Trends in Surface Elevation and Accretion in a Retrograding Delta in Coastal Mississippi, USA from 2012 – 2016

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Trends in surface elevation and accretion in a retrograding delta in coastal Mississippi, USA from 2012 – 2016

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Abstract

The Grand Bay estuary is in the north-central Gulf of Mexico and lacks riverine sediment input for marsh elevation maintenance. This study quantified trends in surface elevation change and accretion along an elevation gradient within the estuary. Elevation change rates were compared to short (13.71 mm/yr; 95% CI: -2.38 – 29.81), medium (6.97 mm/yr; 95% CI: 3.31 – 10.64), and long-range (3.50 mm/yr; 95% CI: 2.88 – 4.11) water level rise (WLR) rates for the region. Elevation change rates ranged from 0.54 mm/yr (95% CI: -0.63 – 1.72) to 5.45 mm/yr (95% CI: 4.27 – 6.62) and accretion rates ranged from 0.82 mm/yr (95% CI: -0.16 – 1.80) to 3.89 mm/yr (95% CI: 2.90 – 4.89) among marsh zones. Only the elevation change rate at a *Juncus roemerianus* marsh located high in the tidal frame was lower than long- ($P<0.001$) and medium-range WLR rates ($P<0.01$). The elevation change rate at a lower elevation *J. roemerianus* marsh was higher than the long-range WLR rate ($P<0.05$). No marsh zones had elevation change rates that were significantly different from short-range WLR. These results suggest that *J. roemerianus* marshes higher in the tidal frame with limited sediment delivery are the most vulnerable to increases in sea level. Lower elevation marshes had higher rates of elevation change driven by sediment accretion and biogenic inputs. Other local research suggests that shoreline erosion is a threat to marsh persistence but provides elevation capital to interior marshes. Marsh migration is potential solution for marsh persistence in this relatively undeveloped area of the Gulf Coast.

Key words: salt marsh, surface elevation table, accretion, sea level rise

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Introduction

Coastal marshes are complex ecosystems that provide a wide range of valued ecological functions, but they are also subjected to a variety of stressors that could impact their persistence in the landscape. Anthropogenic development is a prominent threat, but sea level rise (SLR) is being increasingly discussed as an additive threat to marshes that has the potential to affect marsh function (Cahoon et al. 2018; Osland et al. 2017). Development and SLR have additive impacts on marshes through "coastal squeeze," where anthropogenic barriers (e.g., roads, residential development, etc.) limit upslope movement of marshes as sea level rises (Borchert et al. 2018). The most obvious impact of coastal squeeze in heavily developed areas would be reductions of marsh extent and the degradation or loss of the ecological functions they provide. In the absence of transgression upslope, marshes must gain elevation at a rate equal to or greater than relative SLR to maintain their current footprint in the landscape.

Marsh elevation maintenance relies on sediment or biogenic accretion through biofeedback mechanisms often associated with marsh vegetation (e.g., sediment trapping by stems, root production) (Cahoon et al. 2006, 2021). Trends in surface elevation and accretion differ geographically, with the relative importance of physical and biological contributions to elevation maintenance varying within and among different wetland types. For example, in Atlantic coast estuaries, marshes have been shown to have high rates of surface accretion suggesting resilience to increasing sea level, whereas subsurface processes were drivers of elevation maintenance in forested wetlands (Stagg et al. 2016). In other areas along the Atlantic coast, variation in surface elevation change has been noted where local variability in elevation change among habitat types within an estuary was higher than seasonal or long-term variability (Childers et al. 1993). In the Chesapeake Bay, elevation change rates across an elevation gradient ranged from -9.8 ± 6.9 mm/yr to 4.5 ± 4.3 mm/yr from high to low marsh habitats, suggesting that marsh loss was imminent in some areas, but other areas appeared to be stable (Beckett et al. 2016).

Elevation change and accretion rates in the Gulf of Mexico are also highly varied, with high rates of marsh loss reported for some areas. For example, several Louisiana marshes are experiencing decreases in elevation from subsidence. Byrnes et al. (2019) documented subsidence rates of 2 – 7 mm/yr within the Barataria Basin, while Lane et al. (2006) measured subsidence rates that ranged from 5.9 – 27.8 mm/yr in estuaries receiving inputs from freshwater diversions. In St. Joseph Bay, Florida, marsh elevation was decreasing, while in Apalachicola Bay, Florida marsh elevation was increasing in some areas, decreasing in others, and in some cases no trend was detected (Program for Local Adaptation to Climate Effects 2021). Elevation change rates differed with wetland type in Ten

Thousand Islands, Florida with salt marsh and marsh-mangrove ecotones losing elevation (-1.67 ± 0.39 mm/yr and -6.45 mm/yr ± 2.10, respectively), mangrove-dominated areas gaining elevation (4.36 mm/yr ± 0.31), and brackish marsh experiencing no change in elevation (0.00 mm/yr ± 0.67) (Howard et al. 2020).

The Grand Bay estuary, which contains the Grand Bay National Estuarine Research Reserve (GNDNERR) and Grand Bay National Wildlife Refuge, is a relatively undeveloped coastal wetland complex in the north-central Gulf of Mexico adjacent to the Mississippi-Alabama border. The GNDNERR was established in 1999 and was later designated as a marine protected area. The system is unique due to its low level of anthropogenic development and lack of freshwater inflow. Riverine inputs to the estuary ceased several thousand years ago at which time the system became a retrograding delta with high erosion rates (Otvos 2007). Shoreline erosion rates for the estuary from 1848 – 2017 ranged from 0.1 – 6.5 m/yr (Terrano et al. 2019). A long-term monitoring program was established in 2011 to understand changes in elevation, accretion, and marsh vegetation communities as part of the National Estuarine Research Reserve System Sentinel Site Monitoring Network. Data generated from this program will provide important information to guide conservation and management activities in a historically understudied geographic region.

The objectives of this study were to quantify trends in surface elevation change and accretion among different marsh zones spanning a coastal elevation gradient within the Grand Bay estuary. Further, we compared elevation change rates to short-, medium-, and long-range water level rise (WLR) rates. Accomplishing these objectives should improve our understanding of elevation trends and the potential impacts of SLR, while also enhancing our understanding of potential drivers of variability in elevation maintenance within and among wetlands of the Gulf Coast.

Methods

Study Area

The GNDNERR is in southeastern Mississippi in Jackson County (Fig. 1) with a total area of approximately 7,400 ha. The Reserve is within the Coastal Streams Basin Watershed and contains a variety of habitats including, but not limited to, salt marsh, salt pannes, bays, bayous, wet pine flatwoods, coastal bayhead swamps, freshwater marshes, and maritime forests. Tides are primarily wind-driven with an average tidal range of approximately 0.6 m (Dillon and Walters 2007) and water depths ranging from 0.5 – 3 m (Otvos 2007). Water column salinity across the Reserve ranges from 0 – 33.5 psu depending on site and season, with an overall median of 20 psu from 2004 – 2020 (Grand Bay National Estuarine Research Reserve, unpublished data).

While most intertidal marshes at the GNDNERR are dominated by black needlerush (*Juncus roemerianus*), several habitat types are represented along the coastal transition from open water to upland habitats. A transect spanning the coastal transition was established that extends from open water at its southernmost extent, through low-, mid-, and high-elevation brackish marshes, and into a slash pine (*Pinus elliottii*) forest at its northern extent. Along the transect, five sites were selected for establishment of Surface Elevation Tables (SETs) and marker horizon (MH) plots that cover the full range of wetland types found across the elevation gradient. These sites included a low elevation marsh dominated by smooth cordgrass (*Spartina alterniflora*) interspersed with small stands of *J. roemerianus* (SPAL), two mid-elevation marshes dominated by *J. roemerianus* (JURO Low and JURO Mid), a slightly higher elevation *J. roemerianus* marsh along the marsh-upland boundary that contains several salt pannes (JURO High), and a relatively diverse site containing a variety of herbaceous and woody species including dense stands of sawgrass (*Cladium jamaicense*) surrounded by slash pine (*Pinus elliottii*) (CLMAJ). The CLMAJ site is infrequently inundated by tides but represents a potential corridor for marsh migration. All sites are densely vegetated with little evidence of marsh die-back, except for the salt pannes at JURO High. Geographic coordinates, NAVD88 elevation, and vegetation community information for each site are provided in Table 1.

Table 1. Site characteristics for locations within the Grand Bay National Estuarine Research Reserve chosen for placement of Surface Elevation Tables (SETs) and marker horizon (MH) plots monitored from 2012 – 2016.

Site	Latitude	Longitude	Elevation[a]	Dominant vegetation[b]
CLMAJ-1	30.40998	-88.41356	0.599	***Cladium jamaicense***, *Spartina patens, Dicanthelium* spp.
CLMAJ-2	30.40961	-88.41356	0.575	
CLMAJ-3	30.40940	-88.41351	0.607	
JURO High-1	30.39993	-88.41392	0.163	***Juncus roemerianus***, *Spartina patens, Borrichia frutescens*
JURO High-2	30.39995	-88.41425	0.170	
JURO High-3	30.39997	-88.41392	0.111	
JURO Mid-1	30.39767	-88.41349	0.040	***Juncus roemerianus***, *Fimbristylis* spp., *Distichilis spicata, Borrichia frutescens*
JURO Mid-2	30.39798	-88.41351	0.099	
JURO Mid-3	30.39828	-88.41363	0.143	
JURO Low-1	30.37526	-88.41245	0.058	
JURO Low-2	30.37552	-88.41247	0.080	***Juncus roemerianus***, *Spartina alterniflora*
JURO Low-3	30.37576	-88.41241	0.163	
SPAL-1	30.36248	-88.41403	0.004	
SPAL-2	30.36231	-88.41411	0.077	***Spartina alterniflora***, *Juncus roemerianus*
SPAL-3	30.36219	-88.41421	0.075	

[a]Elevation data references the North American Vertical Datum of 1988 (m)
[b]The species listed were those most commonly encountered during vegetation surveys conducted from 2014 – 2016, with the site dominant indicated in bold

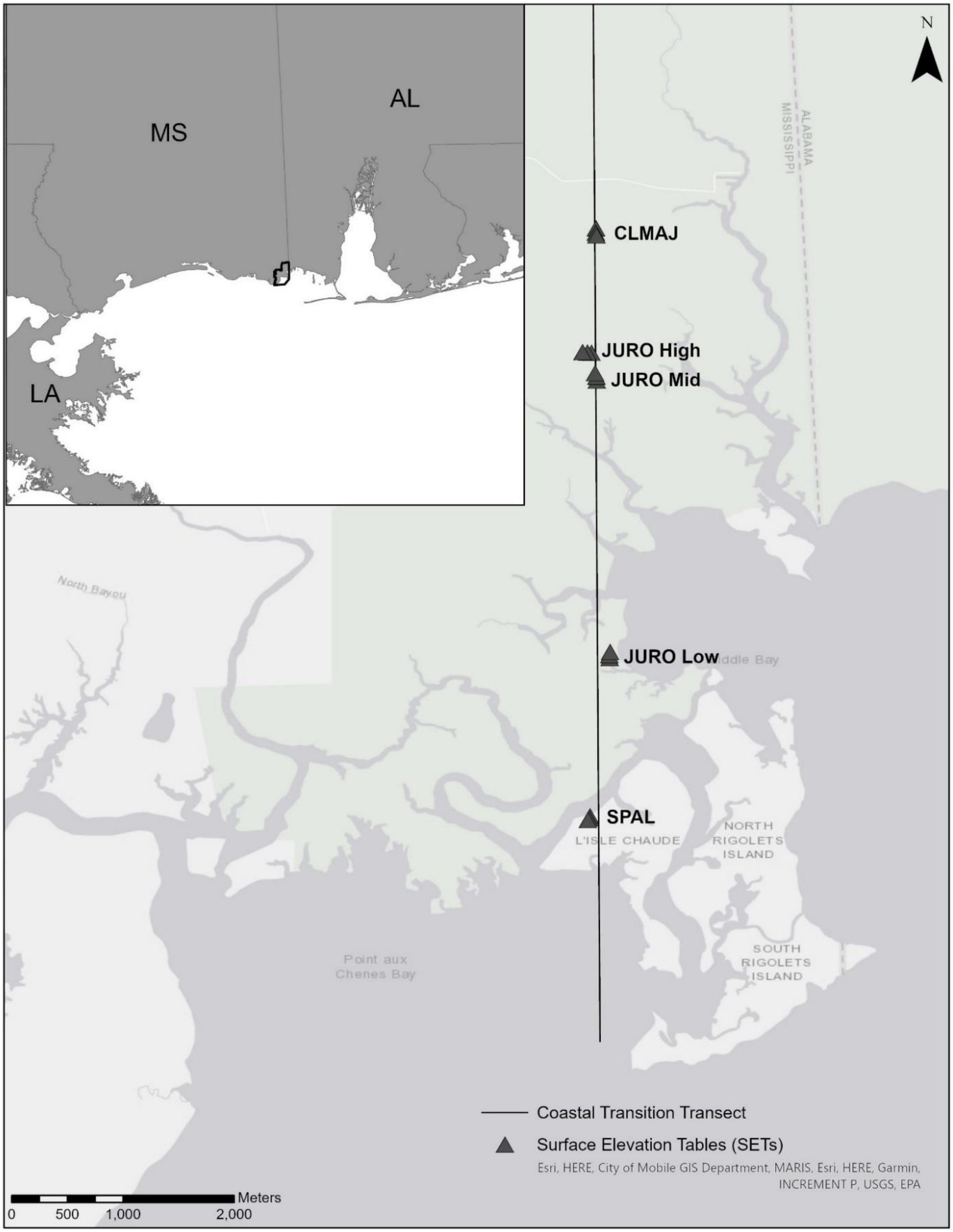


Fig. 1 Location of Surface Elevation Tables (SETs) and marker horizon (MH) plots monitored from 2012 – 2016 to quantify trends in surface elevation and accretion within the Grand Bay National Estuarine Research Reserve. Site names are shown adjacent to each site, which contains three replicate SET/MH sampling stations. The inset map shows the boundary of the Reserve and its geographic location within the north-central Gulf of Mexico

Marsh elevation monitoring

Following procedures established in Cahoon et al. (2002), Deep rod Surface Elevation Table (SET) benchmarks were established within each site in 2011 at three locations, 20 – 40 m apart in similar geomorphic positions (e.g., similar vegetation type, similar elevation, etc.) by driving stainless steel rods to refusal (10 – 30 m). Affixed to the end of each steel rod was a concrete collar and a receiver for SET attachment. The two-sided SET arm was rotated to two positions around the receiver (0° & 90°) so that during each sample, a total of 36 measurements of marsh surface elevation were collected. Quarterly (winter (Dec – Feb), spring (Mar – May), summer (June – Aug), and fall (Sept - Nov)) measurements began in winter 2012 and continued through fall 2016 to track changes in surface position over time. The same field technician was present to read or observe the reading of SETs throughout the study period. No effort was made to remove any material on the marsh surface prior to reading SETs. Each pin was slowly lowered until it rested on the marsh surface to avoid penetrating the soil. A GPS occupation campaign involving a simultaneous static Global Navigation Satellite System (GNSS) was conducted in December 2012 to obtain North American Vertical Datum (NAVD88) elevations for each SET.

Accretion monitoring

Three feldspar MH plots (0.5 m × 0.5 m) were established adjacent to each SET to measure accretion of sediment and organic material. Markers were established by laying feldspar (approximately 2 cm thick) in each quadrat during summer 2011 (Cahoon and Turner 1989). Accretion above the marker was sampled quarterly during the study period, typically at the same time SET measurements were made, by collecting soil cores that were extracted from 2012 – 2014 using a cryogenic soil-coring method (Cahoon et al. 1996). However, this method was abandoned in 2015 – 2016 for a simpler approach using a large knife to extract cores. In either case, a small core (approximately 3 × 3 × 5 cm) was extracted from the marsh surface and accretion was measured using Fowler Pro-Max digital calipers (Newton, Massachusetts) as the minimum distance from the feldspar marker to the top of the core (i.e., marsh surface) on each of four sides. Accretion was negligible (i.e., zero) if feldspar was visible on the surface of the core. Feldspar was re-laid periodically if the marker was not visible after repeated samples.

Elevation and accretion trends

Similar to Cahoon et al. (2019), elevation and accretion rates were estimated by fitting a linear mixed model (LMM) with a random intercept using the function 'lme' in the 'nlme' package (Pinheiro et al. 2019) within Program R 4.0.2 (R Core Development Team 2020). Background information regarding LMMs and their use is available in Zuur et al. (2009). Parameter estimation was performed using restricted maximum likelihood (REML) (Hocking 2003). Elevation change determined from SET pin readings and accretion as determined from marker horizons were treated as response variables in their respective models, and site, which was analogous to zone within the marsh (e.g., low marsh, mid marsh, etc.), was treated as a fixed effect. To account for dependence among SET measurements, random effects for SET, arm within SET, and pin within arm within SET were incorporated into the LMM. For MH models, random effects were incorporated for SET, plot within SET, and measurement within plot within SET. Total accretion for a given period was regressed on the number of days since feldspar application (not on the actual date of feldspar application) to account for the varied timing of feldspar re-application between plots over the sampling period. To compare mean rates of change for zones, we constructed 95% confidence intervals using the function 'glht' in the R package 'multcomp' to adjust p-values and confidence intervals to control the family-wise error rate (Hothorn et al. 2008; Bretz et al. 2010). *A priori* significance for these tests was set at $\alpha < 0.05$.

While unadjusted SET and MH measurements were used in statistical models as described above, slight modifications of the SET and MH data yielded more useful data visualizations. These modifications included using only the longest time series of MH readings (>1,500 days), which excluded a portion of the data from JURO High, JURO Mid, and SPAL. Also, SET measurements were adjusted to be cumulative-since-baseline by 1) subtracting the first reading from all subsequent readings for each individual pin, 2) averaging the differences for the nine pins within each of the arm positions for each date, and 3) averaging the arm positions, resulting in one series of cumulative change per SET.

Comparisons to Water Level Rise

Estimated elevation change rates were compared to estimated WLR rates using data from the National Water Level Observing Network station at Dauphin Island Sea Lab, Dauphin Island, Alabama. The term "water level rise" was used because the medium- and short-range rates we used in our comparisons were calculated from less than 19 years of data (i.e., less than a metonic cycle) and thus are not technically considered sea level rise rates. WLR rates were estimated using a linear model with errors that follow an autoregressive integrated moving average

(ARIMA) model of order 1,0,0 (National Oceanic and Atmospheric Administration 2009). The ARIMA (1,0,0) is equivalent to an autoregressive model of order 1, or AR(1) (Brockwell et al. 2016). WLR rates were based on three different time scenarios: long-range (1966 – 2016), medium-range (1998 – 2016), and short-range (2012 – 2016). The corresponding rate estimates of WLR were 3.50 mm/yr (95% CI: 2.88 – 4.11), 6.97 mm/yr (95% CI: 3.31 – 10.64), and 13.71 mm/yr (95% CI: -2.38 – 29.81) for long, medium, and short-range rates, respectively. Note that shorter time series are composed of fewer observations; therefore, the corresponding parameter estimates will have a higher degree of uncertainty, resulting in wider confidence intervals and less powerful hypothesis tests.

The elevation change rate for each site was compared to the WLR estimate from each of the three scenarios via an asymptotic Z-test, which is a preferred alternative to the common practice of determining significance based on whether corresponding confidence intervals overlap (Schenker and Gentleman, 2001). Resulting p-values were adjusted using Holm's method (Holm 1979). Standard errors for the WLR estimates were obtained from their respective ARIMA models, while standard errors for the rate of elevation change at each site were obtained from the LMMs. *A priori* significance for these tests was set at $\alpha < 0.05$.

Results

Elevation and accretion trends

Elevation change rates ranged from 0.54 mm/yr (95% CI: -0.63 – 1.72) at JURO High to 5.45 mm/yr (95% CI: 4.27 – 6.62) at JURO Low (Fig. 2). Pairwise comparisons showed a variety of similarities and differences across sites. Notable findings included a significantly lower elevation change rate at JURO High compared to other sites except for JURO Mid (2.46 mm/yr; 95% CI: 1.29 – 3.64). Also, elevation change rates at JURO Low, SPAL (5.00 mm/yr; 95% CI: 3.82 – 6.17), and CLMAJ (4.27 mm/yr; 95% CI: 3.10 – 5.45) were not statistically different from each other.

Accretion rates ranged from 0.82 mm/yr (95% CI: -0.16 – 1.80) at JURO Mid to 3.89 mm/yr (95% CI: 2.90 – 4.89) at JURO High. Pairwise comparisons showed that JURO High was significantly different from JURO Mid and JURO Low (1.89 mm/yr; 95% CI: 0.91 – 2.86), but not significantly different from CLMAJ (2.75 mm/yr; 95% CI: 1.81 – 3.70) or SPAL (3.35 mm/yr; 95% CI: 2.33 – 4.36).

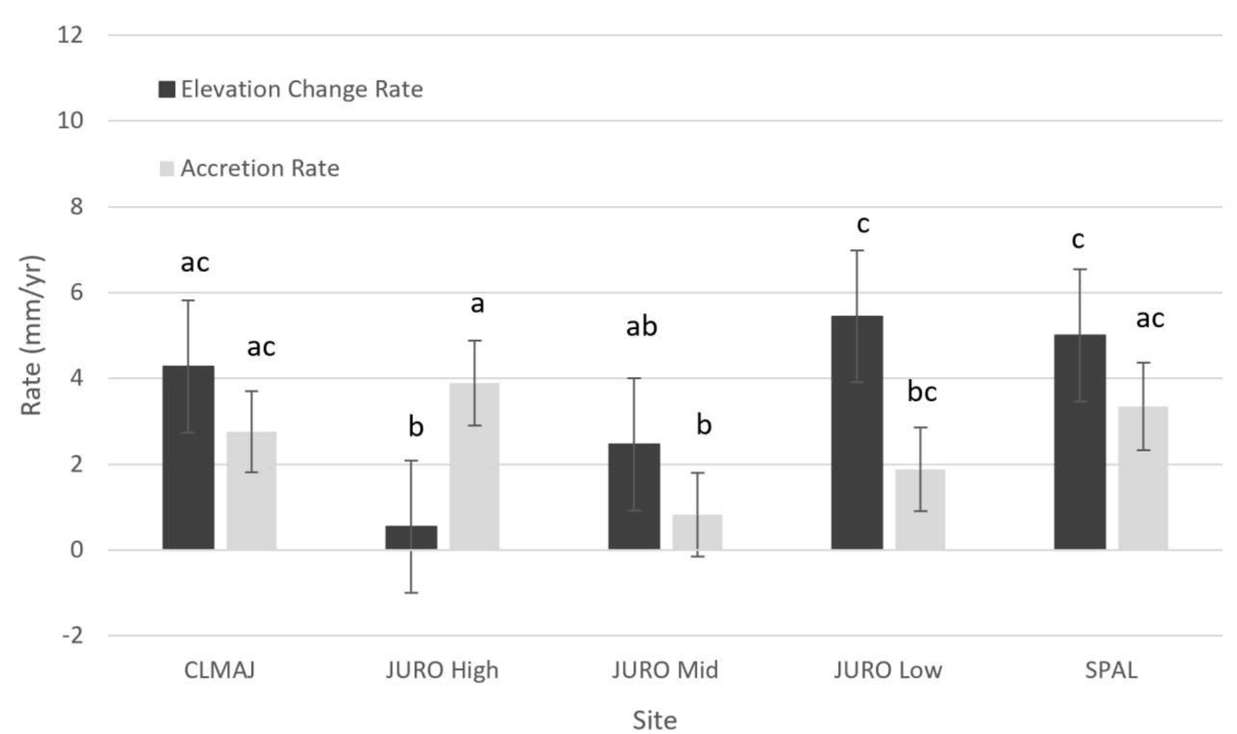


Fig. 2 Elevation change and accretion rates along a coastal elevation gradient from 2012 – 2016 within the Grand Bay National Estuarine Research Reserve. Error bars show 95% confidence intervals and letters above each bar denote groupings determined by pairwise comparisons for elevation change or accretion rates. *A priori* significance for these tests was set at $\alpha < 0.05$

Elevation and accretion showed similar trajectories across the study period, with some notable exceptions (Fig. 3). For example, accretion at JURO High was consistently higher and had greater variation than elevation change throughout the study period. Elevation at JURO Low increased consistently from 2012 – 2016, except for a prominent drop in 2014 when accretion was higher than elevation change across all three SET plots. Elevation and accretion trajectories at the other sites (i.e., CLMAJ, JURO Low, and SPAL) were similar suggesting that accretion was a major driver of elevation change across the study period at these sites.

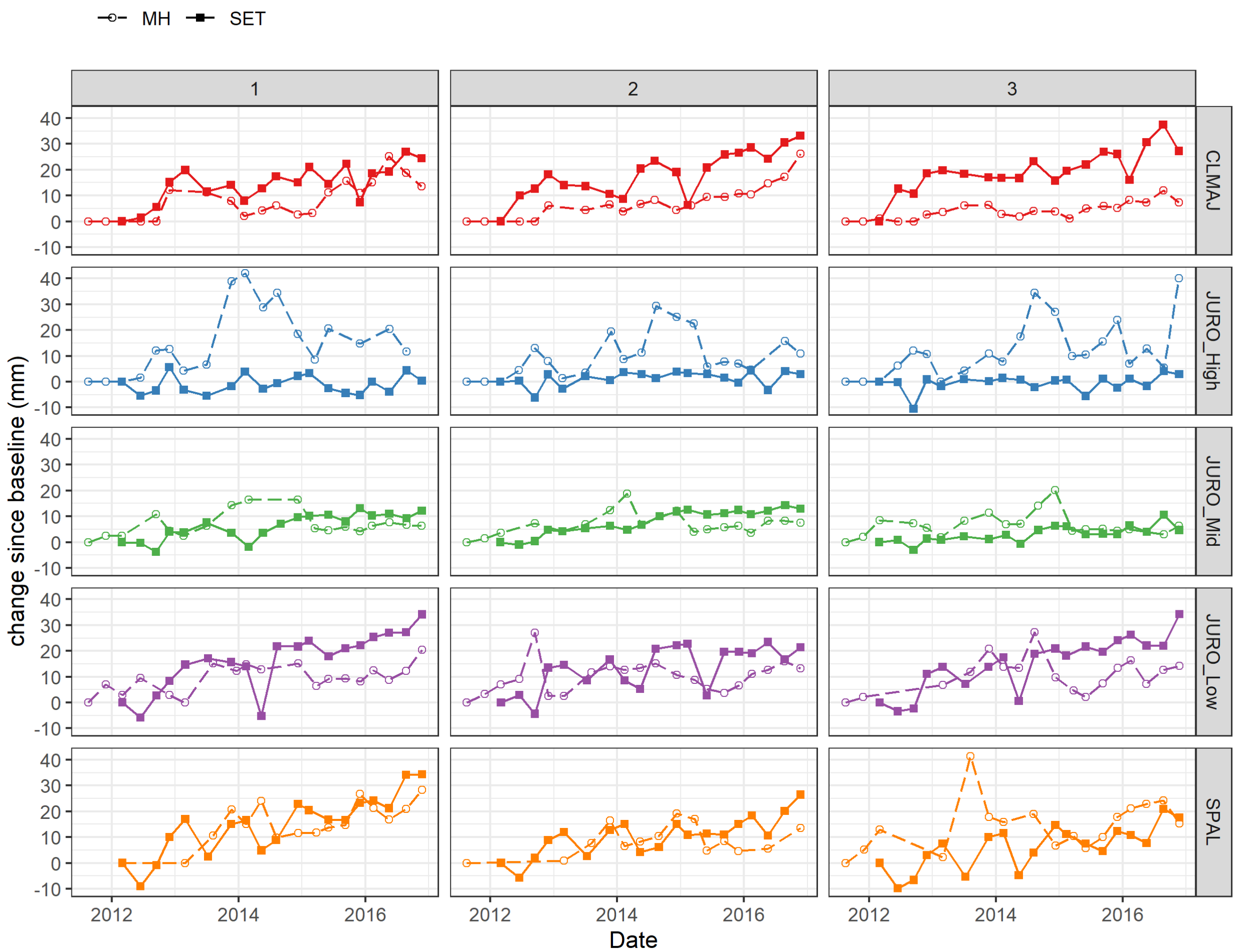


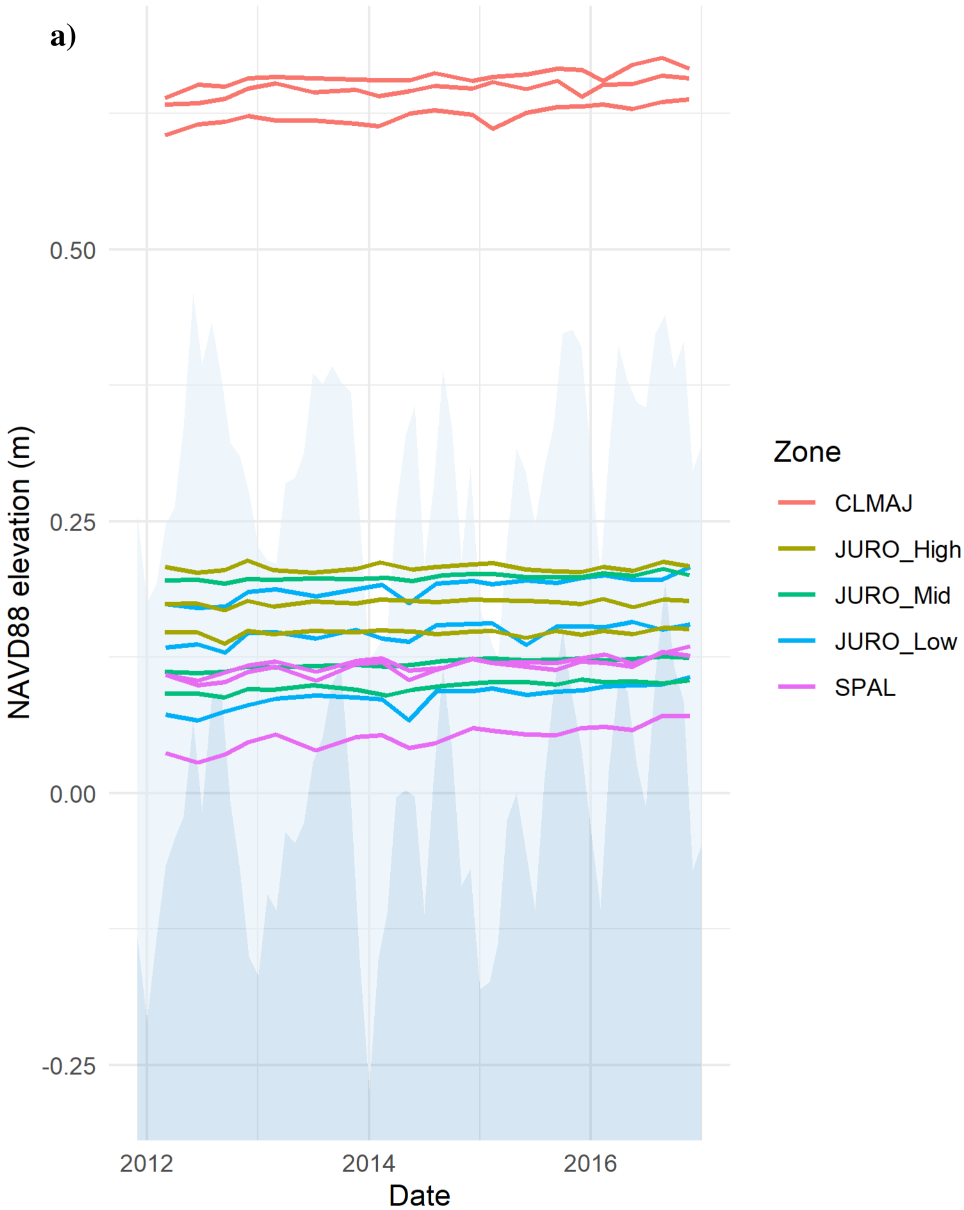
Fig. 3 Change in marsh elevation and accretion from baseline as determined by Surface Elevation Table (SET) and marker horizon (MH) measurements from five sites along an elevation gradient from 2012 – 2016 in the Grand Bay National Estuarine Research Reserve. The y-axis shows the change in elevation or accretion from baseline (i.e., zero) when the monitoring program began. The x-axis shows the date measurements were taken. Site names are shown on the right side of the figure. The three replicate SET/MH plots at each site are designated by the numbers across the top of the figure (i.e., 1, 2, and 3)

Comparisons to Water Level Rise

The elevation change rate at JURO High was significantly lower (*P*<0.001) than the long-range WLR rate of 3.5 mm/yr (*P*=0.016; Table 2), while the elevation change rate at JURO Low (5.45 mm/yr; 95% CI: 4.272 – 6.621) was significantly higher (Fig. 4). No other sites had elevation change rates that were significantly different from long- range WLR. JURO High was the only site with a significantly lower elevation change rate compared to the medium-range WLR rate (6.97 mm/yr; *P*=0.005). No sites had elevation change rates that were significantly different from short-range WLR.

Table 2. Elevation change rates, 95% confidence intervals, and Holm-adjusted P-values (Holm 1979) from Z-tests comparing elevation change rates from five sites along an elevation gradient in the Grand Bay National Estuarine Research Reserve to three water level rise (WLR) rate estimates calculated using data from a National Water Level Observing Network station at Dauphin Island Sea Lab, Dauphin Island, Alabama. WLR rates were 3.50 mm/yr (1966 – 2016), 6.97 mm/yr (1998 – 2016), and 13.71 mm/yr (2012 – 2016). Confidence intervals (95% CI) for WLR rates are also provided. Arrows indicate significance (α <0.05) and the relation of the elevation change to WLR (i.e., ↓ means the rate of elevation change was significantly lower than WLR rate, while ↑ indicates it was higher than WLR rate).

Site	SET Elevation Change		Long-range WLR: 3.50 (95% CI: 2.88-4.11)	Medium-range WLR: 6.97 (95% CI: 3.31-10.64)	Short-range WLR: 13.71 (95% CI -2.38-29.81)
	Rate (mm/yr)	CI	p-value	p-value	p-value
CLMAJ	4.272	3.098 – 5.447	0.253	0.508	0.755
JURO High	0.544	-0.630 – 1.718	↓ <0.001	↓ 0.005	0.549
JURO Mid	2.462	1.288 – 3.636	0.249	0.087	0.688
JURO Low	5.447	4.272 – 6.621	↑ 0.016	0.629	0.755
SPAL	4.996	3.821 – 6.170	0.081	0.629	0.755


a)
NAVD88 elevation (m)
0.50
0.25
0.00
-0.25
2012
2014
2016
Date
Zone
CLMAJ
JURO_High
JURO_Mid
JURO_Low
SPAL

235

b)

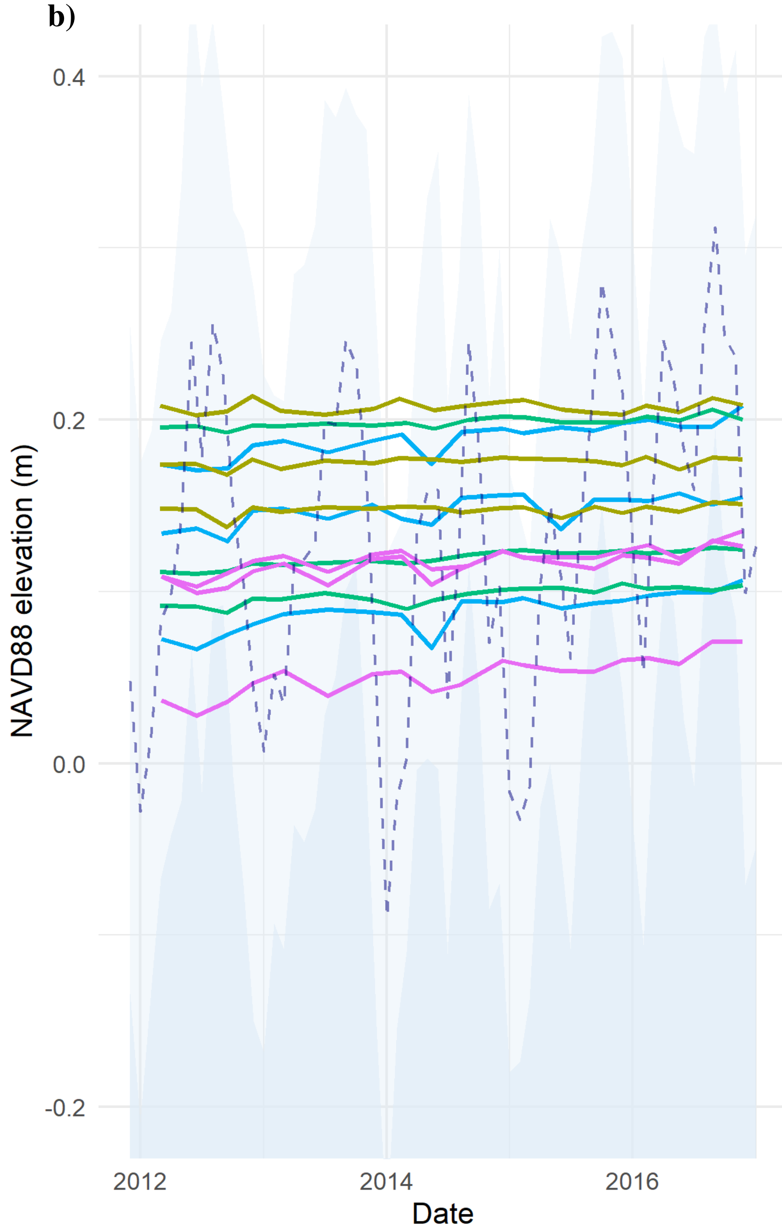


Fig. 4 Elevation change rates for a) all sites along an elevation gradient and b) the four lowest elevation sites in the Grand Bay National Estuarine Research Reserve from 2012 – 2016. Lines represent the mean elevation of each surface elevation table (SET) relative to a baseline measurement. Each line is anchored at the SET's NAVD88 elevation on the y-axis. The dashed line represents mean sea level, and the darker and lighter blue shading are monthly mean low water and high water, respectively. Monthly mean water levels were downloaded from the National Water Level Observing Network station at Dauphin Island Sea Lab, Dauphin Island, Alabama

Discussion

Elevation change and accretion rates

Different elevation change rates among sites in this study suggest that position in the tidal frame is related to marsh vulnerability to SLR in a retrograding deltaic system. Marshes higher in the tidal frame dominated by *J.*

roemerianus appear to be the most vulnerable to SLR, as was evident when comparing elevation change at mid and high marsh with WLR rates. Inundation frequency of mid and high marsh could be increasing because average monthly mean high water, mean sea level, and mean low water (MLW) impacted these sites more frequently across the study period (e.g., average monthly MLW exceeded the elevation at JURO High in 2016) (Fig. 4). Aerial imagery from these areas in 1968 compared to 2016 shows a >40% reduction in the spatial extent of salt pannes (i.e., roughly 11.7 acres in 1968 compared to 6.8 acres in 2016) (Fig. 5). Relatively low elevation change rates and shifts in the areal extent of salt pannes could be the result of increased inundation coupled with limited sediment delivery for elevation maintenance. Sedimentary inputs to the Grand Bay estuary from upland sources occur primarily through two small drainages (i.e., Bayou Heron and Bayou Cumbest) and overland flow (i.e., sheet flow) (Otvos 2007). JURO High and Mid are also >1000 m from an open water embayment, Middle Bay, and >400 m from Middle Bayou to the west. This suggests that high marshes with limited potential for sediment delivery could experience higher inundation frequency similar to mid-marsh if SLR rates increase as predicted for this region. It should be noted that this hypothesis is not supported by a relatively high accretion rate at JURO High, which is discussed below.

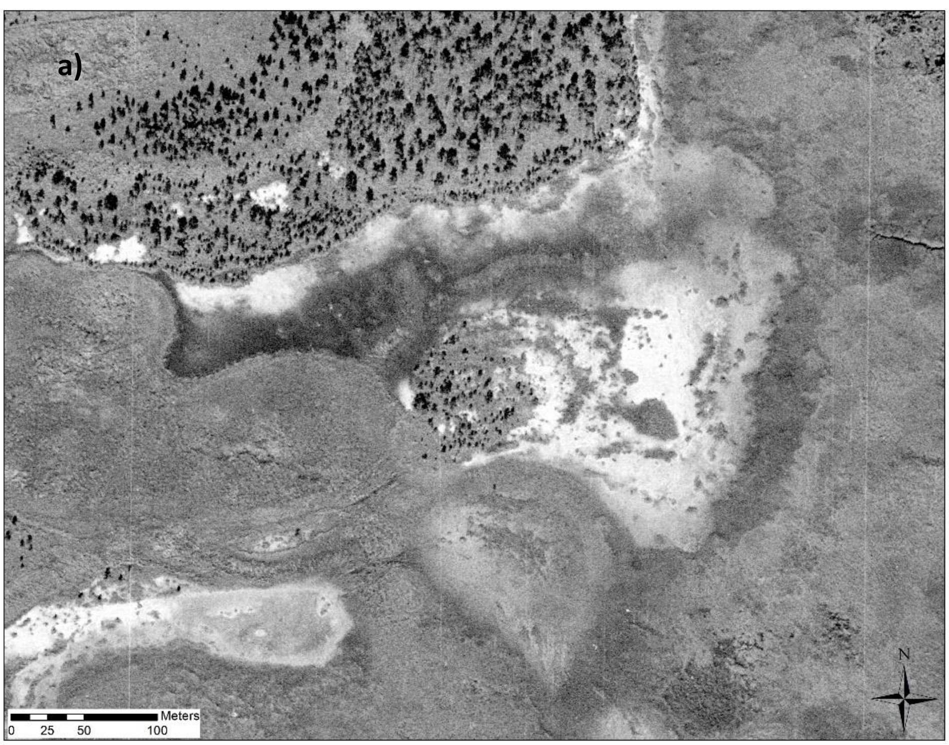


Fig. 5 Aerial images of the JURO High and JURO Mid sites in a) 1968 (Mississippi Department of Marine Resources, 2008) compared to b) 2016 (Office for Coastal Management Partners, 2021) in the Grand Bay National Estuarine Research Reserve

Accretion rates and temporal variation in accretion at JURO High was higher than at all other sites (3.89 mm/yr; 95% CI: 2.59 – 5.19). One explanation is that this site is near an erosional scarp where a salt panne transitions to a slash pine flatwood. The nearby scarp could be a source of sediment when storm-induced high tides recede and/or heavy rains occur. Another explanation relates to soil composition. Surface Elevation Tables at JURO High were installed in a narrow band of salt pannes bordered by a dense stand of *J. roemerianus* to the south and a slash pine upland to the north (Fig. 5). Soil samples collected adjacent to JURO High SETs in 2017 were identified as fine-silty, mixed epiaquepts and epiaquents (United States Department of Agriculture 1999), which were unique among the SET/MH plots at Grand Bay (Natural Resources Conservation Service, unpublished data). These soils are likely more susceptible to fracturing from wet-dry cycling, flocculation, and/or salinity and sodicity effects that could cause feldspar to migrate into deeper soil horizons (Page Sanderson, personal communication), which may have led to higher apparent accretion rates noted in this study.

Elevation change rates were highest in the low marshes, dominated by *J. roemerianus* or *S. alterniflora*, where JURO Low and SPAL gained elevation at higher rates than the long-range WLR rate (3.50 mm/yr). The mechanisms through which low marshes maintain elevation may differ depending on the vegetation community. For example, the elevation change rate to accretion rate ratio at JURO Low was 0.34 compared to 0.67 at SPAL, suggesting that accretion is a major driver of elevation change in low marsh habitats dominated by *S. alterniflora* while subaerial processes are major drivers of elevation change at low elevation marshes dominated by *J. roemerianus*. Further support for this hypothesis is that belowground biomass collected from JURO Low in 2015 (5,527 g/m^2) was higher (though not significant) than at SPAL (3,989 g/m^2) (Archer et al. 2021). This finding agrees with other studies documenting that *J. roemerianus* root production is a major driver of marsh elevation maintenance in frequently inundated marshes (Wu et al. 2020; Turner 1990).

Elevation maintenance

Marsh persistence may depend on stimulated biomass production as inundation rates increase. Although less studied historically than abiotic processes (e.g., accretion), biotic feedbacks are an important component of marsh habitats that allow them to keep pace with rising sea levels. These biotic processes include indirect (e.g., sediment trapping by marsh vegetation) and direct (e.g., accumulation of organic material, root production) feedbacks to elevation (Cahoon et al. 2006). For example, changes in atmospheric conditions associated with climate change or nutrient enrichment could also result in greater belowground production. Mesocosm experiments in Louisiana have shown that increases in CO_2 can reduce salinity stress and increase shoot-base expansion in a C_3 species (*Schoenoplectus americanus*) (Cherry et al. 2009), while field studies in the Chesapeake Bay area demonstrated that a combination of elevated CO_2 and nitrogen addition resulted in the greatest rates of elevation gain through root zone expansion (Langley et al. 2009). *Juncus roemerianus*, also a C_3 species, is often dominant in marshes in the north-central Gulf of Mexico. Future increases in atmospheric CO_2 could promote subsurface biomass production in *J. roemerianus*, helping marshes maintain elevation as sea level rises.

Accretionary inputs to lower marshes in Grand Bay were relatively high despite limited sediment delivery from upland sources. Considering that most southeastern facing shorelines in Grand Bay have erosion rates that exceed 0.5 m/yr (Terrano et al. 2019), shoreline erosion may be an important source of sediment for marsh elevation maintenance in low marsh habitats. Smith et al. (2021) measured sediment accumulation on the marsh platform in relation to the quantity of eroded sediment from adjacent shorelines in Grand Bay. They found that sediment deposition along erosional edges was typically concentrated within 10 m of the vertical escarpment along the marsh edge, which agrees with other research along the Gulf Coast that has shown high rates of deposition within 10 m of the water-marsh boundary (Leonard et al. 1995). However, during larger erosion events, Smith et al. (2021) noted a lack of deposition in nearshore areas. They hypothesized that larger erosive events exceed an "erosion threshold," where sediment is no longer deposited within 10 m of the marsh edge, but instead is transported to other areas in the estuary. All the sites in this study were further than 10 m from the marsh edge (e.g., SETs/MH plots at SPAL were the closest to the marsh edge at 20 – 45 m away). As such, marsh accretion at these sites could be driven by less frequent, pulse events that erode sediment from the marsh edge, transport it inland, and deposit it on the marsh platform, similar to what was hypothesized by Smith et al. (2021). Sedimentary inputs from storm events have been shown to mitigate marsh subsidence by providing elevation capital in other areas as well. Hurricane Katrina, for example, deposited an average of 5.18 cm of sediment in the deltaic plain of Louisiana (Turner et al. 2006), which resulted in elevation gains in otherwise subsiding marshes at Big Branch and Pearl River, Louisiana (7 mm and 17 mm, respectively) (McKee and Cherry 2009).

Potential limitations

Reliance on SET and MH data for predicting marsh persistence has been criticized by some. For example, Kirwan et al. (2016) indicated that accretion rates at high elevation marshes are not useful predictors. Their meta-analysis suggested that most marshes will maintain elevation, even under high SLR scenarios and point to a common over-estimation of marsh instability in the literature. They also emphasized the ability of marshes to migrate inland and maintain elevation through biophysical feedbacks. Marshes that are most likely to be submerged are those with an accretion deficit (i.e., elevation or accretion rate minus SLR) greater than 0.5 mm/yr. Marshes at JURO High and Mid have accretion deficits that exceed this threshold, even for the long-range SLR scenarios (2.96 and 1.04 mm/yr, respectively when using the long-range WLR of 3.5 mm/yr). According to Kirwan et al. (2016), a closer look at frequently flooded marshes may provide more insight about vulnerability as accretion rates will increase sharply if marshes are in jeopardy of submerging. The lack of a sufficient period of record precludes a reliable assessment of accretion rates in Grand Bay, but the results presented in this manuscript can serve as a baseline from which to compare accretion rates over longer periods of time.

It is important to acknowledge that WLR rates are influenced by a variety of factors (e.g., length of record, seasonal variation, geologic stability of gauge, etc.). Along the Gulf Coast, long-range WLR rates are as high as 9.65

mm/yr in Eugene Island, LA and generally decrease moving east towards a geologically stable gauge at Pensacola, FL, which has a long-range rate of 2.53 mm/yr (Turner 1990). The long-range WLR rate at the closest gauge to Grand Bay, MS at Dauphin Island, AL has risen from 3.5 mm/yr (used in our analyses for 2012 – 2016) to 4.13 mm/yr in 2020 (National Oceanic and Atmospheric Administration 2021), which shows that WLR rates are increasing even over short timescales. However, the short-range WLR rate that was used in this study (13.71 mm/yr) was not significantly different when compared to elevation change rates from any of the sites because of the wide confidence interval (95% CI: -2.38 – 29.81). With an increased emphasis on modeling marsh response to increases in sea level, it is important to recognize that longer periods of record are needed to better define WLR rates when predicting marsh vulnerability. This approach would reduce the amount of uncertainty in predictions, which would enhance marsh restoration planning and conservation.

Modeling sediment dynamics and marsh persistence in Grand Bay estuary

Substantial research has been done to understand sediment and vegetation dynamics and project future conditions for the Grand Bay estuary (Passeri et al. 2015; Raposa et al. 2016; Alizad et al. 2018; Wu et al. 2017; Wu et al. 2020; Nowacki and Ganju 2020; Archer et al. 2021), with long-term projections suggesting that Grand Bay marshes will experience large changes in the coming decades with the magnitude of SLR being an important determinant of marsh persistence. Passeri et al. (2015) used a hydrodynamic modeling approach that included historical changes in sea level and geomorphology. They determined that the estuary has become increasingly ebb dominant over the last 150 years. The determination of ebb dominance helps to explain high erosion rates documented for many seaward shorelines over a similar timeframe (Terrano et al. 2019). Nowacki and Ganju (2020) measured sediment flux in several locations within the estuary in 2016 and determined that Grand Bay is a “self-cannibalizing” sedimentary system with the bulk of suspended sediment leaving the system and only a small portion being available for maintaining marsh elevation. Assessments of marsh resilience to sea level rise (MARS) have shown that low tidal range and accretion rates are risk factors for marsh resilience (Raposa et al. 2016). Grand Bay, being a microtidal system with low rates of sediment accretion, falls into a high-risk category overall for the MARS index. However, two metrics used in MARS, percentage of marsh in the lowest third of the estuary and elevation change rate, were scored as low risk for Grand Bay.

Archer et al. (2021) used updated measures of above- and belowground biomass characteristics in the Marsh Equilibrium Model (MEM) (Morris et al. 2002) to estimate inundation time at SPAL, JURO Low, and JURO High over the next 100 years for three SLR scenarios: 3.74 mm/yr, 7.0 mm/yr, and 20.0 mm/yr. The results showed that a 3.74 mm/yr SLR rate over the next 100 years will increase inundation time 81%, 84%, and 442% at SPAL Low, JURO Low, and JURO High from current levels, respectively. Models showed that the sites will be inundated 100% of the time in 70 – 90 years when using SLR rates of 7 mm/yr, and in 40 – 50 years when using a SLR rate of 20 mm/yr. Wu et al. (2017) developed a mechanistic model that integrates the MEM and is informed by accretion rates presented in this manuscript. The results included estimates of SLR rate thresholds for marsh collapse in Grand Bay of 11.9 and 8.4 mm/yr in 2050 and 2100, respectively. For example, their models showed that exceedance of a SLR rate of 8.4 mm/yr by 2100 will result in a loss of roughly 56% of wetland area. A more recent estimate reduces these thresholds to 10.8 and 7.2 mm/yr by 2050 and 2100, respectively, and stresses the importance of belowground biomass for elevation maintenance and marsh persistence in the marine-dominated Grand Bay estuary (Wu et al. 2020). A coupled-hydrodynamic marsh model called Hydro-MEM predicts changes to marsh extent within Grand Bay under four different SLR scenarios by 2100: 0.2 m, 0.5 m, 1.2 m, and 2 m (Alizad et al. 2018). There was a predicted increase in marsh extent for all scenarios from current levels (e.g., current marsh extent was estimated at 3,612 ha versus 3,800 ha in 2100). However, predicted marsh expansion assumes successful migration of marshes into current upland areas as much of the current marsh footprint is predicted to become open water by 2100, especially in the higher SLR scenarios.

Management Implications

Grand Bay marshes face many challenges for persistence in their current footprint (e.g., shoreline erosion, ebb-dominance, etc.). While the diminishment of a retrograding delta is a natural process, Grand Bay is one of the more pristine and undeveloped marsh ecosystems along the north-central Gulf Coast that is functionally important for many species, including humans. Future increases in SLR and exorbitant shoreline erosion rates suggest that the persistence of marsh habitats will depend on continued accretionary inputs, vegetative growth in response to SLR, landward migration, and potentially the use of natural and nature-based features (NNBFs) (e.g., living shorelines, thin-layer placement, reconstruction of historical barriers). Human intervention on a broad scale would carry some uncertainty. For example, rebuilding the Grand Batture Islands, a set of barrier islands that once protected the Grand

Bay estuary from the larger Mississippi Sound, has been proposed for more than three decades as a strategy to increase habitat and protect inland marshes from erosion (Meyer-Arendt and Kramer 1991; Eleuterius and Criss 1991). However, hydrodynamic models have shown that restoring the islands to their historic footprint would increase tidal velocities, thereby making the system more ebb-dominant (Passeri et al. 2015). The result could be an inadvertent increase in sediment export from the system, causing an acceleration of marsh loss. Constructing shoreline protection structures (e.g., living shorelines) is another option, but this would also carry uncertainty because shoreline hardening neglects to account for impacts on the net sediment budget (Ganju 2019) and could inhibit elevation maintenance in nearshore areas by reducing shoreline erosion (Smith et al. 2021). More research needs to be done in Grand Bay and in other areas of the northern Gulf of Mexico to understand the impact of NNBFs on sediment budgets, including long-term studies that incorporate increases in sea level. Future research should focus on assessing the effects of thin layer placement and/or the effects of NNBFs on sedimentary processes to better understand both the benefits and limitations of these approaches, which would inform restoration planning and implementation within the Grand Bay estuary and beyond.

For undeveloped areas like Grand Bay, marsh migration is a good option for conservation of marsh structure and function (Enwright et al. 2016). Adjacent upland habitats receive periodic applications of prescribed fire, which can facilitate upslope marsh migration (Hacker 2018). The CLMAJ site represents an upland area within a marsh migration corridor that receives prescribed fire. Our comparison of elevation change rate (4.272 mm/yr; 95% CI: 3.098 – 5.447) to WLR showed that the site is maintaining elevation relative to water level. Monitoring efforts in this location over the long-term could prove to be valuable for understanding elevation and accretion dynamics with respect to marsh migration. Regardless, more research needs to be done to better understand the current rate of marsh migration at Grand Bay with an emphasis on the marsh-upland ecotone (e.g., JURO High). Research in other areas has shown that ecotones are excellent places to study SLR impacts, even over short timescales (Wasson et al. 2013). Grand Bay is fortunate to have several "pine islands" adjacent to bayous that have marsh-upland ecotones that are very accessible for study. These areas are the focus of several ongoing research projects aimed at understanding SLR impacts. Future work could be focused on determining the rate of marsh migration along the marsh-upland ecotone in a variety of areas to determine where conservation efforts (e.g., land acquisition, prescribed burning) are most needed to preserve highly valued marsh functions.

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Statements and Declarations

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Author contributions

Study conception and design were performed by Jonathan L. Pitchford, Kimberly Cressman, Julia A. Cherry, Brook T. Russell, and William V. Underwood. Material preparation, data collection and analysis were performed by Jonathan L. Pitchford, Kimberly Cressman, Brook T. Russell, Jay McIlwain, and Michael J. Archer. The first draft of the manuscript was written by Jonathan L. Pitchford, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The elevation and accretion datasets analyzed during the current study are available from National Oceanic and Atmospheric Administration's Centralized Data Management Office at *https://cdmo.baruch.sc.edu/get/landing.cfm*. This data and other generated datasets (e.g., water level rise data) can be provided by the corresponding author on reasonable request.