THE IMPACTS OF BARRIER ISLAND DEGRADATION ON HURRICANE-INDUCED SEDIMENT TRANSPORT

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Hurricanes are recognized as a strong forcing in changing coastal morphology by redistributing sediments. Barrier islands protect estuaries from storm surge and severe waves and confine water and sediment discharge into estuaries during a hurricane event. In this study, we developed a three-dimensional, fully coupled storm surge, waves, and sediment transport model. The impacts of barrier islands degradation on hurricane hydrodynamics and sediment dynamics were evaluated by comparing a hypothetical model configuration for four major barrier islands in Terrebonne Bay and Barataria Bay against a baseline configuration. With the hypothetical deterioration of barrier islands, model results showed that the sediment transport from the shelf to the estuary increased in Terrebonne Bay but decreased in Barataria Bay. In the simulations, most of the deposition on coastal wetland still originated from the bay even when the barrier islands were degraded.

Keywords: full-coupled three-dimensional model, barrier island degradation, sediment flux, wetland deposition.

INTRODUCTION

Louisiana's barrier islands serve as a valuable natural protection for the coastal environment. They not only shelter the estuaries from severe surge flooding and wave attacks (Penland et al., 1988; Stone and McBride, 1998), but also help maintain the environmental framework of the estuaries by separating the higher salinity Gulf of Mexico water and the lower salinity estuarine water and protecting the coastal wetlands from erosion.

While the benefits of barrier islands in mitigating coastal hazards have been widely recognized by the coastal community, only recently did studies start to apply numerical models to quantify the benefits of barrier island systems in reducing surge and waves (Stone et al., 2005; Wamsley et al., 2009; Grzegorzewski et al., 2011; Cobell et al., 2013). Using the Advanced CIRCulation Model (ADCIRC) and SWAN, Stone et al. (2005) modeled the storm surge and waves in the south-central Louisiana with shoreline and bathymetric configurations for 1950, the early 1990s, and 2020. The authors found that most of the study area underwent a considerable increase of combined surge and wave height during the interval from 1950 to the 1990s. They predicted that a significant increase of surge and wave height would occur from the 1990s to 2020 as a result of deterioration of the coastline including the barrier islands. Wamsley et al. (2009) applied the ADCIRC model to evaluate the potential benefits of restoration projects at Caernarvon Marsh and Biloxi Marsh in reducing both the storm surge and wave heights. They also found that the deflation of barrier islands could result in an increase of surge and waves on the lee side of the islands. Grzegorzewski et al. (2011) used the ADCIRC model coupled with the STeady State spectral WAVE (STWAVE) model to simulate the storm surge with restored Plaquemines barrier islands and Ship Islands. The authors reported that the barrier island restoration may significantly influence surge passways and flooding water volume. Cobell et al. (2013) evaluated the barrier island restoration projects in the Louisiana Coastal Master Plan 2012 and the associated benefits for reducing storm surge and wave heights. Through numerical modeling using ADCIRC and SWAN, the authors concluded that the ridge and barrier island restoration reduced the surge level compared with no-action scenarios and the wave heights also decreased at the immediate backside of the restoration structure.

The role of barrier islands in the entire coastal system, however, goes beyond their being a single defense line against surge and waves. Using a depth-averaged model, Liu et al. (2018) showed that hurricanes and storms have the potential to cause a sediment exchange between the estuaries and the continental shelf and redistribute sediment towards coastal wetlands. Since the landscape of barrier islands could influence the surge and wave energy inside the estuary, it is logical to ask what role the barrier islands play in the large-scale sediment dynamics in a hurricane event.

In this paper, the objectives are to (1) develop and validate a three-dimensional fully-coupled modeling system for storm surge, waves and sediment transport; (2) evaluate the impact of the possible deterioration of barrier islands on the large-scale sediment redistribution under hurricane conditions.

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METHODS

Study Area and Hurricane Gustav

Our study area is the wetland-bay-shelf system of Terrebonne and Barataria Basins in the Mississippi River Delta Plain (Fig. 1). This region encompasses 1243 square kilometers of swamp and 4221 square kilometers of marshes. Severe marsh erosion and land loss occurred in these two coastal basins from 1932 to 2010 (Couvillion et al., 2011). This area is impacted by frequent hurricanes and storms and the major hurricanes in the last decade include Katrina and Rita in 2005, Gustav and Ike in 2008 and Isaac in 2012. In this paper, we chose Hurricane Gustav in 2008 as an example because a large number of field observations following the hurricane are available.

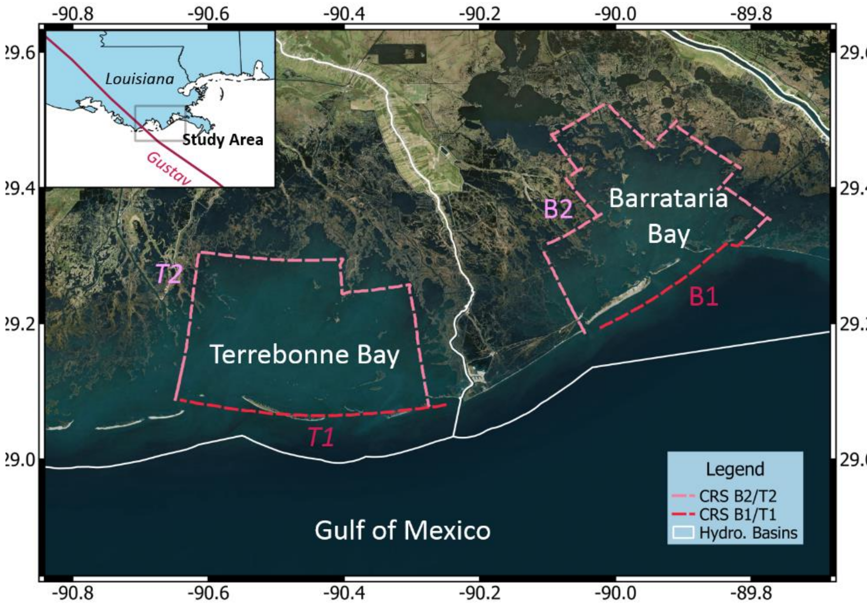

Figure 1. Terrebonne Bay and Barataria Bay on the Louisiana Coast. T1&T2 are the cross sections in Terrebonne Bay, and B1&B2 are the cross sections in Barataria Bay.

Model Description

A Delft3D model was deployed to study the hurricane-induced sediment transport in this paper. In horizontal direction, we designed a nested two-layer curvilinear mesh to resolve the complex geometry on the Louisiana coast. A gulf-scale mesh covered the Gulf of Mexico, the Caribbean Sea and part of the western North Atlantic Ocean to capture the development of the fast-moving hurricane and provide accurate surge level and current velocity to the detailed domain. A local-scale mesh extended from the continental shelf to the inner wetlands. For details of the nested domain, readers are referred to Liu et al. (2018).

To determine a proper vertical structure of the computational mesh, we conducted a literature review on 3D simulations of flow, wave and sediment transport processes. Despite the various models and study areas, a sufficient resolution of 3D flow and sediment phenomena in most coastal applications requires the number of vertical layers to range from four to ten (Table 1). Therefore, in this study, seven vertical layers with a thickness of 5%, 10%, 20%, 30%, 20%, 10%, and 5% of total water depth in the σ-coordinate were used.

Table 1. A summary of vertical mesh structure in 3D hydrodynamics and sediment transport model

Literature	Study Area	Major Physical Process	Numerical Model	Number of Vertical Layers
Horstman et al. (2015)	Mangrove at the Thai Andaman coast	Tidal flow and sedimentation	Delft3D	8 (uniform thickness)
Hu et al. (2015)	Breton Sound under Hurricane Issac (2012)	Storm surge with vegetation.	Delft3D	7 (non-uniform thickness)

Lapetina and Sheng (2015)	Galveston, TX under Hurricane Ike	Storm surge, wave and sediment transport.	CH3D-SWAN	4 and 8 layers (uniform) showing little difference
Weisberg and Zheng (2008)	Tampa Bay, FL under a hypothetical hurricane	storm surge	FVCOM	11 (uniform)
Xu et al. (2015)	LA-TX continental shelf	hurricane surge flow with sediment	ROMS	30 (uniform)
Zheng et al. (2013)	Gulf of Mexico under Hurricane Ike	storm surge	FVCOM	11 (uniform)

A Directional Point Model (DPM) in Delft3D was used to account for resistance to storm surge exerted by vegetation on coastal wetlands. This method has been validated extensively against various datasets, including laboratory experiments (Baptist, 2003; Borsje et al., 2009) and field data on flow patterns in salt marshes, intertidal flats and sandy sites (Temmerman et al., 2005; Bouma et al., 2007). Readers are referred to Uittenbogaard (2003) for more details about DPM.

Four major vegetation types, namely saline marsh, brackish marsh, intermediate marsh, and freshwater marsh, on coastal Louisiana have been modeled through the 3D DPM. Their spatial distribution of vegetation types was determined according to a coastal-wide aerial survey by USGS in 2007 (Sasser et al., 2008). The stem diameter and density were assumed to be vertically uniform. The background Manning's coefficient was set to be 0.025, approximately the value for the shallow water in open bays to account for the friction to flow due to a bare bed.

Since the 3D DPM assumed the vegetation stem to be rigid, we reduced the vegetation stem height to 60% of its original value, which was similar to other studies (Hu et al., 2015; Kuiper, 2010), to account for the flexibility of vegetation. We should note that the exact reduction of vegetation height in 3D DPM is not necessary to be the same as in the literature, and an optimum setting might require further calibration with field measurements.

Two sediment types, mud and sand, were considered in our model. The initial composition of mud and sand on the bed was interpolated from over 47,000 historical surficial grain-size data points in the usSEABED dataset (Williams et al., 2006; Liu et al., 2018).

The median diameter of sand is 0.14 mm, and muddy material has an erosion parameter of 0.5×10^{-4} kg/m^2/s and a settling velocity of 0.25 mm/s in the model. The critical shear stress was 0.1 Pa for mud in the sea and coastal bays and 1.0 Pa for vegetated land to account for the fact that vegetation roots can strengthen the soil layer and enhance its resistance to erosion. The temperature and salinity stratigraphy and their effects in sediment properties were not considered in the model.

The background horizontal eddy viscosity was set to be 1.0 m2/s. A $k - \epsilon$ turbulence closure was applied to account for the 3D turbulence. The effects of surface waves and wave-current interactions were included by coupling the storm surge model with the third-generation spectral wave model SWAN (Booij et al., 1999). The surge level and the depth-averaged velocity were provided for wave computation. The modeled wave field was also used to predict the bed shear stress. The wave calculation was performed every 60 min and the exchange of information between the wave model and the storm surge model took place at the same interval. The sediment transport model was then coupled with the simulation of hurricane wind, storm surge and waves. The detailed data flow in the coupled modeling system was summarized in Fig. 2 below.

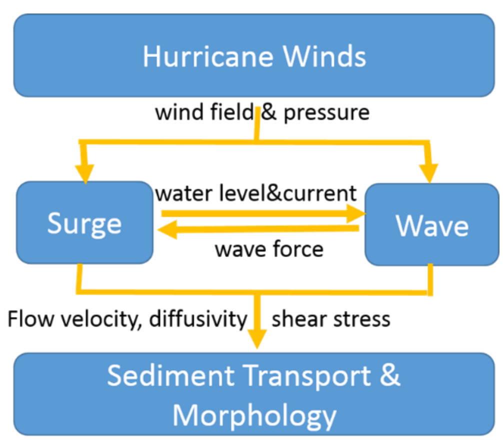

Figure 2. A flow-chart of the coupled modeling system

Baseline Case and Degradation Case

To assess the potential impact of the deterioration of barrier islands on the hydrodynamic process and sediment dynamics in the shelf-bay-wetland system, three-dimensional simulations for hurricane-induced sediment transport were conducted for a baseline configuration and a degradation configuration.

The bathymetric data from multiple sources were used to construct the realistic bathymetry in the baseline configuration, including the SL16 mesh (Dietrich et al., 2008), the Digital Elevation Model (DEM) output from the wetland and barrier shoreline morphology models (Hughes et al., 2012; Couvillion et al, 2013), and LIDAR data from the national elevation dataset (NED, http://nationalmap.gov/elevation.html). For the degradation configuration, the bathymetry and landscape at four barrier islands in Terrebonne Bay and Barataria Bay were modified corresponding to a hypothetical degradation scenario (Fig. 3). To be specific, the barrier islands were degraded into submarine shoals by lowering the crest elevations from approximately +1.0 m (MSL) to -1.6 m (MSL). The Manning's coefficients at the islands were reduced to 0.02, which was the value used in the shallow bays. Table 2 summarized the simulation configurations for the barrier islands and the submarine shoals in this section. The wind field for Hurricane Gustav, the tidal boundary condition, and the river discharge were kept the same for both configurations. It should be noted that the degradation configuration was for illustration purpose only. It represented one possible degradation scenario and the practicality was not verified here.

Next, we will validate the baseline configuration against field measurements during Hurricane Gustav and then investigate the impact of barrier island degradation on hurricane-induced sediment transport by comparing the simulation results from the baseline configuration and the degradation configuration.

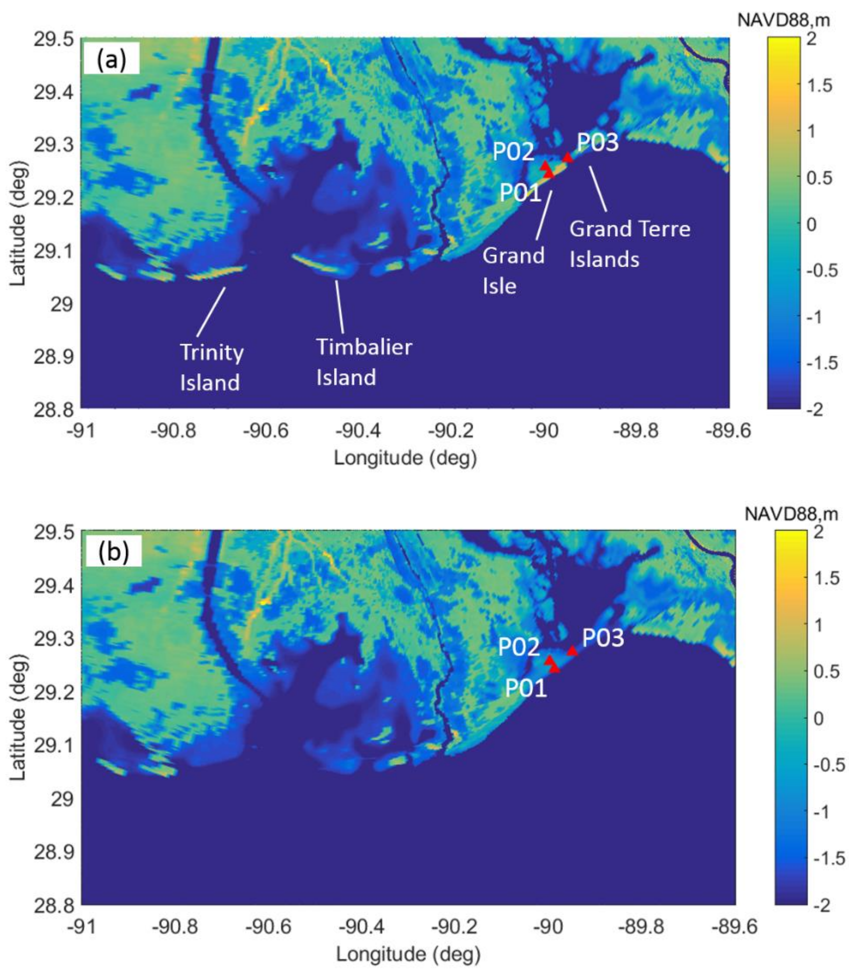

Figure 3. The model bathymetry in the baseline case (a) and the degradation case (b). P02/P02/P03 are the locations of model observation points (details in Figure 10). Note the positions of the barrier islands in (a).

Table 2. Model settings for the selected barrier islands in the baseline configuration and the degradation configuration

	Crest Elevation of the Islands or the Shoals (m, MSL)	Manning's Value at the Islands or the Shoals
Baseline Config.	~ +1.0 m	0.03 to 0.05
Degradation Config.	~ -1.6 m	0.02

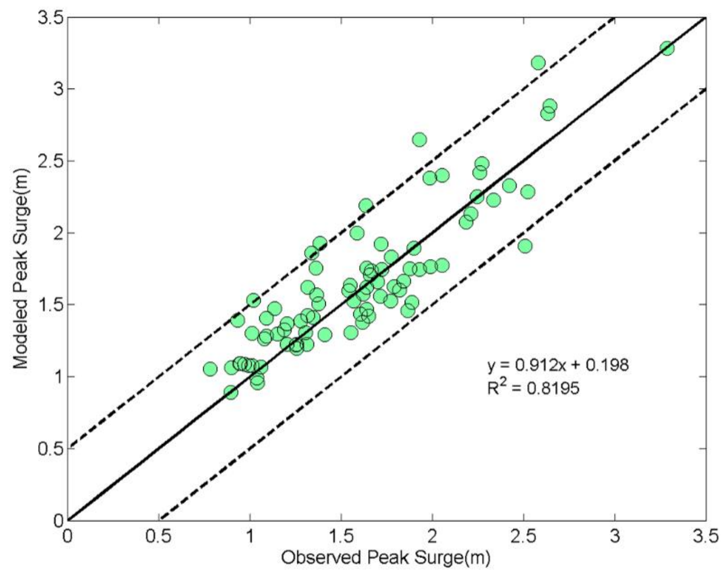

Figure 4. Modeled peak surge at CRMS stations compared with observations

MODEL VALIDATION

In this study, we simulated the hydrodynamics and sediment transport during Hurricane Gustav from August 28 to September 5, 2008, following a one-month spin-up time. The model predictions of storm surge and waves were validated against the water level at the eleven NOAA tide stations, the peak surge at the eighty-seven CRMS stations, the water level, wave heights and wave periods at the six wave gauges in Kennedy et al. (2010). For a detailed description of the datasets, readers are referred to Section 2.2 in Liu et al. (2018).

A comparison of the modeled peak surge with the observations at CRMS stations was plotted in Fig. 4. The normalized bias and scatter index of the modeled surge and wave time series were summarized in Table 3. The accuracy of the depth-averaged (2D) model (in Liu et al. 2018) was also listed in table 3 as a reference. The model predictions of storm surge, wave heights and wave periods showed similar agreement with the measurements as the 2D model (Table 3), although no intention was made to reproduce the surge and waves in Liu et al. (2018). When most of the physical parameters are kept the same, it is safe to say that the 3D model can serve as a platform to study the hurricane-induced sediment transport processes with a better representation of the 3D flow field, vertical mixing and possible stratification of sediment, and at least the same level of accuracy in hydrodynamics can be achieved as in the 2D model.

To validate the model prediction of sediment transport, the predicted post-hurricane deposition on wetlands were compared to the measurement in Tweel and Turner (2012). As pointed out by Xu et al. (2015), two types of "deposition" should be distinguished: the "net deposition" is simply the arithmetical difference between the bed elevation after the hurricane and that before the hurricane; and the "post-hurricane deposit" is the amount of deposition above the deepest cut. In general, post-hurricane deposition is always positive while net deposition can be negative if an erosion under strong waves and currents is followed by a deposition.

In the Terrebonne Basin, the modeled post-hurricane deposition (spatially-averaged) is 4.2 cm from the 3D model and 4.3 cm from the 2D model in Liu et al. (2018), and the net deposition is 3.6 cm from the 3D model and 3.8 cm from the 2D model. In the Barataria Basin, the modeled post-hurricane deposition (spatially-averaged) is 2.6 cm from the 2D and 2.2 cm from the 3D model, which agrees with the observation (3.2 cm). However, the net deposition in

Barataria Basin is negative (-1.4 cm from the 2D and -1.7 cm from the 3D model) which reveals that the net change of the sediment layer thickness at the selected survey locations could be considerably different from the fresh deposition measured after the hurricane.

Since Tweel and Turner (2012) measured the thickness of a fresh event layer without records of pre-hurricane elevation, it is the post-hurricane deposit, instead of the net deposition, from the model that corresponds to the measurements. The predicted post-hurricane deposition matches the field measurement in Tweel and Turner (2012), 2.9 cm in Terrebonne and 3.2 cm in Barataria, with a reasonable accuracy.

Table 3. A summary of model accuracy compared against surge and wave measurements (3D: the 3D model described in this paper; 2D: the depth-averaged model in Liu *et al*. (2018))

	Variable	Number of Stations	Bias (3D/2D)	Scatter Index (3D/2D)
NOAA tide stations (southeastern LA)	Water Level (m)	6	-0.07/-0.08	0.20/0.18
NOAA tide stations (total)	Water Level (m)	11	-0.06/-0.06	0.36/0.35
Kennedy *et al*. (2010)	Water Level (m)	6	0.07/0.07	0.28/0.28
Kennedy *et al*. (2010)	Wave Height (m)	5	0.10/0.10	0.27/0.27
Kennedy *et al*. (2010)	Peak Wave Period(s)	6	0.17/0.17	0.41/0.41

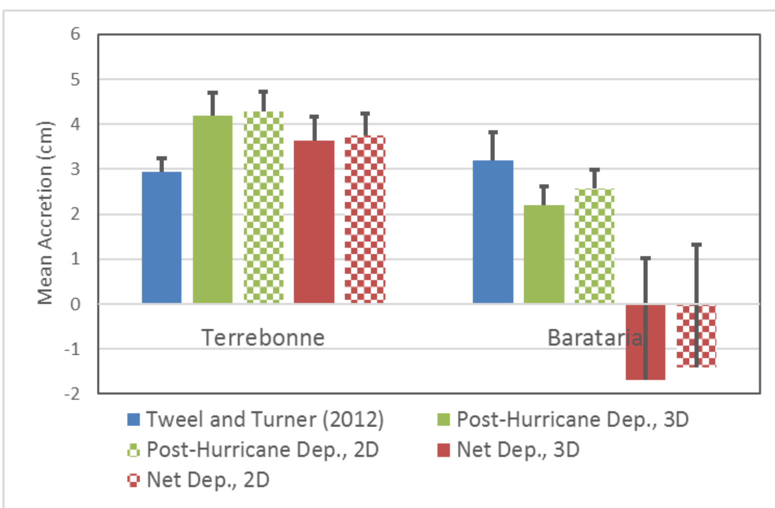

Figure 5. Modeled post-hurricane deposition and net deposition (3D model): in comparison with measurements in Tweel and Turner (2012) and Liu et al. (2018)

MODEL RESULTS

The impacts on storm surge

The modeled maximum storm surge during Hurricane Gustav was presented in Fig. 6, and an evaluation of the benefits of barrier islands in surge reduction can be obtained by comparing the maximum surge level from the baseline configuration and those from the degradation configuration. To be specific,

$$y_{\text{reduce}} = y_{degrd} - y_{base}$$

where $y_{\text{degrd}}/y_{\text{base}}$ are the maximum storm surge in the degradation/baseline configurations, respectively. The analysis focused on the change near the barrier islands and within the estuaries. Blue indicates an increase of peak surge in the degradation configuration, and red indicates the opposite.

When barrier islands were removed, the peak surge level increased within both Terrebonne Bay and Barataria Bay, and this effect decreased with the distance from the islands (Fig. 7). The maximum increase of surge was about a half meter, and most of the area within the bay experienced an increase of more than 0.1 m. In contrast, surge level on the seaward side of the islands dropped slightly in the degradation configuration as more surge water can flush into the estuaries without the obstruction of barrier islands.

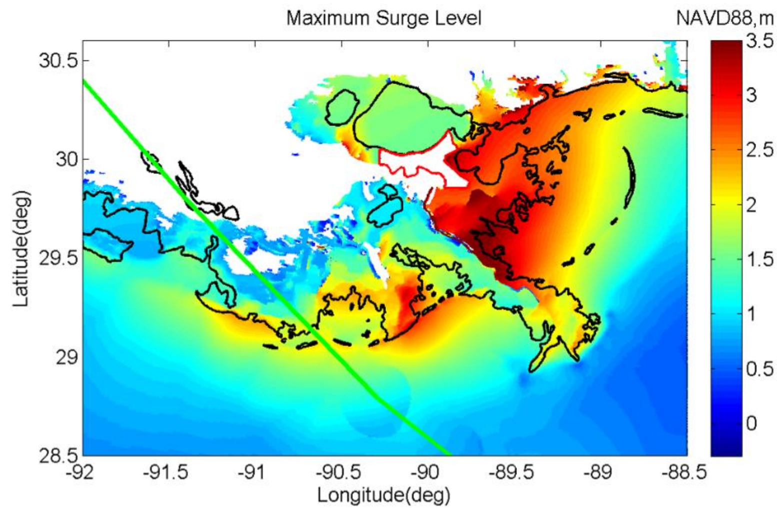

Figure 6. The modeled maximum storm surge during Hurricane Gustav (2008): baseline configuration (green line: the track of Gustav)

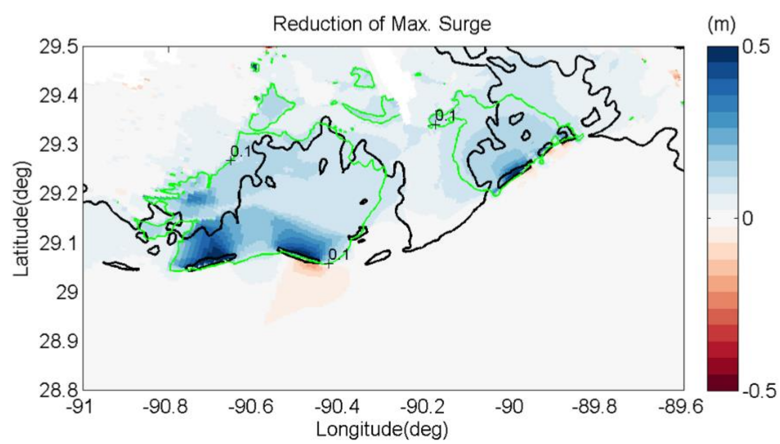

Figure 7. The reduction of storm surge due to the barrier islands during Hurricane Gustav (2008) (green line: 0.1 m contour line for storm surge reduction)

Impacts on sediment transport and morphology

The total sediment transport, including the suspended sediment transport and the bedload, of all the sediment classes from the degradation configuration was plotted in Fig. 8. When Gustav was making landfall, the suspended sediment was moving along the coastline from east to west, following the direction of longshore currents. Because of different orientations of the estuaries, the sediment fluxes outside Terrebonne Bay were mainly shore-parallel, while the fluxes outside Barataria Bay were turning from shore-normal to shore-parallel. The largest sediment flux occurred on the inner shelf to the east of Gustav's landfall location, where the longshore current was strong. Although the barrier islands have been removed in this case, the sediment fluxes through the offshore boundary of the estuaries were still small compared with the transport either inside the bay or on the adjacent continental shelf.

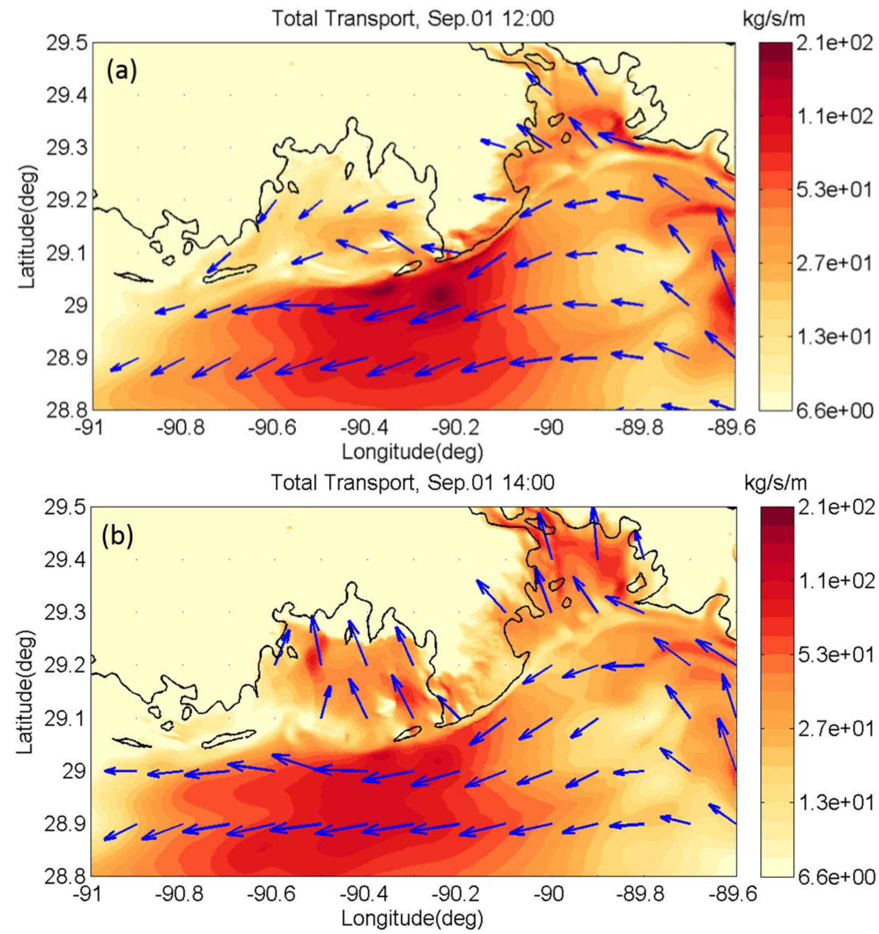

Figure 8. The total transport of the summation of all the sediment classes from degradation configuration when Gustav (2008) was making landfall: (a) 12:00 UTC, Sep 01, or approximately 2 hours before landfall, (b) 14:00 UTC, Sep 01, or approximately landfall.

The relative difference in total transport rate can be defined as

$$\Delta \mathrm{M}_{\mathrm{rel}} = \frac{|\mathrm{M}_{\mathrm{base}}| - |\mathrm{M}_{\mathrm{degrd}}|}{|\mathrm{M}_{\mathrm{base}}|} \times 100\%$$

where $\mathrm{M}_{\mathrm{base}}$ and $\mathrm{M}_{\mathrm{degrd}}$ are the sediment flux in the baseline model and the degradation model, respectively. Thus a positive $\Delta \mathrm{M}_{\mathrm{rel}}$ indicates the transport was larger in the baseline configuration, while a negative value means the transport was smaller in the baseline configuration. A direct comparison of model results from the baseline configuration and the degradation configuration gave the relative change of transport flux at the Terrebonne and Barataria Basins (Figure 9). In general, the degradation of barrier islands enhanced the sediment transport through overtopping the islands, but the transport through the previously existing narrow inlets between the islands dropped. The relative change in the sediment flux could be as much as $\pm 50\%$ near the barrier islands.

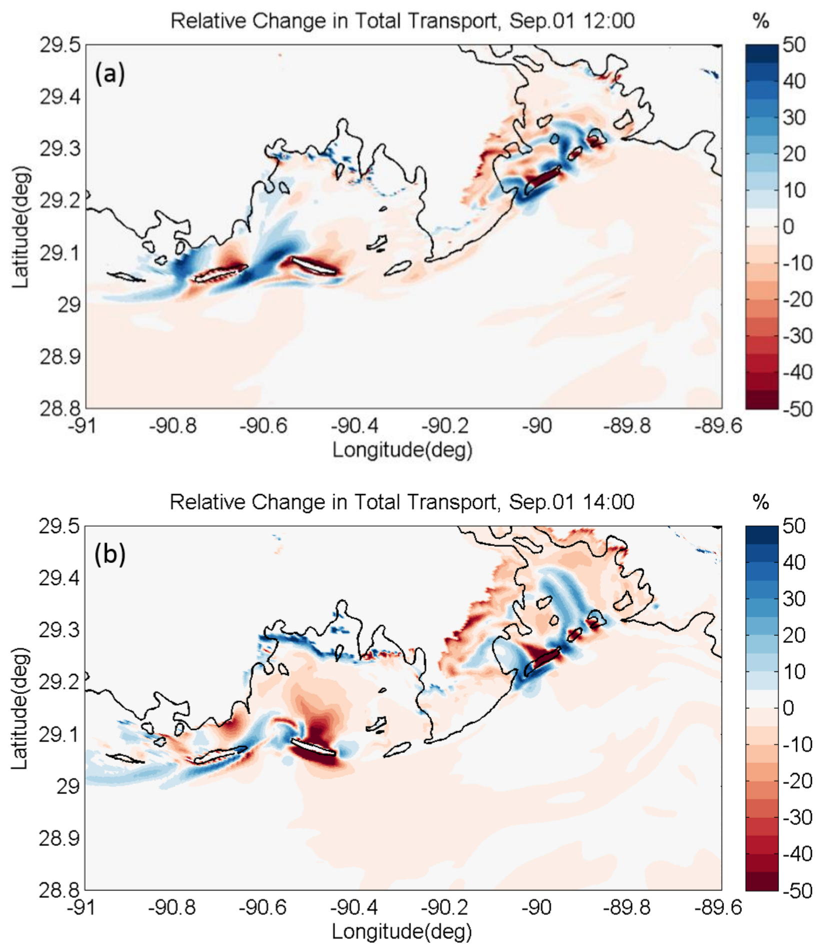

Figure 9. The relative difference of the magnitude of total transport between the baseline configuration and the degradation configuration: Times (a)-(b) are as in Fig. 8.

In order to evaluate the temporal evolution of water and sediment flux corresponding to the degradation of barrier islands and their deviation from the baseline configuration, three observation points close to Grand Isle were selected (Fig. 10): P01 was located on the Grand Isle, P02 was on the protected side of Grand Isle, and P03 was located in the gap between Isle Grande Terre and Grand Isle (the locations of P01/P02/P03 were defined in Fig. 3). At P01 (on the barrier island), current velocity and sediment transport through the barrier island significantly increased as a result of the island degradation. At P02 (the protected side of the barrier island), however, the impacts of barrier island degradation on current speed and sediment transport were limited. At P03 (inlet between two barrier islands), the degradation of the barrier islands on both two sides filled the narrow inlet and the current speed and sediment transport both decreased, especially after the landfall of hurricane.

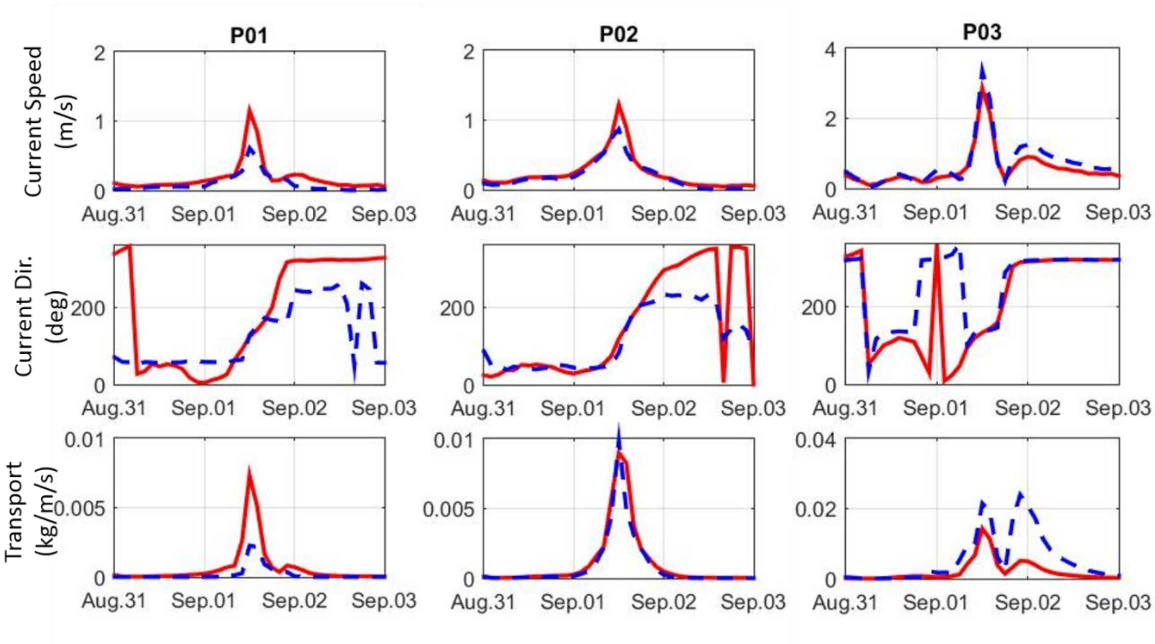

Figure 10. Time series of the depth-averaged current speed/direction and the total sediment transport at observation points P01, P02 and P03 (blue dashed line: baseline configuration; red solid line: degradation configuration).

The sediment fluxes through the entire cross-section T1/T2/B1/B2 (illustrated in Fig. 1) were integrated over the hurricane event, from 08/28/2008 to 09/05/2008, and some components of the net transport in the Terrebonne and Barataria Basins were listed in Table 4 and Table 5. In the degradation scenario, the sediment transport from the inner shelf to Terrebonne Bay and that from Terrebonne Bay to wetlands increased by 6.18% and 6.70% compared with the baseline case. The net deposition on wetlands increased by 6.84% while the percentage of deposition originating from the bay was nearly unchanged in the degradation scenario for Terrebonne Bay. In Barataria Bay, although the transport from the shelf to the open bay decreased by 10.0%, the transport from the bay to wetlands and the net deposition on wetlands increased by 8.05% and 10.5%, respectively.

Table 1. The effects of barrier islands on net transport in shelf-bay-wetlands: Terrebonne

Transport Components	Baseline Configuration	Degradation Configuration	Relative Change
transport from inner shelf to bay (MMT)	6.47	6.87	+6.18%
transport from bay to wetland (MMT)	7.46	7.96	+6.70%
net deposition on wetland, TDW (MMT)	8.77	9.37	+6.84%
Ratio of deposition from estuary, PB (%)	85.1	85.0	-0.12%

Table 2. The effects of barrier islands on net transport in shelf-bay-wetlands: Barataria

Transport Components	Baseline Configuration	Degradation Configuration	Relative Change
transport from inner shelf to bay (MMT)	2.20	1.98	-10.0%
transport from bay to wetland (MMT)	12.3	13.3	+8.05%
net deposition on wetland, TDW (MMT)	12.4	13.7	+10.5%
Ratio of deposition from estuary, PB (%)	99.2	97.1	-2.12%

CONCLUSIONS

A three-dimensional, fully coupled storm surge, waves, and sediment transport model was developed for the Louisiana coast, and the impact of barrier islands degradation on hurricane hydrodynamics and sediment dynamics was studied using a hypothetical model configuration for four major barrier islands in Terrebonne Bay and Barataria Bay.

Numerical simulations showed that the degradation of barrier islands resulted in an increase of storm surge on the protected side of the islands, and the increase was more than 0.1 m in most area in the estuaries. Since the barrier islands could obstruct current from flowing into the estuaries, more sediment transport from the shelf to the bays and a larger contribution of marine sediment to the wetland deposition might be expected in the degradation configuration. From the model results, the exact impact turned out to be insignificant. With the hypothetical deterioration of barrier islands, model results showed that the onshore transport through overtopping the islands was enhanced while the transport through the previously existing narrow inlets was decreased. The net effect on sediment transport from the shelf to the bays varied by location. In Terrebonne Bay, the net transport from the inner shelf to the bay and from the bay to wetlands both slightly increased. In Barataria Bay, in contrast, the transport from the shelf to the bay decreased by 10%.

Despite all these changes in sediment fluxes in the shelf-bay-wetland system as the barrier islands were removed, the net deposition on wetlands only showed a slight increase of 6.84% and 10.5% for Terrebonne and Barataria, and the degradation scenario did not change the fact that most of the deposited material on coastal wetland originated from the bay.

The above analysis provides valuable information on the trend of the change of large-scale hurricane-induced sediment transport in response to topography change in the coastal zone but should not be taken as a definitive quantitative assessment of the impact of barrier islands. The exact benefits of barrier islands in reducing storm surge and waves and altering sediment transport could vary significantly with hurricane parameters (including hurricane track, intensity and approaching angle), the crest height of the islands relative to the surge level, the bathymetry in the adjacent estuary and continental shelf, even the distance from the islands to the mainland (Wamsley et al., 2009; Cobell et al., 2013). The accuracy of the modeled effects of barrier islands was also limited by the relatively coarse mesh, which has only few grid points across the islands in the shore-normal direction. In addition, the passage of hurricanes could cause severe morphological effects on the barrier islands, for example, channel incisions, dune scarps, and overwash fans, which were not considered in this study. A larger set of storm parameters and a better representation of different barrier island topography using higher-resolution local grid are desired for future study.

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