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Hurricane sedimentation in a subtropical salt marsh-mangrove community is unaffected by vegetation type

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ABSTRACT

Hurricanes periodically deliver sediment to coastal wetlands, such as those in the Mississippi River Delta Complex (MRDC), slowing elevation loss and improving resilience to sea-level rise. However, the amount of hurricane sediment deposited and retained in a wetland may vary depending on the dominant vegetation. In the subtropical climate of the MRDC, the black mangrove (*Avicennia germinans*) has been expanding and replacing salt marsh (*Spartina alterniflora*). Because these vegetation types differ in structure, their influence on sedimentation may also differ. We conducted a survey along 160 km of coastline to determine if the spatial deposition pattern in saline wetlands by Hurricanes Gustav and Ike in September 2008 was differentially influenced by vegetation type. Sampling was initiated two months after landfall at eighteen sites in the MRDC containing side-by-side stands of *A. germinans* and *S. alterniflora* along the shoreline, with *S. alterniflora* marsh landward. Average thickness of hurricane sediment across sites varied from 0.6 to 5.6 cm with an overall mean of 2.6 ± 0.4 cm. Within sites, hurricane-layer thickness varied from 1.3 cm at the shoreline to 4.8 cm in the marsh interior, but this pattern was unaffected by vegetation type. Despite greater canopy height, stem density (including pneumatophores), and leaf area, mangroves did not capture more hurricane sediment than salt marsh nor did they attenuate the delivery of sediment to the marsh interior. Data recorded at thirty-six monitoring stations in Louisiana's Coastwide Reference Monitoring System further showed that rates of accretion, as well as elevation change, in saline wetlands (*S. alterniflora*) of the MRDC were temporarily increased by Hurricanes Gustav and Ike. These findings agree with previous work showing the beneficial effects of hurricane sediments on coastal wetlands, but suggest that a climate-driven shift from *S. alterniflora* to *A. germinans* in the MRDC will not necessarily alter hurricane sediment capture.

1. Introduction

Hurricanes—the powerful tropical cyclones originating in the Atlantic basin—are transformative forces that sculpt the geomorphology and ecology of coastal wetlands in North America through effects on physical, chemical, and biological processes (Michener et al., 1997; Swiadek, 1997; Davis et al., 2004; Morton and Barras, 2011). Although the negative influence of hurricanes on coastal erosion and land loss has been emphasized in the scientific literature (e.g., Barras, 2006; Day et al., 2007), these natural disturbances redistribute sediments, transporting some to sediment-deficient wetlands (Turner et al., 2006; McKee and Cherry, 2009; Baustian and Mendelssohn, 2015; Bianchette et al., 2016). Such sediments are especially needed in rapidly subsiding wetlands where rates of relative sea-level rise (eustacy plus isostacy) exceed rates of vertical land building. The Mississippi River Delta Complex (MRDC) is an extreme example of this condition, where 4833 km^2 of land, mostly wetland, have disappeared since 1932 (Couvillion et al., 2017).

The vast MRDC system, which began developing ca. 7000 years ago, was formed by deposition of alluvial sediments in overlapping lobes (Coleman et al., 1998). Wetlands developed wherever the river deposited sediment but later deteriorated when the river switched course and abandoned the lobe. However, new wetlands continued to emerge as the river built subsequent lobes. This natural sequence of wetland

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development, degeneration, and renewal was halted when the Mississippi River was fixed in its current course by construction of levees and flow-control structures. These actions stopped over-bank flooding and, consequently, reduced delivery of sediment and nutrients to marshes. Without significant sediment inputs, continuing compaction of thick sedimentary sequences, fluid withdrawal, tectonic activity, crustal down-warping, and decomposition of organic matter have resulted in high subsidence rates (Nienhuis et al., 2017), which, along with eustatic sea-level rise (Dangendorf et al., 2017), have generated submergence rates exceeding 1 cm yr^{-1}.

In the modern situation of rapid subsidence and sediment deficiency, hurricanes and other storms, such as winter cold fronts, play an important role in promoting wetland sedimentation in the MRDC from distant sources, such as coastal bays and lakes (Reed, 1989) or offshore (Turner et al., 2006). Several studies have documented hurricane-induced sedimentation in coastal marshes of the MRDC (Rejmánek et al., 1988; Cahoon et al., 1995; Nyman et al., 1995a; Turner et al., 2006; McKee and Cherry, 2009; Tweel and Turner, 2012). For example, Hurricanes Katrina and Rita caused an average deposition of 5 cm of sediment (range = 0–68 cm) in wetlands across coastal Louisiana and eastern Texas in 2005 (Turner et al., 2006). Furthermore, the sediment delivered by Hurricane Katrina slowed elevation loss in subsiding brackish marshes in the MRDC, demonstrating the positive effects of storm deposits (McKee and Cherry, 2009). A subsequent study documented the direct relationship between emergent plant productivity and vegetative resilience in response to hurricane sedimentation (Baustian and Mendelssohn, 2015). Storm surge deposits during Hurricane Ike accounted for 42–73% of sedimentation in Texas coastal marshes between 1950 and 2008, also suggesting the importance of hurricane sediment for long-term aggradation (Williams and Denlinger, 2013). Another study, using records from a network of monitoring stations, found that sediment deposited by Hurricane Isaac in 2012 increased accretion rates in coastal wetlands of Louisiana (Bianchette et al., 2016). In other research, hydraulically dredged sediment additions to deteriorating marshes increased marsh primary production and resilience compared to reference sites that received no sediment (Mendelssohn and Kuhn, 2003; Slocum and Mendelssohn, 2008). In a greenhouse mesocosm study, simulated hurricane sedimentation increased plant productivity under moderate, but not high, sea-level rise scenarios (Baustian and Mendelssohn, 2018). These investigations together indicate that hurricane-delivered sediments can have positive effects on marsh resilience and, ultimately, sustainability.

The subtropical climate of the MRDC supports both salt marsh (*Spartina alterniflora* Loisel.) and black mangrove (*Avicennia germinans* (L.) L.) vegetation in the most seaward wetland zones. Because marsh and mangrove vegetation differ substantially in aboveground structure, their capacity to accumulate hurricane-generated sediment may also differ. Global changes in sea level, atmospheric CO_2, temperature, and storm activity may promote shifts in plant species dominance in subtropical wetlands with consequences for coastline stability, primary production, food-web support, and other functions (McKee and Rooth, 2008; Bianchi et al., 2013; Saintilan et al., 2014). Examination of hurricane sedimentation where salt marsh and mangrove distributions overlap can provide insights into whether vegetation shifts will alter coastal vulnerability to sea-level rise and other global factors. A few studies have compared salt marsh and mangrove stands along the Louisiana-Texas coast in terms of sediment accretion or elevation change rates (Perry and Mendelssohn, 2009; Comeaux et al., 2012; McKee and Vervaeke, 2018; Armitage et al., 2019). However, no study, to our knowledge, has examined how mangrove and salt marsh vegetation compare in terms of their capacity to capture hurricane sediment or alter its spatial distribution. In fact, limited information exists about within-marsh patterns of hurricane sedimentation in the MRDC (Nyman et al., 1995b; McKee and Cherry, 2009).

On September 1, 2008, Hurricane Gustav (Category 2) came ashore near Cocodrie, Louisiana, to the west of the Mississippi River, bringing a substantial storm surge and sediment into coastal wetlands. Hurricane Gustav was followed by Hurricane Ike (Category 2), which made landfall on September 13, 2008 near Galveston, Texas, but with a second storm surge that inundated Louisiana's wetlands. Preliminary observations indicated that several centimeters of sediment were deposited in co-occurring salt marsh and mangrove wetlands near Port Fourchon, Louisiana (IAM, personal observation). Hurricanes Gustav and Ike thus provided an opportunity to determine how sediment deposition patterns might be influenced by vegetation type. Our main objective was to compare salt marsh and mangrove stands in terms of: (1) relative capacity to capture hurricane sediment along shorelines and (2) attenuation of sediment delivery to interior (landward) marshes. We hypothesized that mangrove vegetation, with its greater structural complexity and canopy height, would capture more storm sediment than salt marsh, and that shorelines fringed by mangroves would reduce delivery of sediment to the marsh interior, which is most vulnerable to sea-level rise due to its lower elevation and lower sedimentation rate (DeLaune et al., 1983; Baumann et al., 1984). In an effort to examine how sediment delivered by Hurricanes Gustav and Ike may have contributed to vertical accretion and elevation change in saline wetlands of the MRDC, we additionally analyzed data recorded by a regional network of wetland sites across coastal Louisiana. A better understanding of hurricane sediment effects on coastal wetlands will aid in predicting consequences of salt marsh-to-mangrove shifts globally, as well as inform conservation and restoration efforts in the MRDC (Coastal Protection and Restoration Authority of Louisiana, 2017)().

2. Materials & methods

2.1. Study site

A field survey of hurricane sediment was conducted to assess spatial patterns in relation to the dominant vegetation. The sampled area extended along the outer coast of Louisiana from Oyster Bayou (29°14′39″ N, 91°07′08″ W) to just west of the Mississippi River (29°18′36″ N, 89°44′35″ W), a distance of about 160 km (Fig. 1). These wetlands are dominated by *S. alterniflora*, but stands of *A. germinans* have been expanding in recent decades due to lack of severe freezes, e.g., total mangrove area in the Port Fourchon, LA region increased from 41 ha in 1993 to 670 ha in 2011 (Osland et al., 2017). In this deltaic setting, black mangrove stands often occur in narrow, monospecific bands along tidal creeks, canals, and bays with salt marsh in the wetland interior. The individual mangroves are typically short in stature (1.0–1.5 m tall at study sites) and exhibit extensive branching and stump sprouting, which leads to a dense canopy of small, evergreen leaves (Fig. 2). Although short in stature, these mangroves are fully mature and produce abundant fruit annually. In addition to the shoot, a mangrove plant produces hundreds of aerial roots, called pneumatophores, which are pencil-like structures (10–20 cm tall) extending upward from the soil.

By comparison, the salt marsh dominated by *S. alterniflora* has a lower canopy height (0.6–0.8 m tall at study sites) (Fig. 2) and undergoes partial winter senescence. Individual grass culms are composed of five to ten linear leaves arranged alternately on straight, smooth stems. Mangroves invade salt marsh via propagule dispersal and seedling establishment (Patterson et al., 1993; Alleman and Hester, 2011). The buoyant propagules are spread by tides and initially establish along creekbanks where soil elevations are highest and the opportunity for stranding and survival is greatest (Patterson and Mendelssohn, 1991; Patterson et al., 1997).

The tidal regime in this region is diurnal with a 0.32 m amplitude (1983–2001 Epoch; NOAA Tides and Currents Station #8761724, www.tidesandcurrents.noaa.gov). The climate along the coast is humid subtropical with temperatures ranging from 7 to 8 °C (January) to 31–32 °C (July) and rainfall averaging 1575 mm annually (1981–2010) (Louisiana State Office of Climatology, www.losc.lsu.edu). In recent decades, severe freezes have occurred in south Louisiana in 1983–84 and 1989,

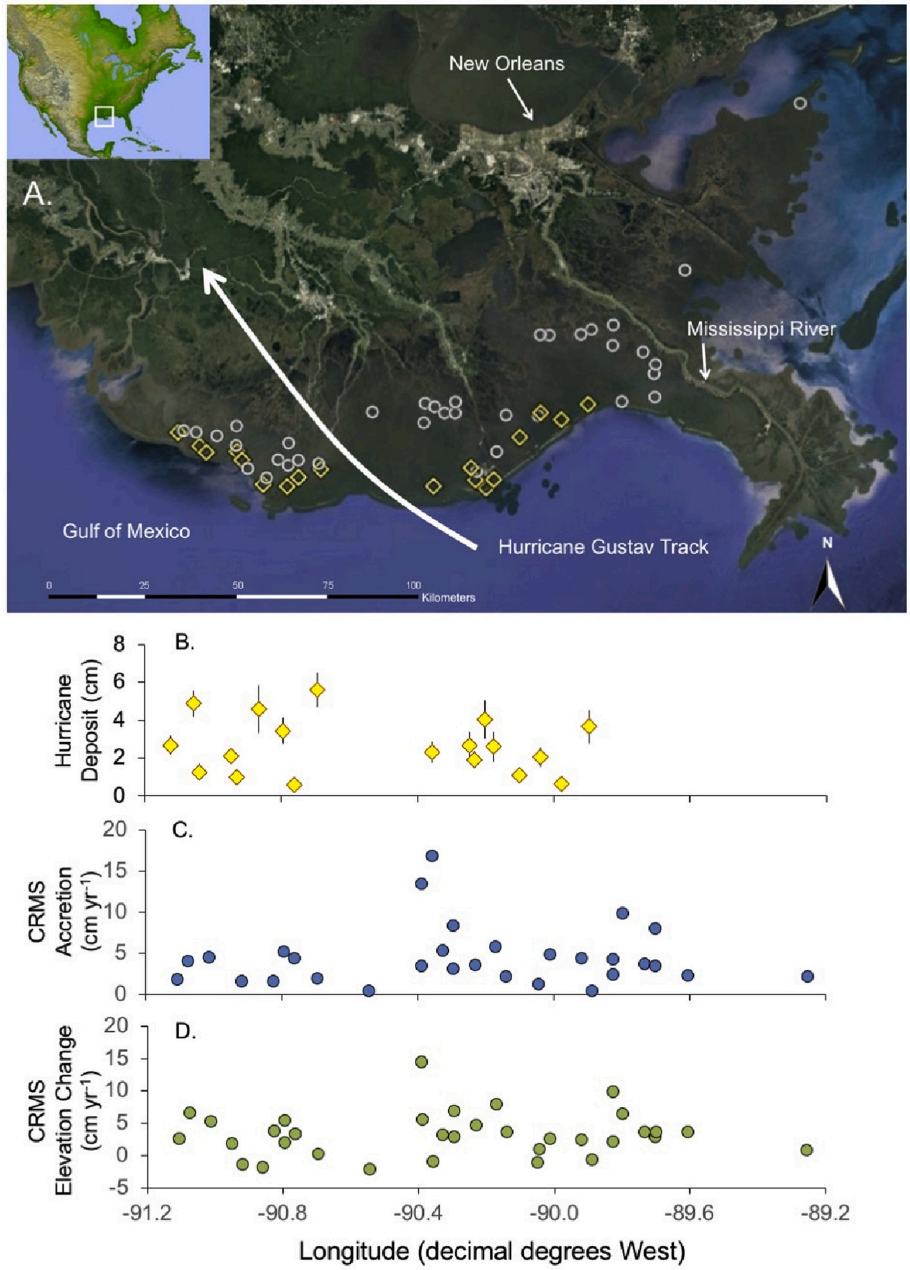

Fig. 1. A. Location of eighteen sampling sites (yellow diamonds) in the Mississippi River Delta Complex containing adjacent stands of mangroves (*Avicennia germinans*) and salt marsh (*Spartina alterniflora*) and thirty-six monitoring stations (white circles) in the Coastwide Reference Monitoring System (CRMS) used to assess effects of Hurricanes Gustav and Ike (track outside bounds of map) on vertical accretion and surface elevation change. B. Average hurricane sediment thickness measured at eighteen sampling sites; values are the mean ± SE (n = 8–13 per site). C & D: Rates of vertical accretion above a marker horizon and elevation change measured with rSETs at CRMS stations during the April–October 2008 hurricane interval. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

but none in the period from 1990 until this study in 2008 (New Orleans International Airport Station ID 166660, www.losc.lsu.edu). The December 1989 freeze caused widespread mortality of mangroves in Louisiana, but an abundant crop of propagules survived (KLM & IAM, personal observation). Propagules of *A. germinans* have been found to survive low temperatures (−6.5–2.5 °C) for up to 24 hours (Pickens and Hester, 2011). The current mangrove population in Louisiana likely originated from these surviving propagules.

2.2. Hurricanes Gustav and Ike

Coastal Louisiana has been struck by multiple hurricanes and tropical storms (Roth, 2010). The period from 2005 to 2009 was particularly active, with a total of ten events, including Hurricanes Cindy (July 5, 2005), Dennis (July 10, 2005), Katrina (August 29, 2005), Rita (September 24, 2005), Humberto (September 13, 2007), Gustav (September 1, 2008), Ike (September 13, 2008), and Ida (November 10, 2009). Hurricane Gustav formed on August 25, 2008 southeast of Haiti and strengthened to a Category 4 before striking Cuba (Roth, 2010). The hurricane then moved into the Gulf of Mexico where it weakened to a Category 2 before making landfall on September 1 near Cocodrie, Louisiana. The storm surge from Hurricane Gustav was reported to reach 3–4 m in height along parts of the coast (Dietrich et al., 2011). Hurricane Ike made landfall on September 13, 2008 in east Texas, but generated a storm surge in southeast Louisiana of 1–2 m (Roth, 2010).

2.3. Site selection and sampling design

Sampling sites were selected using aerial photography, maps, and publicly available records from the State of Louisiana's Coastwide Reference Monitoring System (CRMS) (https://www.lacoast.gov/crms_viewer2/#) (Coastal Protection and Restoration Authority of Louisiana, 2015). We used CRMS stations, which were randomly sited across the Louisiana coast, as the total population of potential sampling

Fig. 2. Views of shoreline vegetation dominated by either *Spartina alterniflora* (left panels) or *Avicennia germinans* (right panels) and vegetative cover within a 0.25 m^2 quadrat (bottom panels).

sites for our research. We identified eighteen sites (nine east and nine west of the track of Hurricane Gustav) (Fig. 1) that met our selection criteria: (1) proximity to a CRMS station in a wetland classified as saline, (2) presence of side-by-side, monospecific stands of *A. germinans* (hereafter *Avicennia*) and *S. alterniflora* (hereafter *Spartina*) along a shoreline (Fig. 2a, c), and (3) an interior marsh dominated by *Spartina*.

During November–December 2008, we accessed all eighteen sites by helicopter. At each site, two transects were established from shoreline to marsh interior and designated as either "mangrove-to-marsh" or "marsh-to-marsh" based on the vegetation types at either end (Fig. 3). Hurricane sediment thickness was initially measured at ca. 3 m intervals along each transect (as described below); however, number of samples and exact distances depended on site topography and vegetation zonation. Thus, the average thickness and average distance was calculated for each of six distance intervals (0–2.9, 3–4.9, 5–9.9, 10–14.9, 15–19.9, and ≥20 m). Intensive sampling (sediment, vegetation, and elevation) was conducted at two shoreline and two interior positions along each transect (at equivalent distances from the water's edge) (Fig. 3). One shoreline station was situated in a mangrove stand (*Avicennia*) and the other in a salt marsh stand (*Spartina*), both about 3 m from the water's edge (Figs. 2 and 3). Interior stations were located at the most landward sediment sampling position in salt marsh dominated by *Spartina*.

At each of the intensive sampling stations at each of the eighteen sites, the following variables were measured:

Vegetation Structure. Percent cover was visually estimated within a 0.25 m^2 quadrat (Fig. 2), and stem density (including mangrove pneumatophores) was determined in a consistent 0.1 m^2 area within the larger quadrat. Average canopy height was measured with a stadia rod. Leaf area index was determined according to instrument instructions at consistent heights with a LI-COR 2000 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, Nebraska USA), which measures light interception by the vegetation canopy.

Hurricane Sediment. The hurricane sediment was readily identified by differences in color and texture from pre-hurricane layers and by absence of plant roots, as noted in previous studies (Nyman et al., 1995b; McKee and Cherry, 2009). Duplicate cores were collected at each intensive station with a piston corer, extruded onto a board, and the thickness of the storm deposit measured with a ruler.

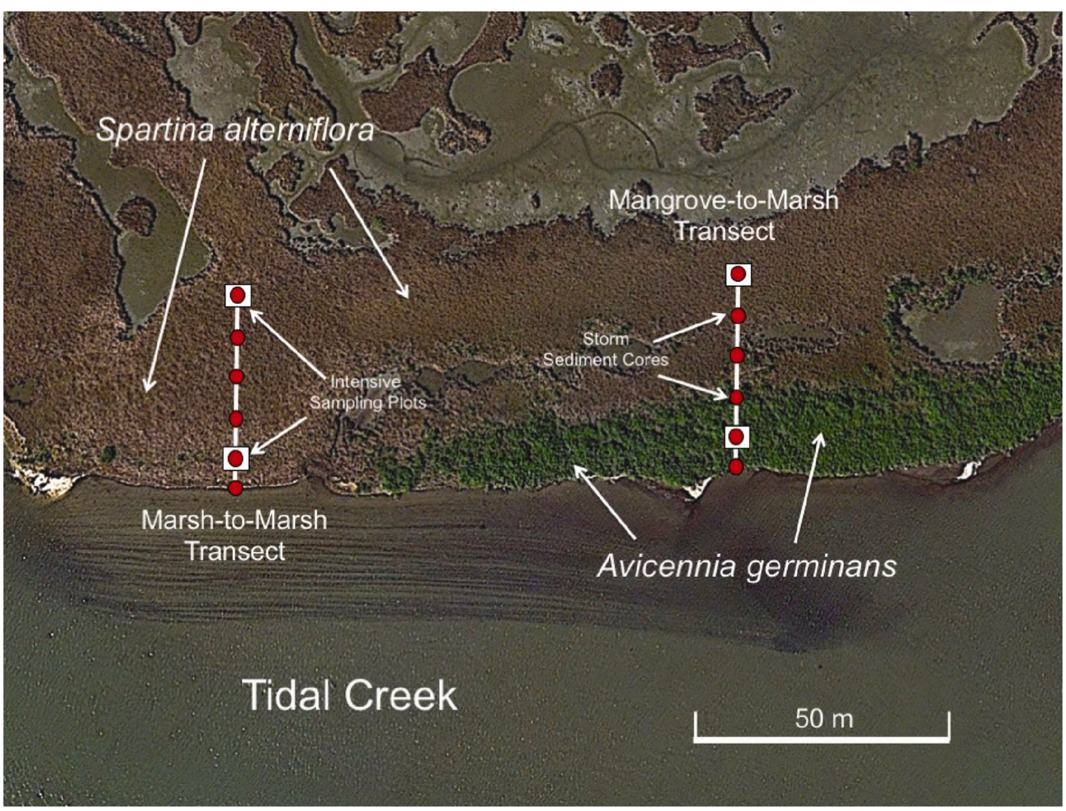

Fig. 3. Sampling design used at eighteen sites across the Mississippi River Delta Complex. At all sites, two transects were established, each with up to six sediment coring stations (circles) and two intensive sampling stations (squares), one along the shoreline and another in the marsh interior. The mangrove-to-marsh transect traversed a monospecific stand of *Avicennia germinans* along the shoreline and ended in the marsh interior dominated by *Spartina alterniflora*. The marsh-to-marsh transect was dominated by *S. alterniflora* in both shoreline and interior positions. At each intensive station, vegetation structure and marsh surface elevation were measured in addition to hurricane sediment thickness.

The hurricane layer was separated from one of the cores, avoiding the pre-hurricane layer, and transferred to a plastic bag. The sediment was dried to constant mass at 70 °C and weighed; dry bulk density was calculated as the dry mass per volume (g cm^{-3}). The dried sediment was ashed at 550 °C for 6 h to determine mineral mass after organic loss on ignition.

Marsh Elevation. On June 17 and 18, 2010, all eighteen sites were revisited to measure surface elevations. Marsh surface elevations were measured relative to the North American Vertical Datum of 1988 (NAVD88) with a Trimble R8 Real-Time-Kinematic (RTK) global positioning system (GPS) linked to a Continuously Operating Reference Station (CORS) network (Louisiana State University's GulfNet Real-Time Network). Measurements were made at each of the four intensive sampling stations at eighteen sites and corrected to NAVD88 (5 of 72 total stations could not be measured due to cellular connectivity failure).

2.4. Storm surge, accretion, and elevation change

To assess the effects of Hurricanes Gustav and Ike on storm surge height and duration, vertical accretion, and elevation change rates in the MRDC saline wetlands, we used publicly available records from the Coastal Information Management System (CIMS: http://cims.coastal.louisiana.gov), which include data collected at monitoring stations in the CRMS network (Coastal Protection and Restoration Authority of Louisiana, 2015). This network encompasses more than 350 stations in freshwater, intermediate, brackish, and saline wetlands across coastal Louisiana. We used records from a subset of thirty-six stations in saline wetlands extending from Fourleague Bay (29°14′41″ N, 91°06′24″ W) to Oyster Bay, east of the Mississippi River (30°05′58″ N, 89°15′10″ W) (Fig. 1).

At each CRMS station, data on vegetation, soils, and hydrology were recorded at select intervals (detailed descriptions of CRMS station establishment, protocols, and sampling schedules are given in a procedures manual (Folse et al., 2014)). Relevant to this study, each station included a water level recorder and a rod Surface Elevation Table (rSET)-Marker Horizon (MH) system. The latter was used to determine changes in surface elevation and sediment accretion on the marsh surface (Cahoon et al., 2002; Lynch et al., 2015). Across the thirty-six CRMS stations, the rSET-MH system was situated in the marsh interior (average distance from shore = 12.1 m), but the distance was variable (range = 1.9–30.9 m). At each rSET, nine fiberglass pins were lowered to the marsh surface through a leveled measuring arm in four directions, and the height above the arm recorded (total = 36 measurements per rSET per sampling date). Adjacent to each rSET, a series of marker horizons of feldspar clay were established. On each sampling date, a cryogenic core through each marker horizon was collected, and the thickness of the overlying sediment was measured at four positions around the core. A minimum of three feldspar plots were established initially, with additional plots added as these became unreadable over time. In addition, ten vegetation plots per station were sampled annually (in a 200 m^2 area, between June and September). Total vegetation cover (%) was visually estimated within a 2 m × 2 m quadrat, and all species recorded. Height of five stems of the dominant species was measured and averaged. Thirty-two stations were dominated by *S. alterniflora*, two by *Juncus roemerianus*, and one each by *A. germinans* or *Iva frutescens*. Marsh elevations, determined by Real-Time Kinematic (RTK) survey of 20 points per CRMS station, were also recorded (see detailed Survey Reports for each CRMS site: https://www.lacoast.gov/crms_viewer2/#).

We downloaded data for thirty-six CRMS stations that had records spanning the relevant time period. In general, the accretion and elevation change data were derived from rSET-MH stations established as early as April 2006 and sampled through March 2012. This time interval encompassed Hurricanes Gustav and Ike but excluded other major hurricanes (but not other storms, which may have added some sediment). The data were divided into three time periods relative to Hurricanes Gustav and Ike: before (ca. May 2006 to April 2008), during (ca. April to October 2008), and after (ca. October 2008 to March 2012) (the exact time interval varied because CRMS stations were not all established or measured on the same dates). For each rSET-MH station, heights of 36 pins were averaged for each sampling date; thicknesses of sediment above all marker horizons established at each station were also averaged. Data from each CRMS station were plotted over time, and a linear model fit to the data was used to calculate the rates of change (= slope) in elevation and accretion during each time interval. To estimate the contribution of the hurricanes to vertical accretion and elevation change at each CRMS site, the pre-hurricane rate measured during April to October 2007 (reflecting normal tidal contributions) was subtracted from the rate measured during the hurricane interval.

To assess storm surge effects on height and duration of flooding, water level variation from August 29 to September 20, 2008 was compared to that measured during the same three-week period in 2007 using records from CRMS stations ($n = 29$ or 24, respectively; some stations failed to record). Hourly water levels relative to the marsh surface for the relevant periods were downloaded and analyzed.

2.5. Statistical methods

Spatial variation in sediment thickness at eighteen sites was analyzed with repeated measures Analysis of Variance (ANOVA) using a mixed model (fixed effect = transect type (mangrove-to-marsh, marsh-to-marsh); repeated measure = distance-interval (1–6); random effect = site). Data from the four intensive sampling plots at each site were assessed with ANOVA using a mixed model (fixed effects = spatial position (shoreline, interior), transect type (mangrove-to-marsh, marsh-to-marsh); random effect = site). The accretion and elevation change rates at CRMS stations were analyzed with a repeated measures ANOVA in which the repeated measure was time interval (before, during, and after hurricanes). Maximum water level height and percent time flooded were analyzed with a repeated measures ANOVA using a mixed model (repeated measure = year (2007, 2008), random effect = CRMS station). Post-ANOVA multiple comparisons were conducted with Tukey's HSD. Some data were log-transformed to equalize variance prior to analysis; when variance homogeneity could not be achieved, Welch's ANOVA (testing equal means, given standard deviations not equal) was used. Pearson's correlation coefficient was used to examine bivariate relationships among variables. For CRMS accretion and elevation change data, we wanted to determine if their linear relationship differed with time period (before, during, and after hurricanes). This relationship was tested with ANCOVA (i.e., a test of the homogeneity of regression slopes); the lack of an interaction between the continuous variable and the categorical variable would support a null hypothesis that the linear slopes were similar. Statistical analyses were performed in JMP Pro 14.0 (SAS, 2018).

3. Results

3.1. Hurricane water levels

Water levels recorded in 2007 and 2008 at CRMS stations during the same three-week period showed effects of the hurricanes on height and duration of flooding along the Louisiana coast (Fig. 4). During the time period from August 29 to September 20, 2007, average water levels fluctuated from −0.337 to 0.312 m relative to the marsh surface. In 2008, storm surge from Hurricanes Gustav and Ike raised average water levels across the study area to 1.3 m on September 1 and 1.7 m on September 12 (Fig. 4). Water levels remained above the soil surface for 127 (Gustav) and 257 (Ike) hr. Together, the two hurricanes raised water levels above the average height of *Avicennia* (1.3 m) for ca. 33 hr and that of *Spartina* (0.7 m) for ca. 82 hr, whereas water levels never exceeded plant canopies during the same three-week period in 2007 (Fig. 4). The marsh surface was flooded 83 ± 2% of the time in 2008

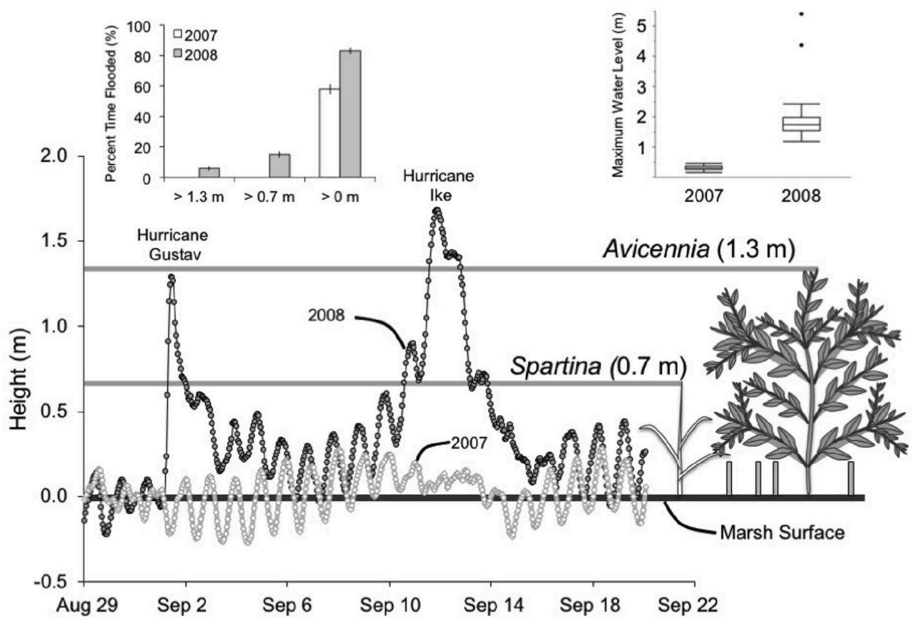

Fig. 4. Variation in hourly water level relative to the marsh surface measured at Coastal Reference Monitoring System (CRMS) stations dominated by saline vegetation (primarily *Spartina alterniflora*) in the Mississippi River Delta Complex between August 29 and September 20 in 2007 (n = 24) and 2008 (n = 29). Hurricanes Gustav and Ike made landfall on September 1 and 13, 2008, respectively. Average canopy heights of mangroves (*Avicennia germinans*) and salt marsh (*S. alterniflora*) are shown for comparison. Inset graph (top left) shows percent of time flooded above marsh surface (>0 m) and above average heights of *S. alterniflora* (>0.7 m) and *A. germinans* (>1.3 m) in 2007 and 2008 (values are the mean ± SE). Inset box plot (top right) shows distribution of maximum water levels recorded each year (single points are outliers: CRMS stations 0178 and 0179).

compared to 58 ± 3% in 2007 ($F_{1,\ 23.4} = 107.2$, $P < 0.0001$) (see inset graph, Fig. 4). Peak water levels recorded at CRMS stations were significantly higher in 2008 (Welch's ANOVA: $F_{1,\ 28.6} = 98.3$, $P < 0.0001$) and more variable compared to 2007 (see box plot, Fig. 4). During Gustav, peak water levels on September 1 varied across CRMS sites from 0.8 to 4.4 m relative to the marsh surface. During Ike, peak water levels on September 12 varied across sites from 1.1 to 5.0 m. Maximum water heights recorded were 5.4 m above the marsh surface on September 10 at CRMS station 0178 and 4.1 m on September 12 at CRMS station 0179 (outliers in box plot, Fig. 4).

3.2. Hurricane sedimentation

The sediment deposited by Hurricanes Gustav and Ike had an average bulk density of 1.27 ± 0.07 g cm^{-3} and a mineral content of 95 ± 1%, which did not differ significantly with spatial position ($F_{1,30} =$ 0.19 and 0.12, respectively, $P > 0.05$) or transect type ($F_{1,30} = 1.54$ and 0.62, respectively, $P > 0.05$). Average thickness of storm sediment across eighteen sampling sites varied from 0.6 to 5.6 cm, with an overall mean of 2.6 ± 0.4 cm, and there was no consistent pattern of sediment deposition relative to the Hurricane Gustav track (Fig. 1b). There were differences, however, within sites. Hurricane sediment thickness increased from 1.3 cm at the water's edge to 4.8 cm in the marsh interior (Fig. 5) (main effect of distance: $F_{5,\ 135.2} = 12.3$, $P < 0.0001$) and was greater along the marsh-to-marsh (3.0 cm) than the mangrove-to-marsh (2.4 cm) transect (main effect of transect: $F_{1,\ 130.6} = 3.97$, $P = 0.0484$) (inset graph, Fig. 5). However, the pattern with distance did not differ significantly with transect type (no interaction effect: $F_{5,\ 130.9} = 0.70$, $P > 0.05$). Comparison of four intensive plots at consistent distances from open water further confirmed that less sediment was deposited on the creekbank compared to the marsh interior ($F_{1,51} = 52.13$, $P < 0.0001$) and that this pattern did not differ with transect (no interaction effect; $F_{1,51} = 0.64$, $P > 0.05$) (Fig. 6a). Also, the marsh-to-marsh intensive plots had more sediment (3.5 cm) than the mangrove-to-marsh plots (2.6 cm) (main effect of transect: $F_{1,51} = 11.98$, $P = 0.0011$). These results show that the mangrove stands did not capture more sediment than salt marsh nor was there a significant "shadow effect" of mangroves on sedimentation in the interior marsh.

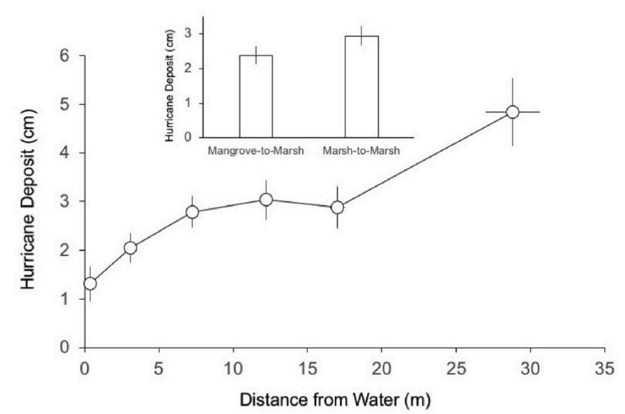

Fig. 5. Variation in thickness of the hurricane deposit with distance from water (tidal creek or bay) at eighteen sites in the Mississippi River Delta Complex, averaged across transect type (mangrove-to-marsh, marsh-to-marsh). Sediment depth varied significantly with distance and was significantly higher along the marsh-to-marsh transect (inset graph). Values are the mean ± SE (note that some SE bars are smaller than symbols).

3.3. Vegetation structure

No visible damage to vegetation structure was evident at any of the sampling stations during the initial survey conducted in 2008. Overall, the results confirmed that vegetation structure differed between *Avicennia* and *Spartina*, but also indicated differences with spatial position (Table 1). Canopy height, stem density (including pneumatophores), and LAI (Leaf Area Index) were significantly higher in the shoreline plots dominated by *Avicennia* compared to shoreline or interior marsh plots dominated by *Spartina* ($P < 0.0001$, Tukey's HSD). In *Avicennia* plots, the average number of pneumatophores was 484 m^{-2} (range: 210–830 m^{-2}) and accounted for the majority of stems present (Table 1). Percent cover was greater in shoreline (72%) compared to interior (50%) plots, but this pattern did not differ significantly with transect (Table 1). Vegetation cover was significantly higher, however, across the mangrove-to-marsh transect (68%) compared to the marsh-to-marsh transect (53%) (Table 1). Vegetation structure was not positively correlated with hurricane sediment thickness, which instead decreased

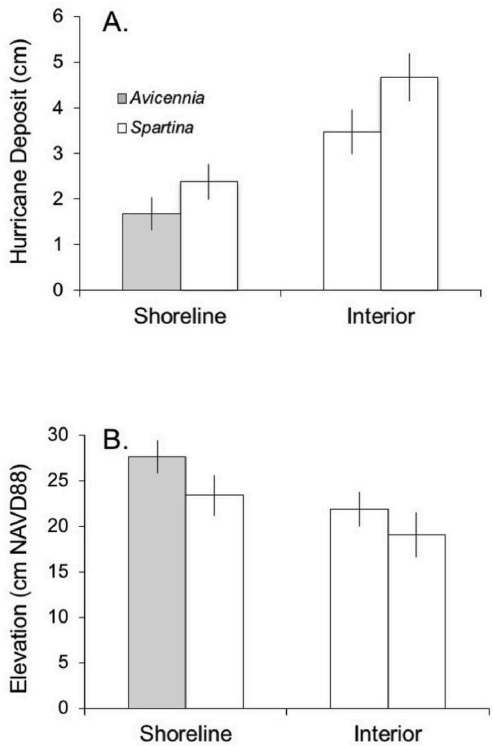

Fig. 6. Comparison of shoreline and interior intensive plots along mangrove-to-marsh and marsh-to-marsh transects (first and second bars, respectively, for shoreline and interior positions). A. Average sediment thickness in intensive plots along the shoreline (average distance from water: 3.3 m) dominated by either *Avicennia germinans* or *Spartina alterniflora* and in the marsh interior (average distance from water: 18.8 m) dominated by *S. alterniflora*. B. The elevation of marsh surface relative to NAVD88 at intensive plots. Values are the mean ± SE (n = 18).

with increasing canopy height, stem density, percent cover, and LAI (Table 2).

3.4. Marsh elevation

Marsh elevation measured at eighteen study sites in 2010 was significantly higher in shoreline plots (0.255 m NAVD88) compared to interior plots (0.205 m NAVD88) (main effect of spatial position: $F_{1,47.1} = 17.39$, $P < 0.0001$) (Fig. 6b). This difference was consistent across both transect types (no interaction effect; $F_{1,47.1} = 0.18$, $P > 0.05$), suggesting no difference in elevation of mangrove plots relative to salt marsh plots. Considering shoreline plots only, elevation was higher in *Avicennia* than *Spartina* plots at ten sites, but equal or lower at seven sites. Although storm sediment at individual sampling stations was not correlated with plot elevation ($r = -0.07$, $P > 0.05$), average sediment thickness was greatest in interior sites where elevations were lowest on average (Fig. 6).

3.5. Accretion and surface elevation change at CRMS stations

Rates of accretion and elevation change measured at CRMS stations during the six-month period encompassing both hurricanes varied across the coast with highest rates occurring just east of the Hurricane Gustav track (Fig. 1c and d). Coastwide accretion rate during the hurricane interval averaged 4.4 cm yr^{-1} (range: 0.3–16.7 cm yr^{-1}), and elevation change averaged 3.2 cm yr^{-1} (range: 2.3–14.3 cm yr^{-1}). Sediment delivered during Hurricanes Gustav and Ike increased rates of accretion and elevation change at CRMS stations by 2.3 and 2.6 cm yr^{-1}, respectively, above the pre-hurricane rate. The coastwide rates were two times higher during the hurricane interval than rates measured before or after the hurricanes (Fig. 7) (repeated measures effect for accretion: $F_{2,49.2} = 9.26$, $P = 0.0004$ and Welch's ANOVA (unequal variance) for elevation change: $F_{2,58.6} = 9.38$, $P = 0.0003$). These results show that the hurricanes temporarily raised rates of accretion and elevation gain, but that rates later returned to pre-hurricane levels.

The coastwide pattern of elevation change during the hurricane interval was positively correlated with accretion rate ($r = 0.77$, $P < 0.0001$ with one outlier excluded), and the slope of the linear relationship was greater than that before and after the hurricanes (ANCOVA testing equal slopes: $F_{2,87} = 7.54$, $P = 0.001$). Hurricane accretion rates were not correlated with percent vegetative cover (range: 46–88%) or plant height (range: 51–128 cm) measured at CRMS stations just prior to the hurricane (July–August 2008) ($r = 0.01$ or 0.14, respectively; $P > 0.05$), or with distance from water (range: 1.9–30.9 m) ($r = 0.11$, $P > 0.05$). Accretion, however, was negatively correlated with marsh elevation (range: 0.024–0.302 m NAVD88) ($r = -0.44$, $P = 0.0162$).

4. Discussion

In the MRDC, where the requirement for sediment exceeds the amount delivered by tides and currents, hurricanes can be major forces that remobilize bay and offshore sediments and transport them into subsiding wetlands. In our survey, we found that an average of 2.6 cm of sediment was deposited by Hurricanes Gustav and Ike across the

Table 2
Relationship between hurricane sediment depth and vegetation variables at eighteen study sites across the Mississippi River Delta Complex (n = 72). The Pearson correlation coefficient (*r*) and significance probability (*P*) are given.

Vegetative variable	*r*	*P*
Canopy height	−0.39	0.0007
Stem density	−0.35	0.0023
Percent cover	−0.38	0.0011
Leaf area index	−0.47	<0.0001

Table 1
Vegetation structure measured at eighteen sites in the Mississippi River Delta Complex (mean ± SE). ANOVA sources of variation were transect type (Mangrove to Marsh, Marsh to Marsh) and spatial position (Shoreline, Interior); values are the *F*-ratio ($P \leq 0.05$*, 0.01**, 0.001***, 0.0001****, ns = not significant); post-ANOVA multiple comparisons (Tukey HSD) indicated by letters; Welch's ANOVA was used to test means when variance homogeneity could not be achieved.

Variable:	Mangrove to Marsh		Marsh to Marsh		ANOVA Results		
	Shoreline	Interior	Shoreline	Interior	Transect	Position	Transect x Position
Dominant species	*Avicennia*	*Spartina*	*Spartina*	*Spartina*	$F_{1,51}$	$F_{1,51}$	$F_{1,51}$
Plant height (cm)	130 ± 7a	60 ± 3c	78 ± 4b	67 ± 3bc	15.50***	81.78****	39.98****
Percent cover (%)	82 ± 4	55 ± 3	62 ± 4	45 ± 3	18.54****	40.89****	1.70ns
Leaf area index	3.03 ± 0.12a	1.58 ± 0.13c	2.01 ± 0.14b	1.32 ± 0.08c	35.40****	99.40****	12.68***
Density (m^{-2})							
Total stems	511 ± 44a	291 ± 22c	255 ± 16b	216 ± 15bc	43.01****	24.41****	6.14*
Pneumatophores	484 ± 44	0.6 ± 0.6	0.6 ± 0.6	1.7 ± 1.7	Welch's ANOVA: $F_{3,35} = 39.24$****		
Shoots	27 ± 4	291 ± 22	254 ± 16	214 ± 15	Welch's ANOVA: $F_{3,31} = 139.3$***		

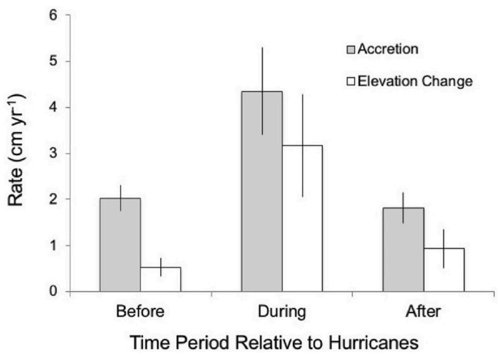

Fig. 7. Rates of accretion and elevation change recorded at Coastal Reference Monitoring System (CRMS) stations dominated by saline vegetation in the Mississippi River Delta Complex (Coastal Protection and Restoration Authority of Louisiana, 2015). Rates for three time periods relative to Hurricanes Gustav and Ike are plotted: Before (ca. May 2006 to April 2008), During (ca. April to October 2008) and After (ca. October 2008 to March 2012). Values are the mean ± SE (n = 29–33).

Louisiana coast, in agreement with previous work showing additions of one or more centimeters to MRDC coastal marshes by a hurricane (Rejmánek et al., 1988; Turner et al., 2006; McKee and Cherry, 2009; Tweel and Turner, 2012; Baustian and Mendelssohn, 2015; Bevington et al., 2017). The positive effect of this hurricane sediment on rates of vertical accretion and elevation change in the MRDC during 2008 was evident in records from a coastwide monitoring system (Fig. 7). Sediment deposition by the 2008 hurricanes varied spatially, among and within sites (Figs. 1, 5 and 6). Deposition patterns may reflect the influence of biological factors such as vegetation structure or physical factors such as marsh elevation and hydroperiod, which we consider next.

4.1. Controls on hurricane sedimentation patterns

Our main objective in this study was to determine if hurricane sedimentation was influenced by vegetation type. Prior work has shown effects of vegetation on sedimentation rates and patterns in the laboratory (Horstman et al., 2018) and in the field during normal tidal action (Bird, 1986; Leonard et al., 1995; Krauss et al., 2003; Li and Yang, 2009; Kumara et al., 2010; Mudd et al., 2010; Kamal et al., 2017; Kelleway et al., 2017; Phillips et al., 2017; Chen et al., 2018). For example, in a study conducted in China's Liaohe River Delta, Wang et al. (2017) observed lower sediment accretion rates in *Suaeda heteroptera* marshes than in *Phragmites australis* marshes, suggesting a differential effect of vegetation structure. In another study, sediment accretion in Australian coastal marshes varied with intertidal position and species (Kelleway et al., 2017). The accretion rate in high marsh dominated by the rush *Juncus kraussii* (1.74 mm yr^{-1}) was greater and less variable than in middle to low marsh with the succulent *Sarcocornia quinqueflora* (0.78 mm yr^{-1}) and the grass *Sporobolus virginicus* (0.88 mm yr^{-1}).

Vegetation may influence sediment deposition by reducing water flow and turbulence during a tidal cycle, allowing sediment particles to settle onto the soil surface (Leonard and Luther, 1995), or by trapping particles on plant surfaces (Li and Yang, 2009). The reduction in flow velocity through marsh grasses has been documented in several studies using real or artificial marsh grass (Shi et al., 1996; Tempest et al., 2015; Smith et al., 2016). Mangroves and their aerial root systems also influence sedimentation by slowing water movement and by trapping and binding sediment, preventing its resuspension (Bird, 1986; Krauss et al., 2003; Kumara et al., 2010).

Vegetation can also dissipate higher energy flows such as waves (Table 1 in Tempest et al., 2015). In marshes with different species arrayed in monospecific or mixed zones and/or spatial variation in plant height and stem density, flow dissipation can correlate with differences in canopy structure. For example, one study in China's Yangtze Estuary found that marsh vegetation reduced wave heights up to 80% over a distance of 50 m or less and that *S. alterniflora*, with its higher standing biomass, reduced wave energy more than *Scirpus mariqueter* (Ysebaert et al., 2011). A flume study with natural salt marsh showed that up to 60% of observed wave reduction was due to the vegetation (Möller et al., 2014). In a study of Thailand mangroves, the vegetation increased wave attenuation rates, which enhanced net sediment deposition (Horstman et al., 2014).

The relative influence of the vegetation on water flow velocity or wave dissipation has been linked directly to canopy structure (Leonard and Reed, 2002), stem density (Neumeier and Ciavola, 2004; Horstman et al., 2014; Montgomery et al., 2019), plant height (Shi et al., 1995), aboveground biomass (Rejmánek et al., 1988), and shoot flexibility (Bouma et al., 2009). A study conducted in micro-, meso-, and macrotidal marshes along Atlantic, Pacific, and Gulf of Mexico coasts and a marsh in the UK on the North Sea found that hydrodynamics reflected complexity of canopy structure and individual plant morphology (Leonard and Reed, 2002). As flow velocity through the marsh canopy slows, sediment particles fall out of suspension (Leonard and Luther, 1995). Particle settling due to dense vegetation slowing water velocity (rather than vegetation capture of sediment particles) accounted for most of the inorganic sediment deposited in a South Carolina salt marsh dominated by *S. alterniflora* (Mudd et al., 2010). However, not all studies report vegetation effects on sediment deposition. One study of salt marshes (dominated by *S. alterniflora*) in the St. Jones River estuary in Delaware, USA found that plant stem density (range: 640–1237 m^{-2}) had no effect on sediment deposition (Moskalski and Sommerfield, 2012). Another study of a mudflat-marsh edge in Argentina found no apparent attenuation of currents or waves by the vegetation (*S. alterniflora*), and the deposition of sediment mainly occurred on the mudflat just seaward of the salt marsh edge (Pratolongo et al., 2010).

A recent study directly compared the capacity of salt marsh (invasive *S. alterniflora*) and mangrove (*Kandelia obovata*, *Aegiceras corniculatum*, and *Avicennia marina*) vegetation to capture sediment (Chen et al., 2018). This study, conducted in the Zhangjiang Estuary along the southeast China coast, found that both vegetation types enhanced sediment capture relative to bare mudflat, but the salt marsh with higher stem density trapped more sediment (especially on leaf surfaces). In our study, *Avicennia* had higher stem density, canopy height, and LAI than adjacent salt marsh (Tables 1 and 2), features that might slow water movement or enhance vegetation capture of sediment particles. In addition, the woody structure of mangrove plants may offer greater resistance to water flow than a more flexible grass (Tempest et al., 2015). However, these differences in vegetative structure had no apparent effect on the amount of hurricane sediment deposited within these mangrove- and salt marsh-dominated stands or in landward salt marsh (Fig. 6a). This finding agrees with that of two previous studies conducted in the MRDC near Port Fourchon, LA, which found no significant difference in vertical accretion rates between shoreline plots dominated by *A. germinans* or *S. alterniflora* (Perry and Mendelssohn, 2009; McKee and Vervaeke, 2018).

There are three possible reasons why the vegetation had no discernible effect on deposition patterns: (1) *Avicennia* and *Spartina* influence sediment capture similarly, (2) the vegetation has little or no effect on sedimentation patterns under hurricane hydrodynamic conditions, and/or (3) physical factors such as marsh elevation and flooding depth and duration override vegetation effects in this environmental setting.

First, the structural features of *Avicennia* and *Spartina* may have been too similar to promote differential capture of hurricane sediment. As discussed above, significant vegetation effects on sediment accretion involved species that differed substantially in morphology and/or biomass (e.g., Kelleway et al., 2017; Wang et al., 2017; Chen et al., 2018). However, few studies have examined effects of vegetation type on hurricane sedimentation patterns. A study conducted in coastal

Louisiana found that *J. roemerianus* marsh with 2095 stems m^{-2} trapped 6.6 cm of sediment during Hurricane Andrew (August 1992) compared to 3.9 cm trapped by *S. alterniflora* marsh with 428 stems m^{-2} (Nyman et al., 1995b). In our study, average stem density was two times greater in *Avicennia* than in adjacent *Spartina* plots (Table 1). This difference, although significant statistically, may not translate into differential sediment capture. One reason may be that the majority of stems counted in *Avicennia* plots were pneumatophores less than 20 cm in height (Table 1), which may have had little effect on sedimentation when water levels were high. Short, dense structures such as pneumatophores may even enhance turbulence and reduce sediment deposition (Norris et al., 2019).

A second possibility is that vegetation has less influence on sediment deposition patterns under the hydrodynamic conditions generated by hurricanes. During astronomical tides, water levels fluctuate diurnally in coastal Louisiana, generating 4 to 7 flood events (each averaging 10–16 h duration) per week, and don't exceed average vegetation heights, except during meteorological events (Cahoon and Reed, 1995). By comparison, hurricanes generate deeper flooding that lasts several days. The study by Cahoon and Reed (1995) documented long-term flood events that raised water levels above normal—one associated with Hurricane Gilbert (September 1988) that lasted 206 h (Cahoon and Reed, 1995). Hurricane Andrew (August 1992) also increased flood height (1.2–1.7 m) and flood duration (48–224 h) across coastal Louisiana (Cahoon et al., 1995). We saw a similar pattern of short-term, shallow flooding events recorded across the coast at CRMS stations during astronomical tides (Fig. 4). These marshes were flooded an average of 14 h each day (range = 4–20 h), and water levels did not exceed 0.3 m above the marsh surface during August 29–September 20, 2007 (Fig. 4). During passage of hurricanes in 2008, the CRMS marshes experienced two long flooding events that lasted 5.3 (Gustav) and 11 (Ike) days. Water levels during these events greatly exceeded those recorded during astronomical tides and overtopped the plant canopies for several hours (Fig. 4). Thus, the effect of the vegetation on flow velocity and turbulence may be minimized during the deeper flooding and prolonged duration of flood events associated with hurricanes. Also, greater wave energy may have influenced the spatial pattern of deposition (Duvall et al., 2019).

The third explanation is that physical factors were more important than vegetation in controlling patterns of hurricane sediment deposition in this plant community. Physical controls on the amount of sediment deposited in coastal marshes include suspended sediment concentration, proximity to the sediment source, and marsh elevation (Cahoon and Reed, 1995; Moskalski and Sommerfield, 2012; Duvall et al., 2019; Palinkas and Engelhardt, 2019). Storm-generated turbulence, which remobilizes bay-bottom and offshore sediments and increases the concentration of suspended sediment in flood waters, likely varied spatially and contributed to coastwide patterns (Fig. 1). Several studies conducted in coastal Louisiana and elsewhere have shown the strong influence of physical factors such as elevation and consequent flooding regime on sedimentation patterns (Cahoon and Reed, 1995; Leonard, 1997; Duvall et al., 2019). Marsh topography influences the number and duration of flooding events, i.e., areas at lower elevations tend to be flooded for longer periods compared to those at higher elevations within the tidal frame (Cahoon and Reed, 1995). The frequency and duration of tidal flooding controls the opportunity for sediment deposition across the marsh surface. Sedimentation rates thus generally decrease with increasing marsh surface elevation and increasing distance from the seaward marsh edge or tidal creeks (Leonard, 1997; Temmerman et al., 2003). However, a different shore-to-inland topography existed in the Louisiana salt marsh-mangrove community. Elevations in the interior marsh were, on average, 5 cm lower than along the shoreline (Fig. 6b). Although we do not know what the marsh elevations were prior to Hurricanes Gustav and Ike, the natural elevations of saline wetlands in the MRDC tend to be 5–10 cm lower in the marsh interior than along creekbanks (DeLaune et al., 1983; Mendelssohn and McKee, 1988). Our coastwide survey found that more sediment was deposited in the marsh interior than along the shoreline (Fig. 6a), showing that distance *per se* did not diminish deposition. Instead, the amount of sediment deposited was greatest where elevations were lowest. This deposition pattern suggests that the difference in accommodation space between shoreline and interior plots was controlling how much sediment was deposited during the two hurricane flooding events. Accommodation space, which describes the space available for sediment accumulation (Jervey, 1988), is delineated in the vertical dimension by the distance between the soil surface and the uppermost tide level. Thus, the greater amount of hurricane sediment deposited in interior marsh compared to the higher elevation creekbank (Fig. 6) could reflect the shore-to-interior marsh topography and its consequent effect on accommodation space. This physical factor, combined with hurricane hydrodynamics, may have overridden any differential effects of the vegetation.

4.2. *Contribution of hurricane sediment to accretion and elevation change*

The beneficial effect of hurricane sediment on deteriorating marshes in the MRDC, which has been recognized for decades (Baumann et al., 1984; Rejmánek et al., 1988; Cahoon et al., 1995; McKee and Cherry, 2009; Baustian and Mendelssohn, 2015), was apparent in our study. Sediment deposited during Hurricanes Gustav and Ike temporarily increased average rates of accretion and elevation gain across saline wetlands in the MRDC relative to the periods before or after the hurricanes (Fig. 7). A previous study of Hurricane Isaac also found that accretion rates at CRMS stations increased 40% and 70%, respectively, relative to pre- and post-hurricane periods (Bianchette et al., 2016). During Hurricane Andrew in 1992, short-term sediment accretion (measured bi-weekly) remained elevated for up to 12 weeks at several marsh sites before returning to pre-hurricane levels (Cahoon et al., 1995). This sustained period of elevated sediment deposition was attributed to the high suspended sediments in waterways and bays, which was distributed through the marsh system post-hurricane by regular tidal flooding. Hurricane Andrew also increased accretion rates above a marker horizon 2- to 12-fold over a similar time period the previous year and raised surface elevations 2.0–2.5 cm (Old Oyster Bayou) (Cahoon et al., 1995), similar to our findings for the 2008 hurricanes. Another study found that Hurricanes Gustav and Ike caused an elevation gain of 1.2 cm in the Wax Lake Delta located at the terminus of a constructed channel of the Atchafalaya River (a distributary of the Mississippi River) (Bevington et al., 2017). Thus, although hurricane-affected rates of accretion and elevation gain varied spatially and temporally, storm sediment broadly contributed to elevation gain in the MRDC.

Coastal wetlands experiencing high rates of relative sea-level rise can benefit from hurricanes when storm-driven sediment offsets elevation deficits, either directly by addition of inorganic material or by stimulation of plant production (McKee and Cherry, 2009; Baustian and Mendelssohn, 2015, 2018). Since this salt marsh-mangrove community experiences an annual elevation deficit of 3–4 mm along creekbanks (McKee and Vervaeke, 2018), the sediment deposited by Hurricanes Gustav and Ike (2.6 cm) thus offset an estimated 7–9 years of accumulated deficit. If the deposited sediment is retained and undergoes minimal compaction, it contributes to elevation capital, i.e., a gain in relative position of the marsh in the tidal frame. The naturally lower elevation of interior marshes in the MRDC (DeLaune et al., 1983) means that the interior marsh has less elevation capital to begin with, rendering it more vulnerable to submergence than creekbank marsh. The deeper and prolonged flooding at lower elevations reduces plant growth and survival in the MRDC salt marshes by generating reducing soil conditions and toxic compounds such as sulfide (Mendelssohn and McKee, 1988). Early work in the MRDC also found that accretion rates in inland marsh (marker horizons: 0.6–0.9 cm yr^{-1}; ^{137}Cs: 0.7–0.8 cm yr^{-1}) were lower than in streamside marsh (marker horizons: 1.1–1.5 cm yr^{-1}; ^{137}Cs: 1.4 cm yr^{-1}) (Baumann et al., 1984). Comparison of these accretion rates to apparent rates of sea-level rise showed that while streamside marsh was keeping pace, the inland marsh was not.

The spatial pattern of 2008 hurricane deposition indicated that, compared to the creekbank, about twice more sediment was added where it was needed the most—in the low-elevation marsh interior (Figs. 5 and 6). Raising elevations of deteriorating marshes, either naturally or artificially, reduces flooding and promotes plant growth (Mendelssohn and McKee, 1988; Mendelssohn and Kuhn, 2003; Stagg and Mendelssohn, 2010). Although some studies show that post-depositional compaction can offset elevation gain, the magnitude of this correction depends on the organic content and porosity of the added material and the underlying substrate (McKee and Cherry, 2009; Graham and Mendelssohn, 2013). The bulk density of the 2008 hurricane deposit was comparable to that deposited in a brackish marsh (Pearl River: 1.36 g cm^{-3}) by Hurricane Katrina, which was more resistant to post-depositional compaction than another marsh (Big Branch: 0.20 g cm^{-3}) receiving storm sediment with high organic and water contents (McKee and Cherry, 2009). Addition of inorganic sediment, regardless of source, also moderates soil waterlogging by contributing sulfide-precipitating metals (e.g., iron and manganese) as well as growth-limiting nutrients (e.g., ammonium and phosphate) (Mendelssohn and Kuhn, 2003). A study of subsided saline marshes in the MRDC found that marsh productivity and resilience were enhanced by hurricane sediment (Baustian and Mendelssohn, 2015). Thus, although hurricanes may cause destruction of MRDC wetlands in some areas, they provide a much-needed sediment subsidy to others, especially to interior saline marshes with low elevation capital and low rates of sediment accretion.

5. Conclusions

Sea-level rise, driven by global warming, threatens coastal wetlands worldwide with potential submergence (IPCC, 2014). Understanding how hurricanes may interact with processes controlling coastal elevations will aid in management of these ecosystems and the services they provide. Assessments of how coastal ecosystems at climatic boundaries are affected by hurricanes will provide better predictions of sustainability and storm-buffering capacity under future climate scenarios. This information becomes increasingly important if sea-level rise and hurricane intensity and frequency increase with global climate change as some models predict (reviewed by Walsh et al., 2016). In addition to changes in sea level and hurricanes, a warming climate will drive vegetation shifts at subtropical boundaries. For example, mangroves have expanded their range and encroached on salt marsh not only in Louisiana, but globally. The most cold-tolerant genus, *Avicennia*, has been particularly noted for its distributional extension along the coasts of the USA, Mexico, Peru, Australia, Africa, and China (reviewed by Saintilan et al., 2014). A few investigators have predicted that mangrove replacement of salt marsh will improve resistance to sea-level rise through enhanced sediment trapping or organic matter accumulation (Rogers et al., 2006; Comeaux et al., 2012; Bianchi et al., 2013; Saintilan et al., 2014). However, field experiments have found no difference in rates of accretion and/or elevation change between adjacent stands of *S. alterniflora* and *A. germinans* in the MRDC (Perry and Mendelssohn, 2009; McKee and Vervaeke, 2018). Our study additionally shows that these two vegetation types can trap similar amounts of hurricane-driven sediment, further indicating that mangrove replacement of salt marsh in the MRDC may not substantially alter sediment accretion. However, this finding may be unique to the particular topographic, hydrodynamic, and sedimentary conditions in the MRDC and the specific structural features of *A. germinans* and *S. alterniflora* at subtropical latitudes. Co-occurring mangrove and salt marsh species in other geographic regions may differ sufficiently to alter sediment trapping and retention features. In addition, it is uncertain how long the Hurricane Gustav/Ike event layer will persist in the sedimentary record or if there will be long-term differences between mangrove and marsh habitats in storm sediment retention or compaction. The fate of this storm layer will depend on multiple factors such as thickness and composition of the hurricane sediment and its source, as well as post-storm sedimentation, erosion, and bioturbation (Reese et al., 2008; Naquin et al., 2014; Yellen et al., 2014). For example, work in brackish marshes has shown that higher organic matter and water contents of hurricane sediment can increase post-storm compaction rates (McKee and Cherry, 2009). Although our study found no vegetation effect on the quantity or composition of the Hurricane Gustav/Ike deposit, habitat differences in factors such as wave energy, bioturbation by burrowing organisms, or root growth could affect hurricane sediment retention. Future conservation and restoration efforts will require a better understanding of factors controlling long-term effects of hurricane sediment on coastal marshes. In particular, more comparisons of side-by-side stands of salt marsh and mangrove with similar hydrology are needed to determine how and under what circumstances these vegetation types may differentially influence sedimentation patterns.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Karen L. McKee: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Funding acquisition. **Irving A. Mendelssohn:** Conceptualization, Methodology, Investigation, Writing - original draft, Project administration, Funding acquisition. **Mark W. Hester:** Conceptualization, Methodology, Investigation, Writing - original draft, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2020.106733.

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