**DERIVING SPATIAL AND TEMPORAL PATTERNS OF COASTAL MARSH
AGGRADATION FROM HURRICANE STORM SURGE MARKER BEDS**

Joshua Hodge and Harry Williams

Department of Geography and the Environment

University of North Texas

Denton, TX 76203, U.S.A.

joshuahodge@my.unt.edu

ABSTRACT

This study uses storm surge sediment beds deposited by Hurricanes Audrey (1957), Carla (1961), Rita (2005) and Ike (2008) to investigate spatial and temporal changes in marsh sedimentation on the McFaddin National Wildlife Refuge in Southeastern Texas. Fourteen sediment cores were collected along a transect extending 1230 m inland from the Gulf coast. Storm-surge-deposited sediment beds were identified by texture, organic content, carbonate content, the presence of marine microfossils and ^{137}Cs dating. The hurricane-derived sediment beds facilitate assessment of changes in marsh sedimentation from nearshore to inland locations and over decadal to annual timescales. Spatial variation along the transect reflects varying contributions from three prevailing sediment sources: flooding, overwash and organic sedimentation from marsh plants. Over about the last decade, hurricane overwash has been the predominant sediment source for nearshore locations because of large sediment inputs from Hurricanes Rita and Ike. Farther inland, hurricane inputs diminish and sedimentation is dominated by deposition from flood waters and a larger organic component. Temporal variations in sedimentation reflect hurricane activity, changes in marsh surface elevation and degree of compaction of marsh sediments, which is time-dependent. There was little to no marsh sedimentation in the period 2008-2014, firstly because no hurricanes impacted the study area and secondly because overwash sedimentation prior to 2008 had increased nearshore marsh surface elevations by up to 0.68 m, reducing subsequent inputs from flooding. Marsh sedimentation rates were relatively high in the period 2005-2008, averaging 2.13 cm/yr and possibly reflecting sediment contributions from Hurricanes Humberto and Gustav. However, these marsh sediments are highly organic and largely uncompacted. Older, deeper marsh deposits formed between 1961 and 2005 are less organic-rich, more compacted and have an average annual sedimentation rate

of 0.38 cm/yr, which is closely comparable to long-term sedimentation rates in similar marsh settings nearby. These results demonstrate the utility of using hurricane storm surge marker beds to investigate marsh sedimentation, provide insights into the sedimentary response of coastal marshes to hurricanes and provide useful guidance to public policy aimed at combating the effects of sea-level rise on coastal marshes along the northern Gulf of Mexico.

KEYWORDS: *sediment accretion, sedimentation rate, sea level rise, overwash, washover, Hurricane Audrey, Hurricane Carla, Hurricane Rita, Hurricane Ike.*

INTRODUCTION

Coastal marshes along the northern Gulf of Mexico provide valuable habitats for a variety of flora and fauna, and serve to protect areas further inland by acting as buffers against storms (Mitsch and Gosselink, 1984; Kennish, 2001; Turner et al., 2006; Yuill et al., 2009; Gedan, et al., 2011; Tweel and Turner, 2014). Rising sea-level caused by thermal expansion of seawater due to increasing global temperatures, regional subsidence due to groundwater extraction, and lack of riverine sediment inputs to fill growing accommodation space, threaten to convert coastal marshes to open water with the consequent loss of valuable marsh functions (DeLaune et al., 1994; Kennish, 2001; Glick et al., 2013; Kent and Dokka, 2013). Rates of northern Gulf of Mexico marsh loss have been dramatic – between 1955 and 1978 the loss of marshes was 127 km² per year – equivalent to the area of Rhode Island every 21 years (Turner, 1997). Blum and Roberts (2009) estimate that in the absence of sediment input an additional 10,000–13,500 km² of Mississippi delta plain marshes will be submerged by the year 2100 owing to subsidence and sea-level rise.

Aggradation of coastal marshes by influx and deposition of inorganic sediment counters declining relative elevation due to subsidence and sea-level rise. DeLaune et al., (2003) demonstrated that diversion of Mississippi River waters into adjoining marshes provided freshwater and sediment inputs that lowered salinity and enhanced marsh accretion and stability. Roberts et al., (2015), working on marshes between the Wax Lake Outlet and the Lower Atchafalaya River in Louisiana, found that the passage of cold fronts raised water levels by up to 1 m and reversed normal river discharge into Atchafalaya Bay, causing overbank flooding into adjoining coastal plain marshes. They found that deposition of suspended sediment carried in

floodwaters resulted in >1 cm/year of fine-grained sedimentation in streamside locations up to 100 m from channels.

Hurricane storm surges represent another mechanism for transport of sediment into marshes. Williams (2012) found that Hurricane Ike (U.S. landfall September 13, 2008) deposited 16.2 million tonnes of sediment into marshes along 160 km of coastline in Texas and Louisiana. The storm surge-derived sediment bed was up to 0.85 m thick and extended up to 3.6 km inland. A number of other studies have also documented the contribution of hurricanes to aggradation of coastal marshes (Mitsch and Gosselink, 1984; Nyman et al., 1995; Stone et al., 1997; Liu, 2004; Törnqvist et al., 2006; Turner et al., 2006; Williams & Flanagan, 2009; Boldt et al., 2010; Williams, 2010; 2011; Tweel and Turner, 2012, 2014; Williams and Denlinger, 2013).

Hurricanes can deposit sediment on marshes along long sections of coasts and in locations that are remote from significant riverine sediment sources (Williams, 2012). Hurricane storm surges, combined with wind-driven waves, erode and entrain sediment from offshore, intertidal flats, bays, beaches and dunes, and transport sediment, usually as a combination of traction load and suspended load, into marsh interiors (Williams, 2010). Although hurricane storm surge deposition often occurs on marshes paralleling the Gulf Coast, sedimentation also occurs on marshes surrounding inland lakes and bays, such as Lake Pontchartrain, Louisiana (Liu et al., 2014; Naquin et al., 2014).

Some coastal marshes experience increased aggradation even as sea-level rise accelerates, due to biotic processes such as the CO₂ fertilization effect and the stimulation of increased above-ground and below-ground biomass production. Increased above-ground biomass production may also increase inorganic sedimentation because of enhanced trapping of suspended sediment from tidal flood waters; although if sea-level rise accelerates beyond a

critical threshold, plant dieback and marsh loss can still occur (Cherry et al., 2008; Hill and Anisfeld, 2015; Ratliff et al., 2015). In contrast, the permanent inundation and conversion to open water of large areas of marsh in the Mississippi delta plain following reductions in Mississippi River suspended sediment inputs, shows that other marshes are sediment-limited and dependent on sufficient inorganic sediment inputs to keep pace with accelerated sea-level rise (Day et al., 2000; Blum and Roberts, 2009).

Tropical cyclones often result in net gains of sediment for marshes subjected to storm surge overwash, counteracting the relative elevation loss from sea-level rise (Stone et al., 1997; Cahoon, 2006; Turner et al., 2006; McKee and Cherry, 2009; Williams, 2012). Consequently, it is important to gain a better understanding of the contributions and consequences of tropical cyclone storm surge deposition to coastal marsh aggradation. Better understanding of tropical cyclone-derived sedimentation could have important consequences for coastal management agencies that build and maintain seawalls, levees, bulk-heads, dikes, weirs, piers, docks, pipelines, dams and other hard structures, which act as physical barriers to storm surges and may inhibit inorganic sediment accretion on marsh surfaces (Deegan et al., 1984; Sasser et al., 1986; Swenson and Turner, 1987; Delaune et al., 1989; Turner, 1990; White and Morton, 1997; Bryant and Chabreck, 1998; Kennish, 2001).

Williams (2010) documented Hurricane Ike storm surge sedimentation on the McFaddin Wildlife Refuge in southeastern Texas in January 2009, four months after the hurricane made landfall. Along a 1230 m-long transect of thirteen trench locations, the storm surge deposit was found to exhibit two distinct styles of sedimentation: a sandy washover fan, up to 0.64 m in thickness, extending about 150 m inland and bounded by an avalanche face, deposited as traction

load; and a thinner, finer, more organic-rich blanket of sediments extending several km inland, deposited from suspension (Fig. 1).

Figure 1a. View to northwest across surface of a sandy washover fan deposited by Hurricane Ike in January, 2009 (viewpoint is near core location 1 on Fig. 3). The fan was approximately 0.6 m thick at this location and was almost entirely devoid of vegetation at this time. Standing vegetation is visible beyond the edge of the washover fan, in the vicinity of core site 4. b. Monolith excavated from near core site 11, approximately 945 m inland (see Fig. 3 for locations). The storm surge deposit, consisting of about 3 cm of sandy mud, has a sharp contact with underlying organic-rich marsh sediments. Stems of live marsh plants protrude through the storm surge deposit (arrowed).

In 2011, a core obtained from the location of trench 5, 265 m inland, revealed three deeper prominent sand beds, below the Hurricane Ike sand bed (Fig. 2). These sand beds appear to share many characteristics with the overlying Hurricane Ike deposit (higher sand content and lower organic content than enclosing marsh deposits; sharp basal contact) and are tentatively interpreted as hurricane storm surge deposits.

Figure 2. Core T5-5 obtained in 2011 from McFaddin National Wildlife Refuge showing sand bed of Hurricane Ike (2008) and three deeper sand beds (Sand beds 2, 3 and 4) (Williams, unpublished data; see Fig. 3 for core location).

This paper reports on a project that expands upon Williams' (2010) study by obtaining sediment cores at the same thirteen trench locations used in the 2010 study, with the goal of using hurricane storm surge marker beds to investigate changes in marsh sedimentation. The objective of the study was to assess the contribution of hurricane storm surge sedimentation to marsh aggradation and the effects of the abrupt elevation gain from storm surge deposition on subsequent non-hurricane-related sedimentation. Information gained from this study provides

insights into decadal-scale sedimentary response of coastal marshes subject to storm surge deposition and useful guidance to public policy aimed at combating the effects of sea-level rise on coastal marshes along the northern Gulf of Mexico coastline.

STUDY AREA

The study area is a transect of marshland located on the McFaddin National Wildlife Refuge, a 23,820 hectare tract of marshes and lakes located in Jefferson County in the far southeastern corner of Texas (Fig. 3). A wide sandy beach, backed by low discontinuous foredunes, forms the boundary between the refuge and the Gulf of Mexico. Highway 87 runs along the seaward edge of the refuge, but after repeated washouts caused by hurricanes, the highway south from Clam Lake Road was closed in 1990.

Clam Lake is a tidally-influenced brackish lake having numerous connections via tidal creeks and ditches to Sabine Pass and the Gulf Intracoastal Waterway, which forms much of the northern boundary of the refuge. The lake, essentially at sea level, has the lowest elevation in the study area. Elevation increases seaward along the transect from 0.3 m NAVD88 at core site 13 to 1.72 m NAVD88 at core site 1. Adjacent to the transect, Highway 87 has an elevation of 1.47 m NAVD88 (Fig. 3).

Flooding of marshes around the lake results from high discharges in the Sabine and Neches rivers (which raises water levels in the Gulf Intracoastal Waterway, Sabine Lake and Sabine Pass), heavy rain, high tides, storm surges and overwash. Marshes on the refuge range from freshwater to brackish and are categorized as temporarily, seasonally or semi-permanently flooded, depending upon subtle variations in elevation. In the study area, a narrow strip of marsh at the seaward end of the transect is characterized as palustrine, emergent, intermittently flooded

(~core sites 1-7) and the lower more landward marsh is characterized as estuarine, intertidal, emergent, irregularly flooded (~core sites 8-13) (U.S. Fish and Wildlife Service, 2016) (Fig. 3). The marshes are dominated by inorganic sediment. Williams (2010) found that the inorganic sediment content of the 2008 marsh surface (pre-Hurricane Ike) at the 13 core sites along the transect ranged from 67-95% and averaged 85% (on a dry weight basis).

Figure 3. Study area at McFaddin National Wildlife Refuge, Texas. Core locations, numbered consecutively from 1 to 13, coincide with trench locations used in Williams' (2010) study. Core T5-5, obtained in 2011, is from the same location as core 5. Google Earth image 2014.

In 2014 when the study was conducted, foredunes along the seaward edge of the study area

reached maximum heights of approximately 1 m above Highway 87. Although these dunes formed a partial barrier to recent storm surge overwash, there were low spots in the dune line and wide gaps in the dunes existed to allow vehicle access to the beach. In 2008, Hurricane Ike generated an unusually large storm surge in the study area exceeding 4 m NAVD88, which overtopped the foredunes, partially eroded them and completely inundated Clam Lake and surrounding marshland.

METHODS

Marsh Stratigraphy

The thirteen trench locations used in Williams' (2010) study were relocated using a hand-held GPS with reported accuracy of ± 10 m (Garmin, 2007). A core was obtained at each location by driving aluminum or PVC tubes into the marsh, until resistance prevented further penetration, typically at a depth of 50-100 cm. Compaction of cores was assessed by comparing the depth of penetration of the coring tube and the distance between the top of the sediment core inside the tube and the ground surface. This allowed compaction to be calculated as a percentage of core length; compaction percentages varied from 2-25%. Most compaction occurred in sand-rich cores from the washover fan (cores 1-4, average compaction 19%). This probably reflects the greater resistance of these sediments to core penetration. Less compaction occurred in the softer, wetter, less sand-rich cores farther inland (cores 5-13, average compaction 6%). Uncompacted depths within cores were estimated by applying the compaction percentage uniformly over the entire length of the core. Although the compaction correction likely introduced a small amount of error, stratigraphy does at least seem consistent between cores with little compaction (e.g. core 6, 2%) and cores with more compaction (cores 7 and 8, 4% and 8% respectively). Cores were sealed and transported to the geomorphology laboratory at the

University of North Texas, where the tubes were cut lengthwise and the sediment cores within were split into two halves longitudinally. Cores were logged and photographed. Selected cores were sampled at selected depths for textural analysis, loss-on-ignition (LOI) analysis and foraminiferal analysis.

Marsh Topography

The elevation of each core site was measured by a level transit set up on Highway 87 near core site 1, at core site 1, at core site 8 and at core site 11 (four level sites were required to cover the 1230 m-long transect). All elevations were tied to a USGS benchmark a few meters north of Highway 87 in the vicinity of the study area (benchmark designation E1015, elevation 1.54 m NAVD88; personal communication, R. Josey, Texas Department of Transportation, August 14, 2015).

Sand Content, Organic Content and Carbonate Content

Sediment samples were collected from selected cores from within, below and above suspected hurricane-storm-surge-deposited sediment beds for textural, Loss-On-Ignition (LOI) and microfossil analyses to help document contrasts in lithology and microfossil content between the sediment beds and the enclosing marsh sediments. Additional samples were taken from sections of cores suspected to contain storm-surge-deposited sediment beds, but lacking in visually distinct sand layers because of a lack of lithologic contrast and/or bioturbation.

All samples were divided into two subsamples for analysis. One subsample was weighed and then oven-dried at 105 °C for 24 hours to determine moisture content (% wet weight). The other subsample was weighed and then wet-sieved through a 63- μ m sieve to retain the sand

fraction. The sand fraction was air-dried and weighed. The measured moisture content was used to calculate the dry weight of the sieved sample, and the weight of the sand fraction was then used to calculate sand content (% dry weight). The dried subsample was weighed and then placed in a muffle furnace at 550 °C for 4 hours to determine organic matter content (% dry weight). After reweighing, the same sample was returned to the muffle furnace for 2 hours at 950 °C to determine carbonate mineral content (% dry weight).

Loss on ignition (LOI) is a widely used technique to estimate the amount of organic matter and carbonate mineral content in sediments (Dean, 1974). The LOI technique has sources of potential error related to variations in sample size, sample composition, furnace temperature, furnace exposure time and furnace position. LOI results may vary, for example, due to dehydration of clay minerals or insufficient furnace temperatures and exposures times (Heiri et al., 2001). These limitations decrease the effectiveness of LOI as a quantitative tool, but LOI results correlate well to results gained from other standard techniques, allowing the use of LOI as a qualitative method (Beaudoin, 2003; Santiseban et al., 2004). LOI procedures used in this study follow the recommendation of Heiri et al. (2001) for consistency; all samples had uniform treatment in terms of sample size, furnace temperatures and furnace exposure times.

Microfossil Analysis

Sand fractions derived from wet sieving were examined under a dissecting microscope to identify and count foraminifers. If the sand fraction was small (<1 g), the entire sample was examined for foraminifers; if the sand fraction was large (>1 g), a dry splitter was used to obtain a subsample (typically 0.2–0.5 g) for analysis and foraminiferal counts were multiplied accordingly to estimate the number of specimens in the entire sample. Foraminifers were

identified to the genus or species level and the percentage of calcareous and agglutinated species in each sample was calculated. The total number of foraminifers in the sample was used to calculate the number of foraminifers per gram of dry sediment.

RESULTS

Marsh Stratigraphy and Identification of Storm-Surge-Deposited Sediment Beds

The sediment bed deposited by Hurricane Ike was either at or close to the marsh surface and was visually identifiable in all fourteen cores (Fig. 4). This sediment bed thins and fines inland; its thickness and texture closely matches descriptions made by Williams (2010) shortly after the hurricane's landfall in 2008. Hurricane Ike's deposit provides a modern analog to aid in identification of older storm surge sediment beds deeper within the marsh. Older sediment beds were readily identifiable in many cores because they are visually distinct, relatively thick, sandy, have sharp basal contacts and contrast lithologically with enclosing finer-grained, more organic-rich marsh sediments. Farther inland, the storm surge deposits become thinner, more lithologically similar to enclosing marsh sediments and more bioturbated (Fig. 4).

Four distinct sediment beds are visible in core T5-5, including Hurricane Ike's deposit at the top of the core (Figs. 2, 4). A relatively thick, sandy sediment bed (sand bed 2) is apparent a short depth below the Hurricane Ike deposit and two thinner, closely-spaced, but distinctly separate, sediment beds are visible near the bottom of the core (beds 3 & 4). These two sediment beds are separated by a thin layer (~5 mm) of marsh sediment. The same four sediment beds are recognizable in cores 6 and 9. In core 9, a sandy sediment bed a short depth below Hurricane Ike's deposit is recognizable, but appears heavily disturbed by bioturbation; in core 6, the two deeper sediment beds (beds 3 & 4) also appear disturbed by bioturbation, but they are still

292 recognizable as distinct sediment beds, separated by a thin layer of marsh deposits. In core 7, all
293 three sediment beds (beds 2, 3 & 4) appear to have been disturbed by bioturbation, to the extent
294 that the two deeper sediment beds have apparently become mixed into a single sandy layer. In
295 core 8, the two deeper sediment beds (beds 3 & 4) are recognizable and separated by marsh
296 deposits, but sediment bed 2, immediately below Hurricane Ike's deposit, is not visible. In cores
297 10-13 there are no visually recognizable sediment beds below the Hurricane Ike deposit (Fig. 4).
298

Figure 4. Storm surge sediment bed deposited by Hurricane Ike (2008) and other sediment beds of suspected hurricane-storm-surge origin (beds 2, 3 and 4) in cores from McFaddin National Wildlife Refuge. Storm surge deposits that are not visually distinct but are identified by LOI analysis are followed by a question mark. Some of the bed 2 deposits include a “mud cap.” Cores 1-13 were obtained in 2014; core T5-5, from the same location as core 5, was obtained in 2011 (Williams, unpublished data, 2011).

The lack of a visually recognizable sediment bed 2 in core 8 and sediment beds 2, 3 and 4 in cores 10-13 may be the result of mixing of the sediment beds with enclosing marsh deposits by bioturbation. To explore this possibility, the results of the LOI analysis (sand%, moisture%, organic% and carbonate%) were examined in an attempt to identify sediment beds that were not visually recognizable in cores (Fig. 5).

Figure 5. LOI analysis results for cores 7, 10 and 13. Core 7 is included to illustrate the LOI signature of known (visually recognizable) storm surge sediment beds (elevated sand%, reduced moisture% and reduced organic%; carbonate% varied little throughout most cores and did not help in interpretation).

The LOI analysis revealed sand-rich zones, tentatively interpreted as bioturbated storm surge sediment beds, only in cores 10 and 13. The sand-rich zones a short depth below Hurricane Ike's storm surge deposit in both cores are assumed to be sediment bed 2 and the deepest sand-rich zones in cores 10 and 13 are assumed to be the result of mixing of the closely-spaced

sediment beds 3 and 4 by bioturbation. These presumably bioturbated storm surge sediment beds have been indicated on Fig. 4.

Foraminiferal analysis did not reveal any additional bioturbated sediment beds within the cores. Samples were examined from selected depths in cores with the aim of identifying calcareous foraminifers presumably transported inland by hurricane storm surges, as had been shown to be the case for Hurricane Ike (Williams, 2010). However, the majority of samples examined were either entirely barren or contained low numbers of agglutinated marsh foraminifers, which are presumably *in-situ* and do not indicate landward transport of marine sediment. The only exception was core 4, where samples from the base of the Hurricane Ike sand bed, the underlying marsh deposits and the sand bed below Hurricane Ike's, contained moderately large numbers of calcareous and agglutinated specimens (Table 1; Fig. 6).

It is notable that Williams (2010) also found large numbers of foraminifers at core site 4. In the 2010 study, 1661 foraminifers per gram of dried sediment, 98% calcareous forms, were found in the base of Hurricane Ike's storm surge deposit at trench site 4 – more than at any of the other 12 trench locations along the transect, where foraminiferal concentrations varied from 85 to 1058 specimens per gram of dried sediment. The spike in foraminiferal concentration at this location may be related to the effects of the topographic step at the landward edge of the washover fan and the presence of standing vegetation beyond the edge of the washover fan on the hydrodynamics of storm surge deposition; for example, foraminifers in suspension may be winnowed out and deposited where there is a substantial reduction in flow energy (Williams, 2010; Fig. 1a).

The virtual absence of foraminifers, particularly calcareous forms, in the majority of samples examined suggests that foraminiferal tests are poorly preserved in the marsh. This

supports Williams' (2010) contention that foraminifers are poorly preserved in nearby Clam Lake (Fig. 3) and is consistent with the substantial reduction in foraminiferal concentrations in the base of the Hurricane Ike deposit at core site 4 – from 1661 specimens per gram of dried sediment in January 2009 to 543 specimens per gram of dried sediment in August 2014 (Table 1; Fig. 6).

Figure 6. Foraminiferal content of core 4. Foraminifers are abundant and almost entirely calcareous marine forms in the storm surge sediment beds. Lower numbers of agglutinated marsh forms are present between the storm surge deposits, recording marsh sedimentation.

The distribution of foraminifers in core 4 also indicates the presence of a “mud cap” on top of sand bed 2. This part of the core is visually distinct from, and finer than, the underlying

sand bed (although still ~50% sand in the case of core 4), but it contains abundant calcareous foraminifers, showing it is part of the storm surge deposit (Fig. 6). Although not as distinctive as underlying sand beds, mud caps are visually apparent in several other cores and have LOI signatures that contrast to overlying marsh deposits; most notably, lower organic and moisture contents and, in most cases, elevated sand contents (Fig. 7). It is assumed that these mud caps were deposited from suspension onto parts of the marsh where ponded flood waters remained for one to several days following passage of the hurricane. Similar mud caps have been reported for Hurricane Rita deposits in Louisiana (Williams, 2009, 2011; Freeman et al., 2015) and in southeastern Texas (Crosby and Reece, 2009). Mud caps are included in some of the sediment bed 2 deposits shown in Fig. 4.

Figure 7. LOI characteristics of a mud cap on sand bed 2 in core 6. The 'mud cap' has lower organic and moisture contents than overlying marsh deposits. The mud cap presumably was deposited from suspension and is considered part of the storm surge deposit.

DISCUSSION

Age and Origin of Storm Surge Sediment Beds.

The presence of abundant calcareous foraminifers in sand bed 2 confirms a marine origin for this sand layer. Significant numbers of foraminifers were not found in sand beds 3 or 4 in any of the cores. Given that Williams (2010) found marine calcareous foraminifers in all 13 cores collected from Hurricane Ike's storm surge deposit four months after landfall (i.e. foraminifers are apparently common in freshly-deposited storm surge deposits at this site), the lack of foraminifers probably reflects poor preservation of foraminifera tests in these older deposits. However, the similarities between all four sand beds – they are sand-rich, they thin and fine landward, they have sharp basal contacts and they extend over 1,000 m inland – strongly suggests they are hurricane storm surge deposits. Tsunamis can also deposit sand sheets in marshes, but there is no historical record of a tsunami strike in the northern Gulf of Mexico. There is no evidence that lower-intensity storms deposit extensive sand sheets over the surface of the marsh and no other known mechanisms can account for these deposits.

A means of estimating the age of the two oldest storm-surge-deposited sediment beds (sand beds 3 and 4) is provided by Williams and Denlinger (2013), who conducted ^{137}Cs dating of marsh sediment underlying the Hurricane Ike storm surge deposit at core site 3. Commonly, this technique is based on the identification of a peak in ^{137}Cs concentration corresponding to the year 1963, after which the Nuclear Test Ban Treaty was implemented, greatly reducing atmospheric fallout from above-ground nuclear weapons testing (Gustafson, 1969). However, many ^{137}Cs profiles from marshes in this area do not have an unambiguous ^{137}Cs concentration peak. This includes the profile from core site 3, which has high concentrations of ^{137}Cs at a shallow depth (Fig. 8). This is a common finding in this area and probably results from erosion

and re-deposition of ^{137}Cs -rich sediments onto a more recent marsh surface (Williams and Flanagan, 2009; Williams, 1995, 2011; Williams and Denlinger, 2013). Instead, dating is based on the assumption that the depth at which the ^{137}Cs concentration falls to zero corresponds to the year 1950, which approximates the onset of large-scale above-ground nuclear weapons testing and widespread fallout of atmospheric ^{137}Cs (Milan, et al., 1995). On this basis, Williams and Denlinger (2013) estimated that the surface of the marsh in the year 1950 is approximately 47 cm below the base of the Hurricane Ike deposit (Fig. 8).

Figure 8. ^{137}Cs concentration profile in sediments underlying Hurricane Ike's storm-surge deposit at core site 3. The 1950 marker horizon is extended to core T5-5. Cores are shown at

404 *their correct elevation, but not their correct horizontal separation.* ¹³⁷Cs data from Williams and
405 *Denlinger (2013).*

406 Extending the 1950 marker horizon from core site 3 to core site T5-5, 90 m away,
407 suggests that sand beds 3 and 4 are a few cm above the level of the marsh surface in 1950 (Fig.
408 8). These two sand beds were probably deposited by hurricanes that occurred shortly after 1950.
409 Sand bed 2 is a relatively short depth below the Hurricane Ike deposit; it was probably deposited
410 shortly before 2008.

411 Twenty-three hurricanes passed within 300 km of the study area between 1950 and 2014
412 (Fig. 9). This radius was chosen because it encompasses Hurricane Carla (1961), which,
413 although making landfall 290 km to the west, generated a well-documented storm tide and
414 hurricane-force winds in the vicinity of the study area. In terms of wind speed, Hurricane Carla
415 was the most intense hurricane to make landfall on the Texas coast in the 20th century and the
416 9th most intense hurricane to affect the United States since 1851 (National Weather Service,
417 2011). In the study area, Hurricane Carla generated a 2.25-m storm tide and sustained winds of
418 76 knots (Table 2).

419 Storm tide is the combined height of storm surge and tide level; this provides a better
420 indication of inundation potential than storm surge alone (i.e. a 1 m storm surge at low tide may
421 not cause inundation, whereas the same storm surge at high tide may lead to inundation). All
422 storm tides in Table 2 are referenced to NAVD88, which allows direct comparison of storm tide
423 height to the height of physical barriers, such as foredunes and Highway 87, and to the height of
424 the marsh surface.

Figure 9. Map of hurricane landfalls within 300 km of study area and locations of tide and wind records. Location key: SP: Sabine Pass, G: Galveston, PA: Port Arthur, BAP: Beaumont Air Port, HI: High Island, TPNWR: Texas Point National Wildlife Refuge, MNWR: McFaddin National Wildlife Refuge, SRSP: Sea Rim State Park, RP: Rollover Pass.

The largest storm tides and strongest sustained winds in the study area have been generated by hurricanes of three kinds: very large and intense hurricanes that make landfall a considerable distance to the west (e.g. Hurricane Carla); lower-intensity, but still powerful hurricanes that make landfall a shorter distance to the west (e.g. Hurricane Ike); intense hurricanes that make landfall a short distance to the east (e.g. hurricanes Audrey and Rita) (Table 2).

The importance of a landfall to the west or east of the study area results from the storm's cyclonic circulation causing a larger storm surge in the right-front quadrant of the landfalling hurricane (Liu, 2004). In this quadrant, onshore winds drive water against the coast causing a large storm surge and large onshore waves: in the left-front quadrant, offshore winds greatly reduce storm surge potential. This is why hurricanes Andrew, Carmen and Betsy had little to no impact in the study area – they were intense storms, but made landfall a relatively large distance to the east of the site (Table 2).

Other lower-intensity storms, such as hurricanes Bonnie and Humberto, even though making landfall a short distance west of the study area, were not powerful enough to generate large storm surges and strong sustained winds and, consequently, apparently did not deposit thick, extensive sand-rich sediment layers over the marsh surface. These storms may have transported smaller amounts of finer sediment into the marsh to form thinner, finer-grained, less extensive deposits; if so, these deposits have presumably been mixed with marsh sediments by bioturbation and no longer form recognizable storm surge sediment beds. A similar fate befell Hurricane Ike deposits in a marsh in southwestern Louisiana; the hurricane formed a thin, muddy sediment bed that was obscured by bioturbation within 20 months after landfall (Williams, 2011).

A combination of a large storm surge and large wind-driven waves are required to entrain nearshore sediment and transport it onto a marsh (Williams, 2013). On this basis, it is likely that

sand beds 2, 3 and 4 were deposited by hurricanes Rita, Carla and Audrey, respectively (Table 2). This interpretation is also consistent with the stratigraphic position of these sand beds with respect to the ^{137}Cs -derived 1950 marker horizon: it is plausible that sand bed 2, a short depth below Hurricane Ike's deposit, could be the result of Hurricane Rita (2005), and that sand beds 3 and 4, a short distance above the 1950 marker horizon, could be the result of Hurricane Carla (1961) and Hurricane Audrey (1957) (Fig. 8).

Additional support for this interpretation is provided by other studies of hurricane deposits in this area: a sediment bed deposited by Hurricane Rita was found at Texas Point National Wildlife Refuge, approximately 18 km east of the study area (Fig. 9). A survey of the marsh made in November 2006, 14 months after landfall, revealed a sand-rich storm surge deposit at the surface of the marsh. The deposit varied from 2 to 15 cm in thickness, extended at least 400 m inland and, in places, was capped by clay, presumably deposited from suspension in standing flood waters (Crosby and Reece, 2009). Williams (2011, 2013) documented storm surge sediment beds deposited by hurricane Audrey and Rita in a marsh in southwestern Louisiana, approximately 34 km east of the study area. Hurricane Audrey's storm surge deposit was predominantly sand, thinned and fined inland, was up to 14 cm thick and extended over 400 m into the marsh. Hurricane Rita's deposit was up to 16 cm thick and extended over 800 m inland.

Spatial and Temporal Variations in Marsh Sedimentation

Identification of hurricane deposits dating from 1957, 1961, 2005 and 2008, provides a means to assess both spatial and temporal variations in hurricane and non-hurricane marsh sedimentation (Fig. 10).

476

477 *Figure 10. Stratigraphic section along transect, showing hurricane-storm-surge-deposited sand beds within marsh deposits. Core*

478 *lengths adjusted to remove compaction. Core 5 is not included because it is from the same location as core T5-5.*

Hurricane Ike's and Hurricane Rita's sediment beds clearly taper inland, most likely reflecting littoral sediment sources and deposition from a landward-directed surge of ocean water (Table 3). Both these storm surge-deposited sediment beds are thickest where washover fans have formed (cores 1-4, Fig. 10; Fig. 1a). The washover fans are almost certainly traction load deposits that built landward into the marsh during passage of the storm. Farther inland, the storm surge deposits become finer-grained and more uniform in thickness and were probably deposited primarily from suspension (Williams, 2010).

Hurricane Carla's and Hurricane Audrey's sediment beds do not display a similar trend in thickness, probably because these sediment beds were only present in cores from the more distal part of the transect, beyond the likely extent of washover fans. It's likely that these sediment beds are present in the vicinity of cores 1-5, but at depths not reached by coring (Fig. 10). There is also greater uncertainty in identifying the exact boundaries of these deposits in the cores; for example, in several cores these sediment beds are bioturbated, probably resulting in an apparent increase in thickness and, in cores 10 and 13, the boundaries of these sediment beds are only tentatively identified by LOI analysis (Fig. 10; Table 3).

There are also apparent spatial trends in the thickness of marsh deposits between and above the hurricane-deposited sediment beds (Figs. 10, 11; Table 3). No sediment had accumulated above Hurricane Ike's sand bed at core sites 1-6 in the period 2008-2014. Farther inland, at lower elevations, ~1-2 cm of marsh sediment had accumulated at five of the remaining seven core sites (Fig. 10; Table 3). Marsh sediment that formed between 2005 and 2008 (between deposition of Hurricane Rita's and Ike's sand beds) shows a clear trend of increasing thickness in a landward direction (Figs. 10, 11). Marsh sediment that accumulated after Hurricane Carla and before Hurricane Rita (1961-2005) is more uniform, typically around 15-20 cm thickness, with no trend

Fig. 11. Spatial trends in the thickness of marsh deposits along the core transect.

with distance inland (Fig. 11). The amount of marsh sediment between Hurricane Audrey's and Carla's sand beds (formed between 1957 and 1961) could only be discerned at four core sites, varied between 0.5 and 1 cm, and showed no apparent spatial trend (Fig. 10; Table 3).

Sediment sources for the marsh include flooding, overwash and organic sedimentation from marsh plants. Flooding in the study area is caused by rising local water levels resulting from high discharges in local rivers, heavy rain, high tides and storm surges (P. Walther, U.S. Fish and Wildlife Service, personal communication, May 9, 2016). Flooding preferentially delivers sediment to lower portions of the marsh, which are more frequently inundated and, along the transect, are farther inland. Flooding also entails seaward transport of sediment along the transect, as flood waters rise from lower, landward elevations, to higher, seaward elevations. Some of the suspended sediment carried into the marsh by flood water presumably settles out onto the marsh surface and some is likely trapped by the filtering effect of marsh vegetation. When floodwaters (including storm surge flooding) recede, some suspended sediment is probably carried back to lower elevations, but the overall effect of flooding is very likely a net gain of sediment for the marsh.

Hurricanes Ike, Rita, Carla and Audrey all generated storm tides that were well above the level of Highway 87 in the study area (1.47 m NAVD88) and, with the exception of the storm tide of Hurricane Carla, may have overtopped foredunes (Table 2). In addition, all four storms had strong sustained winds that probably generated large waves. The combination of waves and storm tides likely caused widespread overwash and transported sediment hundreds of meters into the marsh, forming the four sand beds. Lower intensity storms, in addition to causing storm surge-related flooding of lower parts of the marsh, may also have caused small-scale overwash and transported fine sediment landward into the marsh. Hurricanes Bonnie, Lili, Alicia and

Humberto all generated storm tides that equaled or exceeded the height of Highway 87 in the study area and probably caused overwash, at least where gaps in the dune line existed. In addition, lower intensity storms, such as hurricanes Edith and Chantal, with storm tides below the level of Highway 87 (Table 2), may still have caused overwash if accompanying waves were sufficiently high to overtop the road.

It is notable that vegetation was slow to recover from the impact of Hurricane Ike on the higher, drier parts of the transect, whereas dense vegetation continued to grow on the more landward, lower and wetter parts of the transect (Fig. 1). Consequently, organic sedimentation from in situ plant growth is a more important sediment source on lower more landward parts of the transect; this is supported by Williams (2010) who found that the organic content of marsh sediments markedly increased with distance inland along the transect.

Because marsh sediments along the transect are derived from both landward and seaward sources, the relative contribution of each in any given time period, probably explains spatial variations in marsh sedimentation. The abrupt jump in elevation along the seaward part of the transect (core sites 1-6, Fig. 10), following deposition of Hurricane Ike's sand bed, probably raised this part of the marsh above flooding levels during 2008-2014 and resulted in a lack of flood-derived sedimentation. In the same period, no hurricanes impacted the study area, which probably helped reduce flooding occurrence and resulted in a lack of overwash-derived sedimentation. The slow recovery of vegetation on this part of the transect also appears to have resulted in negligible organic sedimentation. The end result of this lack of sediment inputs was that little to no sedimentation was recorded along the transect in the ~6-year period 2008-2014 (Table 3).

In contrast, between 2005 and 2008, the surface of the marsh along the transect was up to

~56 cm lower (Table 3), increasing the likelihood of flood-derived sedimentation, which presumably was of greater magnitude at lower elevations farther inland (Fig. 11). In the same time period two hurricanes – Humberto and Gustav (Table 2) – and Tropical Storm Edouard (Franklin, 2008) impacted the study area, possibly also resulting in flooding and some overwash-derived sedimentation. Marsh sediment from this period also has a significant organic component (Williams, 2010; Figs. 2, 5, 7). The combination of probable sediment inputs from a seaward source (overwash), a landward source (flooding) and in situ plant growth, resulted in considerable sedimentation along the entire transect, varying from 2.3 to 11.9 cm within this ~3-year period (Table 3).

Between 1961 and 2005, the marsh aggraded at a relatively uniform rate along the transect, with no apparent spatial trend (Fig. 11; Table 3). This suggests a balance between seaward (overwash) and landward (flooding) sediment sources, as well as inputs of organic sedimentation from local plants, along the entire transect. A large number of lower-intensity storms, for example Hurricanes Bonnie (1986) and Lili (2002), impacted the study area in this ~44-year period, generating elevated water levels and strong winds (Table 2). These storms probably contributed sediment to the marsh via flooding and, possibly, overwash, although none of them formed a preserved, visually-recognizable sand bed within the marsh. It is likely that any storm-surge sediment bed resulting from these storms has been mixed into marsh deposits by bioturbation.

Average annual marsh sedimentation rates, derived from the thicknesses of marsh deposits shown in Table 3, reveal large temporal variations in sedimentation (Table 4). Average sedimentation rates are low in the period 2008-2014 when a combination of increased marsh surface elevation and a lack of large storms decreased both overwash- and flooding-sourced

sediment inputs. There is a considerable contrast in sedimentation rates between the period 2005-2008, with sedimentation averaging 2.13 cm/yr, and the earlier periods 1961-2005 and 1957-1961, when sedimentation averaged 0.38 cm/yr and 0.16 cm/yr, respectively (Table 4).

It is very likely that these large differences in sedimentation rates are a reflection of the degree of compaction of the marsh sediments. Marsh deposits formed between 2005 and 2008 are relatively uncompacted and highly organic; in many cores abundant large stems and roots are visible, and the deposits have an open structure with large air pockets (for example, see core T5-5 in Fig. 2). Deeper in the cores, marsh deposits appear much more compacted; large organic fragments and air pockets are not visible. This is supported by LOI results, for example in core 10 organic content of marsh deposits is ~10-11% at a depth of 7-9 cm (just below Hurricane Ike's sand bed), but falls to ~3-5% at depths of 30-32 cm, just below Hurricane Audrey's sand bed (Fig. 5). These results suggest increasing compaction with age and depth within the marsh, as organic matter is compressed, decomposes and air and water are removed from sediments by progressively increasing burial pressure (Brain et al., 2012).

These findings are supported by a study of compaction and sedimentation of marsh sediments in nearby Trinity Bay, Texas (Williams, 2003). At nine core sites in the Trinity Bay marsh, autocompaction of marsh sediments was found to continue to depths of up to 166.5 cm. Compaction increased the bulk density of sediments at depth within the marsh by an average of ~400%. Average annual sedimentation rates in the marsh, derived from ¹³⁷Cs dating, which integrates several decades of sedimentation, averaged 0.37 cm/yr at nine core sites. This result is closely comparable to the average annual sedimentation rate of 0.38 cm/yr obtained in this study on marsh sediments deposited between 1961 and 2005 (Table 4).

The thicknesses of marsh deposits shown in Table 3 also allow calculation of the relative

contribution of hurricane and non-hurricane sedimentation to growth of the marsh along the transect (Table 5). Hurricane sedimentation, defined as the combined thickness of the storm-surge-deposited sand beds, is greatest at the seaward end of the transect and diminishes inland. At core sites 1-5 the contribution of hurricanes to sedimentation above the base of the Hurricane Rita sand bed is equal to or greater than 85%. Farther inland, at core sites 6-13, the contribution of hurricanes to sedimentation above the base of the Hurricane Audrey sand bed progressively decreases, reaching ~24% at core site 13 (Table 5). The contribution of non-hurricane sedimentation, defined as the combined thicknesses of marsh deposits, is the “mirror image” of hurricane contributions, highest at the landward end of the transect at ~76% and decreasing seaward to only 3.3% at core site 3 (Table 5).

These results are not surprising because they reflect the primary sediment sources for different parts of the transect; at the seaward end of the transect, sedimentation in recent years has been dominated by overwash and the deposition of Hurricane Rita’s and Ike’s thick storm surge-deposited sand beds. Inland, storm surge-deposited sediment beds become thinner and less important and sedimentation is dominated by marsh deposits formed by sediment deposition from flood waters and greater organic sediment inputs. It should be noted that the contribution of “non-hurricane” sedimentation to marsh growth is likely exaggerated because some of this sedimentation probably resulted from lower-intensity hurricanes that caused flooding and overwash and transported sediment into the marsh, but did not form distinct sediment beds. A significant finding of the study is that, over the last five decades, hurricanes were a predominant or major sediment source for marsh aggradation along the entire transect extending over 1 km inland.

The results of this study could be of significant interest for coastal management agencies

along the Northern Gulf of Mexico. This study supports other studies that suggest anthropogenic impacts on inputs of inorganic sediment into sediment-limited marshes could be detrimental to the continued sustainment of coastal marshes subject to sea-level rise (DeLuane et al., 1989; Kennish, 2001; Day et al., 2000). On barrier islands, for example, artificial dunes are constructed that prevent overwash and gradual island migration, until a large storm overtops the artificially high dunes and the barrier morphology adjusts rapidly (Magliocca et al., 2011). Dikes and impoundments also form barriers to inputs of inorganic sediment to marsh surfaces. . This is especially true along the coast of Louisiana. Bryant and Chabreck (1998) investigated the vertical accretion of impounded tidal salt marshes at four sites in the Chenier Plain of southwestern Louisiana. Results of their work indicate that impoundment levees preclude flood delivery of mineral sediment during storms, thereby diminishing accretion of the impounded marshes. Walters and Kirwan (2016) found that 5-15 cm of overwash sedimentation enhances marsh productivity and resilience to sea-level rise. With the exception of the unusually thick washover fans deposited by Hurricane Ike, many of the storm surge deposits documented in this study are within this optimal range (Table 3).

Coastal management agencies should consider the results provided in this study, and take into consideration how anthropogenic barriers around coastal marshes could inhibit natural inorganic sedimentation processes. If the highly inorganic marshes in McFaddin National Wildlife Refuge are left in their natural state, without dikes, seawalls, artificial dunes and impoundments; this would allow overwash from future hurricanes to continue depositing inorganic sediment, thereby helping these marshes increase in elevation in order to keep pace with sea-level rise.

CONCLUSIONS

This study demonstrates the utility of using hurricane storm surge marker beds to assess spatial and temporal patterns in marsh aggradation. This technique, like the use of artificial marker beds in marshes, provides highly accurate sedimentation rates because the exact day of deposition of the marker bed is known. This methodology is applicable in many parts of the world where a better understanding of marsh aggradation dynamics are required to guide coastal management policies aimed at encouraging marsh accretion to combat the effects of sea-level rise. In this study, where marshes are dominated by inorganic sediment, the results show that marsh dynamics are controlled by hurricane activity, flood-derived sedimentation, organic sedimentation, changes in marsh surface elevation and degree of compaction of marsh sediments. Long-term sedimentation rates of marsh deposits formed after Hurricane Carla in 1961 and before Hurricane Rita in 2005, average 0.38 cm/yr, which is closely comparable to long-term sedimentation rates in similar marsh settings nearby. Inorganic sediment inputs from Hurricanes Audrey, Carla, Rita and Ike have made major contributions to marsh aggradation in the study area over the last six decades and have helped counteract the effects of sea-level rise on marsh elevation. These results provide improved understanding of the sedimentary response of marshes to tropical cyclone strikes and add support to other studies that encourage coastal management agencies to consider reducing physical barriers to storm surge sedimentation.

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Table 1.
Foraminiferal content of selected samples from core 4.

Depth (cm)	29-30	30-31	31-32	33-34	34-35	35-36	37-38	38-39	39-40	40-41	41-42	43-44	45-46	47-48	49-50	52-53	55-56
Sample Weight (g)	1.340	1.755	1.244	1.186	1.389	1.377	1.217	0.890	1.782	1.073	0.989	1.556	1.552	1.865	0.530	0.665	0.786
Weight Counted (g)	0.274	0.147	0.188	0.215	0.183	0.213	0.086	0.122	0.117	0.110	0.076	0.111	1.552	0.152	0.530	0.223	0.211
Ammonia sp.	35	30	52	1	0	0	5	5	3	6	1	2	1	26	0	0	0
Elphidium sp.	28	30	37	5	1	0	1	11	6	20	11	6	0	19	1	0	0
Haynesina sp	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina sp	3	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ammobaculites sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides sp.	0	0	0	9	3	0	1	0	0	1	0	0	0	0	0	0	0
Miliammina fusca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jadammina macrescens	0	0	0	10	11	7	1	0	1	1	0	0	0	0	0	0	0
Trochammina inflata	0	0	0	9	10	10	0	0	0	0	0	0	0	0	0	0	0
total counted	66	64	102	34	25	17	8	16	10	28	12	8	1	45	1	0	0
calcareous %	100	100	100	18	4	0	75	100	90	93	100	100	100	100	100	0	0
agglutinated %	0	0	0	82	96	100	25	0	10	7	0	0	0	0	0	0	0
Number in sample	323	764	675	188	190	110	113	117	152	273	156	112	1	552	1	0	0
Number per gram	241	435	543	158	137	80	93	131	85	255	158	72	1	296	2	0	0

Table 2.

Storm tides and maximum sustained winds in the vicinity of the study area resulting from hurricanes passing within 300 km, 1950-2014 (in descending order of storm tide height).

Year	Name	Category at landfall	Landfall proximity to study area (km) (East or West)	Conditions in vicinity of study area ¹	
				Storm tide ² (m) (location)	Maximum sustained winds (kts) (location)
2008	Ike	2	75 (W)	4.31 (SP) ^a	65 (SP) ^a
2005	Rita	3	33 (E)	2.81 (PA) ^b	61 (PA) ^b
1957	Audrey	4	35 (E)	2.79 (SP) ^c	74 (SP) ^d
1961	Carla	4	290 (W)	2.25 (SP) ^e	76 (G) ^f
1986	Bonnie	1	26 (W)	1.64 (SP) ^g	54 (PA) ^h
2002	Lili	1	173 (E)	1.64 (BAP) ⁱ	27 (BAP) ⁱ
1983	Alicia	3	117 (W)	1.59 (HI) ^j	35 (PA) ^k
2007	Humberto	1	35 (W)	1.47 (TPNWR) ^l	52 (MNWR) ^l
1971	Edith	2	123 (E)	1.21 (SP) ^m	30 (SP) ^m
1989	Chantal	1	36 (W)	1.19 (SRSP) ⁿ	47 (HI) ⁿ
1963	Cindy	1	37 (W)	1.15 (SP) ^o	36 (PA) ^o
2003	Claudette	1	272 (W)	1.01 (RP) ^p	45 (SRSP) ^p
2008	Gustav	2	322 (E)	0.85 (SP) ^q	32 (SP) ^q
1964	Hilda	2	240 (E)	0.78 (SP) ^r	30 (SP) ^r
1989	Jerry	1	102 (W)	0.69 (SP) ^s	41 (GWSO) ^s
1959	Debra	1	115 (W)	0.48 (HI) ^t	39 (HI) ^t
1992	Andrew	3	262 (E)	0.39 (SP) ^u	22 (PA) ^u
1985	Juan	1	245 (E)	1.1* (SP) ^v	27 (PA) ^v
1985	Danny	1	130 (E)	0.9* (SP) ^v	19 (PA) ^v
2012	Isaac	1	330 (E)	N/A	30 (SP) ^w
1974	Carmen	3	275 (E)	N/A	N/A
1965	Betsy	3	330 (E)	N/A	N/A
1977	Babe	1	267 (E)	N/A	N/A

¹ Tide and wind record locations were selected for close proximity to MNWR study area.

² Storm tide is normal tide plus storm surge (NAVD88).

Location key: SP: Sabine Pass, G: Galveston, PA: Port Arthur, BAP: Beaumont Air Port, HI: High Island, TPNWR: Texas Point National Wildlife Refuge, MNWR: McFaddin National Wildlife Refuge, SRSP: Sea Rim State Park, RP: Rollover Pass.

* Height above normal tide

N/A: significant hurricane-related conditions not recorded in vicinity of study area.

Wind and tide data sources: ^a Berg, 2009;; ^b Knabb et al., 2006; ^c Moore et al., 1957;

^d Landreneau and Shamburger, 2009; ^e Ho and Miller, 1982; ^f U.S. Weather Bureau, 1961;

^g National Weather Service, 2016; ^h Lawrence, 1987; ⁱ Lawrence, 2002; ^j Case and Gerrish, 1983;

^k National Hurricane Center, 1983; ^l Blake, 2007; ^m Simpson and Hope, 1971; ⁿ Case and

Mayfield, 1990; ^o U.S. Weather Bureau, 1963; ^p Beven, 2003; ^q Beven and Kimberlain, 2014;

^r Dunn et al., 1964; ^s Case and Mayfield, 1990; ^t U.S. Weather Bureau, 1959; ^u Rappaport, 1993;

^v Case, 1985; ^w Berg, 2013.

Table 3.

Marsh and hurricane deposit thicknesses¹ (cm): 1957 – 2014.

Core	Marsh: 2008-2014	Hurricane Ike Deposit	Marsh: 2005-2008	Hurricane Rita Deposit	Marsh: 1961-2005	Hurricane Carla Deposit	Marsh: 1957-1961	Hurricane Audrey Deposit	Carla and Audrey Combined ²
1	0	37.8	3.5	15.3	-	-	-	-	-
2	0	48.7	5.8	18.6	-	-	-	-	-
3	0	56.4	2.3	11.5	-	-	-	-	-
4	0	40.0	8.8	12.5	-	-	-	-	-
5	0	22.5	6.4	13.9	-	-	-	-	-
T5-5	0	24.6	7.5	10.7	18.2	3.7	0.5	1.6	-
6	0	14.3	4.1	8.2	16.3	2.0	0.5	2.6	-
7	1.0	9.2	7.1	4.1	19.4	-	-	-	5.1
8	0	12.5	-	-	-	2.1	1.0	5.2	-
9	2.2	9.7	5.4	5.4	15.1	2.2	0.5	0.5	-
10	2.2	4.5	7.8	4.5	11.2	-	-	-	4.5
11	0	5.9	-	-	-	-	-	-	-
12	2.1	3.2	-	-	-	-	-	-	-
13	2.2	2.2	11.9	3.2	19.4	-	-	-	5.4

¹ adjusted to remove compaction, which presumably introduced small uncertainties in estimated thicknesses; ² hurricane deposits apparently combined by bioturbation.

Table 4.

Marsh average annual sedimentation rates (cm/year)

Core	2008-2014 ¹	2005-2008 ²	1961-2005 ³	1957-1961 ⁴
1	0.00	1.19	-	-
2	0.00	1.95	-	-
3	0.00	0.77	-	-
4	0.00	2.95	-	-
5	0.00	2.16	-	-
T5-5	0.00	2.52	0.41	0.13
6	0.00	1.37	0.37	0.12
7	0.17	2.40	0.44	-
8	0.00	-	-	0.25
9	0.36	1.82	0.34	0.13
10	0.38	2.64	0.25	-
11	0.00	-	-	-
12	0.35	-	-	-
13	0.36	3.64	0.44	-
Average	0.12	2.13	0.38	0.16

¹ 5.92 years; ² 2.97 years; ³ 44.04 years; ⁴ 4.21 years

Table 5.
Hurricane and non-hurricane sedimentation¹

Core ²	Depth to Base of Hurricane Audrey Deposit (cm) ³	Depth to Base of Hurricane Rita Deposit (cm) ⁴	Hurricane Sedimentation (cm) ⁵	Non-Hurricane Sedimentation (cm) ⁶	% Hurricane Sedimentation	% Non-Hurricane Sedimentation
1	-	56.6	53.1	3.5	93.8	6.3
2	-	73.1	67.3	5.8	92.1	7.9
3	-	70.2	67.9	2.3	96.7	3.3
4	-	61.3	52.5	8.8	85.7	14.3
5	-	42.8	36.4	6.4	85.0	15.0
T5-5	66.9	42.8	40.7	26.2	60.8	39.2
6	47.9	26.5	27.0	20.9	56.4	43.6
7	45.9	21.4	18.4	27.5	40.0	60.0
8	44.7	-	19.7	25.0	44.2	55.8
9	41.0	22.7	17.8	23.2	43.4	56.6
10	34.7	19.0	13.4	21.3	38.7	61.3
13	44.3	19.4	10.8	33.5	24.4	75.6

¹ adjusted to remove compaction; ² cores 11 and 12 did not contain Hurricane Audrey's or Rita's deposit and are excluded; ³ used to find hurricane/non-hurricane sedimentation in cores T5-5 – 10 and core 13; ⁴ used to find hurricane/non-hurricane sedimentation in cores 1-5; ⁵ combined thickness of hurricane sand beds; ⁶ combined thickness of marsh deposits.

Table 1

Table 1.
Foraminiferal content of selected samples from core 4.

Depth (cm)	29-30	30-31	31-32	33-34	34-35	35-36	37-38	38-39	39-40	40-41	41-42	43-44	45-46	47-48	49-50	52-53	55-56
Sample Weight (g)	1.340	1.755	1.244	1.186	1.389	1.377	1.217	0.890	1.782	1.073	0.989	1.556	1.552	1.865	0.530	0.665	0.786
Weight Counted (g)	0.274	0.147	0.188	0.215	0.183	0.213	0.086	0.122	0.117	0.110	0.076	0.111	1.552	0.152	0.530	0.223	0.211
Ammonia sp.	35	30	52	1	0	0	5	5	3	6	1	2	1	26	0	0	0
Elphidium sp.	28	30	37	5	1	0	1	11	6	20	11	6	0	19	1	0	0
Haynesina sp	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina sp	3	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ammobaculites sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides sp.	0	0	0	9	3	0	1	0	0	1	0	0	0	0	0	0	0
Miliammina fusca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jadammina macrescens	0	0	0	10	11	7	1	0	1	1	0	0	0	0	0	0	0
Trochammina inflata	0	0	0	9	10	10	0	0	0	0	0	0	0	0	0	0	0
total counted	66	64	102	34	25	17	8	16	10	28	12	8	1	45	1	0	0
calcareous %	100	100	100	18	4	0	75	100	90	93	100	100	100	100	100	0	0
agglutinated %	0	0	0	82	96	100	25	0	10	7	0	0	0	0	0	0	0
Number in sample	323	764	675	188	190	110	113	117	152	273	156	112	1	552	1	0	0
Number per gram	241	435	543	158	137	80	93	131	85	255	158	72	1	296	2	0	0

Table 2.

Storm tides and maximum sustained winds in the vicinity of the study area resulting from hurricanes passing within 300 km, 1950-2014 (in descending order of storm tide height).

Year	Name	Category at landfall	Landfall proximity to study area (km) (East or West)	Conditions in vicinity of study area ¹	
				Storm tide ² (m) (location)	Maximum sustained winds (kts) (location)
2008	Ike	2	75 (W)	4.31 (SP) ^a	65 (SP) ^a
2005	Rita	3	33 (E)	2.81 (PA) ^b	61 (PA) ^b
1957	Audrey	4	35 (E)	2.79 (SP) ^c	74 (SP) ^d
1961	Carla	4	290 (W)	2.25 (SP) ^e	76 (G) ^f
1986	Bonnie	1	26 (W)	1.64 (SP) ^g	54 (PA) ^h
2002	Lili	1	173 (E)	1.64 (BAP) ⁱ	27 (BAP) ⁱ
1983	Alicia	3	117 (W)	1.59 (HI) ^j	35 (PA) ^k
2007	Humberto	1	35 (W)	1.47 (TPNWR) ^l	52 (MNWR) ^l
1971	Edith	2	123 (E)	1.21 (SP) ^m	30 (SP) ^m
1989	Chantal	1	36 (W)	1.19 (SRSP) ⁿ	47 (HI) ⁿ
1963	Cindy	1	37 (W)	1.15 (SP) ^o	36 (PA) ^o
2003	Claudette	1	272 (W)	1.01 (RP) ^p	45 (SRSP) ^p
2008	Gustav	2	322 (E)	0.85 (SP) ^q	32 (SP) ^q
1964	Hilda	2	240 (E)	0.78 (SP) ^r	30 (SP) ^r
1989	Jerry	1	102 (W)	0.69 (SP) ^s	41 (GWSO) ^s
1959	Debra	1	115 (W)	0.48 (HI) ^t	39 (HI) ^t
1992	Andrew	3	262 (E)	0.39 (SP) ^u	22 (PA) ^u
1985	Juan	1	245 (E)	1.1* (SP) ^v	27 (PA) ^v
1985	Danny	1	130 (E)	0.9* (SP) ^v	19 (PA) ^v
2012	Isaac	1	330 (E)	N/A	30 (SP) ^w
1974	Carmen	3	275 (E)	N/A	N/A
1965	Betsy	3	330 (E)	N/A	N/A
1977	Babe	1	267 (E)	N/A	N/A

¹ Tide and wind record locations were selected for close proximity to MNWR study area.

² Storm tide is normal tide plus storm surge (NAVD88).

Location key: SP: Sabine Pass, G: Galveston, PA: Port Arthur, BAP: Beaumont Air Port, HI: High Island, TPNWR: Texas Point National Wildlife Refuge, MNWR: McFaddin National Wildlife Refuge, SRSP: Sea Rim State Park, RP: Rollover Pass.

* Height above normal tide

N/A: significant hurricane-related conditions not recorded in vicinity of study area.

Wind and tide data sources: ^a Berg, 2009;; ^b Knabb et al., 2006; ^c Moore et al., 1957;

^d Landreneau and Shamburger, 2009; ^e Ho and Miller, 1982; ^f U.S. Weather Bureau, 1961;

^g National Weather Service, 2016; ^h Lawrence, 1987; ⁱ Lawrence, 2002; ^j Case and Gerrish, 1983;

^k National Hurricane Center, 1983; ^l Blake, 2007; ^m Simpson and Hope, 1971; ⁿ Case and Mayfield, 1990; ^o U.S. Weather Bureau, 1963; ^p Beven, 2003; ^q Beven and Kimberlain, 2014;

^r Dunn et al., 1964; ^s Case and Mayfield, 1990; ^t U.S. Weather Bureau, 1959; ^u Rappaport, 1993;

^v Case, 1985; ^w Berg, 2013.

Table 3.

Marsh and hurricane deposit thicknesses¹ (cm): 1957 – 2014.

Core	Marsh: 2008- 2014	Hurricane Ike Deposit	Marsh: 2005- 2008	Hurricane Rita Deposit	Marsh: 1961- 2005	Hurricane Carla Deposit	Marsh: 1957- 1961	Hurricane Audrey Deposit	Carla and Audrey Combined ²
1	0	37.8	3.5	15.3	-	-	-	-	-
2	0	48.7	5.8	18.6	-	-	-	-	-
3	0	56.4	2.3	11.5	-	-	-	-	-
4	0	40.0	8.8	12.5	-	-	-	-	-
5	0	22.5	6.4	13.9	-	-	-	-	-
T5-5	0	24.6	7.5	10.7	18.2	3.7	0.5	1.6	-
6	0	14.3	4.1	8.2	16.3	2.0	0.5	2.6	-
7	1.0	9.2	7.1	4.1	19.4	-	-	-	5.1
8	0	12.5	-	-	-	2.1	1.0	5.2	-
9	2.2	9.7	5.4	5.4	15.1	2.2	0.5	0.5	-
10	2.2	4.5	7.8	4.5	11.2	-	-	-	4.5
11	0	5.9	-	-	-	-	-	-	-
12	2.1	3.2	-	-	-	-	-	-	-
13	2.2	2.2	11.9	3.2	19.4	-	-	-	5.4

¹ adjusted to remove compaction, which presumably introduced small uncertainties in estimated thicknesses; ² hurricane deposits apparently combined by bioturbation.

Table 4.
Marsh average annual sedimentation rates (cm/year)

Core	2008-2014 ¹	2005-2008 ²	1961-2005 ³	1957-1961 ⁴
1	0.00	1.19	-	-
2	0.00	1.95	-	-
3	0.00	0.77	-	-
4	0.00	2.95	-	-
5	0.00	2.16	-	-
T5-5	0.00	2.52	0.41	0.13
6	0.00	1.37	0.37	0.12
7	0.17	2.40	0.44	-
8	0.00	-	-	0.25
9	0.36	1.82	0.34	0.13
10	0.38	2.64	0.25	-
11	0.00	-	-	-
12	0.35	-	-	-
13	0.36	3.64	0.44	-
Average	0.12	2.13	0.38	0.16

¹ 5.92 years; ² 2.97 years; ³ 44.04 years; ⁴ 4.21 years

Table 5

Table 5.
Hurricane and non-hurricane sedimentation¹

Core ²	Depth to Base of Hurricane Audrey Deposit (cm) ³	Depth to Base of Hurricane Rita Deposit (cm) ⁴	Hurricane Sedimentation (cm) ⁵	Non-Hurricane Sedimentation (cm) ⁶	% Hurricane Sedimentation	% Non-Hurricane Sedimentation
1	-	56.6	53.1	3.5	93.8	6.3
2	-	73.1	67.3	5.8	92.1	7.9
3	-	70.2	67.9	2.3	96.7	3.3
4	-	61.3	52.5	8.8	85.7	14.3
5	-	42.8	36.4	6.4	85.0	15.0
T5-5	66.9	42.8	40.7	26.2	60.8	39.2
6	47.9	26.5	27.0	20.9	56.4	43.6
7	45.9	21.4	18.4	27.5	40.0	60.0
8	44.7	-	19.7	25.0	44.2	55.8
9	41.0	22.7	17.8	23.2	43.4	56.6
10	34.7	19.0	13.4	21.3	38.7	61.3
13	44.3	19.4	10.8	33.5	24.4	75.6

¹ adjusted to remove compaction; ² cores 11 and 12 did not contain Hurricane Audrey's or Rita's deposit and are excluded; ³ used to find hurricane/non-hurricane sedimentation in cores T5-5 – 10 and core 13; ⁴ used to find hurricane/non-hurricane sedimentation in cores 1-5; ⁵ combined thickness of hurricane sand beds; ⁶ combined thickness of marsh deposits.

Figure 1 (Color)

Figure 2 (Color)

Figure 3 (Color)

Figure 4 (Color)

Figure 5 (Color)

Figure 6 (Color)

Figure 7 (Color)

Figure 8 (Color)

Figure 9 (Color)

Figure 10 (Color)

Figure 11 (Color)

Figure 1 (Greyscale)

Figure 2 (Greyscale)

Figure 3 (Greyscale)

Figure 4 (Greyscale)

Figure 5 (Greyscale)

Figure 6 (Greyscale)

Figure 7 (Greyscale)

Figure 8 (Greyscale)

Figure 9 (Greyscale)

Figure 10 (Greyscale)

Figure 11 (Greyscale)