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# Dynamics of sea level rise and coastal flooding on a changing landscape

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**Key Points:**

- Storm surge response to climate change impacts is dynamic
- A framework for constructing dynamic assessments of SLR is developed

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**Abstract** Standard approaches to determining the impacts of sea level rise (SLR) on storm surge flooding employ numerical models reflecting present conditions with modified sea states for a given SLR scenario. In this study, we advance this paradigm by adjusting the model framework so that it reflects not only a change in sea state but also variations to the landscape (morphologic changes and urbanization of coastal cities). We utilize a numerical model of the Mississippi and Alabama coast to simulate the response of hurricane storm surge to changes in sea level, land use/land cover, and land surface elevation for past (1960), present (2005), and future (2050) conditions. The results show that the storm surge response to SLR is dynamic and sensitive to changes in the landscape. We introduce a new modeling framework that includes modification of the landscape when producing storm surge models for future conditions.

## 1. Introduction

Low-lying coastal environments are particularly susceptible to climate change impacts [*McGranahan et al.*, 2007], especially sea level rise (SLR). Short-term effects of rising seas include an increase in coastal flooding, altered inundation patterns, and saltwater intrusion into fresh waters [*Parker*, 1991]. Long-term effects of SLR occur as the coast seeks to reestablish equilibrium and include shoreline erosion, saltwater intrusion into groundwater, and salt marsh migration or transformation to open water if sediment accretion does not keep pace with SLR [*Hagen et al.*, 2013; *Morris et al.*, 2002; *Geselbracht et al.*, 2011; *Nicholls and Cazenave*, 2010; *Smith et al.*, 2010; *Michener et al.*, 1997]. Global coastal environments are also vulnerable to tropical cyclones resulting in storm surges that intensify coastal flooding when coupled with SLR.

Storm surge is a complex process, governed by factors such as storm size and intensity, topography, geometry, and roughness of the impacted areas [*Resio and Westerink*, 2008]. Storm surge escalates as the storm approaches the coast, and the energy of the surge travels into shallower waters. To study the interactions of coastal flooding from hurricane storm surge and SLR, we constructed a physically based numerical model, which describes the physics related to the processes of hurricane storm surges and wind-generated waves at the regional scale. The model can be adapted to simulate various scenarios, including future projections of climatic conditions.

In standard practice, validation of numerical storm surge models consists of comparing observed and computed values (i.e., water levels, currents, and wave heights) for past storm events. These models are developed to represent conditions before the storm to properly describe the physics during the event [*University of Central Florida*, 2011; *Bunya et al.*, 2010]. When designing storm surge models to function for future scenarios, modifications must be made to characterize projected changes to the landscape using an approach that considers the sensitivity of the model to various input factors. Therefore, it is necessary to establish a model development framework to adapt existing storm surge models for past conditions and future scenarios.

The effect of SLR on storm surge has been shown to be nonlinear (i.e., peak surge does not increase linearly by the amount of SLR) and has been attributed to factors other than the static change in water level itself, such as variation of the landscape [*Smith et al.*, 2010; *Atkinson et al.*, 2013; *Mousavi et al.*, 2011; *Ding et al.*, 2013]. However, the impact of the landscape on storm surge in the context of SLR has yet to be investigated [*Irish et al.*, 2010; *Woodruff et al.*, 2013]. With time, sea level varies, as well as the landscape and population density; barrier islands and river inlets change shape, marshes migrate, and populations of coastal cities grow, enhancing urbanization.

This study utilizes a physically based hydrodynamic storm surge and wind wave model to study storm surge response to changes in sea level, topography, and land use/land cover (LULC) along the Mississippi and Alabama coast by simulating SLR and hurricane storm surge for past (1960), current (2005), and future (2050) conditions. We present a novel approach to investigate the flooding extent and depths due to hurricane storm surge that is applicable to other global regions that may experience impacts of SLR.

## 2. Sea Level Rise Scenarios

Global sea levels have been increasing and are projected to continue rising [*Intergovernmental Panel on Climate Change (IPCC)*, 2007]. SLR is engendered by a rise in ocean temperature, ice melt, and changes in runoff patterns. Tide gauge records since 1900 show a rise of approximately 1.7 mm/yr, whereas satellite altimetry data since the 1990s indicate a rise of 3.2 mm/yr [*Parris et al.*, 2012; *Church and White*, 2011; *Ablain et al.*, 2009; *Beckley et al.*, 2007]. Regions with minimal vertical land shift follow the global trend; however, satellite data indicate that mean sea level in the Gulf of Mexico is increasing faster than the global average [*IPCC*, 2007]. Therefore, we apply local SLR predictions rather than global predictions, as the focus is on the regional scale. Three uniformly spaced scenarios of 6, 12, and 18 in. (15.2, 30.5, 45.7 cm) are based on the United States Army Corps of Engineers Climate Change Adaptation Sea Level Change Curve Calculator at Dauphin Island, AL (http://www.corpsclimate.us/ccaceslcurves.cfm), which accounts for both eustatic SLR and subsidence (relative to 2005). The sea state for the 1960 scenario is a linear extrapolation of the long-term tide data and is 13.4 cm lower than the 2005 sea state.

The intention of this study is not to predict future impacts but to examine the sensitivity of surge behavior to changing landscape features under past sea states and land use change for future sea states using a range of generally accepted SLR scenarios.

## 3. Storm Surge Modeling

We employ the tightly coupled Simulating Waves Nearshore + Advanced Circulation (ADCIRC) modeling framework to compute water surface elevations and currents [*Bunya et al.*, 2010; *Dietrich et al.*, 2011b; *Westerink et al.*, 2008; *Zijlema*, 2010]. Here the model is forced with wind and pressure representative of Hurricane Katrina (2005) [*Powell et al.*, 2010]. The model utilizes an adapted version of an unstructured numerical grid that was validated and used for the production of Federal Emergency Management Agency digital flood insurance rate maps [*University of Central Florida*, 2011]. Modifications include enhanced details in Mississippi with model resolution down to 20 m, and 20 km in the deep ocean. Elevation data for 2005 are derived from the most recent lidar data available. We modify the base model (2005) to reflect the past (1960) and future (2050) conditions. The 1960 elevations were derived from historic U.S. Geological Survey circa 1960 topographic maps (http://geonames.usgs.gov/pls/topomaps). Modifications made in the 1960 model elevations are generally morphologic and located along the Mississippi Sound barrier islands, which have migrated westward as a result of longshore drift causing up-drift erosion and down-drift deposition [*Davis*, 1997; *Byrnes et al.*, 1991; *Morton*, 2008; *Otvos*, 1970]; also, the Pascagoula Naval Complex was created in 1985 near the Pascagoula River (Figure 1). In addition to elevation changes, circa 1960 LULC was assimilated into the model. For the future scenario, 2050 LULC was applied to reflect projected changes for the future using the A2 scenario (http://landcover-modeling.cr.usgs.gov/), and elevations were held constant from the 2005 model (Figure 2). LULC is used to parameterize surface roughness in the forms of bottom friction, wind reduction as a result of vertical obstacles, and vegetation canopy coefficients that limit wind influence under dense canopies.

Twelve simulations were executed to explore the various influences and sensitivities of surge response to changes in sea level, topography, and LULC. For three scenarios representing 1960, 2005, and 2050 with 45.7 cm of SLR, maximum simulated water levels of 7.95 m, 8.08 m, and 8.67 m, respectively, were located along the Mississippi coast near Gulfport. The difference in maximum storm surge is not necessarily equal to the SLR, as observed between 2005 and 2050, where the difference (59 cm) is greater than the SLR (45.7 cm). This quick calculation introduces the significance of the dynamic interactions that are occurring and furthers the motivation to examine the sensitivity of storm surge response on a changing landscape in addition to SLR.

The goal is to determine the influencing factors on the nonlinearity of storm surge ($L$). To examine the nonlinear interaction and sensitivity of storm surge inundation to a change in sea state, LULC, and morphology,

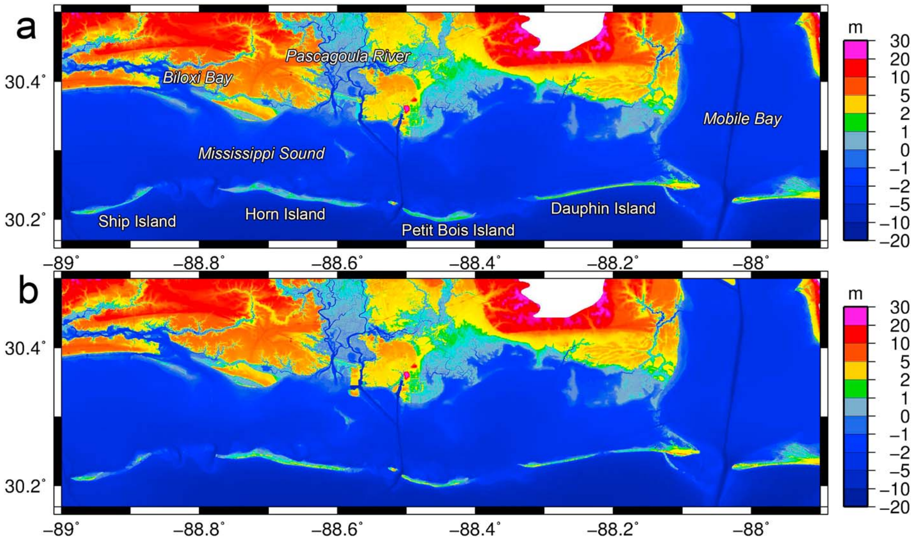

**Figure 1.** Nearshore topography and bathymetry for the Mississippi Sound barrier islands and the Pascagoula River inlet representative of (a) circa 1960 and (b) 2005. Major differences are the splitting of Dauphin and Ship Islands, the westward migration of Petit Bois and Horn Islands, and the urbanization of the eastern Pascagoula River inlet.

the difference in maximum surge heights to the amount of SLR ($\lambda$) is normalized to the change in sea level $\left(\frac{L}{\lambda}\right)$ and called the Normalized Nonlinearity (*NNL*) index

$$NNL = \frac{\eta_2 - \eta_1 - \lambda}{\lambda} = \frac{\eta_2 - \eta_1}{\lambda} - 1 \tag{1}$$

where $\eta_1$ and $\eta_2$ are the maximum generated surges for the lower and higher sea states, given an amount of SLR.

## 4. Effect of Topography

To consider the nonlinearity in the storm surge response to a change in elevation, three simulations representative of the 1960 sea state are compared via the *NNL* to the baseline simulation of 2005. Figure 3 shows the *NNL* between the 2005 baseline simulation and the 1960 sea state simulation that includes the 2005 elevation and 2005 LULC (Figure 3a) and circa 1960 LULC (Figure 3b). Similarly, Figure 3c shows the *NNL* of the 2005 baseline to the 1960 sea state scenario but includes elevation representative of 1960 along the Mississippi Sound barrier islands and Pascagoula River inlet. Including the elevation changes drastically enhances maximum storm surge offshore of the barrier islands, within the eastern portion of Mississippi Sound, and Mobile Bay.

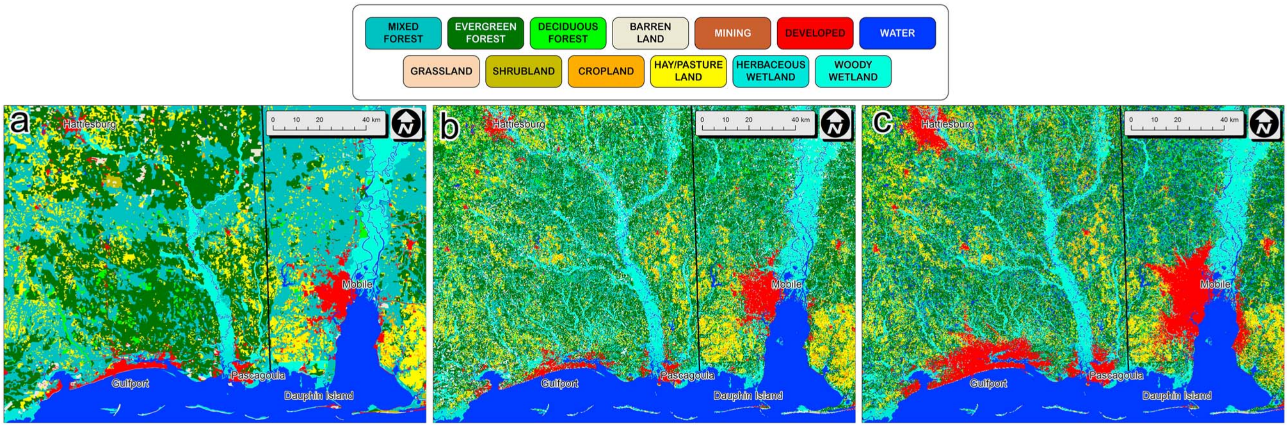

**Figure 2.** LULC (a) circa 1960, (b) 2005, and (c) 2050 projection using the A2 climate scenario. Colors represent the different LULC classifications. The black line divides the states of Mississippi and Alabama.

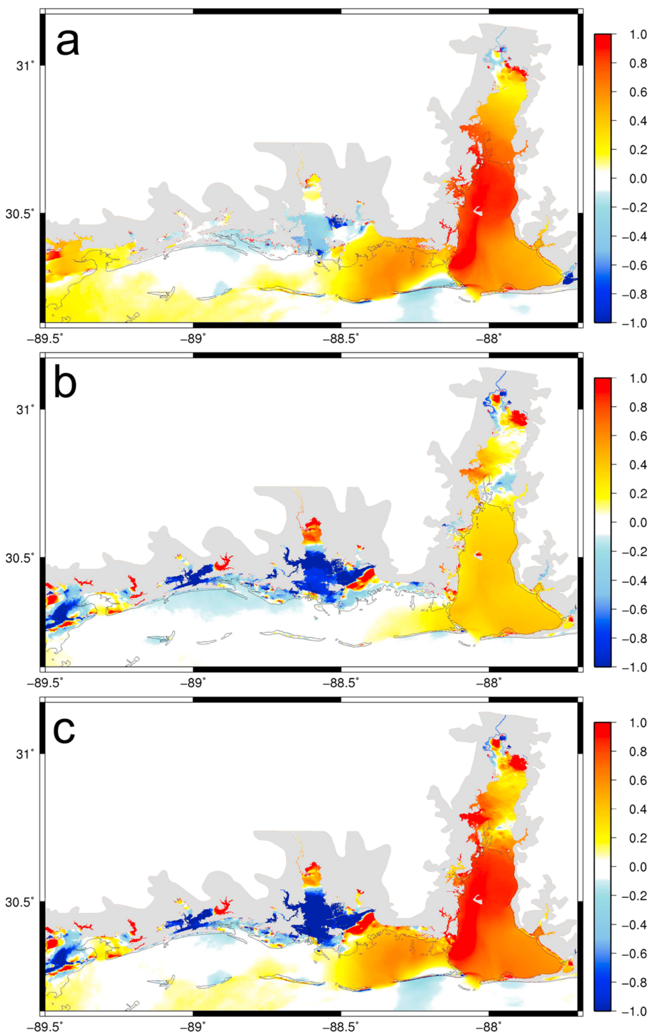

**Figure 3.** *NNL* index of maximum storm surge from Hurricane Katrina for Mississippi Sound and Mobile Bay between 1960 and 2005 with model parameters of 2005 sea state/LULC/elevation compared to (a) 1960 sea state and 2005 LULC/elevation, (b) 1960 sea state/LULC and 2005 elevation, and (c) 1960 sea state/LULC/elevation. White shows a rise in maximum water level equal to the SLR, warm colors indicate an amplification, cool colors a deamplification in maximum storm surge, and gray represents nonwetted (or dry) areas. The black line represents the coastline.

There are regions, primarily off the coast, with a purely static increase (i.e., $NNL = 0$). The dynamic effect of the coastline and nearshore regime (i.e., shoreline geometry and bottom friction) decrease with increasing offshore distance. Thus, a static model would tend to underpredict maximum water levels. This is shown from decreasing the sea state from 2005 to 1960, which indicates that the difference in maximum water levels are generally larger than the change in sea state (Figure 3a). Much of the maximum water level around the Pascagoula River and Biloxi Bay are less than the SLR, indicating that surge levels in these regions do not increase by the amount of SLR. Here the surge is mainly driven by wind setup. Differences in the water levels at the surge extent is larger than the SLR, causing a lower set-down downstream (Figure 3). However, in most areas (e.g., Mobile Bay and western Mississippi Sound), the maximum water level increases an additional 80% of the applied SLR, resulting in amplification of storm surge greater than the amount of SLR. Higher water levels are found within Pascagoula, MS, near U.S. Highway 90 because water and wave run-up accumulates against the raised roadbed, but the road is not overtopped. The sharp gradient in *NNL* around U.S. Highway 90 is caused by storm surge moving from south to north from the Escatawpa River, but the road holds back surge in both directions.

Higher water levels are observed in eastern Mississippi Sound and Mobile Bay because of the transformation of the barrier islands since 1960, primarily illustrated by Dauphin Island (Figure 2), which has migrated

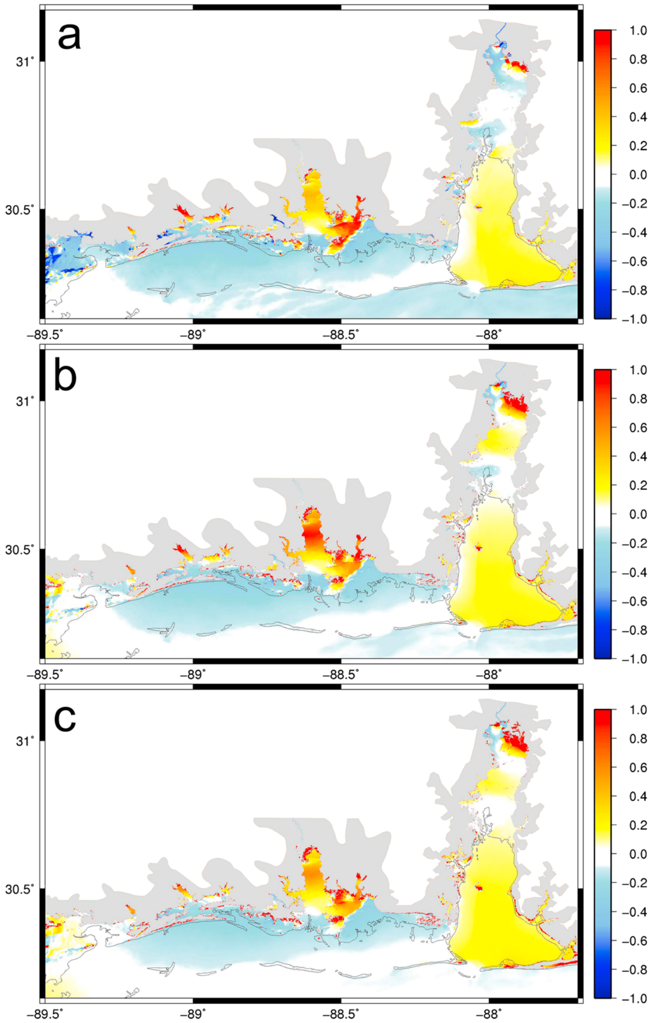

**Figure 4.** *NNL* index of maximum storm surge from Hurricane Katrina wind forcing for Mississippi Sound and Mobile Bay for SLR scenarios of (a) 15.2 cm, (b) 30.5 cm, and (c) 45.7 cm. White colors show no change (static), warm colors indicate that changing the LULC to 2050 from 2005 increases differences in maximum surge larger than the SLR, cool colors indicate the 2005 LULC results in lower maximum surge than the applied SLR, and gray regions show noninundated regions within the model. The black line represents the coastline.

westward and was breached during Hurricane Katrina [*Morton*, 2008]. The breach lessens the protective effect of the barrier island and permits additional water to enter the Sound and Mobile Bay, thereby increasing the amount of overland flooding (Figure 3c).

Although maximum water levels vary, analysis of the total inundated area between the two simulations with varying topographic representation shows little difference. This indicates that changes in the barrier islands do not enhance the total flooding area but rather modify the path and pattern of maximum water levels.

Given the nominal amount of SLR from 1960 to 2005 (13.4 cm) as established from long-term tide records, the Mississippi barrier islands have migrated westward and have been reshaped by hurricanes. This shoreline morphology is indisputable and can be traced back to pre-1900 when Grand Batture Island, now a submerged shoal, was once a protective barrier island for Grand Bay, MS [*Eleuterius and Criss*, 1991]. With this, it is only intuitive that with projected SLR on the order of meters that barrier island and shoreline morphology will be accelerated [*Irish et al.*, 2010]. Thus, the results demonstrate that it is incumbent that we incorporate shoreline morphology in making projections of flooding due to hurricane storm and SLR.

## 5. Effect of LULC

Storm surge response to the altered LULC (between 2005 and 1960), as shown in Figure 3b, tends to decrease the differences in maximum surge, bringing it closer to a static solution; however, within the Pascagoula River and marsh as well as around Biloxi Bay and the Bay of St. Louis, the *NNL* converges to −1, indicating that a static approach would significantly overpredict the maximum surge water levels caused by generally lower bottom friction in 1960. In some cases the difference in storm surge is zero (e.g., if $NNL = -1$, then $\eta_2 - \eta_1 = 0$). Comparing the pure 2005 to 1960 scenarios (Figure 3c) further increases the nonlinearity, by enhancing the maximum surge in eastern Mississippi Sound and Biloxi Bay, but further drives surge differences within the Pascagoula River and Biloxi Bay to zero.

Projections of LULC in 2050 are incorporated into the model along with three SLR scenarios (15.2, 30.5, and 45.7 cm) to investigate the surge response to changes in the LULC, but do not account for changes due to coastal geomorphology or marsh accretion from 2005 to 2050. These projections include variations to vegetation and anthropogenic development associated with urbanization. A changing landscape not only affects the roughness of the land but also alters the effects of the wind, as mentioned previously.

Figure 4 shows the *NNL* between simulations employing the 2050 LULC for each of the three SLR scenarios (15.2, 30.5, and 45.7 cm) and the 2005 simulation. A similar pattern exists between the three SLR scenarios, in that much of the area along the Pascagoula River floodplain and Mobile Bay experience surge amplified by 70% and 20% higher than that of the SLR, respectively. Additionally, areas within Mississippi Sound show a decrease in surge of 30% relative to the amount of SLR. This effect may be caused by deeper water depths in shallow waters, reducing bottom friction, and therefore decreased storm surge. As the SLR values increase, flooding area increases. However, the relationship is not linear; the differences in flooding area between 2005 and each of the 2050 scenarios are 1174 km$^2$, 2159 km$^2$, and 2463 km$^2$, respectively, with slopes (inundated area divided by SLR) of 7703 km$^2$/m, 7083 km$^2$/m, and 5387 km$^2$/m. The slope of inundated area versus SLR decreases with the larger change in sea level because the topography becomes the dominant controlling factor, and the high gradient in elevation obstructs an increase in flooding extent. This can be observed via the *NNL* under the 30.5 and 45.7 cm scenario (Figure 4). The nonlinear component is larger in the 30.5 cm case, indicating that a threshold may exist between 30.5 and 45.7 cm of SLR that introduces more flooding area due to an additional overtopping of raised features. The increase in surge along the Pascagoula River is attributed to the intertidal zone marsh becoming less resistant to flow as mean low water approaches that of the marsh table elevation, converting some regions to open water. Similarly, larger surge elevations are observed when increasing the amount of SLR in the marsh north of Mobile Bay. Removing the SLR and analyzing differences in maximum water level between simulations employing the 2050 and 2005 LULC reveals differences of $\pm$ 0.25 m in much of the floodplain, with bias toward +0.25 m.

The change in frictional characteristics amplifies surge, but adjusting the elevations of the barrier islands and east inlet reduces surge, as previously described. This directly illustrates the many complex physical processes that are at play and elucidates the dynamic effects of SLR and storm surge inundation on a changing landscape; when evaluating future projections of coastal flooding, changes to the landscape cannot be overlooked.

## 6. Discussion and Conclusions

Urbanization of coastal cities, nearshore geomorphology, and SLR will continue to affect the behavior of storm surge in coastal communities throughout the world. Because of these factors, new regions will become vulnerable to flooding and areas that already flood may experience increases in both frequency and depth. We have evaluated the interaction between a change in LULC, topography, and coastal flooding for past (1960) and present (2005) sea states in addition to projections of LULC and SLR scenarios for future (2050) conditions. Simulating past conditions provides an accurate approach to understanding how storm surge may be altered by the landscape. Changes to the nearshore topography can amplify storm surge by more than 80% over the amount of SLR in many regions but may also decrease surge levels by over 100% of the applied SLR, as shown around the Pascagoula River floodplain. On the other hand, adjusting the model for projections of future urbanization amplifies maximum surge by 70% over the applied SLR.

We also find that modifying the barrier islands does not necessarily change the amount of area inundated, but it considerably modifies the flow path of storm surge, which in this case counteracts the LULC changes, as shown in the Pascagoula River floodplain. Furthermore, the results provide a corollary finding that the accurate inclusion of raised features within the model is extremely important in simulating correct storm surge patterns.

Results of the nonlinearity of coastal flooding induced by SLR and hurricane storm surge follow that of past studies [*Smith et al.*, 2010; *Rego and Li*, 2010; *Atkinson et al.*, 2013; *Mousavi et al.*, 2011]. However, the approach of examining the nonlinear response of storm surge to a changing landscape is novel. To our knowledge, this is the first study that incorporates past LULC and topography and future LULC change to examine the respective response to hurricane storm surge on coastal flooding. When evaluating coastal inundation due to hurricane storm surge under SLR scenarios, the authors recommend providing additional modifications to the modeling framework along with modifying the sea state. The modeling framework should consider future landscape changes via LULC projections as well as future projections of coastal morphology, such as barrier island and shoreline changes. Although projecting shoreline morphology and LULC for future conditions contains a high degree of uncertainty, including these scenarios in the modeling framework for future flood inundation studies allows for a more comprehensive assessment for long-term coastal management.

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