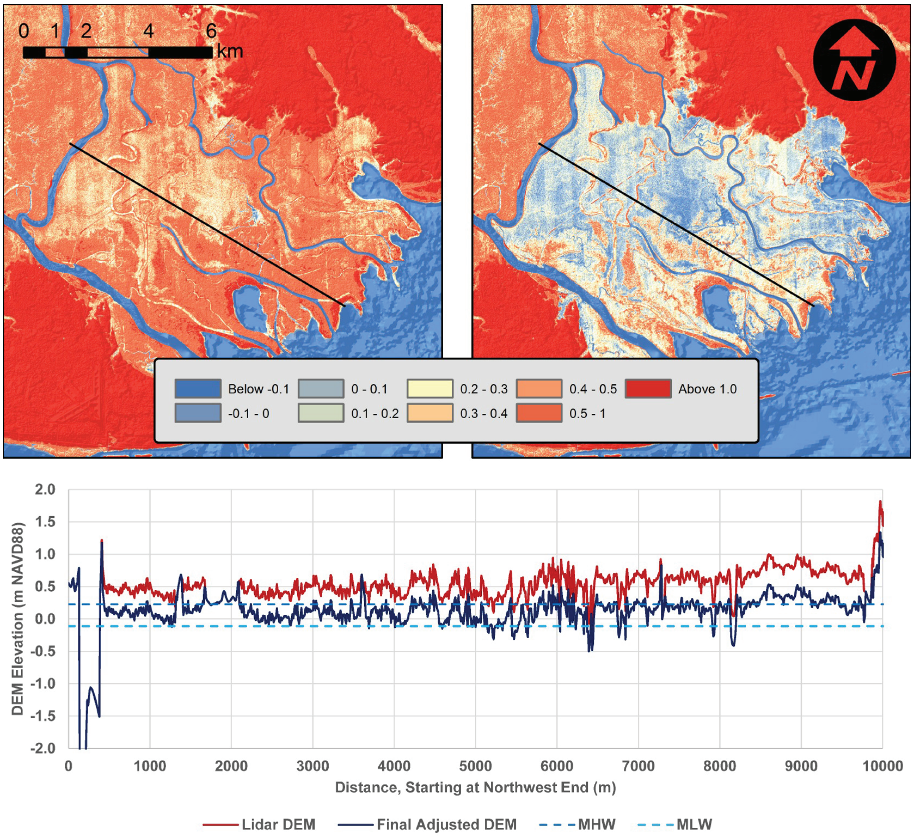

Figure 3. Adjustments to the digital elevation model of the coastal marsh that were essential to capturing the wetting and drying regime of the system.

the wetland's ability to accrete both organic and inorganic material to elevate the marsh platform. Characterizing this dynamic vertical position of the coastal marsh starts with a lidar-derived digital elevation model (DEM) provided by the Northwest Florida Water Management District (http://www.nwfwmdlidar.com/) and Apalachicola River surveyed bathymetric data from the U.S. Army Corps of Engineers, Mobile District, and others. Due to a high bias in the marsh topography documented by *Medeiros et al.* [2015], the DEM was adjusted based on remotely sensed biomass density. While this procedure reduced the high bias of the DEM by nearly 40%, further adjustment was necessary. This was accomplished by lowering the DEM at the southeastern edge of the salt marsh where the vegetation is densest and linearly decreasing the adjustment value to zero moving upriver to the northwest (Figure 3). These adjustments were necessitated by the observation that the majority of the marsh platform was incorrectly characterized to be above mean high water (MHW), which is infeasible for these systems. If the marsh platform elevation were allowed to remain above MHW, the hydroperiod would have been grossly misrepresented, thereby causing a chain reaction that would affect the sediment supply and biomass density predictions.

While *Medeiros et al.* [2015] improved approaches for deriving elevation in marshes, *Morris et al.* [2016] focuses on the collection of data required to inform a biological model of wetland productivity and elevation [*Morris et al.,* 2002; *Hagen et al.,* 2013; *Alizad et al.,* 2016a, 2016b]. Intertidal sediment parameters (e.g., bulk density) derived from data obtained through EESLR-NGOM are combined with samples from over 30 tidal and freshwater wetland sites across 14 states. Striking in this analysis, representing over 5000 discrete measurements, is fidelity in the relationship between organic matter (loss on ignition) and bulk density [see Figure 1, *Morris et al.,* 2016]. This relationship permits calculation of an empirically based indication of baseline relative SLR rates that represent a possible tipping point for marsh function decline. Thus, absent acute inputs of sediment (e.g., storm events) or deltaic inputs, *Morris et al.* [2016] suggests that many East- and Gulf-coast marshes can only sustain SLR rates up to 0.5 cm/yr, and relative SLR levels above this would potentially result in marsh decline and loss.

4. Integrated Models With Dynamic Results and Assessments

The integrated modeling framework of EESLR-NGOM utilized SLR projections developed by *Parris et al.* [2012] for the year 2100 of low (0.2 m), intermediate-low (0.5 m), intermediate-high (1.2 m), and high (2.0 m). These projections were then linked to an individual carbon emission scenario; for example, the A2 carbon emission scenario corresponds to the high SLR scenario. Each scenario was linked to a specific landscape profile that included shoreline position and profile, dune height, state of a marsh system, and LULC. This linkage permitted seamless communication within the EESLR-NGOM multimodel framework and ultimately, via the SLR scenarios, back to the associated carbon emission scenarios.

With this context, and by building on field-derived input data and climate and coastal scenarios, a 2-D ADvanced CIRCulation hydrodynamic model and a 1-D marsh equilibrium model [MEM; *Morris et al.,* 2002] were applied for finite time periods. The results of these intermediate simulations were then fed back into the models for simulation of the next sequential time period. For example, the inundation of coastal salt marshes as a result of SLR caused a decrease or elimination of above-ground biomass density, which changed the surface roughness of the terrain and potentially affected the hydrodynamics of the system in the next time step. In addition, projections of SLR and coastal development were incorporated into the modeling workflow to describe the future state of the system as accurately as possible. This process, coupling system hydrodynamics and biological function [*Hagen et al.,* 2013; *Alizad et al.,* 2016a], results in a modeling framework entitled *Hydro-MEM* and represents one of the first dynamic modeling systems capable of predicting marsh response to varying scenarios of SLR.

Following development of *Hydro-MEM*, *Alizad et al.* [2016b] focuses the first, detailed application of *Hydro-MEM* in the Apalachicola NERR. In addition to providing an assessment of regional marsh vulnerability and response to SLR, this study also highlights the dynamic response of these systems to SLR. The rate of overall marsh extent loss and function decline are projected to accelerate over time in conjunction with the increased rate of SLR rates, a pattern demonstrated by numerous assessments in low-gradient coastal regions. However, marsh response at the low and intermediate-low SLR scenarios will be variable, with some regions keeping pace with SLR and others experiencing loss. Much of this variation is attributable to changes in the inundation, accretion, and elevation characteristics of the marsh systems. Significant losses in marsh extent predicted in the intermediate-high and high SLR scenarios reflect an initial reduction in productivity as inundation frequency increased, resulting in a negative feedback of decreasing accretion and increasing water levels. Though not a focus of this Apalachicola assessment, results from *Hydro-MEM* also indicate some upland migration of tidal wetlands, particularly under the higher SLR scenarios.

Predicted changes in marsh extent under varying SLR scenarios reflect one of a suite of factors that will influence future shoreline conditions and change. In *Plant et al.* [2016], the dynamic feedbacks between SLR, dune height, and shoreline change are predicted through a statistical modeling approach. Long-term shoreline-change rates are combined and used with dune-height data collected regularly and after storms for a 10-year time period in the northern Gulf of Mexico, and then applied as input to a Bayesian network. Predictions of shoreline change have less uncertainty, but similar accuracy when dune heights are included as input, thus demonstrating the combined effects of these processes. An optimized model is then applied to forecast scenarios with low and intermediate-low SLR rates in a subregion spanning from eastern Louisiana to the Florida panhandle. The erosion rate will increase, but with higher uncertainty and spatial variability, and the shoreline change by 2100 could be comparable to the widths of barrier islands in this subregion. This predictive model can be used to determine the likelihood of adverse impacts of future SLR to shorelines and dunes, and informs studies of hydrodynamics and flooding in coastal regions.

Future changes in shoreline position, barrier island width and location, and dune crest heights may increase inundation and alter the amplitude and propagation speed of tides in back bays. *Passeri et al.* [2016] examines these effects of SLR on tidal hydrodynamics in the bays and estuaries from Mississippi to Florida. The predictive model of *Plant et al.* [2016] is used to project the shoreline change and dune heights at 4 km sections along this coastline, and then the 50th percentile projections were selected to represent an average projection of future morphodynamics. In regions where these projections show the shoreline will recede beyond infrastructure or even the width of the barrier island, a decision-making flowchart was introduced to account for nourishment of beaches and/or dunes. This flowchart considers the present and projected land use, and limits the shoreline erosion in regions near urban areas, thus allowing a realistic representation of future conditions. A high-resolution hydrodynamic model is used to predict the combined effects of SLR and morphodynamics on tidal amplitudes and velocities along coastal bays in the region. Deeper waters in these bays, and especially their increased inlet cross-sectional areas, act to enhance the propagation of tides. In a forecast scenario with a high rate of SLR, by 2100, the tidal amplitudes increase by as much as 67%, and the tidal velocities increase and even double in one bay. These projections are being used to inform coastal managers and policy makers, and can be integrated with other studies of storm surges and ecological assessments of SLR.

These advances are combined into a study of storm surge-induced flooding by *Bilskie et al.* [2016]. In contrast to a static ("bathtub") framework in which the SLR is added a posteriori as a constant increase to the water levels, this study introduces a modeling system that considers changes to shoreline and barrier island morphodynamics, marshes, and LULC. Four SLR scenarios for 2100 are considered via an increase in the initial water level, and then the effects are considered for 10 hurricane events that contributed to the majority of observed peak surges in the northern Gulf of Mexico. Shoreline and dune height evolution are included via the methods of *Plant et al.* [2016] and *Passeri et al.* [2016], and marsh evolution is included via the method of *Alizad et al.* [2016b]. The resulting changes to storm surge and coastal inundation are highly nonlinear, with most regions seeing an increase in water level above the SLR. The inundated total land area increases by 87%, with higher increases in inundated developed and agricultural land areas. The SLR-induced reductions in dune heights allows surge overtopping that increased water levels by as much as 1 m. The increase in sea level also changes the duration and timing of surge, including an earlier arrival of the peak surge. This dynamic framework is a culmination of the paradigm shift beyond bathtub approaches and has broad implications for future studies here and elsewhere.

Climate change effects can be taken from the coast up the watershed. Projected LULC changes can be used to examine the impact of conversion of forested regions into agricultural and urban areas. Temperature and precipitation projections can be downscaled from general circulation model data. *Hovenga et al.* [2016] combine these methods with a physics-based, long-term hydrologic model to assess runoff and sediment loading in the Apalachicola River Basin, which drains into Apalachicola Bay and the northern Gulf of Mexico. Their study uses present-day and three forecast scenarios from the Intergovernmental Panel on Climate Change, and combines them with LULC changes and downscaled data from three climate models in a way that allows intercomparisons to be made. While the individual climate models have disagreement on future rainfall seasonal patterns [e.g., *Janssen et al.,* 2014 and *Wang and Kotamarthi,* 2015], they agree that peak runoff and minimum sediment loading will be shifted earlier in the year as compared to present-day conditions. Further, LULC changes did not affect runoff, but the shift from forested to agricultural and urban areas will increase the sediment loading in the estuarine system. The combination of LULC and climate changes has nonlinear effects, as changes in one forcing factor may amplify or dampen the effects of the other. Both factors should be included in studies of future hydrological conditions.

The outputs from the hydrologic model of *Hovenga et al.* [2016] can be used for biological assessments of the system ecology. *Huang et al.* [2017] uses the hydrologic outputs of flow and sediment transport as boundary conditions and inputs to models for total suspended solids (TSS) near oyster habitats. Higher levels of suspended sediments have been shown to inhibit the recruitment, growth and development of oysters, including in the once-lucrative oyster fisheries in Apalachicola Bay. The forecast scenarios in *Hovenga et al.* [2016] are used by *Huang et al.* [2017] to establish values for 2100 for SLR, streamflow, and sediment loading inputs. Then a well-validated, three-dimensional hydrodynamic model is coupled with a widely used sediment module, so the density-driven circulation can be used to transport TSS in the estuarine system. SLR is shown to cause a decrease in the TSS at the oyster reefs, with larger decreases associated with larger SLR scenarios. At one of the two primary oyster habitats in this system, the maximum sediment concentration will be close or equal to zero, thus causing a substantial loss of nutrients and a decrease in oyster production. These projections can be used to assess existing and prepare new oyster habitats in Apalachicola Bay, and these methods can be extended to assess vulnerabilities in other regions.

5. Conclusion and Discussion

This collection of articles on the coastal dynamics of SLR represents a shift in the paradigm of how climate change and SLR can be assessed at coastal land margins, particularly for low-gradient landscapes. While static (a.k.a., "bathtub") models have proved quite useful in providing first approximations, the utility of dynamic assessments are demonstrated and their appropriateness warranted by numerous examples of the highly nonlinear response of ecosystem components and hydrodynamics to SLR. As with any modeling framework, the accuracy and validity of outputs are highly sensitive to input parameters.

Coastal wetlands are widely considered to be highly vulnerable to the effects of SLR, given their sensitive location along the land–water interface. Results from *Alizad et al.* [2016b] project high wetland loss under higher scenarios of SLR by 2100. However, the dynamic feedbacks between physical (e.g., tidal dynamics) and biological (e.g., accretion rates and productivity) require a more nuanced perspective of marsh vulnerability to SLR. Regional variability in SLR rates and local factors, such as marsh migration and accretion potential, provide critical context to marsh vulnerability assessments [e.g., *Enwright et al.,* 2016; *Kirwin et al.,* 2016; *Morris et al.,* 2016]. Low scenarios of SLR can increase marsh extent and productivity, or greatly extend the time before marsh collapse [*Alizad et al.,* 2016a, 2016b]. Quantifying these thresholds is critical for informed mitigation actions, and the analysis by *Morris et al.* [2016] of 0.5 cm/yr accretion potential (absent significant sources of mineral sediment) provides a key baseline from which to start. Within this context, caution is advised when using static models and/or nonlocation-specific input parameters.

Perhaps no other input parameter is more critical in low-gradient, micro-tidal systems than the accuracy of the baseline DEM. Lidar-derived elevation error in low marsh systems dominated by *Spartina alterniflora* and *Juncus roemerianus* can range from 0.4 to 0.8 m in the northern Gulf of Mexico. This error results in a DEM that does not accurately reflect marsh platform elevation and topography, and can significantly influence projections of marsh vulnerability to SLR. A number of approaches for correcting this bias in coastal wetlands [e.g., *Medeiros et al.,* 2015; *Buffington et al.,* 2016] have emerged in recent years and must be used prior to modeling SLR effects on coastal wetlands.

Barrier islands along Mississippi (MS), Alabama (AL), and the Florida (FL) panhandle, as well as low-lying marshes, become more vulnerable not only to storm surge inundation, but also tidal inundation, especially under the higher projections of SLR. Under a 2-m SLR, tidal inundation from MS through the FL panhandle increases by 1472 km^2, which is equivalent to 20% of the total surface area of the bays within this region at present day. Barrier islands in this region are projected to have increased shoreline and dune erosion under higher rates of SLR, which have significant consequences for coastal infrastructure.

Storm surge response to SLR is not simply additive. Storm surge flooding of developed areas for the MS, AL, FL panhandle regions more than double with an overall increase of 138% from present day (282.7 $km^2$of flooding) to a 2.0-m SLR (672.3 $km^2$of flooding). To put this into perspective, the average land area of a coastal city in MS, AL, and the FL panhandle is 50–100 km^2. The most vulnerable areas include Florida's Big Bend, the western FL panhandle, AL, and MS. In the same SLR scenario, agricultural lands in the region will see an increase in inundation area by 189%, and total inundated land area will increase by 87%. In addition, those areas that are presently being flooded with storm surge will be flooded at greater depths. The peak surge will increase by as much as 1 m above the applied SLR in some areas; however, other regions will have a reduction in peak surge. The nonlinear response to SLR is likely not limited to the northern Gulf of Mexico or low-gradient landscapes. For example, *Lentz et al.* [2016] found that 70% of the coastal landscape in the northeast U.S. responded dynamically to SLR. Thus, the ability to better predict the effects of SLR will require expanded development and application of dynamic modeling approaches.

While the multimodel framework highlighted in this special issue represents significant advancement in how predictions of SLR impacts are modeled, the ultimate intent of EESLR-NGOM is to address explicit needs of coastal managers. To ensure that products and tools developed through this project are relevant and usable by stakeholders, *DeLorme et al.* [2016] describes a transdisciplinary approach to facilitate collaboration between project scientists and a stakeholder advisory committee. Pre-project engagement, annual workshops, and periodic webinars are key tools that were used to facilitate objective feedback and analysis of EESLR-NGOM science activities. As with most multi-institution science projects, EESLR-NGOM had a lead principal investigator that provided oversight and coordination for project tasks and activities. However, coupled with this traditional project structure was a funded "management principal investigator" charged with ensuring collaboration, providing oversight to stakeholder advisory committee activities, and facilitating the transition from research to application. This collaborative approach resulted in model products and capabilities applicable to stakeholder needs that have been applied to evaluate storm surge and marsh vulnerability in the northeast U.S. and informed watershed management planning and land acquisition activities in the Gulf of Mexico.

The interconnected built and natural environment demands integrative inclusion of a suite of solutions to mitigate coastal vulnerability. Although the methodologies presented are by no means comprehensive, the systems approach exemplified in Figure 2 and pursued through the research presented herein provides a strong foundation from which we can adapt to rising sea levels and facilitate coastal resilience.

References

Alizad, K., S. C. Hagen, J. T. Morris, P. Bacopoulos, M. V. Bilskie, and J. F. Weishampel (2016a), A coupled, two-dimensional hydrodynamic-marsh model with biological feedback, *Ecol. Modell.*, *327*, 29–43, doi:10.1016/j.ecolmodel.2016.01.013.

Alizad, K., S. C. Hagen, J. T. Morris, S. C. Medeiros, M. V. Bilskie, and J. F. Weishampel (2016b), Coastal wetland response to sea level rise in a fluvial estuarine system, *Earth's Future*, *4*(11), 483–497, doi:10.1002/2016EF000385.

Bilskie, M. V., S. C. Hagen, K. A. Alizad, S. C. Medeiros, D. L. Passeri, and H. Needham (2016), Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico, *Earth's Future*, *4*(5), 177–193, doi:10.1002/2015EF000347.

Buffington, K. J., B. D. Dugger, K. M. Thorne, and J. Y. Takekawa (2016), Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes, *Remote Sens. Environ.*, *186*, 616–625, doi:10.1016/j.rse.2016.09.020.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*(1), L01602, doi:10.1029/2005GL024826.

Church, J. A., and N. J. White (2011), Sea-level rise from the late 19th to early 21st century, *Surv. Geophys.*, *32*(4–5), 585–602, doi:10.1007/s10712-011-9119-1.

DeLorme, D. E., D. Kidwell, S. C. Hagen, and S. Stephens (2016), Developing and managing transdisciplinary and transformative research on the coastal dynamics of sea level rise: Experiences and lessons learned, *Earth's Future*, *4*(5), 194–209, doi:10.1002/2015EF000346.

Enwright, N. M., K. T. Griffith, and M. J. Osland (2016), Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise, *Front. Ecol. Environ.*, *14*(6), 307–316, doi:10.1002/fee.1282.

Hagen, S. C., J. T. Morris, P. Bacopoulos, and J. F. Weishampel (2013), Sea-Level Rise Impact on a Salt Marsh System of the Lower St. Johns River, *J. Waterway Port Coastal Ocean Eng.*, *139*(2), 118–125, doi:10.1061/(ASCE)WW.1943-5460.0000177.

Hay, C. C., E. Morrow, R. E. Kopp, and J. X. Mitrovica (2015), Probabilistic reanalysis of twentieth-century sea-level rise, *Nature*, *517*, 481–484, doi:10.1038/nature14093.

Hayes, M. O. (1979), Barrier island morphology as a function of tidal and wave regime, in *Barrier Islands* edited by S.P. Leatherman, pp. 1–27, Academic Press, New York, N. Y.

Hovenga, P. A., D. Wang, S. C. Medeiros, S. C. Hagen, and K. A. Alizad (2016), The response of runoff and sediment loading in the Apalachicola River, Florida to climate and land use land cover change, *Earth's Future*, *4*(5), 124–142, doi:10.1002/2015EF000348.

Huang, W., S. C. Hagen, D. Wang, P. A. Hovenga, F. Teng, and J. F. Weishampel (2017), Suspended sediment projections in Apalachicola Bay in response to altered river flow and sediment loads under climate change and sea level rise, *Earth's Future*, *4*, 428–439, doi:10.1002/2016EF000384.

Janssen, E., D. J. Wuebbles, K. E. Kunkel, S. C. Olsen, and A. Goodman (2014), Observational- and model-based trends and projections of extreme precipitation over the contiguous United States, *Earth's Future*, *2*, 99–113, doi:10.1002/2013EF000185.

Jevrejeva, S., A. Grinsted, J. Moore, and S. Holgate (2006), Nonlinear trends and multiyear cycles in sea level records, *J. Geophys. Res.*, *111*, C09012, doi:10.1029/2005JC003229.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago? *Geophy. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

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

Lentz, E. E., E. R. Thieler, N. G. Plant, S. R. Stippa, R. M. Horton, and D. B. Gesch (2016), Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood, *Nat. Clim. Change*, *6*, 636–700, doi:10.1038/nclimate2957.

Medeiros, S., S. Hagen, J. Weishampel, and J. Angelo (2015), Adjusting Lidar-derived digital terrain models in coastal marshes based on estimated aboveground biomass density, *Remote Sens*, *7*(4), 3507, doi:10.3390/rs70403507.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon (2002), Responses of coastal wetlands to rising sea level, *Ecology*, *83*(10), 2869–2877, doi:10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2.

Morris, J. T., D. C. Barber, J. Callaway, R. Chambers, S. C. Hagen, B. J. Johnson, P. Megonigal, S. Neubauer, T. Troxler, and C. Wigand (2016), Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state, *Earth's Future*, *4*(4), 110–121, doi:10.1002/2015EF000334.

Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum (2010), Estimating mean sea level change from the TOPEX and Jason Altimeter Missions, *Mar. Geod.*, *33*(1), 435–446, doi:10.1080/01490419.2010.491031.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. (2012), Global sea level rise scenarios for the us national climate assessment. NOAA Tech. Memo OAR CPO-1, 37 pp.

Passeri, D. L., S. C. Hagen, S. C. Medeiros, M. V. Bilskie, K. Alizad, and D. Wang (2015), The dynamic effects of sea level rise on low gradient coastal landscapes: A review, *Earth's Future*, *3*(6), 159–181, doi:10.1002/2015EF000298.

Passeri, D. L., S. C. Hagen, N. G. Plant, M. V. Bilskie, and S. C. Medeiros (2016), Tidal hydrodynamics under future sea level rise and coastal morphology in the Northern Gulf of Mexico, *Earth's Future*, *4*(5), 159–176, doi:10.1002/2015EF000332.

Plant, N. G., E. R. Thieler, and D. L. Passeri (2016), Coupling centennial-scale shoreline change to sea-level rise and coastal morphology in the Gulf of Mexico using a Bayesian network, *Earth's Future*, *4*(6), 143–158, doi:10.1002/2015EF000331.

Wang, J., and V. R. Kotamarthi (2015), High-resolution dynamically downscaled projections of precipitation in the mid and late 21st century over North America, *Earth's Future*, *3*, 268–288, doi:10.1002/2015EF000304.