Continental Shelf Research 111 (2015) 150–158

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Impacts of historic morphology and sea level rise on tidal hydrodynamics in a microtidal estuary (Grand Bay, Mississippi)

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ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form
30 June 2015
Accepted 1 August 2015
Available online 7 August 2015

Keywords:
Tidal hydrodynamics
Sea level rise
Morphological changes
Barrier islands
Estuary
Mississippi sound

ABSTRACT

This study evaluates the geophysical influence of the combined effects of historic sea level rise (SLR) and morphology on tidal hydrodynamics in the Grand Bay estuary, located in the Mississippi Sound. Since 1848, the landscape of the Mississippi Sound has been significantly altered as a result of natural and anthropogenic factors including the migration of the offshore Mississippi–Alabama (MSAL) barrier islands and the construction of navigational channels. As a result, the Grand Bay estuary has undergone extensive erosion resulting in the submergence of its protective barrier island, Grand Batture. A large-domain hydrodynamic model was used to simulate present (circa 2005) and past conditions (circa 1848, 1917, and 1960) with unique sea levels, bathymetry, topography and shorelines representative of each time period. Additionally, a hypothetical scenario was performed in which Grand Batture Island exists under 2005 conditions in order to observe the influence of the island on tidal hydrodynamics within the Grand Bay estuary. Changes in tidal amplitudes from the historic conditions varied. Within the Sound, tidal amplitudes were unaltered due to the open exposed shoreline; however, in semi-enclosed embayments outside of the Sound, tidal amplitudes increased. In addition, harmonic constituent phases were slower historically. The position of the MSAL barrier island inlets influenced tidal currents within the Sound; the westward migration of Petit Bois Island allowed stronger tidal velocities to be centered on the Grand Batture Island. Maximum tidal velocities within the Grand Bay estuary were 5 cm/s faster historically, and reversed from being flood dominant in 1848 to ebb dominant in 2005. If the Grand Batture Island was reconstructed under 2005 conditions, tidal amplitudes and phases would not be altered, indicating that the offshore MSAL barrier islands and SLR have a greater influence on these tidal parameters within the estuary. However, maximum tidal velocities would increase by as much as 5 cm/s (63%) and currents would become more ebb dominant. Results of this study illustrate the hydrodynamic response of the system to SLR and the changing landscape, and provide insight into potential future changes under SLR and barrier island evolution.

1. Introduction

SLR has the potential to alter astronomic tidal hydrodynamics by increasing tidal ranges, tidal prisms and inundation, as well as changing current velocities and circulation patterns (French, 2008; Leorri et al., 2011; Hall et al., 2013; Valentim et al., 2013). Within estuaries, tidal asymmetries and resulting sediment transport patterns may be fundamentally altered if rising seas increase channel depths or alter the volume of water stored in the intertidal zone (Friedrichs et al., 1990). In addition, changes in coastal topography can influence the hydrodynamic response under SLR (Bilskie et al., 2014; Passeri et al., 2015). Changes in tidal hydrodynamics have important implications for navigation, fisheries, coastal flooding, and the evolution of the coastline. However, the complexities in coastal processes make determining the future impacts of SLR and coastal topography a difficult task. Evaluating historic changes in hydrodynamics under a changing landscape coupled with SLR can provide insight as to how water levels and currents may change in the future.

The marine dominant Grand Bay estuary is one of the few remaining coastal marsh environments in Mississippi. Over the past century, the estuary has undergone natural and anthropogenic induced landscape changes including the diversion of the estuary's sediment source and the erosion of its protective barrier island, Grand Batture. As a result, Grand Bay's marshes are being eroded

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http://dx.doi.org/10.1016/j.csr.2015.08.001

away faster than any other marsh in the state (Mississippi Department of Marine Resources, 1999). The fate of the estuary depends on scientifically informed managerial decisions regarding factors such as SLR and changes in coastal morphology. This research examines the geophysical influence of SLR and historic morphology on tidal hydrodynamics. A high resolution large-domain hydrodynamic model was used to simulate present (circa 2005) and past conditions (circa 1848, 1917, and 1960) with unique sea levels, bathymetry, topography and shorelines that represent the conditions at those times. Additionally, a hypothetical scenario was performed in which Grand Batture Island exists under 2005 conditions to observe the influence of the island on tidal hydrodynamics. Changes in variables such as harmonic constituent amplitudes, phases and current velocities were examined. Comparison of past and present conditions illustrates the tidal hydrodynamic response of the system to SLR and the changing landscape. This yields a better understanding of the function of coastal morphology and the role of SLR on tidal hydrodynamics, while providing insight into potential future changes.

2. Study domain

The Grand Bay estuary is located within the Mississippi Sound at the MSAL border in the northern Gulf of Mexico (Fig. 1). The estuary is comprised of two bays (Point aux Chenes Bay and Grand Bay), bayous, and marsh shorelines. The bays are shallow with average water depths ranging from 0.5 m to 1.8 m, and up to 3.0 m at the tidally scoured entrance to Point aux Chenes Bay (Peterson et al., 2007). The estuary supports recreational and commercial fisheries with an abundance of marine life including shrimp, crabs and oysters (Eleuterius and Criss, 1991). This portion of the Gulf of Mexico is a diurnal, microtidal environment. The offshore MSAL barrier islands (namely Cat Island, Ship Island, Horn Island, Petit Bois Island and Dauphin Island) define the boundary between the Mississippi Sound and the Gulf of Mexico. Three of the barrier island inlets have been modified and connected to mainland ports via navigation channels: Mobile Ship Channel at the inlet to Mobile Bay, Pascagoula Channel at Horn Island Pass, and Gulfport Ship Channel at Ship Island Pass. In addition, the dredged Gulf Intracoastal Water Way (GIWW) navigation channel extends east to west through the Mississippi Sound.

Historically, the Escatawpa River flowed south–southeast and emptied into the Mississippi Sound at Grand Bay, creating a delta that encompassed the entire estuary and was sheltered by Dauphin Island. At this time, erosion was limited due to weak tidal and wave forces within the Sound, and was typically counteracted by sediment deposited by the Escatawpa River. However, prior to 1848 (exact time unknown) the river diverted its course and became a tributary of the Pascagoula River, which terminated the direct sediment supply to Grand Bay (Eleuterius and Criss, 1991). During the period of 1740–1766, a hurricane bisected Dauphin Island, creating an inlet and a new island called Petit Bois (Otvos, 1979). By 1848, waves and currents in Grand Bay had shaped deposited deltaic sediments into the Grand Batture Island, an elongated barrier island that sheltered the estuary from northerly directed waves (Eleuterius and Criss, 1991). Dredging of the navigation channels began in the mid-1800s. By 1857, the Mobile Ship Channel was in place; as early as 1880, construction began on the Pascagoula Channel, and in 1899, the Ship Island Pass began.

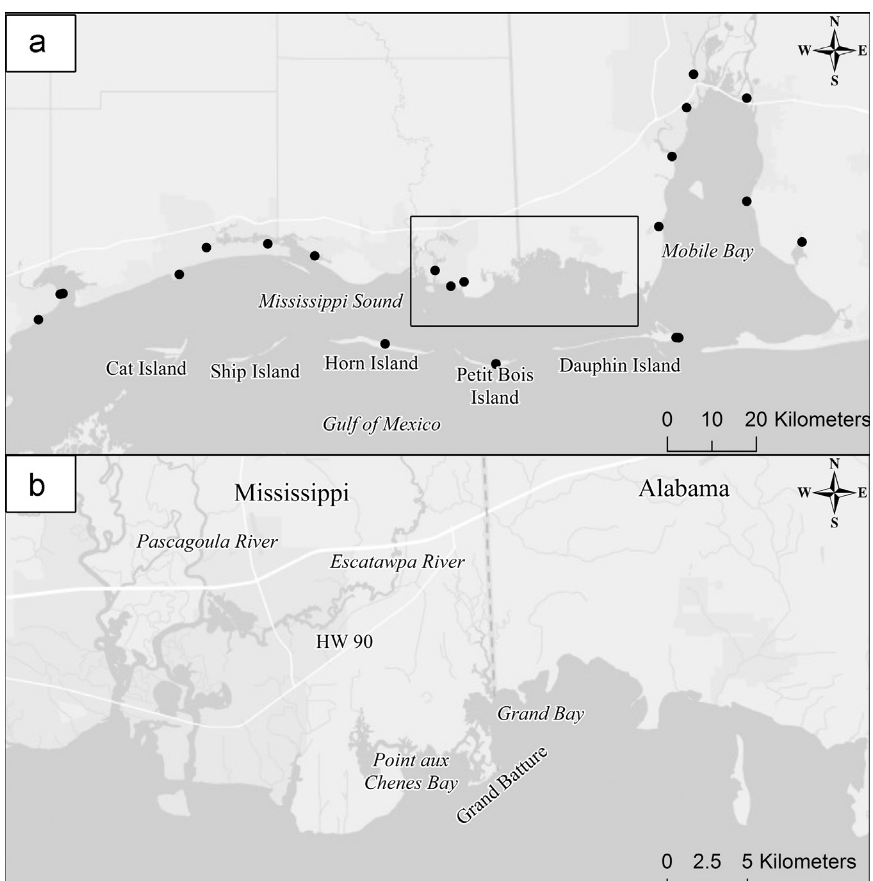

Fig. 1. (a) Present day Mississippi Sound study area; (b) zoomed in inset of Grand Bay estuary; black dots indicate locations of NOAA gauge stations used for model validation.

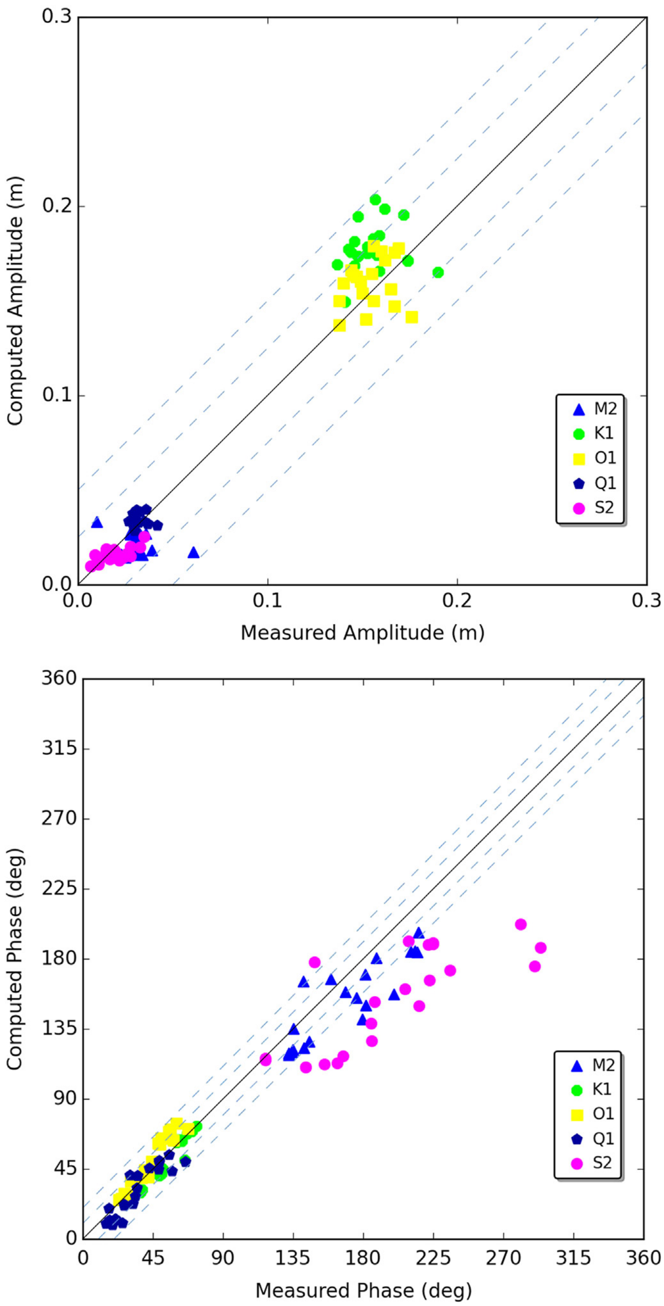

Fig. 2. Comparison of amplitudes (top) and phases (bottom) measured by NOAA and predicted by the hydrodynamic model. Difference bands are located at 0.025 m and 0.05 m in the amplitude plot, and 10° and 20° in the phase plot.

Various studies have examined the influence of the shipping channels on sediment transport in the Mississippi Sound and have found strong evidence that the channels prevent sediment bypassing around the ebb-tidal deltas, thereby depriving the downdrift shorelines of the barrier islands (Morton, 2008; Douglass, 1994; Cipriana and Stone, 2001; Rosati et al., 2007).

During the 20th century, Grand Bay and the Mississippi Sound underwent major landscape changes due to erosion from normal tidal and wave forces, as well as hurricanes. The eastern end of Dauphin Island, fixed by its Pleistocene core, remained in place but the western end grew through lateral spit accretion (Byrnes et al., 1991; Morton, 2008; Rosati and Stone, 2009). Petit Bois Island began narrowing and rotated counterclockwise on the eastern spit as a result of wave refraction and storm driven overwash, which widened the pass to Dauphin Island. The eroded sediment was deposited on the western end of Petit Bois Island and in Horn Island Pass (Morton, 2008). Horn Island and Horn Island Pass also migrated westward (Byrnes et al., 1991). By 1921, multiple hurricanes and tropical storms within the area had fragmented the Grand Batture Island into several islands (Eleuterius and Criss, 1991). Meanwhile, the pass between Petit Bois Island and Dauphin Island continued to widen. In the late 1920s, Highway 90 was constructed in Mississippi, solidifying the diversion of the Escatawpa River from Grand Bay. Since 1957, the western end of Petit Bois Island has remained in place against the Horn Island Pass due to the maintained navigation channel (Byrnes et al., 1991). The Grand Batture Island continued to erode until 1969 when Hurricane Camille reduced the majority of the island to sand shoals (Eleuterius and Criss, 1991). By 1980, all remnants of the former islands were submerged (Peterson et al., 2007). Lack of protection from the Grand Batture Island and the offshore barriers allowed continuous erosion to reshape Grand Bay's shoreline under normal and extreme conditions. In addition, higher saline waters entering the estuary from the Sound altered marine life, significantly reducing the oyster population in the estuary over the past century (Peterson et al., 2007).

3. Methodology

3.1. Hydrodynamic model

To simulate historic changes in tidal hydrodynamics, ADCIRC-2DDI (Luettich et al., 1992), a two-dimensional code that solves the depth-integrated shallow water equations for water surface elevations and currents was employed. The unstructured finite element mesh describes the Western North Atlantic Tidal (WNAT) model domain west of the 60° W meridian (open ocean boundary), including the Caribbean Sea and the Gulf of Mexico. Higher resolution elements (on the order of 20–100 m) were incorporated within the MSAL coast, which permits localized adjustments of the landscape to be made. The model was developed to represent elevations circa 2005 (post-Katrina) using a Digital Elevation Model (DEM) constructed with lidar data, as well as NOS (National Ocean Service) hydrographic surveys, U.S. Army Corps of Engineers (USACE) channel surveys and NOAA (National Oceanographic and Atmospheric Administration) nautical charts. Within the Grand Bay marsh, an elevation correction based on biomass density was used to adjust the lidar-derived elevations. This technique uses ASTER and IfSAR satellite imagery along with lidar-derived canopy heights to classify the above-ground biomass density as high, medium or low. This biomass density class was then used to lower the lidar DEM by 32, 23 and 16 cm, respectively (Medeiros et al., 2015). Further information on mesh development and topographic elevations can be found in Bilskie et al. (2015).

The hydrodynamic model was validated with available historic storm surge data for Hurricane Katrina (Bilskie et al., 2015) and astronomic tide data. The tidal validation was performed at 18 NOAA tide gauges located throughout the study domain (see locations in Fig. 1). Astronomic tides were simulated for 45 days beginning from a cold start with a 10-day hyperbolic tangent ramp function. The model was forced with water surface elevations of eight harmonic constituents (K1, O1, M2, S2, N2, K2, Q1, and P1) along the open ocean boundary (Egbert et al., 1994; Egbert and Erofeeva, 2002). Model output consisted of 23 tidal constituents, which were validated against reported tidal constituents at each of the tide gauge stations (http://tidesandcurrents.noaa.gov/) by comparing resynthesized observed and simulated tidal signals. A comparison of the NOAA-measured and model-computed amplitudes and phases for five dominant constituents (K1, O1, M2, Q1 and S2) is shown in Fig. 2. Difference bands are plotted at 0.025 m and 0.05 m in the amplitude plots, and 10° and 20° in the phase plots. All of the constituent amplitudes fell within the 0.05 m difference band, and for the most part, the phases of the three most dominant constituents (K1, O1 and M2) fell within the 20° difference band. Although the S2 phases deviated the most, the contribution of this constituent is minimal in comparison with K1, O1 and M2.

3.2. Historic simulations

When conducting historic (or future) evaluations of the effects of SLR, it is necessary to properly represent the dynamics in the physical system; this study aims to recreate historic conditions to observe the changing tidal hydrodynamic response. Historic shoreline positions in the Grand Bay estuary circa 1848, 1917 and 1960 were obtained from the Mississippi Department of Environmental Quality Office of Geology. Historic bathymetric DEMs within the Mississippi Sound for the time periods of 1847–1856, 1917–1920, and 1960–1970 were obtained from Buster and Morton (2011). The DEMs were constructed using historic bathymetric soundings and digitized shoreline positions from historic NOAA T-sheets. The most significant changes in the bathymetry were surrounding the MSAL barrier islands as a result of the migration of the islands, as well as the construction of the dredged shipping channels; elsewhere, changes were minimal. The overall vertical uncertainty in the DEMs is 0.5 m (Buster and Morton, 2011).

Using the historic data, the hydrodynamic model representing present day (i.e., 2005) conditions was altered to reflect historic conditions circa 1848, 1917 and 1960. To do so, the DEM was updated with the historic shoreline positions and bathymetric data. This included removing the dredged shipping channels and the GIWW within the Mississippi Sound, altering depths within the Mississippi Sound according to the historic bathymetry, and shifting shoreline positions within the Grand Bay estuary and along the MSAL barrier islands. In addition, the DEM was altered to reflect historic marsh surface elevations in Grand Bay; assuming the marsh is currently in equilibrium, the historic marsh elevation is equal to the present elevation minus the amount of sea level change, determined from the mean sea level trend. Historic sea levels were estimated using the linear mean sea level trend at a nearby NOAA tide gauge located near Dauphin Island. The mean sea level trend inclusive of vertical land movement is 2.98 mm/year, based on monthly mean sea level data from 1966 to 2006. Therefore, historic sea levels were 0.47 m, 0.26 m, and 0.13 m below present day sea level (circa 2005) for the years 1848, 1917, and 1960, respectively. Lastly, a fifth hypothetical scenario was devised in which Grand Batture Island exists under 2005 conditions; the Grand Bay shoreline in the 2005 model was modified to include the Grand Batture Island (this is herein referred to as the 2005-GBI scenario). The purpose of this scenario is to examine the influence of the island on tidal hydrodynamics, which may aid future assessments of barrier island reconstruction. Additionally, this will provide insight on the role of barrier islands on estuarine hydrodynamics, which may be beneficial for studies elsewhere.

Inspection of the model elevations illustrates the elevation changes in the barrier islands (Fig. 3). In 1848, Petit Bois Island was longer than in 2005 and sheltered most of the Grand Bay estuary. The significant erosion of the eastern spit is visible in the 1917 and 1960 models. In addition, Dauphin Island had elongated westward from 1848 to 1917, although a large breach existed in the middle of the island in 1917 as a result of a hurricane. In 1960, the island was reconnected, but was breached again in 2005 by Hurricane Katrina. In Grand Bay, the Grand Batture Island was still in place in 1848, was breached in two locations in the center in 1917 (Eleuterius and Criss, 1991), and was reduced almost completely to a sand shoal in 1960 as it remains today.

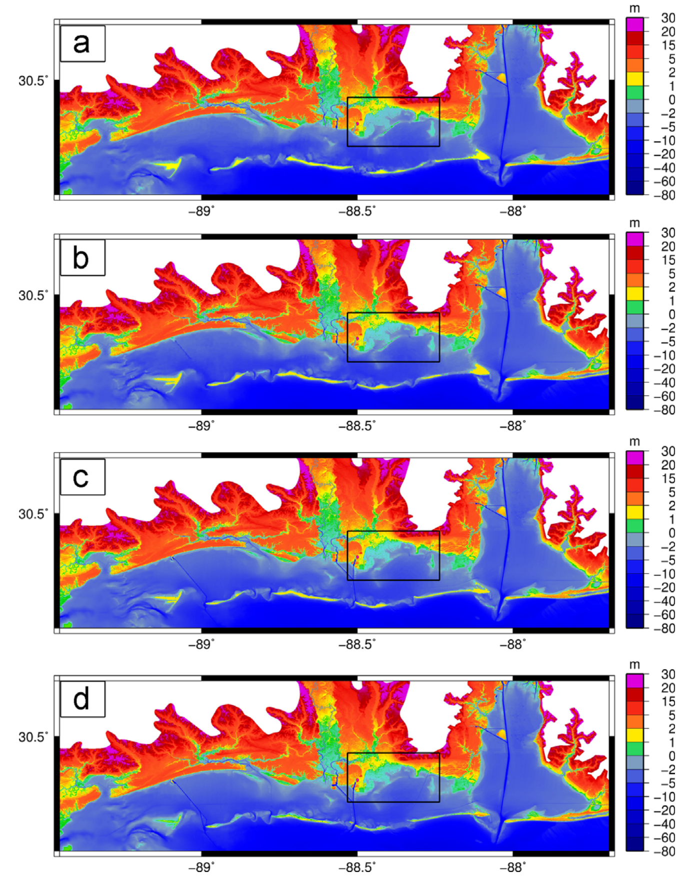

Fig. 3. Model elevations circa (a) 1848, (b) 1917, (c) 1960 and (d) 2005 using historic bathymetry and shoreline positions in the Mississippi Sound; black boxes indicate location of the Grand Bay estuary. Notable changes include gains and losses of land along the offshore MSAL barrier islands, presence and size of inlets, the existence of the dredged shipping channels, and the submergence of the Grand Batture Island in the Grand Bay estuary. White regions are outside of the model boundary.

For each of the five scenarios (1848, 1917, 1960, 2005, and 2005-GBI) astronomic tides were simulated for 45 days from a cold start with a 10 day ramp. In addition to forcing the eight harmonic constituents at the open ocean boundary, a ninth “steady” component was included with an amplitude equal to the amount of sea level change for the given scenario to lower the sea level accordingly. As the goal was to simulate tidal hydrodynamics in response to SLR and landscape changes, morphologic processes were not simulated concurrently. Model output consisted of depth-integrated velocities, amplitudes and phases of harmonic constituents, as well as maximum elevations of water and maximum velocities obtained at each node of the mesh for the duration of the simulation.

4. Results

The diurnal K1 (principal lunar and solar) and O1 (principal lunar) harmonic constituents dominate tides along this portion of the Gulf of Mexico; the semidiurnal M2 (principal lunar) tide is almost an order of magnitude smaller than the diurnal tides. In 2005, the simulated total tidal amplitude (i.e., the sum of the constituent amplitudes) was 45 cm west of Cat Island, 50–55 cm within the Mississippi Sound, and 45–50 cm in Mobile Bay. Tides propagate parallel to the coast from east to west and enter the Sound through the inlets of the MSAL barrier islands. Tidal current speeds increase up to 30 cm/s within the inlets. Inside the Sound,

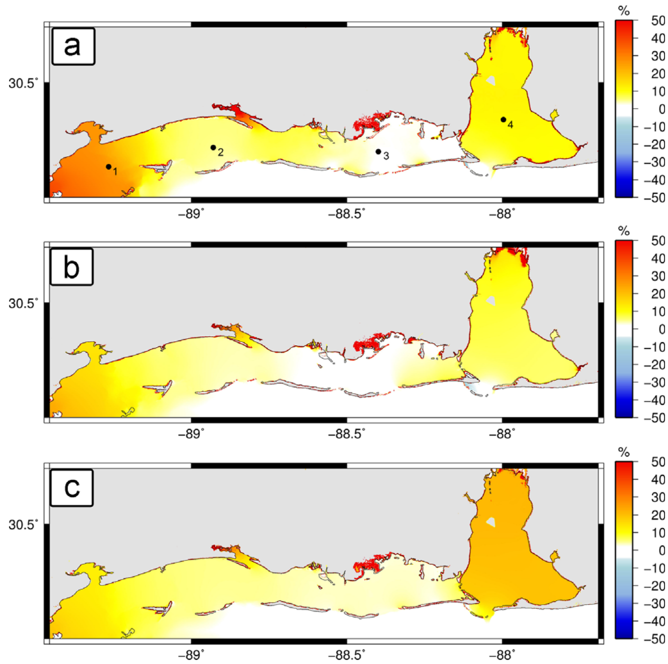

Fig. 4. Percent change in total tidal amplitude from (a) 1848 to 2005, (b) 1917 to 2005 and (c) 1960 to 2005. The black line represents the 2005 shoreline; differences greater than 0 indicate percent increases in tidal amplitude from the historic condition to 2005, differences less than 0 indicate percent decreases in the tidal amplitude from the historic condition to 2005. The dots in (a) represent locations where constituent amplitudes are measured in Table 1.

current speeds decrease. Semidiurnal overtides and compound tides, which are enhanced within the inlets, result in an asymmetric distortion of the tides with maximum ebb-directed currents and double peaked flood currents (Seim and Sneed, 1988).

4.1. Water levels

Percent changes in the total tidal amplitude from the historic conditions to 2005 were examined (Fig. 4). Differences greater than 0 indicate the tidal amplitude increased from the historic condition, differences less than 0 indicate the tidal amplitude decreased from the historic condition and differences equal to 0 indicate the tidal amplitude is unchanged from the historic condition. Overall, the magnitude of change was relatively small as a result of the system being microtidal. The largest change occurred west of Cat Island, with increases of 28% (10.0 cm), 15% (6.2 cm) and 13% (5.3 cm) from 1848, 1917 and 1960, respectively. Tidal amplitudes were also altered in Mobile Bay, with increases of 11% (4.4 cm), 7% (3.0 cm) and 20% (7.5 cm) from 1848, 1917 and 1960, respectively. The increase in Mobile Bay from the 1960 scenario resulted from the submergence of the southern spit off of eastern Dauphin Island; the spit was longer in 1960 which restricted tidal flow through the inlet. Within the Mississippi Sound, changes in tidal amplitudes were not as significant. Amplitudes minimally increased in the western portion of the Sound by 5% (2.7 cm), 4% (2.2 cm) and 5% (2.7 cm) from 1848, 1917 and 1960. In the eastern portion of the Sound and within Grand Bay, amplitudes were unaltered from 1848 and 1917, and minimally increased by 3% (1.6 cm) from 1960. This indicates that barrier island migration was not impactful in altering tidal amplitudes. SLR was more influential in altering amplitudes in Mobile Bay than in the Sound, most likely due to the bay having a semi-enclosed shoreline that connects to the Gulf of Mexico with a single inlet. There were no changes in tidal amplitudes offshore, illustrating the greater influence of SLR on the embayments than in the open ocean. Also, there were no changes in the 2005 vs. 2005-GBI scenario, again illustrating the greater influence of SLR than the morphological changes.

To further examine changes in tidal amplitudes, percent changes in the K1, O1 and M2 constituents at the locations specified in Fig. 4 were examined (Table 1). Spatial changes in the amplitudes of the diurnal K1 and O1 constituents were similar in magnitude and pattern. As seen with the total tidal amplitudes, the largest increases from the historic conditions occurred west of Cat Island and within Mobile Bay (as much as 3.1 cm increase west of Cat Island, and 2.5 cm increase in Mobile Bay from 1848). In the eastern portion of the Sound, changes from the historic conditions were minimal. In Mobile Bay, increases in the diurnal constituent amplitudes from 1848 to 2005 were almost equivalent to the increases from 1960 to 2005, indicating that the combined effects of SLR and morphological changes were influential in altering the constituent amplitude, rather than the effects of SLR alone. Within the Sound, the percent change in the M2 amplitude was typically larger than the changes in the diurnal constituents, especially at locations 1 and 3, which were stationed immediately behind barrier island inlets. This is due to the enhancement of the semidiurnal tides within the barrier island inlets (Seim and Sneed, 1988). However, the changes in the M2 amplitudes were small relative to the total tidal amplitude and therefore were not influential.

Tidal propagation throughout the Mississippi Sound and Grand Bay also changed from the historic conditions. In the 2005 simulation, constituent phases were equal inside of the Sound and offshore of Ship Island. East of Horn Island, phases were lagged within the Sound in comparison with the offshore, indicating slower propagation through the eastern inlets. Differences in harmonic constituent phases were examined to observe changes in tidal propagation; the difference in the K1 amplitude from the historic conditions to 2005 is summarized in Fig. 5. Differences equal to 0 indicate the constituent phase was unchanged in 2005 from the historic scenario, differences greater than 0 indicate the constituent phase sped up from the historic scenario, and differences less than 0 indicate the constituent phase was slower than in the historic scenario.

Similar to the constituent amplitudes, changes in the K1 and O1 phases were nearly the same in pattern and magnitude. The effects of SLR strongly influenced tidal propagation within the Mississippi Sound. In 2005, the K1 phase was approximately 19 min faster in the Sound and 28 min faster in Mobile Bay than in 1848. Directly behind the 1848 location of Petit Bois Island and within Grand Bay,

Table 1
Percent change in constituent amplitudes from 1848 to 2005, 1917 to 2005 and 1960 to 2005 at locations 1–4, illustrated in Fig. 4.

	2005 Amplitude			% Change from 1848			% Change from 1917			% Change from 1960		
	K1	*O1*	*M2*	*K1*	*O1*	*M2*	*K1*	*O1*	*M2*	*K1*	*O1*	*M2*
1	0.16	0.14	0.02	24	24	20	12	11	14	8	8	18
2	0.19	0.18	0.03	5	4	6	4	3	5	3	3	12
3	0.17	0.16	0.02	−1	0	60	1	1	15	2	2	16
4	0.16	0.15	0.01	18	13	2	14	9	−13	16	17	34

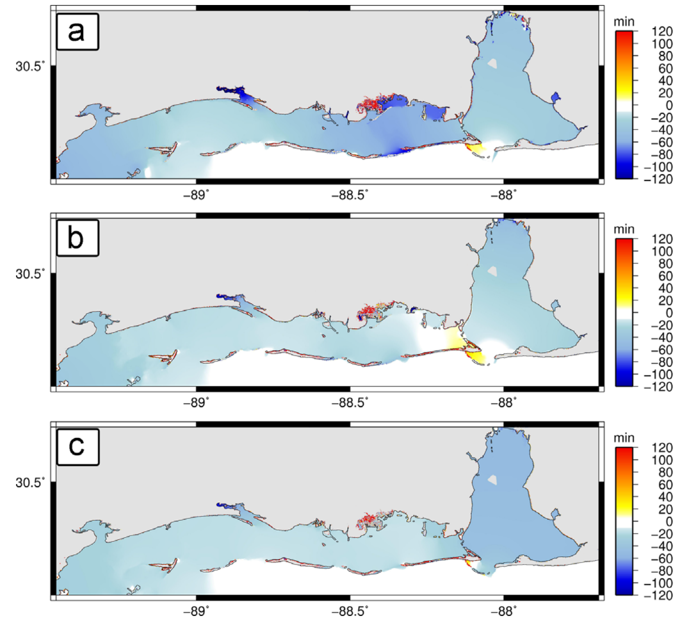

Fig. 5. Phase differences of the K1 constituent from (a) 1848 to 2005, (b) 1917 to 2005 and (c) 1960 to 2005. The black line represents the 2005 shoreline; differences equal to 0 indicate the constituent phase is unchanged from the historic scenario, differences greater than 0 indicate the constituent phase is slower in 2005 than the historic scenario, and differences less than 0 indicate the constituent phase is faster in 2005 than the historic scenario.

the phase sped up in the 2005 scenario as a result of the westward migration of the island; within Grand Bay, the K1 phase was faster by approximately 90 min in 2005. Overall, the magnitude of change in the K1 phase in the 1917 vs. 2005 scenario was less than in the 1848 vs. 2005 scenario. The 1917 breach in Dauphin Island influenced tidal propagation into the Sound. Immediately behind the breach (which also existed in 2005, but was wider in 1917) there was no difference in the K1 phase, although the phase was faster by approximately 10 min on the eastern side of Dauphin Island in 1917. In the 1960 vs. 2005 scenario, differences in the K1 phase were more uniform across the Sound, with phases being approximately 17 min faster in 2005. This change was driven more by SLR, since changes in barrier island morphology were minimal from 1960 to 2005. In Mobile Bay, phases were faster by 47 min in 2005 than in 1960, further illustrating the influence of the spit off of Dauphin Island inhibiting tidal flows. No phase changes were observed in the diurnal or semidiurnal constituents in the 2005 vs. 2005-GBI scenario.

4.2. Currents

The migration of the MSAL barrier islands also influenced tidal currents within the Mississippi Sound and Grand Bay. Changes in the maximum tidal velocities between the 1848 vs. 2005, 1917 vs. 2005, 1960 vs. 2005 and 2005 vs. 2005-GBI scenarios are summarized in Fig. 6. Differences larger than 0 indicate the maximum velocity has increased from historic conditions, differences less than 0 indicate the maximum velocity has decreased from historic conditions. Maximum differences on the order of 20 cm/s occurred within the historic and present locations of the inlets between the MSAL barrier islands, further illustrating the role of the barrier islands in tidal propagation to the Sound. The size and position of the inlets not only control the strength of the currents, but also where the currents are directed in the Sound. As Petit Bois Pass migrated westward, stronger tidal velocities were centered along Grand Batture Island (approximately 5 cm/s stronger in 2005 than in 1848, and 10 cm/s stronger in 2005 than in 1917). This could

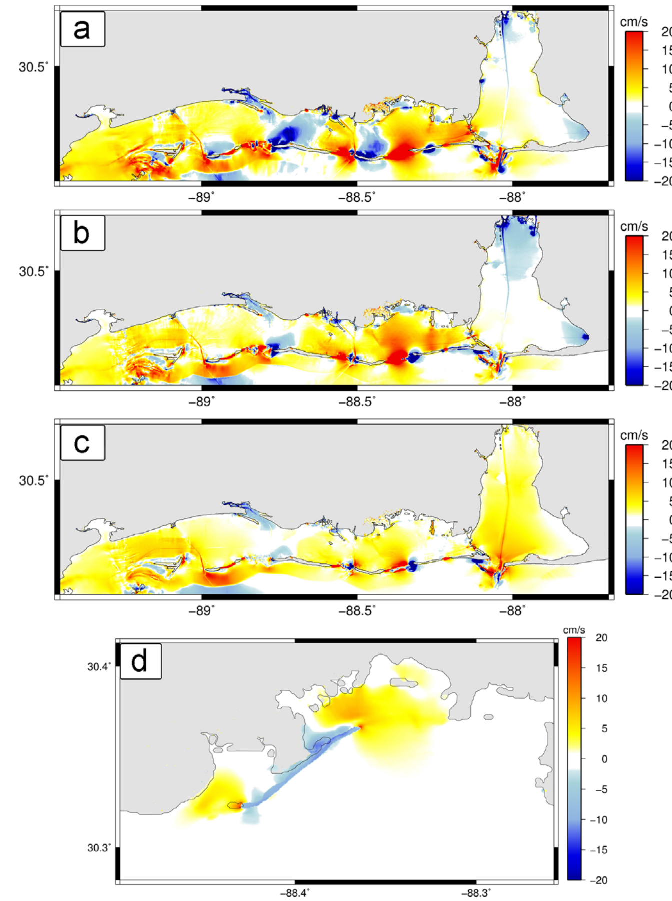

Fig. 6. Differences in maximum tidal velocities from (a) 1848 to 2005 (b) 1917 to 2005 (c) 1960 to 2005 (d) 2005 to 2005-GBI. The black line represents the 2005 shoreline; differences greater than 0 indicate maximum tidal velocities have increased from the historic condition, differences less than 0 indicate maximum tidal velocities have decreased from the historic condition, differences equal to 0 indicate maximum velocities have not changed.

have contributed to the erosion of the island. Maximum tidal velocities did not change within Point aux Chenes Bay, but were approximately 5 cm/s (63%) faster in Grand Bay in 1848 than in 2005. Similarly in the 2005-GBI simulation, maximum velocities were approximately 5 cm/s (63%) faster in both Point aux Chenes and Grand Bay when Grand Batture Island was present. Since 1960, tidal velocities have increased by less than 5 cm/s in the shadow of Petit Bois Pass, with minimal changes in Point aux Chenes Bay and Grand Bay. Velocities also increased from the historic conditions within the dredged shipping channels and the GIWW. Magnitudes of residual currents (i.e., the tidal cycle average of the tidal current) minimally increased from historic conditions (on the order of millimeters) in the Grand Bay estuary, with slight directional changes from predominately northerly directed currents in the 1848 scenario (and 2005-GBI) to more easterly directed currents in the 2005 scenario.

The flood-ebb ratio (R), the ratio of the magnitude of the maximal flood (U_{flood}) to the maximal ebb (U_{ebb}) currents, indicates if asymmetry exists in the current velocities

$$R = \frac{U_{flood}}{U_{ebb}}$$

where ratios equal to 1 indicate equal magnitudes of flood and ebb currents (no asymmetry), ratios larger than 1 indicate stronger flood currents than ebb currents (flood dominance), and ratios less than 1 indicate stronger ebb currents than flood currents (ebb dominance). Flood-ebb ratios for 1848, 1917, 1960 and 2005 are

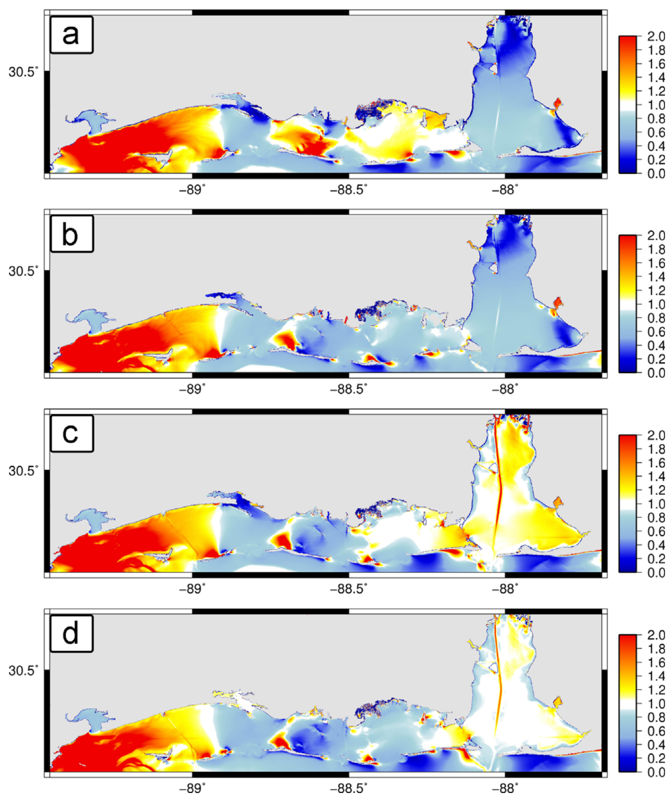

Fig. 7. : Flood-ebb ratios for (a) 1848, (b) 1917, (c) 1960, and (d) 2005. The black line represents the 2005 shoreline; flood-ebb ratios greater than 1 indicate stronger flood currents; ratios less than 1 indicate stronger ebb currents.

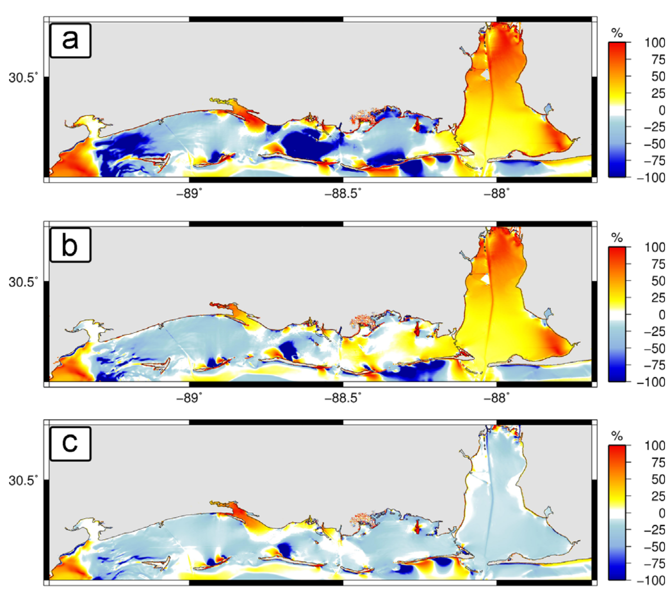

Fig. 8. Percent change in flood-ebb ratio from (a) 1848 to 2005, (b) 1917 to 2005 and (c) 1960 to 2005.

summarized in Fig. 7 as well as percent changes in flood-ebb ratios for 2005 vs. 1848, 2005 vs. 1917 and 2005 vs. 1960 in Fig. 8. Percent changes equal to 0 indicate no change in the flood-ebb ratio, percent changes greater than 0 indicate currents have become more flood dominant, percent changes less than 0 indicates currents have become more ebb dominant. In the 2005 scenario, the majority of the Sound, Point aux Chenes and Grand Bay had ebb dominant currents. In 1848, portions of the eastern Sound and Grand Bay had flood dominant currents. From 1848 to 2005, the flood-ebb ratio decreased by approximately 9% in Point aux Chenes Bay and 77% in Grand Bay. Since 1917, the flood-ebb ratio remained relatively the same in Point aux Chenes Bay, but decreased by approximately 20% in Grand Bay. In addition, the ratio decreased by approximately 17% landward of Petit Bois Island. Since 1960, the flood-ebb ratio decreased by approximately 10% to 20% throughout most of the Sound. Within the estuary, the ratio decreased by approximately 12% in Point aux Chenes Bay and 23% in Grand Bay. Lastly, the flood-ebb ratio decreased by approximately 20% in Grand Bay in the 2005 vs. 2005-GBI scenario, indicating that currents would be more ebb-dominant if the Grand Batture Island was reconstructed under present day conditions.

5. Implications

The results of this study reinforce the necessity of considering changes in morphology in SLR assessments, as previous studies have concluded (Bilskie et al., 2014; Passeri et al., 2015); this allows for more comprehensive evaluations. Changes in tidal hydrodynamics are an important consideration for how ecology within the estuary has evolved historically, and how reconstruction of the Grand Batture Island could affect various species. For example, tidal asymmetries affect sediment transport in marsh tidal creeks, which influences sediment supply. Flood dominant currents in tidal creeks tend to move sediment landward, whereas ebb dominant currents tend to move sediment seaward. Flood dominant currents also increase suspended sediment concentrations at the creek/marsh boundary, which supplies more marine sediment to the marsh and allows for accretion on the marsh platform. Conversely, ebb dominant currents can reduce the sediment supply. As currents within Grand Bay became progressively ebb dominant through time, the sediment transport to the marshes may have been altered. Microtidal marsh systems such as Grand Bay are especially sensitive to changes in suspended sediment concentrations because they are unable to easily adjust their mean platform elevation with respect to the tidal elevation; a relatively small increase in sea level or a decrease in accretion can cause a microtidal marsh to become submerged (Friedrichs and Perry, 2001). Additionally, vertical land movement in conjunction with reduced sediment supply and SLR may lead to marsh submergence (Day et al., 2007; Morton et al., 2002; Reed 2002; Roberts 1997). Marsh conversion to open water may increase fetch and erosional processes (Reed, 2002). Tidal currents also transport nutrients to seagrass beds (Koch et al., 2007). Similar to marshes, seagrass growth is influenced by flood and ebb current strengths (Boer, 2000). Changes in the magnitudes of currents could alter the amount of sediment and nutrients in the water column, thereby affecting seagrass productivity. This is an important consideration for the seagrass beds located in Point aux Chenes and Grand Bay. If the Grand Batture Island was reconstructed, currents would become more ebb dominant which could alter the productivity of these beds. Lastly, increased flow rates can negatively affect oyster recruitment. Flow rates affect larvae delivery and position maintenance during and after settlement (Boudreaux et al., 2009). Again, this is an important consideration if the Grand Batture Island was reconstructed, which would increase current velocities by 5 cm/s.

Examining historic changes in tidal hydrodynamics can also provide insight into the effects SLR and future landscape changes. Within 157 years, the Mississippi Sound and Grand Bay experienced significant changes in morphology in conjunction with approximately 47 cm of SLR. As sea levels continue to rise and the MSAL islands evolve, tidal hydrodynamics within the Mississippi Sound and the Grand Bay estuary will be further altered. The future of the MSAL barrier islands is dependent on the strength of the islands cores and whether sufficient sand will be available as sea levels rise and storms continue to modify the landscape. The western three fourths of Dauphin Island is presently in a transgressive state; predominant transport is onshore rather than alongshore which allows the barrier to preserve a minimum volume as it migrates landward. Although it is unclear if Petit Bois Island and Horn Island will also enter transgressive phases, it is likely that longshore transport driven by winds, waves and currents will continue in the future. Petit Bois Island is prevented from moving further westward because of the dredged shipping channel at Horn Island Pass. It is expected that Petit Bois Island will continue to erode on the eastern end and narrow under updrift erosion. In addition, it is likely that the island will breach along the narrowest, concave-landward area, where overwash frequently occurs. Horn Island is also expected to narrow, but breaching is unlikely because of the beach-ridge topography that is oriented obliquely to the mainland shoreline (Morton, 2008).

By the year 2100, sea levels are projected to rise between 20 cm and 2 m; the 47 cm of SLR in the study domain between 1848 and 2005 is roughly equivalent to the intermediate-low projection of SLR for the year 2100 (Parris et al., 2012). Under this moderate amount of SLR, it is expected that tidal amplitudes will continue to increase west of Cat Island and Mobile Bay, whereas changes within the Mississippi Sound will be minimal. As Petit Bois Island continues to erode on the eastern end, the widening of Petit Bois Pass most likely will not affect tidal amplitudes. The phases of the constituents are expected be altered under future SLR; as seen in the historic scenarios, future SLR may speed up tidal phases within the Sound, Mobile Bay and Grand Bay. Stronger tidal currents in the inlets will continue to shift westward as Petit Bois Pass and Horn Island Pass migrate. Currents within the Grand Bay estuary are likely to become more ebb dominant under future SLR. Under higher rates of SLR, changes in tidal hydrodynamics may be exacerbated and should be evaluated.

The findings of this study are unlikely unique to the Grand Bay estuary and the Mississippi Sound. In microtidal environments with open exposed shorelines (similar to the study area presented herein), it is expected that tidal amplitudes will minimally change as sea level rises, although phases of harmonic constituents will likely speed up. Tidal velocities may be altered as a result of changes in inlet size and location due to barrier migration or breaching. These effects could be mitigated through nourishment and inlet stabilization. Changes in flood and ebb dominance in tidal velocities are likely to result from SLR or barrier island loss. Changes attributed to SLR (such as those seen in the 1960 vs. 2005 scenario) will be difficult to alleviate.

6. Conclusions

Comparison of past and present tidal hydrodynamics illustrates the response of the system to SLR and the changing landscape. This provides a better understanding of the function of coastal morphology and the role of SLR on hydrodynamics. SLR had more of an impact on tidal amplitudes than the westward migration of the MSAL islands. Tidal amplitudes significantly increased in the semi-enclosed regions west of Cat Island and within in Mobile Bay, although changes within the Sound were minimal due to the open exposed shoreline. Overall, constituent phases sped up across the study domain from historic conditions as a result of SLR. The position of the MSAL barrier island inlets influenced tidal currents within the Sound; the westward migration of Petit Bois Island allowed stronger tidal velocities to be centered on the Grand Batture Island. Overall, there was a reduction in maximum tidal velocities in Point aux Chenes and Grand bays from the historic conditions. In addition, current velocities in both bays became more ebb dominant since 1848. If the Grand Batture Island was reconstructed under 2005 conditions, tidal amplitudes and phases would not be altered, indicating that the offshore MSAL barrier islands and SLR have a greater influence on the harmonic constituents within the estuary. However, maximum tidal velocities in Point aux Chenes and Grand Bay would increase by 5 cm/s and the flood-ebb ratio would decrease by 20% in Grand Bay, resulting in currents becoming more ebb dominant.

Ultimately, the results of this study provide insight into potential changes in tidal hydrodynamics under future SLR scenarios and further evolution of the MSAL barrier islands. This study highlights the importance of considering morphological changes in SLR assessments. Investigating historic changes in tidal hydrodynamics provides insight as to how coastal systems may evolve under future scenarios, and which hydrodynamic parameters may be altered. Although simulations of hurricane storm surge were beyond the scope of this study, future work will examine the influence of the dredged shipping channels and barrier island evolution on storm surge. Historical analyses of similar systems will improve the understanding of the effects of SLR and morphological changes on hydrodynamics in estuaries, and aid in coastal management decision making.

Acknowledgments

This research was funded in part under Award no. NA10-NOS4780146 from the Center for Sponsored Coastal Ocean Research, National Oceanic and Atmospheric Administration and the Louisiana Sea Grant Laborde Chair endowment. The STOKES Advanced Research Computing Center (ARCC) (webstokes.ist.ucf.edu) provided computational resources for the simulations. The authors would like to thank W. Underwood from the Grand Bay National Estuarine Research Reserve for providing data used herein, M. Donnelly for providing insight into potential ecological changes, and K. Alizad and the anonymous reviewers for their constructive comments. The statements and conclusions are those of the authors and do not necessary reflect the views of NOAA-CSCOR, the Louisiana Sea Grant Laborde Chair endowment, STOKES ARCC, or their affiliates.

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