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Storm Dynamics Control Sedimentation and Shelf-Bay-Marsh Sediment Exchange Along the Louisiana Coast

Ioannis Y. Georgiou[1], Duncan M. FitzGerald[2], Md Mohiuddin Sakib[3], Francesca Messina[1], Mark A. Kulp[3], and Michael D. Miner[1]

[1]The Water Institute, New Orleans, LA, USA, [2]Department of Earth and Environment, Boston University, Boston, MA, USA, [3]Department of Earth and Environmental Sciences, Pontchartrain Institute for Environmental Sciences, University of New Orleans, New Orleans, LA, USA

Key Points:

- Hurricane modeling indicates forward speed and intensity dominate net sediment exchange and transport along a shelf-bay-marsh system
- As hurricane forward speed slows, more sediment is moved onshore due to longer storm duration which entrains and transports more sediment
- Most scenarios show inner shelf does not fully replenish sediment moved to wetlands suggesting long-term sediment deficit and Bay deepening

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

I. Y. Georgiou,
igeorgiou@thewaterinstitute.org

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Author Contributions:

Conceptualization: Ioannis Y. Georgiou
Data curation: Ioannis Y. Georgiou, Francesca Messina
Formal analysis: Duncan M. FitzGerald, Md Mohiuddin Sakib, Francesca Messina
Funding acquisition: Ioannis Y. Georgiou
Investigation: Ioannis Y. Georgiou, Duncan M. FitzGerald, Md Mohiuddin Sakib
Methodology: Ioannis Y. Georgiou, Md Mohiuddin Sakib
Software: Md Mohiuddin Sakib
Supervision: Ioannis Y. Georgiou
Visualization: Md Mohiuddin Sakib
Writing – original draft: Ioannis Y. Georgiou, Duncan M. FitzGerald

Abstract Hurricanes can benefit wetland accretion by augmenting the delivery of mineral sediment, an essential process allowing marshes to offset submergence during rising sea levels. Using Hurricane Gustav (2008, Louisiana) as a control, we examined eight synthetic storms with varying characteristics (track, speed, intensity, size) to evaluate sediment exchange between the inner shelf and bay and bay-to-marsh interfaces. All storms showed net landward sediment exchange from the inner shelf to the bay to the marsh—storms with closer proximity, higher intensity, and slower forward speed positively correlated with net sediment exchange; storm size had little impact. Except for slow-moving storms (½ speed of Gustav), our analyses suggest that most hurricane scenarios cause net bay erosion, because more sediment is conveyed to landward wetlands than is replenished from erosion of the inner shelf. Our results suggest that the ongoing deepening of the bay will likely worsen because of rising sea levels.

Plain Language Summary Under most circumstances, hurricanes are perceived as agents of destruction that erode coastlines and destroy dwellings and infrastructure. However, for marshes and wetlands they can add much needed sediment and new sources of nutrients helping them to build vertically. As hurricanes move onshore, the accompanying large waves and currents suspend sediment into the water column followed by surge waters that carry this sediment onto wetlands. We have modeled this process using category 2 Hurricane Gustav that struck near Terrebonne Bay on the central Louisiana coast in 2008. By changing various hurricane characteristics, we find that in addition to the importance of storm track, forward speed and intensity cause the greatest net sediment exchange from inner shelf to landward bay and from bay to adjacent wetlands. Moreover, under most conditions a deficit of sediment replenishing bays will lead to their deepening and ultimately less sediment transferred to wetlands, hastening their demise.

1. Introduction

Much of the research in the coastal zone is now focused on the future of marshlands and if the loss of existing marsh area can be compensated by migration onto uplands (Chen & Kirwan, 2024; Fagherazzi et al., 2019; Farron et al., 2020; Kirwan et al., 2016; Torio & Chmura, 2013). Similarly, other studies are aimed at determining if ecogeomorphic feedbacks may help counter sea level rise (SLR) by increasing mineral sedimentation due to greater tidal inundation and by grasses transitioning to species that produce more belowground biomass (Morris et al., 2002; Mudd et al., 2010). In the Gulf Coast region and eastern seaboard of the United States vertical accretion of marshes can be substantially aided by hurricane and storm sedimentation (FitzGerald et al., 2020; Hein et al., 2024; Reed, 1989; Tweel & Turner, 2012).

Various investigators have conducted field studies detailing the extent of hurricane sedimentation (see FitzGerald & Hughes, 2019) documenting extensive reworking (Goni et al., 2007) of the Louisiana shelf by Hurricanes Katrina and Rita in 2005. A study of these same hurricanes showed that a blanket of sediment consisting of more than 131 million metric tons (MMT) was deposited in the chenier and lower delta plains of Louisiana averaging 5.18 cm in thickness (Turner et al., 2006), while another study (McKee & Cherry, 2009) measured similar average thicknesses of the Hurricane Katrina storm layer at Big Branch Marsh, LA, and Pearl River, MS. A detailed study of Hurricane Ike sedimentation spanning the coast from western Louisiana to Galveston Island, Texas documented these deposits extending 3–6 km inland with an estimated quantity of 13.7 MMT (H. F. L. Williams, 2012).

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Likewise, modeling studies of the northern Gulf of Mexico have advanced our understanding of hydrodynamics and sediment transport conditions during hurricanes as well as determining provenance of the storm deposits. For example, a study simulating Hurricane Ike conditions (Lapetina & Sheng, 2015) used a three-dimensional storm surge-wave model (CH3D-SWAN) and reproduced the hydrodynamics and onshore sediment fluxes corroborating findings in Louisiana (Tweel & Turner, 2012), while another study (Liu et al., 2018) estimated sediment deposition during Hurricane Gustav in Terrebonne and Barataria basins and successfully replicated field observations by Tweel and Turner (2012). They estimated that approximately 27 MMT of sediment was transported to the wetlands and that most of this sediment (approximately 89%) was sourced from the adjacent open-water bays.

Although the extent and benefits of hurricane sedimentation are well-established (Smith et al., 2015; Turner et al., 2007), there are few studies that have attempted to correlate sedimentation trends to physical conditions during the storm such as wave suspension, storm intensity (Saffir-Simpson category), and transport pathways. One exception (Liu et al., 2018), estimated net sediment deposition in the coastal wetlands, identified major sources of the sediment, and produced sediment budgets for Terrebonne and Barataria Basins that agreed favorably with field measurements (Tweel & Turner, 2012).

In this study, we use Hurricane Gustav which made landfall in Louisiana in 2008, to calibrate a hydrodynamic, sediment transport, and morphology model for the central Louisiana coast. The study benefitted from extensive post-storm data collection (Liu et al., 2018; Tweel & Turner, 2012) and oceanographic and meteorologic data gathered during the storm (Dietrich et al., 2010). We then use the calibrated model to construct eight synthetic hurricanes, varying the size, intensity (Saffir-Simpson scale), forward speed, and track of the storm to examine resulting sediment exchange between the inner continental shelf and Terrebonne Bay, and between Terrebonne Bay and the landward marshes surrounding the Bay.

2. Study Site

Our study area encompasses the inner continental shelf and bay-marsh system of Terrebonne Basin located in south-central coastal Louisiana (Figure 1). Terrebonne Basin contains approximately 627 km^2 of swamp (tree and shrub wetland) and 2,323 km^2 of marsh (grass wetland), grading from fresh marsh inland to brackish and saline marsh near open water (CWPPRA, 2024). These wetlands are separated from the Timbalier Islands by the broad shallow Terrebonne and Timbalier bay system (1–3 m in depth) with a combined width of 10–20 km. Tides in the region range from 0.2 to 0.8 m (Georgiou et al., 2005), but often are overprinted by strong wind set-up and set-down accompanying the passage of frontal systems (Feizabadi et al., 2023; Georgiou et al., 2005; Hiatt et al., 2019; Zhang et al., 2022). The wide and low gradient Louisiana continental shelf tends to enhance the height of storm surges (Rego & Li, 2010; Resio & Westerink, 2008; C. Zhang & Li, 2019), but the low elevation of the Timbalier Islands and intervening shallow tidal inlets are still effective in dampening storm wave energy and surge elevation (Barbier et al., 2013; Day et al., 2007; Loder et al., 2009; Wamsley et al., 2010).

3. Methods and Data

Hurricane Gustav was selected for the study because of an extensive field data set of marsh sediment deposition (Tweel & Turner, 2012) that was collected during and after the storm, and subsequently used to help validate the model (Delft3D hydrodynamic and sediment transport model, Lesser et al., 2004; see in Supporting Information S1). Hurricane Gustav was then used as a reference to generate additional synthetic storm events by changing various storm characteristics including intensity (wind speed and central air pressure), forward speed, and size (radius to maximum winds) (Table 1). Synthetic storms were altered further using the Delft Dashboard tropical cyclone tool (see in Supporting Information S1) to include additional tracks such as the track of Hurricane Katrina (2005) (Table S3 in Supporting Information S1) and additional intensities replicating Hurricanes Katrina (2005, high) and Isaac (2012, low). Collection of these storms allowed us to evaluate how each storm characteristic affected erosional or depositional patterns, as well as determine net sediment exchange between the inner shelf and bay and the bay and marsh platform (Liu et al., 2018). To calculate the quantity of sediment exchanged between components of shelf-bay-marsh system in Terrebonne Bay, we invoked cross-sections across the shelf-bay interface (Figure 1a; T1) and bay-marsh boundaries (Figure 1a; T2). At each of these cross-sections, instantaneous and cumulative sediment quantities (by mass) were used in the sediment exchange analysis for each of the scenarios simulated (Table 1). Detailed descriptions of the characteristics of the eight storm scenarios are

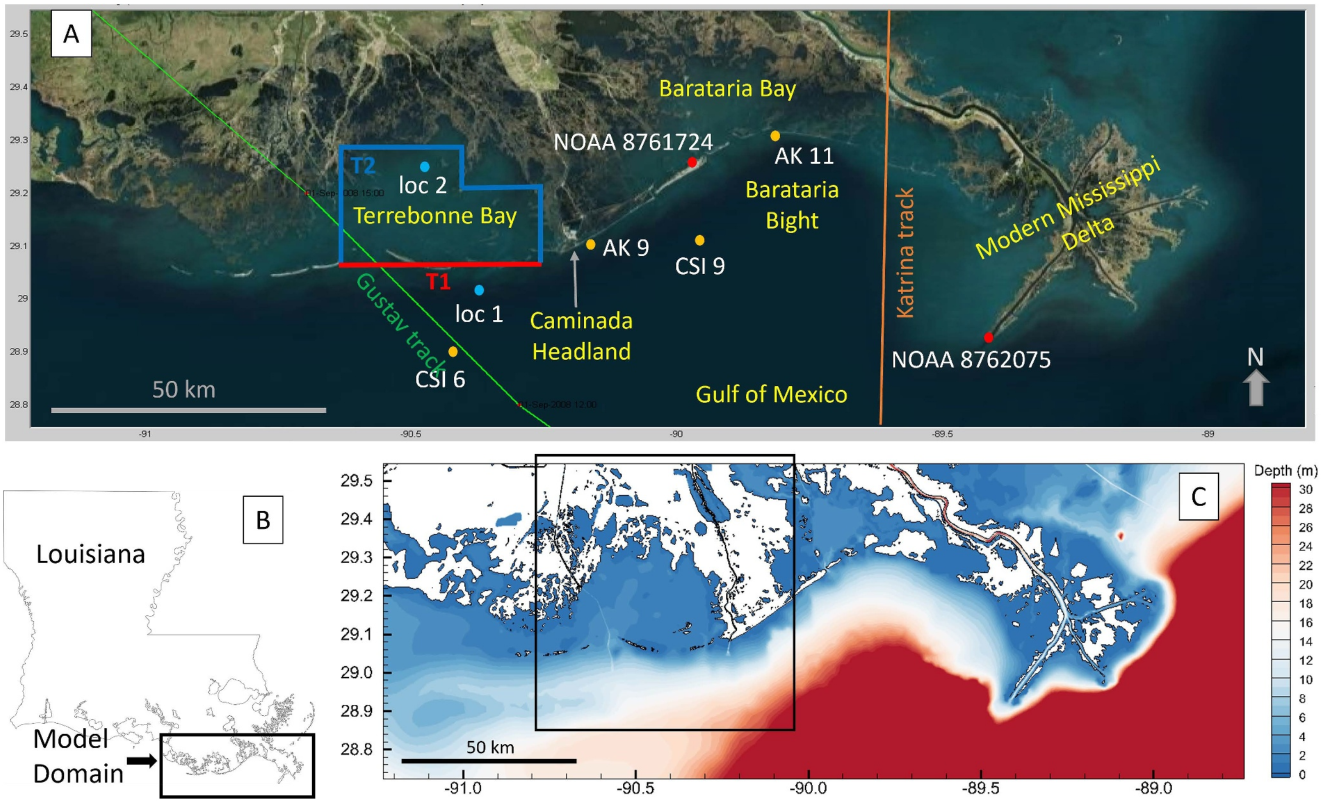

Figure 1. (a) Aerial view of south-central Louisiana coast and Terrebonne Bay showing: model validation locations at CSI 6, CSI 9, AK 9, AK 11, NOAA Buoys 8,761,724 and 8,762,075; cross-section locations (T1 red, T2 blue), model output locations (loc 1, loc 2), Hurricane Gustav and Katrina tracks. (b) Location of south-central Louisiana coast and extent of the model domain. (c) Model bathymetry below mean sea level (MSL) of south-central Louisiana coast. Spatial extent of sub-plots in Figure 3 is shown by the black box in panel (c).

provided in Table 1. The various geographic regions discussed in our analysis included Terrebonne and Barataria Bays, and the Barataria Bight, west of the Modern Mississippi Delta (Figure 1).

4. Results

4.1. Cumulative Erosion and Deposition

To investigate the cumulative effects for each of the eight storm scenarios, we selected a period of 2 days after Gustav (and for each other storm) made landfall (Figure 2) when surge water levels had returned to predicted astronomic tidal elevations (see Figure S4 in Supporting Information S1; NOAA, 2024). Results from all storms at the time of landfall are presented in the Supplemental (see Figure S6 in Supporting Information S1). One striking pattern observed after the passage of each storm is the extensive deposition that occurs in the Barataria Bight (Figure 2), which varies in thickness from 5 to 20 cm for faster moving storms (S1, S2, S4, S6, S7) and more than 25 cm for slower storms (S3, S5, S8). Widespread sedimentation also occurs landward of the barriers extending into the bays, which is attributed to a long period of sediment reworked from the inner shelf (Figure S7 in Supporting Information S1) and overwashing the barriers (Figure 2). Additional sediment reworked from ebb- and flood-tidal deltas is moved onshore by storm-generated flood currents and transported through inlets to sheltered areas behind the barriers (Figure 2; Miner et al., 2009). In Barataria Bay and mid-Terrebonne Bay, most scenarios indicate overall erosion, except for deposition in the northern portion of Terrebonne Bay ranging from 2 to 15 cm. One uniform trend observed in all scenarios is sedimentation occurring on the marsh system abutting northern Terrebonne Bay (Figure 2). Moreover, the landward transfer of sediment by up to 56% (Table 1) was a product of increased duration of storm conditions for slower moving storms (e.g., S3, S8). The depth of deposition varied depending on the storm characteristics but was greatest (15 cm) for slow-moving and intense storms (S3

Table 1
Storm Characteristics for Hurricane Gustav and Other Simulated Storms Examined

Scenario and description	S1	S2	S3	S4	S5	S6	S7	S8
Size[a]	Gustav as Observed	twice the size of S1	same as S1	same as S1	same as S1	same as S1	same as S1	same as S1
Intensity (Saffir-Simpson category	Gustav as Observed	same as S1	same as S1	Hurricane Katrina (cat 3)	Hurricane Issac (cat 1)	Hurricane Issac (cat 1)	same as S1	same as S1
Forward Speed	Gustav as Observed	same as S1	half speed of S1	same as S1	three quarter speed of S1	same as S1	same as S1	three quarter speed of S1
Track	Gustav as Observed	same as S1	same as S1	same as S1	same as S1	same as S1	Hurricane Katrina	same as S1

Storm Speed	Net Sediment Exchange Inner Shelf—Bay (MMT)	Net Sediment Exchange Bay—Marsh (MMT)
S1 - Gustav speed	4.7	7.2
S8 - Three-quarter speed	6.5 (+1.8; +38%)	8.5 (+1.3; +18%)
S3 - half the speed	12.4 (+7.7; +164%)	11.2 (+4.0; +56%)
Storm Intensity		
S6 - Hurricane Issac (cat 1)	0.9 (−3.8%; −81%)	3.3 (−3.9%; −54%)
S1 - Hurricane Gustav (cat 2)	4.7 (0)	7.2 (0)
S4 - Hurricane Katrina (cat 3)	6.8 (+2.1; +45%)	9.2 (+2.0; +28%)
Remaining storms		
S2 - Twice size of Gustav	4.7 (0)	7.4 (+0.2; +3%)
S5 - Isaac, half speed of Gustav	1.3 (−3.4%; −72%)	3.7 (−3.5%; −49%)
S7 - Gustav with Katrina track	0.2 (−4.5%; −96%)	0.3 (−6.9%; −96%)

Note. Net Sediment Exchange (NSE) is the quantity of sediment exchanged (in MMT) between inner shelf and bay and bay and marsh and is calculated as a function of storm forward speed and intensity. Numbers in parenthesis show relative change in NSE compared to the control simulation S1. All quantities were calculated 2 days after each storm made landfall. [a]Note that size is measured from center to where strength of winds diminishes to less than tropical storm force (40 mph or less).

and S4; Figure 2). The pattern of deposition is also seen in the Barataria Bay on the marsh and in wetlands immediately east of the Caminada headland/distributary system (Figure 2).

4.2. Sediment Exchange

The Net Sediment Exchange (NSE), defined by the net transport directions (onshore-offshore) between the inner shelf, Terrebonne Bay, and the landward marsh were computed for each storm scenario and summarized in Figure 3.

4.2.1. Shelf—Bay Exchange

For Hurricane Gustav (S1), NSE from the shelf to the bay is approximately 4.7 MMT (Figure 3). Doubling the size of the storm (S2) does not change the quantity of sediment moved into the bay, however increasing the intensity of the storm to a Katrina level (S4) or slowing Gustav to three quarter forward speed (S8) substantially increases the NSE into the bay to 6.8 and 6.5 MMT, respectively. At closer inspection of increased storm intensity (S4), we find that the model predicts increases in surge levels, waves and depth-averaged velocities (Figure S5 in Supporting Information S1) at loc 1, located offshore in approximately 9 m of water depth (see Figure 1). The higher wave energy causes increased erosion of the inner shelf substrate (Figure S7 in Supporting Information S1) while the increased flow velocity produces landward transport of suspended sediment into Terrebonne Bay (Figure 3). In contrast, when intensity is reduced to an Isaac level (S6), results indicate that surge levels, significant wave height, and depth averaged flow velocities are reduced (Figure S5 in Supporting Information S1). Consequently, net sediment exchange into Terrebonne Bay decreases to 0.9 MMT.

In evaluating the effect of forward speed of the storm, we compare Gustav (S1) to a condition where forward speed is slowed to half that of Gustav (S3) (Table 1). Slowing of the storm causes only moderate increases in surge level, significant wave heights, and depth-averaged velocity (Figure S5 in Supporting Information S1). However,

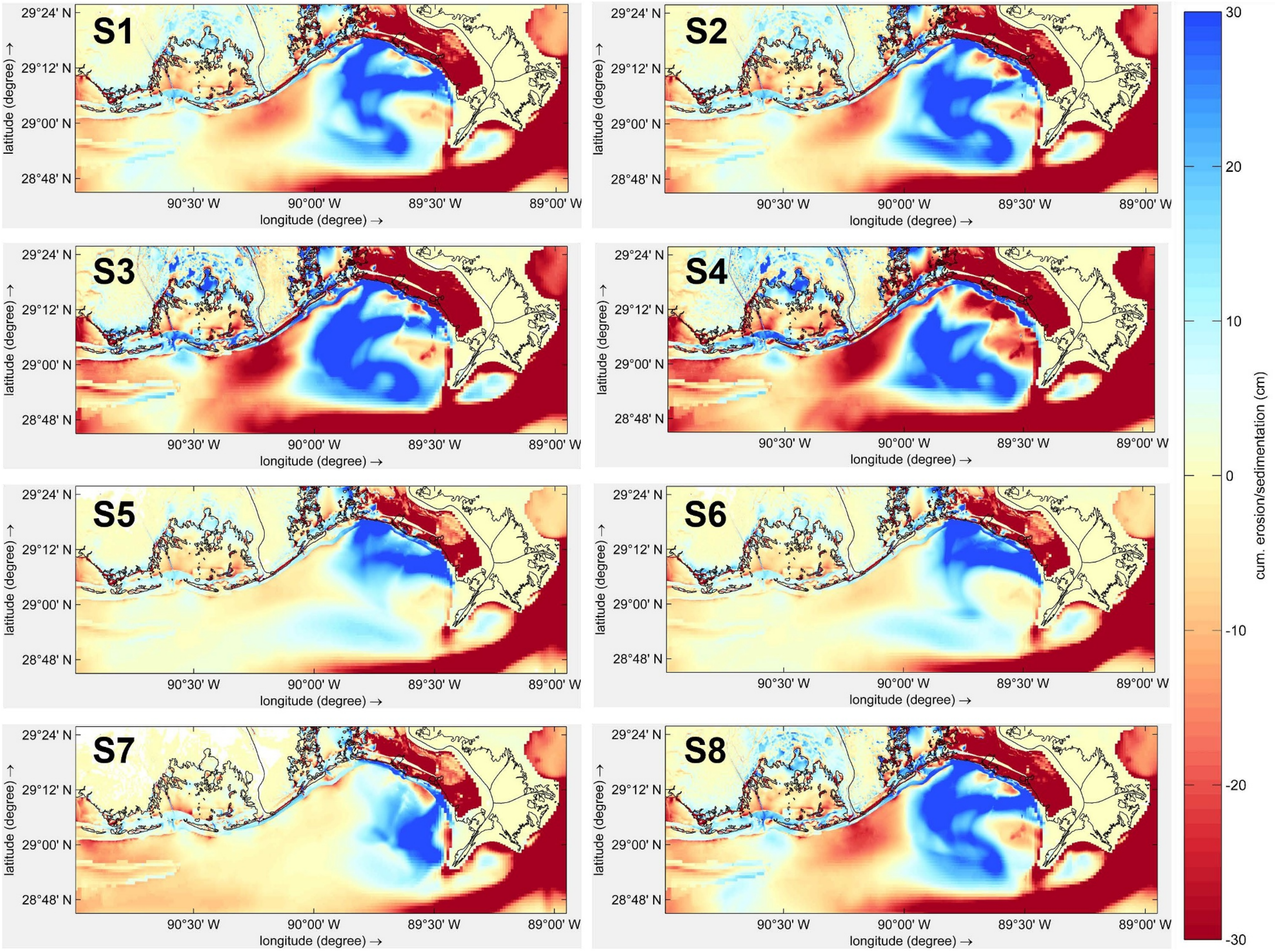

Figure 2. Net erosion/deposition 2 days after landfall time for the simulated storm conditions. Red shades (negative values) indicate erosion and blue shades (positive values) indicate deposition.

on the inner shelf, despite these moderate differences, the slower-moving storm (S3) produces longer duration of bed shear (~36 hr) compared to S1 (Figure S7 in Supporting Information S1), resulting in more than 2.5 times the NSE (from 4.7 to 12.4 MMT) being transported into Terrebonne Bay (Figure 3; Table 1). In comparison, decreasing the forward speed to three quarters of the Gustav speed (S8) increases the NSE from 4.7 to 6.5 MMT, which is approximately half the quantity transported by a storm moving at half speed (S3; 12.4 MMT). This overall trend demonstrates the importance of storm speed in controlling onshore sediment transport, and the effect of storm speed being inversely related to NSE. Finally, S3 is the only scenario demonstrating a positive bay sediment budget, due to prolonged inner shelf bed shear and sediment suspension (Figure S7 in Supporting Information S1; Table 1).

4.2.2. Bay—Marsh Exchange

Modeling results indicate that all storm scenarios transport sediment onto the marsh (Figure 3, Blue line/arrow), a finding that is consistent with many field studies of hurricane sedimentation in the region (e.g., Baustian & Mendelssohn, 2015; McKee & Cherry, 2009; Smith et al., 2015; Turner et al., 2006; Tweel & Turner, 2012) and modeling studies (Cortese et al., 2024). For the baseline storm, Gustav (S1), 7.2 MMT was transported from the Terrebonne Bay onto the adjacent marsh and wetlands. This value increases slightly to 7.4 MMT for S2, which is the same as S1, but is double the storm size. Sediment transported onto the marsh platform and wetlands increases to 11.2 MMT for S3, which has the same characteristics as Gustav, but half the forward speed. Comparisons of the modeled hydrodynamic conditions in more detail are presented in Supporting Information S1. Scenarios S3 and

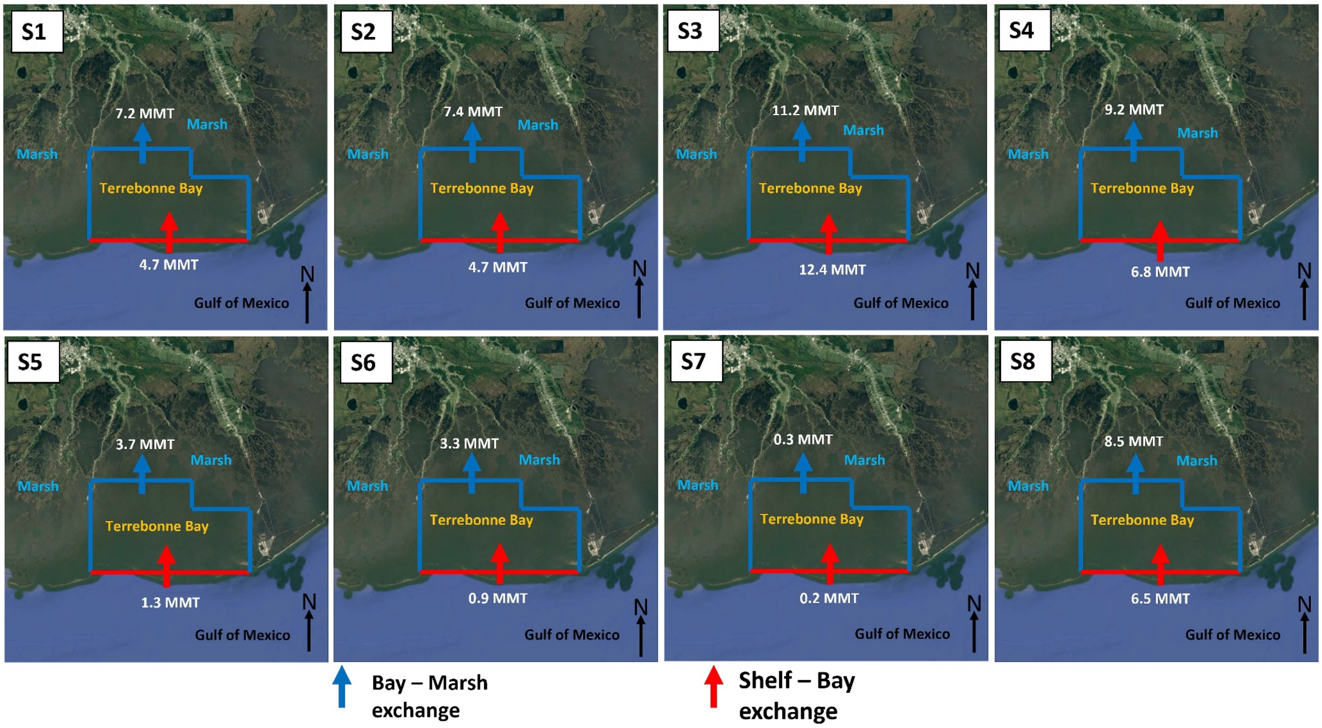

Figure 3. Net sediment exchange (MMT) between the Inner Continental Shelf and Terrebonne Bay (red line) and Terrebonne Bay and landward Marsh area of Terrebonne Basin (blue line).

S8 produce NSE of 11.2 and 8.5 MMT (respectively) having Gustav's intensity but with one half and three quarters the forward speed of Gustav, respectively. Thus, for sediment movement from Terrebonne Bay to the marsh, hurricane forward speed is again a significant factor like it is for transport from inner shelf to the bay. However, as S4 (9.2 MMT) demonstrates, hurricane intensity like that of Katrina may be equally important.

The least amount of sediment conveyed onto the marsh occurs for scenario S7 (0.3 MMT), which has the same characteristics as Gustav (S1), but with the track of Katrina indicating that distance of landfall and approach angle of the storm, even for intense storms, clearly affects wave energy and sediment transport (Figure S5 in Supporting Information S1). Storms S5 and S6 move modest amounts of sediment onto the marsh (3.7 and 3.3 MMT, respectively), with intensities of Hurricane Isaac and three quarters the forward speed of Gustav (S1) for S5. Lessening wind velocity distinctly affects wave energy, sediment suspension, and depth averaged current velocity.

5. Discussion

5.1. Modeling Storm Characteristics

While our modeling study of Hurricane Gustav was similar to that of (Liu et al., 2018), we extended the experimental design and results to contain how different storm characteristics, including storm intensity, storm size, forward speed of the storm, and storm track affect storm surge levels, significant wave height, depth-averaged current velocity (Figure S5 in Supporting Information S1), and ultimately sediment exchange (Figure 3). We find that the quantity of sediment exchanged between the inner shelf and bay, and the bay and marsh is dominated by forward speed of the storm and intensity and with storm size having a lesser impact. For example, doubling the size of the storm (S1 vs. S2) results in little change in the NSE (Figure 3). Storm track is a well-known important storm parameter (i.e., compare S1 to S7) and as such, this factor was not explored in detail. The effect of storm speed on inner shelf—bay exchange is demonstrated by comparing the results of Gustav at full speed (S1), three quarters speed (S8), and half speed (S3), which yield NSE of 4.7 (0%), 6.5 (+38%), and 12.4 (+164%) MMT, respectively. We show that for slower moving storms the inner shelf is reworked for a longer period by waves and attendant bed shear (Figure S7 in Supporting Information S1) producing greater amounts of suspended sediment, which are transported onshore into Terrebonne Bay (Table 1; Figure 3; Figure S7 in Supporting Information S1). We establish that storm speed has similar influence on sediment movement from the bay to the marsh as the net sediment exchange is progressively larger as storm speed decreases (7.2, 0%; 8.5, +18%; 11.2, +56%, MMT respectively; Table 1).

The effect of storm intensity is evaluated by comparing simulations of Isaac (S6), Gustav (S1), and Katrina (S4) with all other characteristics (e.g., size, speed, track) being equal to Gustav (Table 1). Sediment (NSE) is uniformly transported landward in all scenarios (Figure 3) for both the inner shelf–bay and bay–marsh. The importance of intensity is well illustrated by comparing cat 1 Isaac (S6) to more intense cat 3 Katrina (S4) in Figure 3. Note that NSE of bay to marsh during Isaac versus Katrina increased from 3.3 to 9.6 MMT and likewise, the NSE from inner shelf increased from 0.9 to 6.6 MMT. These model findings demonstrate the importance of wind speed affecting wave energy and storm surge height and resulting sediment transport. Moreover, it is noteworthy that except for S3 (½ speed of Gustav), a larger quantity of sediment is transported onto the marsh versus into the bay with model results ranging from 0.1 to 2.7 MMT. The overall greater movement of sediment onto the marsh versus into the bay from the shelf is explained by the shallowness of the bay resulting in large bottom shear stresses and high sediment suspension (Figure S8 in Supporting Information S1). Although the ocean waves are larger on the inner shelf offshore, as they approach the upper shoreface fronting barrier islands they shoal producing high shear stresses on the seabed (Figure S7 in Supporting Information S1).

5.2. Sediment Budget

Except for S3 (½ speed of Gustav), all the model simulations show that more sediment is transported from the bay to the marsh than from the inner shelf to the bay. And even for S3, the NSE for the inner shelf to bay (12.4 MMT) is not vastly different (~90%) from the NSE transported from the bay to the marsh (11.2 MMT). The slower moving storms (S3, S8) produce larger waves and bed shear for a prolonged time compared to faster moving storms (S1) entraining and transporting more sediment (Figure S7 in Supporting Information S1). For the Gustav simulation (S1), the NSE results are similar in magnitude and direction to those previously calculated (Liu et al., 2018), but their overall sediment budget is slightly different (into the bay: 4.7 vs. 2.2 MMT and onto marsh: 7.2 vs. 10.8 MMT, respectively). The difference in results may be explained by model setup (see in Supporting Information S1). One significant trend observed in our study and that of Liu et al. (2018) is that except for ½ speed Gustav (S3), our scenarios show a net sediment deficit in Terrebonne Bay varying from 0.1 to 2.7 MMT, or 30%–267% relative to the incoming sediment from the shelf (Figure 3), with an average of 1.8 MMT (S3 excluded). This trend has important implications - if the bays are the primary source of mineral sediment deposited on the marsh, and the inner shelf is not replenishing this sediment in the bay at the same rate, then the bays will gradually deepen. The computed sediment deficit in Terrebonne Bay during Gustav is equal to an average sediment thickness of 1.6 mm (volume of sediment deficit divided by the area of bay). This storm deepening of the bay combined with that attributed to SLR (9 mm/yr; NOAA, 2024) will diminish shear stresses imparted to the bay floor, thereby reducing suspended sediment entrainment and the conveyance of sediment transported to the marsh.

5.3. Relevance

The ability of marshes and other wetlands to maintain elevation above tidal waters is an important issue because of their vulnerability caused by accelerating sea-level rise. Marshes exposed to large storms are at an advantage because of increased mineral sedimentation that can occur during a single event. Moreover, in addition to the Gulf Coast regions, storm sedimentation in coastal wetlands has been documented in other comparable settings including large deltaic areas (e.g., Ganges-Brahmaputra: Kuehl et al., 2005, M. Allison and Kepple, 2001; Yangtze: Yang, 1999, Ren et al., 2021, Fan et al., 2006) and broad estuaries (e.g., The Wash: French & Tom Spencer, 1993; Southwest Wales: Jardine et al., 2022). Contrastingly, marshes that exist in the protection of well-developed barrier island systems (occupying >10% of the world's coasts; Stutz & Pilkey, 2011) have restricted shallow-water fetches and are much less affected by storms; they receive suspended sediment primarily during normal tidal flooding (Morris et al., 2002).

6. Conclusion

Hurricane Gustav provides an excellent platform for studying hurricane characteristics and their effects on storm surge and sediment exchange between the inner continental shelf, Terrebonne Bay, and the surrounding wetlands. The eight modeled scenarios show a consistent trend of net landward sediment transport from the shelf to the bay and from bay to the marsh. As expected, storm track has a significant influence on the NSE as evidenced by comparing Gustav to a storm with the same characteristics but with the track of Katrina. An increase in storm intensity (cat 1 to 3) shows a corresponding substantial increase in sediment delivery onshore with more than seven times increase in NSE from the inner shelf to the bay. The same comparison indicates approximately a threefold increase of NSE from the bay to the marsh. Based on limited model results, we find an inverse relationship between forward storm speed and NSE for inner shelf to bay and bay to marsh transport. This trend does not reflect the magnitude of storm conditions (e.g., waves, storm surge) for the shelf and bay, but the duration over which these storm processes operate, including bed shear, sediment suspension, and onshore water and sediment flux. Finally, we note that with the exception of slow moving hurricanes, bays are losing sediment during storms, corroborating the results of previous studies (Liu et al., 2018). This sediment deficit, in combination with SLR will gradually deepen the bay, eventually leading to less sediment conveyed to the marsh, hastening their submergence.

Data Availability Statement

Model is available at Georgiou and Sakib (2024), and includes model setup files, initial conditions, and delineation of the sediment provenance zones for all the storms that were simulated, as well as the model output at each of the cross sections where net sediment fluxes were evaluated. The numerical model used in the analysis is the Delft3D-4 modeling suite and is available in the public domain. The software and computer source code are available at https://oss.deltares.nl/web/delft3d/downloads.

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