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RESEARCH ARTICLE

Morphological responses of the Wax Lake Delta, Louisiana, to Hurricanes Rita

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This study examines the morphodynamic response of a deltaic system to extreme weather events. The Wax Lake Delta (WLD) in Louisiana, USA, is used to illustrate the impact of extreme events (hurricanes) on a river-dominated deltaic system. Simulations using the open source Delft3D model reveal that Hurricane Rita, which made landfall 120 km to the west of WLD as a Category 3 storm in 2005, caused erosion on the right side and deposition on the left side of the hurricane eye track on the continental shelf line (water depth 10 m to 50 m). Erosion over a wide area occurred both on the continental shelf line and in coastal areas when the hurricane moved onshore, while deposition occurred along the Gulf coastline (water depth < 5 m) when storm surge water moved back offshore. The numerical model estimated that Hurricane Rita's storm surge reached 2.5 m, with maximum currents of 2.0 m s^{-1}, and wave heights of 1.4 m on the WLD. The northwestern-directed flow and waves induced shear stresses, caused erosion on the eastern banks of the deltaic islands and deposition in channels located west of these islands. In total, Hurricane Rita eroded more than 500,000 m^3 of sediments on the WLD area. Including waves in the analysis resulted in doubling the amount of erosion in the study area, comparing to the wave-excluding scenario. The exclusion of fluvial input caused minor changes in deltaic morphology during the event. Vegetation cover was represented as rigid rods in the model which add extra source terms for drag and turbulence to influence the momentum and turbulence equations. Vegetation slowed down the floodwater propagation and decreased flow velocity on the islands, leading to a 47% reduction in the total amount of erosion. Morphodynamic impact of the hurricane track relative to the delta was explored. Simulations indicate that the original track of Hurricane Rita (landfall 120 km west of the WLD) produced twice as much erosion and deposition at the delta compared to a hurricane of a similar intensity that made landfall directly on the delta. This demonstrates that the wetlands located on the right side of a hurricane track experience more significant morphological changes than areas located directly on the hurricane track.

Keywords: sediment balance; hurricanes; vegetation; hurricane track; waves; Wax Lake Delta

1. Introduction

Hurricanes are among the most severe hazards in coastal zones, imperiling coastal wetlands, properties and human lives (Huang et al., 2001; Li and Ellingwood, 2006; Michener et al., 1997; Pielke et al., 2008). Normalized hurricane damage for the continental United States is estimated to be \$10 billion yr^{-1} over 1900–2005 (Pielke et al., 2008). This number is predicted to rise with increasing hurricane intensities (Emanuel, 2005; Landsea, 2005) and as the coast becomes more vulnerable by subsidence, sea level rise and population growth (Li and Ellingwood, 2006; Pielke et al., 2008; Syvitski, 2008; Syvitski and Kettner, 2011; Irish et al., 2014). Forming a coastal buffer zone, wetlands can effectively reduce damage from hurricanes by decreasing storm surges and wave heights (Smith et al., 2010; Wamsley et al., 2010; Gedan et al., 2011). Constant attenuation rate, such as 1 m reduction of storm surge per 14.5 km of marsh (The Corps of Engineers, 1963), are insufficient to represent the realistic surge attenuation by wetlands. Recent studies have shown that the effect of wetlands on storm surge during hurricanes is complicated, as influenced by both wetlands and hurricane properties, e.g., marsh health, tide height, groundwater level, storm intensity, track and forward speed (Wamsley et al., 2010; Loder et al., 2009; Resio and Westerink, 2008; Cahoon 2006). The availability of observational hydrodynamic and wave parameters during hurricanes have made it possible to develop more accurate numerical models to study the hydrodynamics during hurricanes (Dietrich et

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al., 2010; Smith et al., 2010). Applying numerical experiments, marsh morphology (e.g., horizontal extent of marsh, marsh vertical elevation, frictional characteristics, and degree of segmentation) has shown to significantly influence the surge height during hurricanes (Loder et al., 2009; Wamsley et al., 2009).

On the other hand, the impact of hurricanes on morphological changes of wetlands is less well studied, although hurricanes-driven wetland changes could have important ecological consequences (Cahoon, 2006). Most previous studies are based on field observations and analysis of satellite images before and after hurricane passages (Barras, 2006; Kiage et al., 2005; Howes et al., 2010). Barras (2006), by comparing Landsat images before and after the hurricane season, demonstrated that 15% of wetlands within Louisiana coastal plains were converted to open water due to Hurricanes Katrina and Rita (2005). Jackson et al. (1992) stated that hurricanes cause erosion to coastal wetlands, and that the magnitude and extent of erosion are influenced by wetland properties. For example, broken marshes with a poorly consolidated substrate are more vulnerable to hurricanes. Hurricanes also bring sediment and nutrients to coastal wetlands and in aid of wetland maintenance, particularly for wetlands that experience subsidence and sea level rise (McKee and Cherry, 2009; Williams, 2009; Cahoon 2006; Horton et al., 2009). For example, Cahoon et al. (1995) and Guntenspergen et al. (1995) found that hurricane Andrew caused the short-term sediment deposition to increase by up to 3 orders of magnitude compared to pre-storm rates in Louisiana coastal wetlands. Furthermore, Cahoon et al. (1995) stated that a single low frequency, high magnitude storm can deposit more sediment on a marsh than an entire year of high frequency, low magnitude cold fronts. Williams (2009) observed a shallow marine sediment layer in coastal wetlands, and claimed that the marine sediment was deposited during Hurricane Rita. Observations of both sediment erosion and deposition during the same hurricane event demonstrate the complexity of morphological changes. However, systematic studies on the morphological changes of wetlands during hurricane events are still rare.

The wetlands along the Gulf coast are under threat from reduced sediment input, high rates of sea level rise and subsidence. Mississippi River Delta has lost 4,850 km^2 of land in the past 30 years (Batker et al., 2010), and coastal Louisiana is predicted to lose 4,677 km^2 of land in the next 50 years (Couvillion et al., 2013). Early studies indicated that the creation of new river outlets to force freshwater and fluvial sediments to shallow areas, such as the Wax Lake Delta, would reduce the land loss of coastal areas (Kim et al., 2009). As such, from 1973 to 1994, 84.2 km^2 of land has been built at the Wax Lake outlet area (Roberts et al., 2003). The Coastal Protection and Restoration Authority is implementing river diversions at Barataria and Breton Sound basins along the Mississippi River bank to replenish coastal wetlands with fluvial sediment, which has been considered as one of the major coastal restoration approaches of the coastal Louisiana Master Plan (Couvillion et al., 2013; Batker et al., 2010). Unlike coastal wetlands which are located more inland, these recently-built deltas are usually located in shallow bays, which makes them more susceptible to hurricanes induced current and wave energy to the deltaic area. However, the morphological responses of these recently-built deltas to hurricanes is not well understood.

In this manuscript, we applied the Delft3D model to explore the impact of hurricanes on the hydrodynamics and morphological changes of a recently-built delta, the Wax Lake Delta (WLD) during Hurricane Rita (2005). We described the patterns of morphological changes on the continental shelf line and coastal wetlands close to the hurricane track, and the detailed hydrodynamic and morphological changes of the WLD area in response to Hurricane Rita. We also evaluated the roles of waves, fluvial force, vegetation and hurricane tracks on determining the morphodynamics of the WLD during Hurricane Rita. The spatial and temporal uncertainty of modeled morphological changes in response to sediment properties were also discussed.

2. Regional setting

2.1. Wax Lake Delta (WLD)

The WLD is a relatively recently formed fluvial depositional lobe within the Atchafalaya Bay, along the Gulf of the Mexico in Louisiana. It was formed by rapid deposition of fluvial sediments following the construction of a canal (the Wax Lake Outlet, or WLO) in 1941, which connected the upstream Six-Mile Lake and the Atchafalaya Bay (**Figure 1A**). The accumulation of fluvial sediment near the mouth of the outfall canal led to the formation and progradation of the subaqueous delta. The delta became subaerial in 1973 after a large river flood (peak discharge of 20,000 $m^3 s^{-1}$ measured at Atchafalaya River (Simmesport, USACE station 03045, Louisiana), compared to the mean discharge of 5,781 $m^3 s^{-1}$ from 1935 to 2007) that transported significant amounts of sediment to the river mouth, both from fluvial sediments of the Mississippi River and from erosion of the sediments formerly deposited in the canal (Roberts et al., 1997).

Fluvial water and sediment discharges towards the WLD have strong seasonal variations, with annual river floods occurring in spring (Mossa and Roberts, 1990). The mean flood velocity is approximately 2–2.5 times higher than the non-flood velocity for an average-discharge year, and suspended sediment concentration during floods can be up to 20 times higher than during non-flood conditions (DuMars, 2002). The WLO transports approximate 30 Mt of sediment per year to the shallow Atchafalaya Bay (~2m deep, Kim et al., 2009), leading to yearly average subaerial delta growth rate of ~0.81 km^2 (FitzGerald, 1998; Roberts et al., 2003). The mean fluvial sediment layer (topset) thickness of the delta is 2.4 m, of which approximately 70% is sand (Roberts et al., 1997).

Typically tides and waves are relatively mild, compared to fluvial forces in Atchafalaya Bay. The tidal range is around 0.3 m (DuMars, 2002), and the mean significant wave height is less than 0.5 m (Wright, 1977). The area is exposed to two major weather systems: winter cold fronts and summer and fall tropical storms. Cold fronts occur every 4–7 days from October through March, or 20–30 times per year (Chuang and Wiseman, 1983). During cold fronts, wind speed can exceed 10 m/s (Walker and Hammack, 2000). The high winds and wind-generated waves can effectively re-suspend and transport the bottom sediments, contributing to ~15% of the fluvial sediment being transported outside the bay system every year (Roberts et al., 1997). Tropical storms affect this area primarily in summer and fall, producing significant damage to coastal wetlands (Barras, 2006; Howes et al., 2010). Sixteen major hurricanes (Category 3 or higher on the Saffir-Simpson scale) have been recorded to impact the WLD between 1941 and 2008 (Bunya et al., 2010).

The WLD has been predominately colonized by freshwater species on the high-lying areas of the islands due to the freshwater sequestration in this river-dominated system. The plant community is in a dynamic early successional phase, and its composition is mainly determined by fluvial discharge, elevation, disturbance, salinity, organic content of sediment, and nutrient availability (Rejmanek et al., 1987; Shaffer et al., 1992; Holm and Sasser, 2001).

2.2. Hurricane Rita

Hurricane Rita was one of the most intense Atlantic hurricane ever recorded in the Gulf of Mexico (Beven et al., 2008). Rita initially formed as a tropical depression on September 17th, 2005 near the Turks and Caicos Islands, starting its path westwards through the Florida Straits. The system intensified over time but remained a Category 2 hurricane until it entered the Gulf of Mexico. Rita strengthened rapidly when it passed over the warm Loop Current during midday September 21st, reaching Category 5 at 18:00 Coordinated Universal Time (UTC) with a minimum barometric pressure of 897 mbar and a maximum wind speed of 175 mph. The system weakened on September 23rd as it approached the north-central coast of the Gulf of Mexico (**Figure 1A**). Simultaneously, the track changed from westerly to northwesterly. Rita made landfall in western Cameron Parish, Louisiana, 120 km

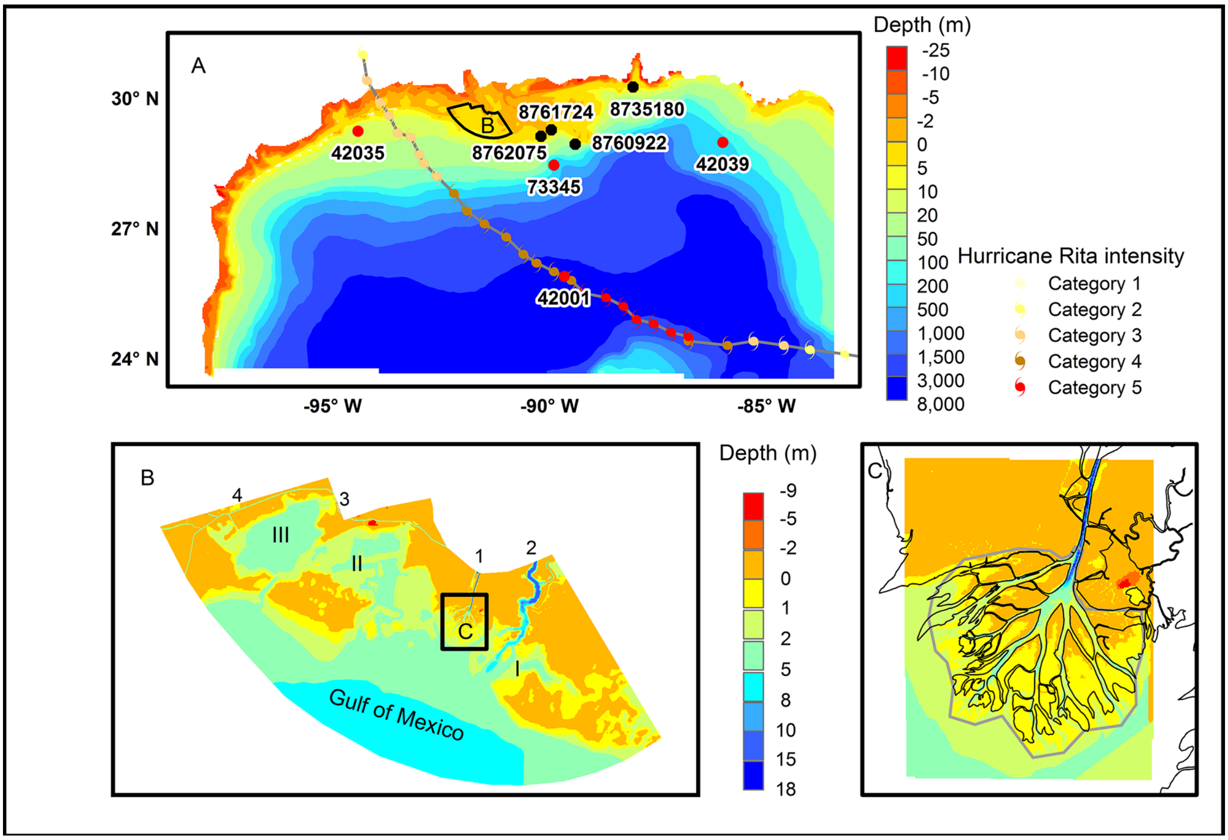

Figure 1: Bathymetry and topography of the model domains. A) Shows the largest model domain: Gulf of Mexico (GoM). The dotted line displays the track of Hurricane Rita, and the colors demonstrate the hurricane intensity. Red dots show three National Data Buoy Center (NDBC) stations and one station from Wave Information Study for wave observations (significant wave heights, peak wave periods, and mean wave directions). Black dots show four NOAA tidal stations along the Louisiana and Texas coasts for storm surge observations. **B)** and **C)** Show detailed bathymetry and topography of the Atchafalaya domain and the Wax Lake domain. The numbers 1, 2, 3, and 4 in Fig. 1B are the four rivers that are included in the simulations: the Wax Lake Outlet, Atchafalaya River, Jaws River, and Vermilion River, respectively. I is Atchafalaya Bay, II is West Cote Blanche Bay, and III is Vermilion Bay. The solid grey line in Fig. 1C shows the deltaic area used to estimate the sediment balance. DOI: https://doi.org/10.1525/elementa.125.f1

west of the WLD, on September 24th as a Category 3 hurricane, causing a storm surge of 4–5 m close to the landfall area (Williams, 2009). Significant inundation and wetland damage was observed along the Louisiana coast (Bunya et al., 2010; Howes et al., 2010; Rego and Li, 2010). High water mark data indicate the storm surge was more than 3 m in Vermilion Bay (**Figure 1B**, Rego and Li, 2010). After entering the inland area, Rita weakened, moving northward through Texas and western Louisiana, eventually turning northeastward and dissipating when it merged with a cold front on September 26th, 2005.

3. Methodology

3.1. Delft3D model

The Delft3D software package, a widely used computational fluid dynamics model (Lesser et al., 2004), is applied for this study. The Delft3D FLOW module uses a finite difference solution of the three-dimensional shallow water equation and the k-ε turbulence closure model (Rodi, 1980) to compute flow characteristics under the hydrostatic pressure assumption. The model uses a flooding and drying algorithm to determine the active computational grid cells: a cell is included in the calculation when its water depth increases to be higher than 0.02 m, and excluded from the calculation when its water depth decreases to be lower than 0.01 m. The Morphology module (MOR) allows suspended sediment transport (both cohesive and non-cohesive) to be calculated simultaneously with flow computation using the advection-diffusion equation. Bed level is updated every time step based on hydrodynamic results using the Exner equation (WL|Delft3D Hydraulics, 2011). The third-generation fully spectral wave module Simulating Wave Nearshore (SWAN) is coupled with Delft3D FLOW to calculate wave parameters with the discrete spectral action balance equation (WAVE|Delft3D Hydraulics, 2011). A vegetation routine that represents vegetation as rigid cylindrical rods is studied through sensitivity test to explore the influence of vegetation on hydrodynamics and morphological changes (Uittenbogaard, 2003). In the vegetation model, the rigid rods would add extra source terms for drag and turbulence to influence the momentum and turbulence equations. The vegetation approach has been tested in field observations to be effective for cohesive sediment transport in tidal marshes (Temmerman et al., 2005). A more detailed description of the model structure is given in Lesser et al. (2004) and Temmerman et al. (2005).

3.2. Model input parameter settings

The Delft3D FLOW, WAVE and MOR modules were coupled and applied to three nested domains with curvilinear grids in order to acquire a detailed hydrodynamic field for the WLD area. The grids have a varied spatial resolution, higher resolution close to the study area and lower towards the deep ocean. The largest domain (GoM) consists of a considerable part of the Gulf of Mexico with a resolution of 0.020 degrees; the second domain includes the coastal shallow areas of the WLD (Atchafalaya, Vermilion, and Cote Blanche Bay) and surrounding low-elevated wetlands with an average resolution of 200 m; and the third domain (WLD) includes the WLD and surrounding wetlands, with an average resolution of 50 m (**Figure 1**). The GoM model was initiated by: a) tides at the ocean boundaries which were extracted from the TPXO 7.2 Global Inverse Tide Model (http://volkov.oce.orst.edu/tides/TPXO7.2.html), b) equal-distance wind fields with a spatial resolution of 0.05 degrees and a temporal resolution of 15 minutes, achieved from the combination of NOAA Hurricane Research Division Wind Analysis System (H*WIND, Powell et al., 1998), and the Interactive Objective Kinematic Analysis (IOKA) kinematic wind analysis (Cox et al., 1995). Bathymetry was derived from the Louisiana Virtual Coast Data Archive (http://virtual-coast.c4g.lsu.edu/), in which NOAA's bathymetry sounding database, the Digital Nautical Charts database, and the 5-minute gridded elevations/bathymetry for the world (ETOPO5) database were combined (National Geophysical Data Center, 1988; National Ocean Service, 1997; U.S. Department of Defense, 1999; Mukai et al., 2002). Three sediment classes: sand, silt and clay, were included in the model and seabed properties in the GoM domains were extracted from seabed sediment distribution map (dbSEABED) reported by Jenkins (2002). The bed roughness is parameterized using Manning's n as calculated through an empirical equation:

$$n = 0.015 + \frac{0.01}{|depth|} \tag{1}$$

Which has been validated in previous coastal hydrodynamic simulations (Xing, et al., 2012). The depth is in meters. For the WLD domain, a higher resolution bathymetry and island topography obtained from 1998 hydrological survey with an averaged resolution of 80 m was used, combined with a Light Detection and Ranging (LIDAR) survey dataset for overbank areas that were not covered in the hydrographic survey (USACE, 2010). River discharges at fluvial boundaries were acquired from observed daily data at USGS Calumet station (Baumann et al., 2005), and sediment concentrations were set up with annual averaged values reported by Dumars (2002). The most significant morphological parameters used for the Atchafalaya and WLD domains are shown in **Table 1** based on the study of Khadka (2013).

3.3. Residual currents

Residual currents provide insight into the net flows after removing the periodic effects of tidal currents, which predominately control net water and sediment transport in estuaries and coastal ocean (Dyer, 1973). The residual current could be induced by fluvial forces, winds, waves, baroclinic effects, and non-linear interactions of controlling forces with local topography (Tee, 1977). A widely-used, low-pass digital filter was used to eliminate the influence of tides, through which waves with periods longer than 12 hours were filtered from the simulated results (Walters and Heston, 1982; Thompson, 1983). In this way, we obtained the water level and flow velocity caused by interactions of the hurricane and rivers on the deltaic area. Residual currents (in m s^{-1}) that are mainly composed of the hurricane and river-driven currents, excluding the effects of tidal currents, were calculated for each grid cell j on the WLD using the following equation for both x- and y- direction:

$$R_j = \frac{1}{dep_j} \sum_{i=1}^{i=n} v_{i,j} \cdot d_{i,j} \quad (2)$$

Where dep_j [m] is mean water depth at cell j, $v_{i,j}$ [m s^{-1}] is velocity at time step i, $d_{i,j}$ [m] is water depth at time step i, and n [–] is the total number of calculating time steps.

3.4. Numerical experiments

To study the impacts of driving forces and model parameters on deltaic morphology during hurricanes, four experiments were designed. The numerical settings for Hurricane Rita were assigned as the base case, and four numerical models were set up to study the influences of waves, fluvial input, aboveground vegetation and hurricane tracks. Experiment 1 (EX1) was set up by deactivating the wave module from the base case so the influence of waves on delta hydrodynamics and morphology could be estimated. Similarly, Experiment 2 (EX2), experiment 3 (EX3) and experiment 4 (EX4) were set up by deactivating the fluvial input, recalculating the drag and turbulence terms in model equations to account for the influence of aboveground vegetation, and changing the direction of hurricane track so that the hurricane would make direct landfall at the Wax Lake Delta (moving the wind field by 120 km to the east) to study the influence of fluvial input (EX2), aboveground vegetation (EX3) and hurricane tracks (EX4) on delta hydrodynamics and morphology, respectively. Distribution of vegetation depends significantly on water depth (Shaffer et al., 1992). As such, the aboveground vegetation in the model was set to be uniform on the delta where water depth was lower than 0.2 m, with a stem height of 1.0 m (plants height varies from 0.3 m to maximum 3.4 m, but is mostly ~1 m (Carle, 2013)) and a density of 50 stems per m^2 (stem density of the dominant species: S. platyphylla was estimated to be ~50 stems per m^2 at the coast of Louisiana (Martin and Shaffer, 2005).

3.5. Model validation

The observed waves (significant wave height, mean wave directions and peak periods) and water levels derived from the National Data Buoy Center (NDBC http://www.ndbc.noaa.gov/), NOAA coastal tides stations (NOAA/NOS/CO-OPS), respectively, (**Figure 1A**) were used to test the model's effectiveness. Wave data from the Wave Information Studies (WIS) was also extracted and compared with modeled results to evaluate the Wave model performance in the coastal shallow areas (**Figure 1A**, Hubertz, 1992; Komen et al., 1994). The comparisons between model results and observations (**Figure 2**) indicate that the modeled results match the observed wave dynamics for the deep ocean and the storm surges in the coastal areas during Hurricane Rita. The simulated wave heights have a RMSE (Root Mean Square Error) of 1 m (mean value of 3.2 m), and the simulated peak wave periods have a RMSE of 2s (mean value of 6s). The filtered water levels from simulation were overall smaller than what was observed but match well with the peak surges, with a RMSE bias of 0.16 m (mean value of 0.24 m) (**Figure 3**). The modeled maximum water level in Vermilion Bay also show great consistency with the high-water marks measured by the Federal Emergency Management Agency (FEMA) during Hurricane Rita (modeled 3.6 m, compared to observed 3–4 m) (FEMA, 2006).

Table 1: Morphological parameter settings for Atchafalaya and WLD domains. DOI: https://doi.org/10.1525/elementa.125.t1

D50 (m)		Clay (N/m^2)		Bed layer thickness (m)		Bed roughness (Chezy: $m^{1/2}$ s^{-1})		Bed sediment proportion (Sand:Silt:Clay)	
Sand	Silt	Cr_{ERO}	Cr_{DEP}	Channels, Ocean	Islands, wetlands	Channel, ocean	Islands, wetlands	Channel, Ocean	Islands, wetlands
1.0E–04	3.0E–05	1.0E + 00	1.0E–02	20	5	100	40	4:1:5	7:1:2

Cr_{ERO}: critical shear stress for erosion of cohesive sediment (clay).
Cr_{DEP}: critical shear stress for deposition of cohesive sediment (clay).

Table 2: Numerical model settings of the experiments of this study. DOI: https://doi.org/10.1525/elementa.125.t2

Scenarios	Hurricane Track	Fluvial process (river)	Waves	Aboveground Vegetation
Base	Side	Y	Y	N
Wave-excluded (EX1)	Side	Y	N	N
Fluvial-excluded (EX2)	Side	N	Y	N
Vegetation-included (EX3)	Side	Y	Y	Y
Direct landfall (EX4)	Direct	Y	Y	N

N: Process excluded; Y: process included.

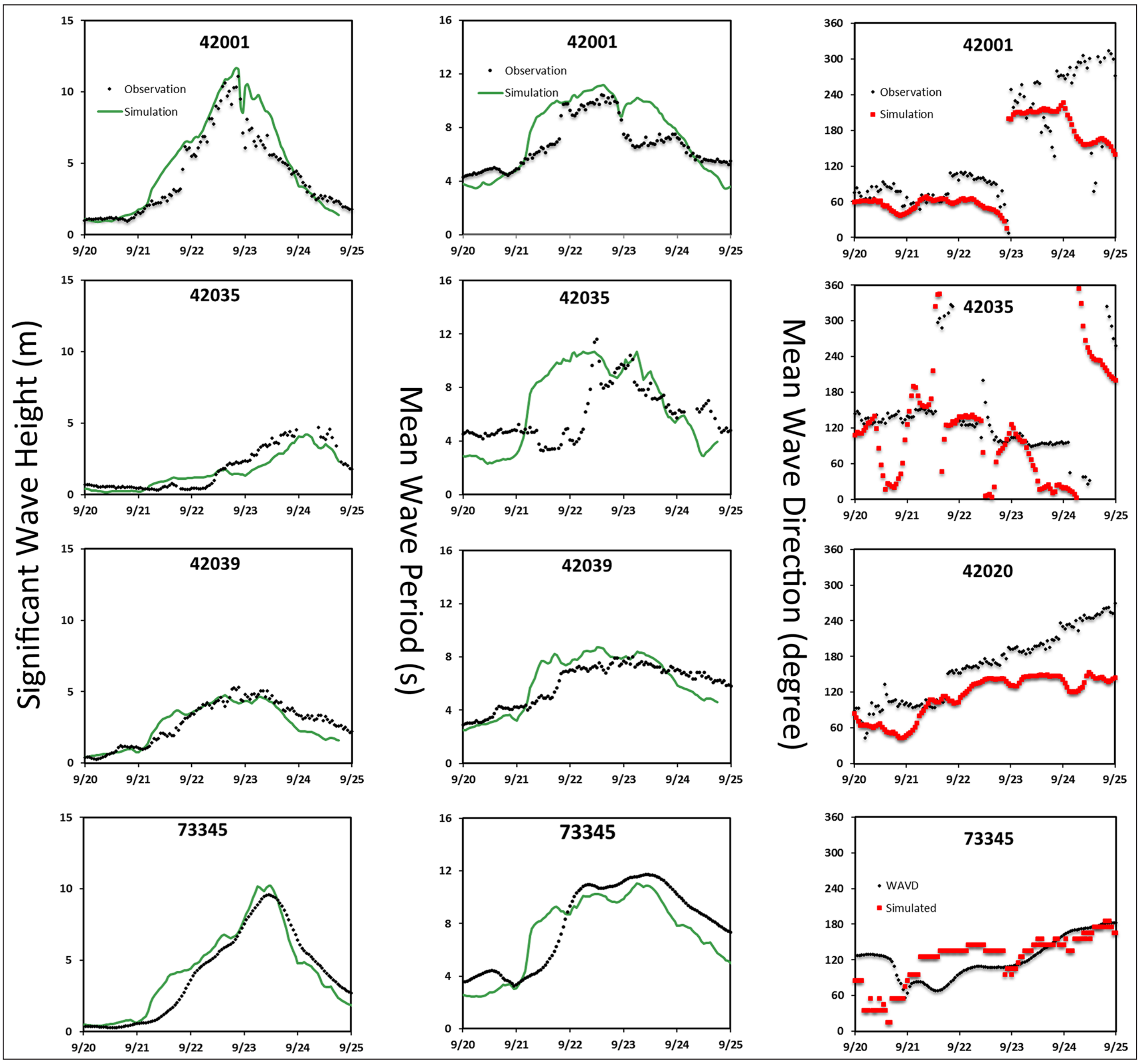

Figure 2: Comparisons of significant wave heights, mean wave periods and mean wave direction over time at selected stations. The selected stations for Fig. 2 include three NOAA buoy stations and one WIS stations (See Fig. 1A), demonstrating that the modeled results capture both the trends and the magnitudes of the observed wave parameters DOI: https://doi.org/10.1525/elementa.125.f2

Because of data scarceness, the Delft3D MOR module could not be validated with field observations during Hurricane Rita. Instead, the parameter sets were derived from the study of Khadka (2013), in which these parameters have been validated against successive mapping of the WLD growth from 1998 to 2012 where the morphological evolution produced by the model compares favorably with the mapping data. Although no direct validation is available, the model results demonstrated a pattern of deposition in wetlands that are located inland along the coast of Texas, Louisiana, Mississippi and Alabama with a depositional layer thickness of less than 0.1 m (**Figure 4A**), which is within the same order with former observations (Horton et al., 2009; Williams, 2009). The simulated deposits located parallel to the Gulf shoreline with a thickness of ~0.2 to 0.3 m, is consistent with field observation from Guidroz et al. (2006), who stated that on average 0.25 m of deposits were observed parallel to the Gulf coast where the maximum flow depth was about 4 m. The consistency of modeled results with field observations ensured us that the model results are reliable to represent the general pattern of morphological changes along the Gulf coast during hurricane events.

3.6. Uncertainty analysis

Applications of numerical models for making quantitatively accurate predictions for scientific or practical purposes are highly dependent on model uncertainty (Murray et al., 2016). Uncertainty of morphodynamical modeling can be caused by a lack of highly accurate input parameters, and the fact that the complicated interactions between hydrodynamics and morphological changes are not well understood. Delft3D software packages have been widely used in both scientific and engineering practices to provide quantitatively accurate predictions. However, the evaluation of its model uncertainty is extremely difficult as simulations are usually computational expensive (Brière et al., 2010; Plüβ and Kösters, 2014; Scheel et al., 2014). In this study, we initiated a quantitative uncertainty analysis of the morphology component of Delft3D during Hurricane Rita using the Dakota software (Adams et al., 2014). The parameters that were used for the uncertainty analysis include observational parameters (sand and silt grain size) and model parameters (critical shear stress for clay erosion and sedimentation) which are of significant importance to estimate morphological changes (WL|Deltares Hydraulics, 2011; Sanford and Maa, 2001; Grabowski et al., 2011). For instance, sediment grain sizes are critical to determine the transport patterns of non-cohesive sediment, while the critical shear stress predominantly determines the dynamics of cohesive sediment. As observations of these input parameters are not always available, most numerical studies use calibration or parameter estimation to determine these values, which vary significantly for different environments and models (Sahin et al., 2012; Xu et al., 2014; Wright, 1997). We applied a range of grain sizes with the largest possible range for two reasons. First, hurricanes are extreme powerful events which could suspend all classes of available sediments. Second, the offshore sediment in the bed layers covers a wide range of sand and silt which could be transported to the study area. The critical shear stresses for erosion and deposition were designed based on studies of Hanegan (2011) and Khadka (2013), which have been validated in studying the long-term evolution of the WLD using Delft3D (**Table 3**). Given the complexity of the Delft3D model and its high computational demand, we applied 3 samples for each of these parameters using the Latin hypercube sampling method (Stein, 1987), leading to 81 simulations in total. Comparing to the commonly used Monte Carlo sampling method which generates random values within the user defined range, requiring a large number of sampling points to produce accurate results; the Latin hypercube sampling method generates a near-random sample of parameter values from a multidimensional distribution, which could significantly reduce the number of sampling points. Thus, the number of simulations needed

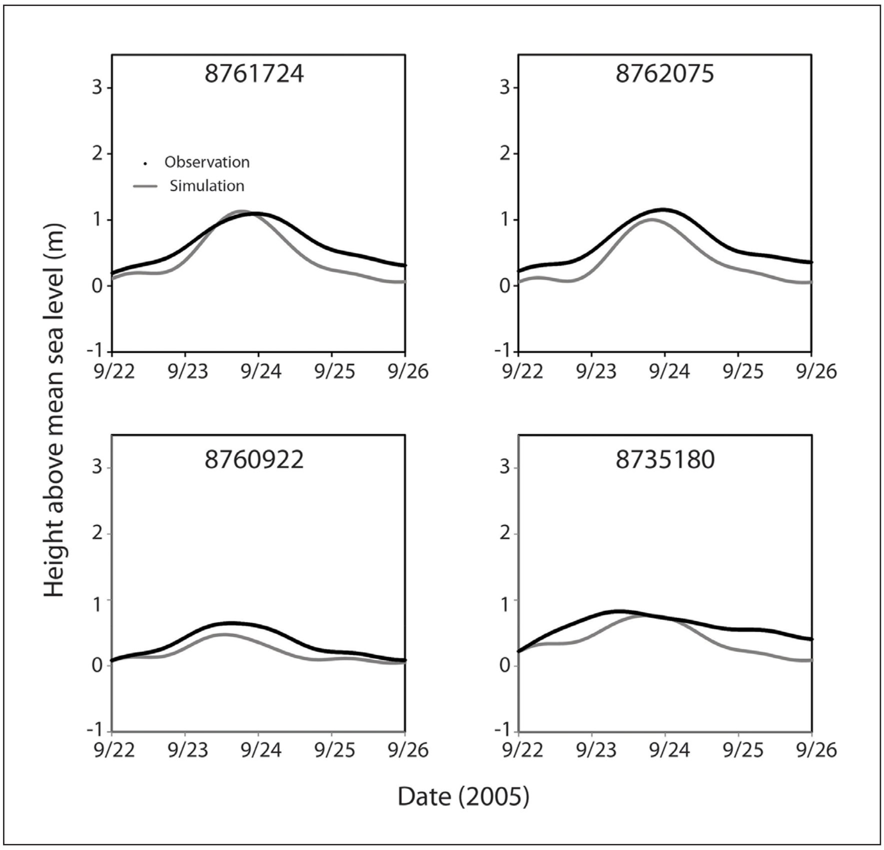

Figure 3: Comparisons of water levels and storm surges over time at four coastal stations. The locations of stations for Fig. 3 are shown in Fig. 1A, indicating that the model successfully simulates the water level rise during a hurricane event. DOI: https://doi.org/10.1525/elementa.125.f3

Table 3: Uncertainties of major input parameters. DOI: https://doi.org/10.1525/elementa.125.t3

Parameters	Sand Grain size (m)	Silt Grain size (m)	Clay Cr_{SED} (N/m²)	Clay Cr_{ERO} (N/m²)
Uncertainty	(62.5–200) × 10–6	(8–62.5) × 10–6	0.05–0.1	0.5–1
References	(Wellner et al., 2005)	(Pankow et al., 1993)	(Hanegan, 2011; Khadka (2013)	(Hanegan, 2011; Khadka (2013)

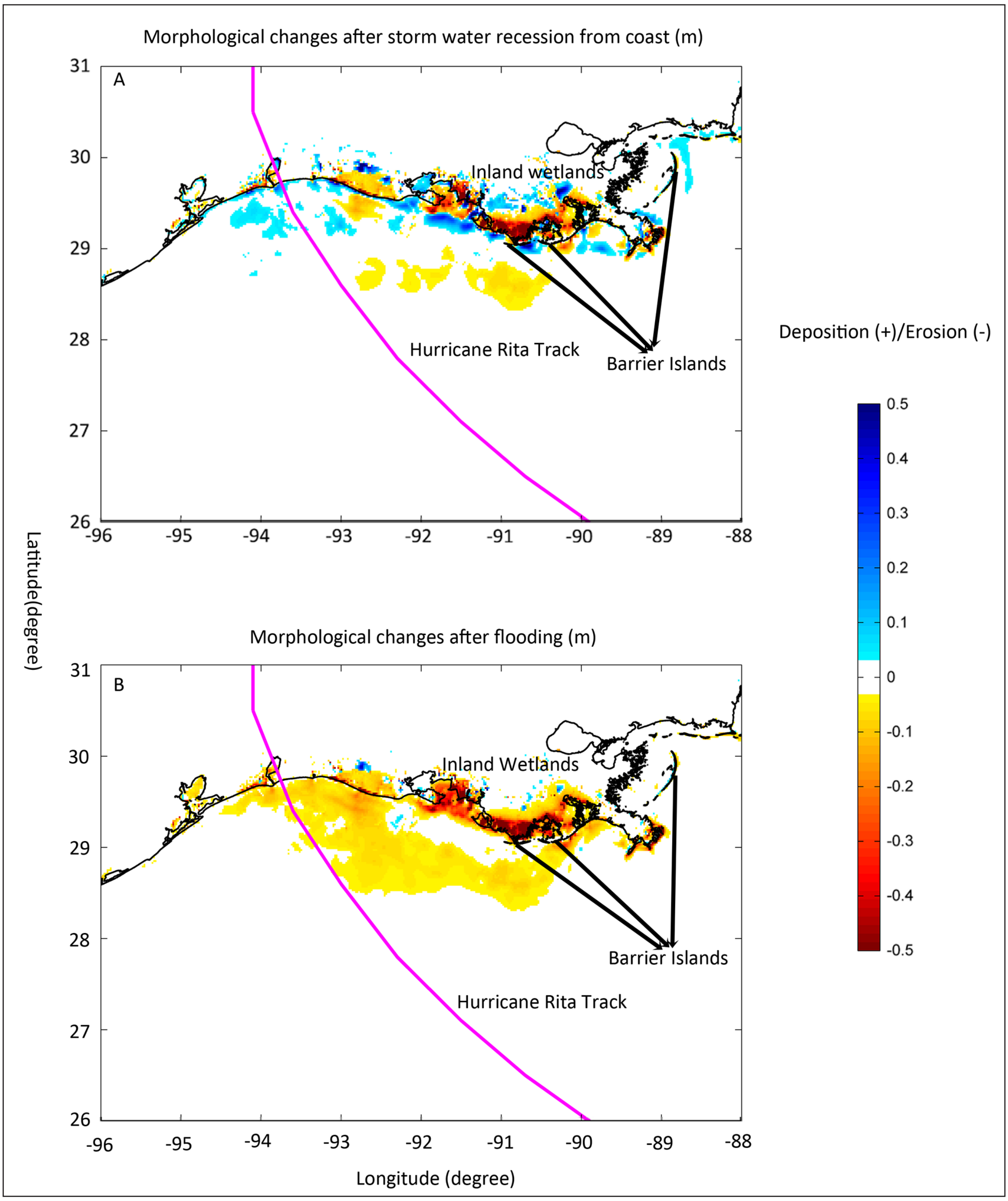

Figure 4: Morphological changes of the continental shelf and coastal wetlands due to Hurricane Rita. A) Showed the morphological changes after the storm event (floodwater has receded from coastal areas), and **B)** Showed the morphological changes during the storm event (after surge water flooded the coastal area and before the surge water receded from coastal areas). DOI: https://doi.org/10.1525/elementa.125.f4

for evaluating model uncertainty analysis could be significantly reduced.

4. Results and discussion

4.1. Hydrodynamic and morphological changes caused by Hurricane Rita

Model results demonstrated that Rita formed a pressure deficit in the hurricane eye, leading to a water level rise of 1.0 m in the deep ocean. As the hurricane system approached shallow water, the reduction in water depth limited the strong vertical momentum diffusion, leading to a significant increase in storm surge because the conservation of the potential vorticity of the mound requires development of marked divergence (Jelesnianski, 1993). Combined with local bathymetric reflections and onshore-directed winds, surge height raised to 4–5 m when Rita made landfall (**Figure 5A**), which is consistent with findings of Williams (2009). At the same time, wave height decreased when Hurricane Rita approached the shallow continental shelf areas. The significant wave height, which was as high as 15 m in the middle of the Gulf of Mexico, decreased to

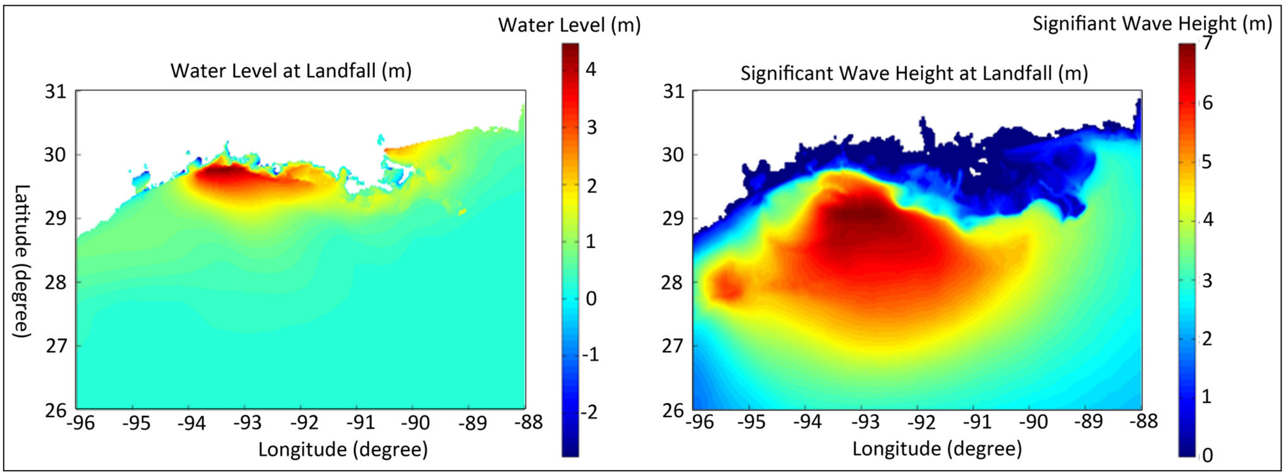

Figure 5: Spatial distribution of water level (left) and significant wave height (right) when Rita made landfall. DOI: https://doi.org/10.1525/elementa.125.f5

~6 m at the time Hurricane Rita made landfall in Texas (**Figure 5B**).

Hurricane Rita caused widely spread erosion when the system approached the Gulf coast (**Figure 4B**). Most erosion was observed on the right side of the hurricane track because the right side of hurricanes experiences the maximum winds and therefore the most significant morphological changes (Coch, 1994; Weisberg and Zheng, 2006). The continental shelf line with water depth between 10 m to 50 m was eroded by less than 0.2 m, while the shallow bay area was severely eroded by more than 0.4 m. Areas located on the left side of hurricane track experienced much less erosion comparing to the areas located on the right side, and the erosional layer thickness was less than 0.2 m for the coastal area. Deposition was rare and mostly occurred in wetlands that located on the inland side of the erosional area (**Figure 4B**). The recession of flood water towards offshore significantly changed the morphological pattern by depositing a lot of sediment along the Gulf coast (**Figure 4A**). A large of offshore area which was eroded when the hurricane system approached the coast converted to be depositional, e.g., the area close to the hurricane track. Deposition occurred in the inland wetlands, and a deposition zone developed on the offshore side of the barrier islands (**Figure 4A**), which was consistent with field observations (Horton et al., 2009; Williams, 2009; Guidroz et al., 2006). The total amount of erosion in the continental shelf area decreased relative to the flooding stage, demonstrating that some of the sediment that was moved from the continental shelf by surge water was carried back to the continental shelf during surge water recession.

Hurricane Rita drastically disturbed the hydrodynamic field in the WLD area. Before the hurricane eye approached the coastal zone, the anti-clockwise wind structure produced offshore-directed winds north of the hurricane system, leading to offshore-directed water flow. The offshore flow caused a significant drop of the water level in the WLD area (–2.0 m, **Figure 6A**). Water then flowed back towards the coastal area when wind direction changed southeast during the storm surge, resulting in a water level rise of 2.5 m (**Figure 6B**). The water level variations during Hurricane Rita were 4–5 times higher than the typical tidal range (+/– 0.5 m, **Figure 6C**), and flow velocities reached 2.4 m s^{-1}, which was 5 times higher than that under non-storm conditions (0.5 m s^{-1}). Hurricane Rita produced a maximum significant wave height of 1.4 m (**Figure 6D**), which was approximately 3 times higher than wave heights under normal conditions (0.5 m from Wright (1977), **Figure 6E**). Waves were higher in the river channels than on the submerged islands because wave energy dissipated in shallow areas (**Figure 6D**). Floodwaters spread beyond the channel banks and overtopped the islands and coastal wetlands. The flow velocities were higher on the island tops than within the channels during floodwater propagation because the floodwater propagating northward (upstream) counteracted with the fluvial discharge flowing southward (downstream) within the channels. The WLD was then dominated by a uniform flow towards the northwest, following the wind field (**Figure 6B** and **7A**).

The residual current was calculated, which flowed towards the northwest in most of the WLD area following the wind direction (**Figures 7A** and **8A**), which was higher on the islands and lower in the channels. The highest residual current occurred on the eastern banks of the islands due to a significant decrease in water depth when floodwater moved northwest from the channels towards the islands (**Figure 8A**). Accordingly, erosion occurred on the islands and deposition occurred generally in the channels. Most significant erosion took place on the eastern banks of the islands, while highest accretion happened in the channels located on the west of the islands due to significant decrease in shear stress when floodwater moved northwest from the islands to the channels (**Figure 9A**). Similar patterns between residual currents and morphological changes revealed that residual currents are one of the major forces controlling sediment transport, leading to the pattern of erosion on islands and deposition in channels. The sediment budget was estimated for the WLD area (see **Figure 1C**), which indicated that Hurricane Rita produced a net erosion of 500,000 m^3 in 100 hours (1600 UTC, September 21st to 1900 UTC, September 25th).

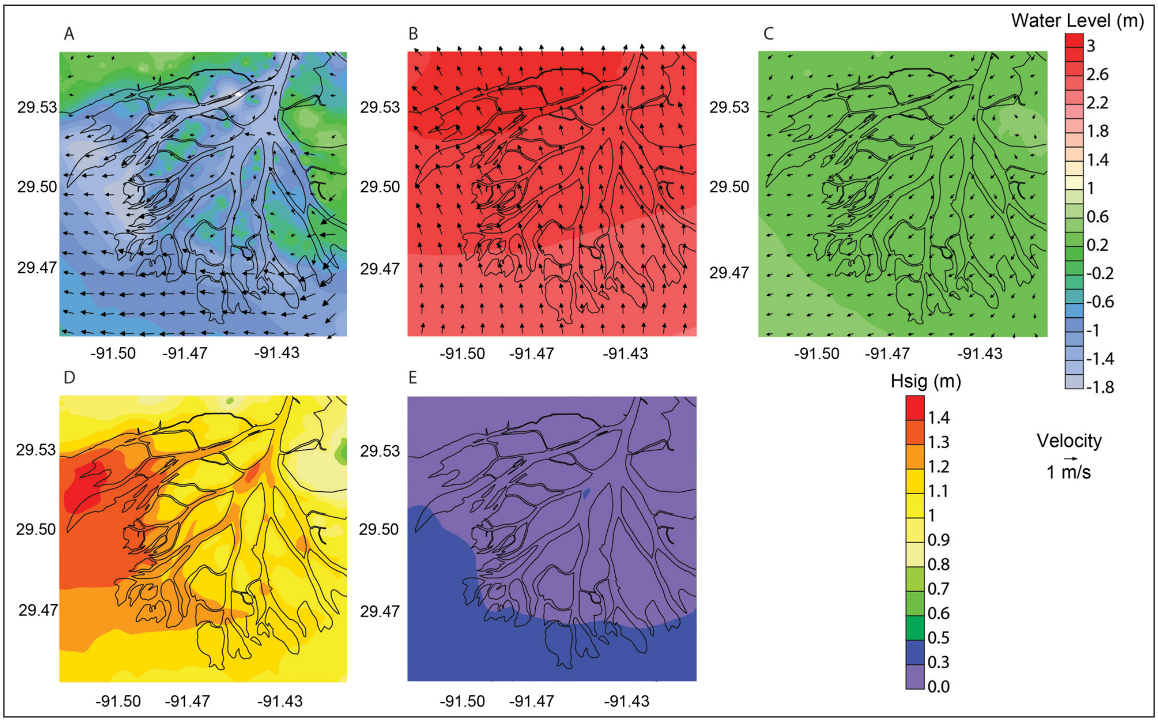

Figure 6: Simulated water levels, current directions, and significant wave heights for the WLD. A) Water level drops before storm surge; **B)** Water level rises at peak storm surge; **C)** Water level rises during high tides; **D)** Significant wave height distribution at peak storm surge; **E)** Significant wave height distribution during high tides. Water level drops significantly before the hurricane system approaches the deltaic area due to dominated offshore winds during that period. Water level then rises when the hurricane pushes water onto the delta. The water level rise caused by Hurricane Rita is ~5 times higher than that under normal conditions (dominated by tides). The significant wave height caused by Hurricane Rita is ~3 times higher than that under normal conditions. DOI: https://doi.org/10.1525/elementa.125.f6

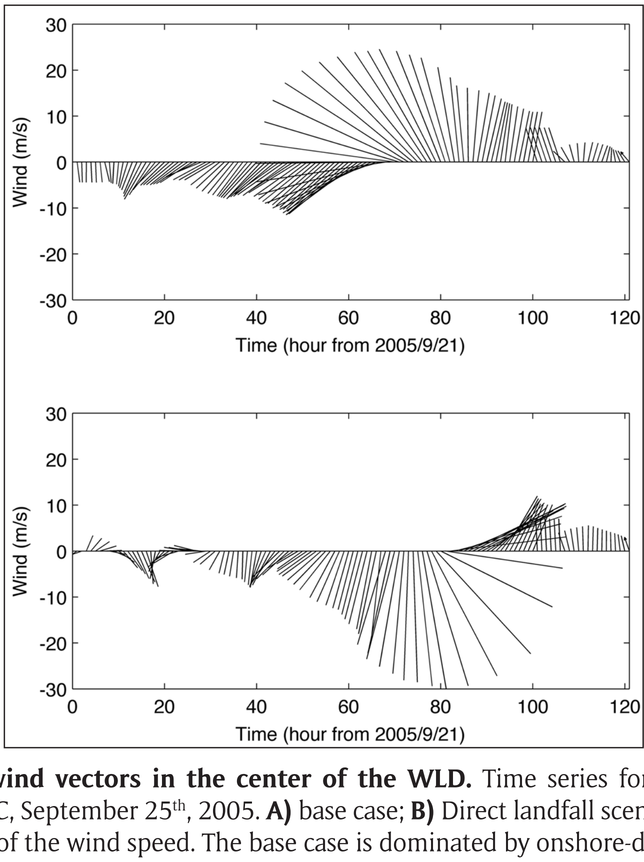

Figure 7: Time series of wind vectors in the center of the WLD. Time series for Fig. 7 was from 0000 UTC September 21st to 0100 UTC, September 25th, 2005. **A)** base case; **B)** Direct landfall scenario (EX4). The lengths of the lines show the magnitude of the wind speed. The base case is dominated by onshore-directed wind, and direct-track scenario (EX4) is dominated by offshore-dominated winds. DOI: https://doi.org/10.1525/elementa.125.f7

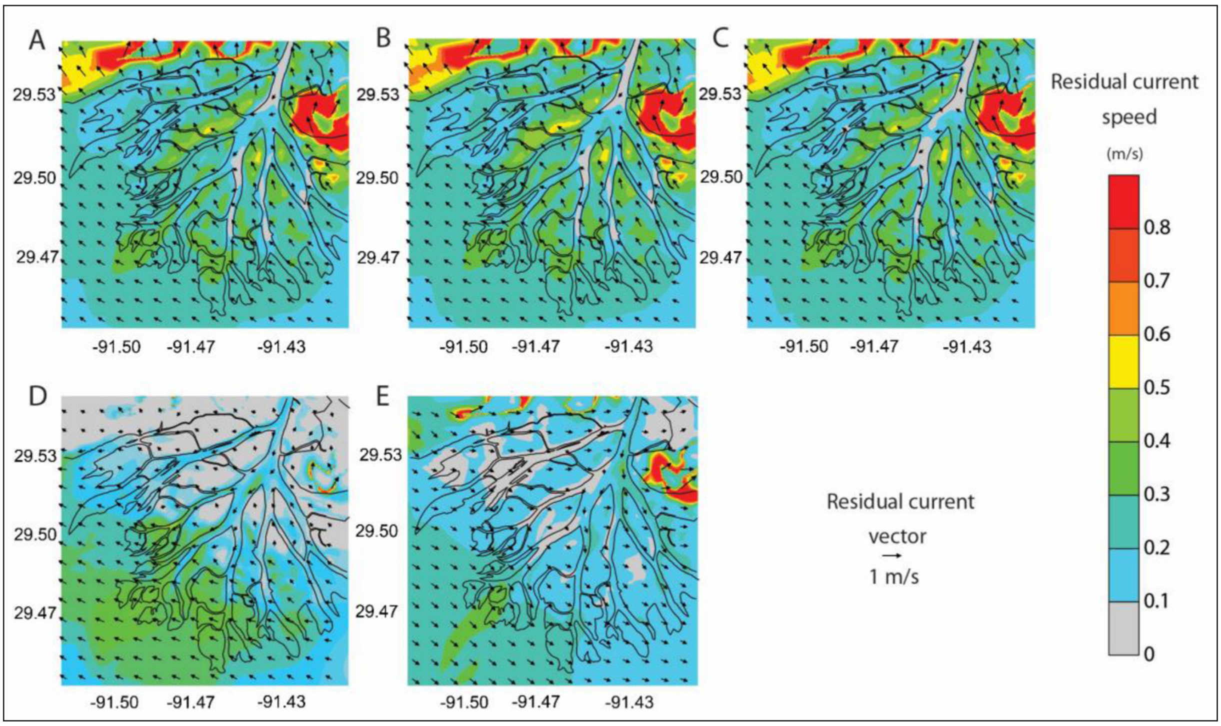

Figure 8: Simulated residual current distributions for the WLD. A): base case; **B)** Wave-excluded (EX1); **C)** Fluvial-excluded (EX2); **D)** Vegetation-included (EX3); **E)** Direct landfall (EX4), which applies a directly-landfalling hurricane track (See also Table 2). Waves and fluvial input have less impact on residual currents, but aboveground vegetation significantly decreases the high residual currents on subaerial part of the delta, and the high currents concentrate on the southwest side of the delta. Hurricane tracks significantly change the distribution pattern of residual currents on the WLD. DOI: https://doi.org/10.1525/elementa.125.f8

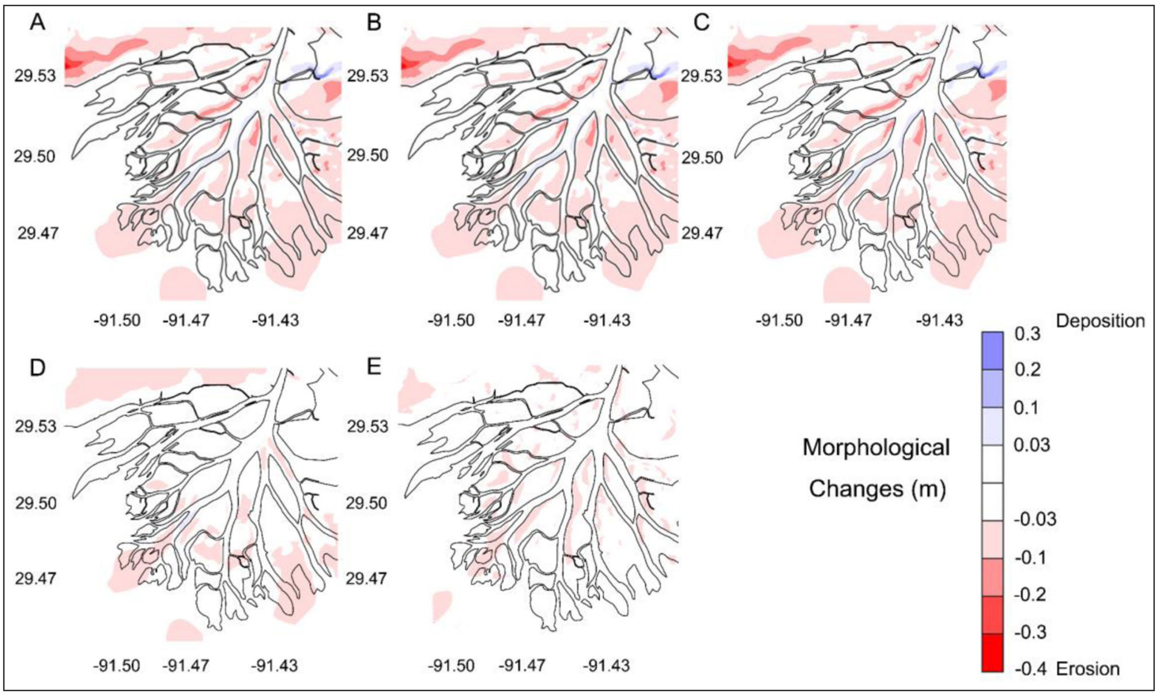

Figure 9: Simulated morphological changes of the WLD after hurricanes. A) base case; **B)** Wave-excluded scenario (EX1); **C)** Fluvial-excluded scenario (EX2); **D)** Vegetation-included scenario (EX3); **E)** Direct landfall scenario (EX4), which applies a directly-landfalling hurricane track (See also Table 2). The deltaic islands are dominated by erosion, and channels are dominated by deposition. Waves are the most critical factor contributing to net erosion on the WLD. The Fluvial inflow has a minor influence on deltaic morphological changes during Hurricane Rita. Aboveground vegetation dramatically decreases the erosion on vegetated areas. The shifts in wind patterns significantly change the pattern in morphological changes when a different hurricane track is applied. DOI: https://doi.org/10.1525/elementa.125.f9

4.2. Numerical experiments: influence of factors on morphological changes

4.2.1. Waves

Wave-induced bottom shear stress plays a significant role in sediment resuspension and transport during hurricanes (Stone et al., 1995; Wang et al., 2006). The impact of waves on morphological changes of the WLD during Hurricane Rita was evaluated by deactivating the wave module through numerical experiment (wave-excluded scenario: EX1). Results indicated that waves have a minor influence on the residual current pattern (**Figure 8A, 8B**), but significantly increase the amount of erosion (**Figure 10A**). When the wave module was deactivated, the areas where the erosional thickness of bed layer was larger than 0.2 m on islands decreased significantly and the maximum erosion reduced from 0.3 m to 0.2 m, compared to the base case (**Figure 9A, 9B**). The reduction of sediment erosion led to a lower suspended sediment concentration in the water column, and consequently deceased the amount of accretion in the channels when water flowed northwest from the islands towards the channels. The total amount of erosion in the WLD area decreased by 48%, and the total amount of deposition decreased by 8%. Consequently, the sediment balance in the WLD area changed from a net erosional system of 500,000 m^3 to a net depositional system of 100,000 m^3 (**Table 4**). The results from the numerical experiment demonstrated that waves played a dominant role in determining the sediment budget of WLD during Hurricane Rita.

4.2.2. Fluvial force

Similar as waves, the influence of fluvial forces on delta morphology during Hurricane Rita was evaluated through numerical experiment (fluvial-excluded scenario: EX2). Fluvial force has a minor influence on the hydrodynamics and the sediment transport pattern dur-

Table 4: Numerically simulation results of net sediment balance for the Wax Lake Delta. DOI: https://doi.org/10.1525/elementa.125.t4

Scenarios	Total change (m^3)	Total erosion (m^3)	Total accretion (m^3)
Hurricane Rita Base Case	–500,000	–1,400,000	900,000
Wave-excluded (EX1)[a]	100,000	–700,000	800,000
Fluvial-excluded (EX2)[a]	–500,000	–1,400,000	900,000
Vegetation-included (EX3)[a]	–300,000	–700,000	400,000
Direct landfall (EX4)[a]	–200,000	–700,000	500,000

[a]See Table 2 for a schematic overview of the scenarios.

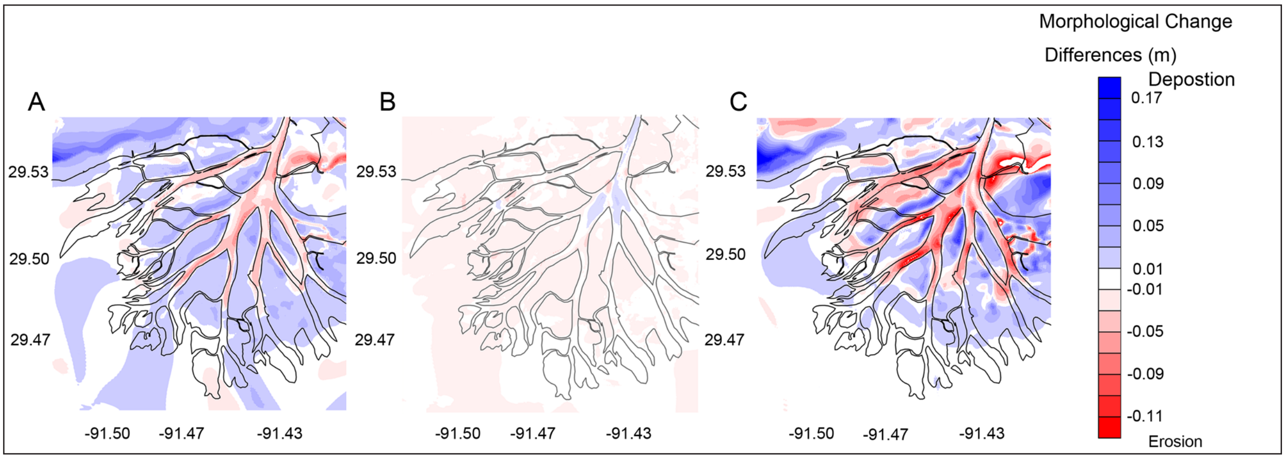

Figure 10: Differences in simulated sedimentation and erosion patterns. A) differences between (Wave-excluded scenario (EX1) – base case), showing that currents induced by winds and waves are very critical factors contributing to erosion on deltaic islands and erosion in channels; **B)** (Fluvial-excluded scenario (EX2) – base case), showing that fluvial input slightly decreases sediment deposition in channels and enhances the erosion on islands; **C)** (Vegetation-included scenario (EX4) – base case), showing aboveground vegetation dramatically decreases both the erosion on vegetated areas and the deposition in channels. DOI: https://doi.org/10.1525/elementa.125.f10

ing Hurricane Rita, although in general the WLD is a river-dominated system. The only significant difference between the fluvial-excluded scenario (EX2) and the base case was the direction of residual current in the channels, which changed from downstream to upstream when fluvial input was not included (**Figure 8A, 8C**). The fluvial-excluded scenario (EX2) slightly increased deposition in the channels and erosion on the islands compared to the base case (**Figure 10B**), with total amounts of erosion and deposition increasing by 2% and 1%, respectively. The influence of freshwater flow is therefore mainly concentrated in the channels, and its influence on morphological changes of the WLD is minor under hurricane conditions. It is therefore reasonable to conclude that fluvial forces play a minor role on determining the morphological changes of the deltaic systems during hurricane conditions, even for a fluvial-dominated deltaic system.

4.2.3. Aboveground vegetation

Temmerman et al. (2005) state that aboveground vegetation increases the flow resistance of wetland areas, leading to flow amplification and erosion over unvegetated areas and flow reduction and deposition over vegetated areas. Aboveground vegetation also effectively attenuates waves, reduces surge height and decreases the area that is inundated (Augustin et al., 2009; Wamsley et al., 2010; Pinsky et al., 2013; Möller et al., 2014; Narayan et al., 2016). It has been observed that both deposition and erosion occur due to vegetation during hurricane events (Yang et al., 2003; Fan et al., 2006; Howes et al., 2010). A numerical experiment (EX3) was set up to study the mechanism how vegetation influences the flow and sediment transport patterns during hurricanes by uniformly distributing of plants on the high-elevated islands of the WLD and surrounding wetlands (water depth < 0.2 m) (vegetation-included scenario: EX3). Comparing to the base case, the vegetation-included scenario (EX3) produced a similar pattern of high surges in the northwestern part of the WLD, caused by the wind field and elevated coastal wetlands in the north of the WLD (11A, 11B). However, the expansion of inundation area was reduced by vegetation, leading to an increased high surge area on the WLD, compared to the base case at the same time step (**Figure 11A, 11B**). High velocities were mostly restricted to deeper waters in the southwest of the islands (**Figure 11B**). The existence of vegetation in the model did not change the distribution pattern of wave heights, but decreased the magnitude of significant wave height by 0.1 m on the islands and increased its magnitude by a maximum of 0.23 m in the channels (**Figure 11C**) during the flood wave propagation. Simulations revealed that vegetation also significantly decreased the magnitude of residual current on islands from 0.3–0.6 m s^{-1} to less than 0.1 m s^{-1} on the eastern banks, but increased the magnitude of residual current in channels by a maximum of 0.16 m s^{-1} (**Figure 8A, 8E**). The changes in both waves and residual current pattern were in favor of decreasing sediment erosion on islands and deposition in channels. When vegetation was included in the model, the maximum erosion on the eastern side of islands decreased from 0.3 m to 0.1 m, and channel accretion decreased from 0.1–0.2 m to less than 0.05m (**Figure 9A, 9E**). As simulations results demonstrated, the total amount of sediment that was eroded and deposited in the WLD area decreased by 50% and 51%, respectively (**Table 4** and **Figure 10A, 10C**). Vegetation can significantly attenuate morphological changes on wetlands during hurricane events.

4.2.4. Hurricane track

Figure 4A demonstrates that coastal areas located on the right side of Hurricane Rita experience stronger hydrodynamics and more significant sediment transport, comparing to areas located on the left side of a hurricane. To study detailed morphological changes of the WLD correlated to the location of hurricane landfall, the direct landfall scenario (EX4) in which hurricane made landfall on the WLD

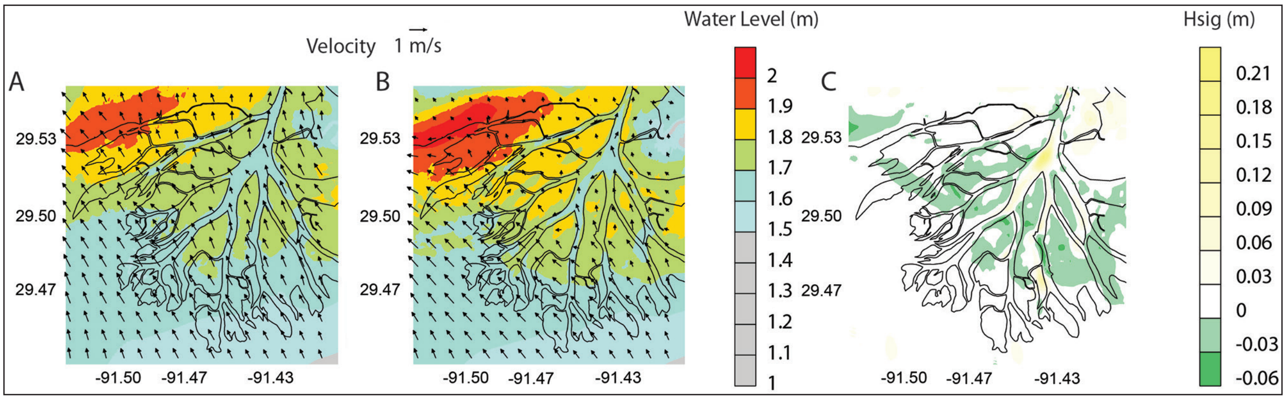

Figure 11: Tide-filtered storm surge and velocity distribution on the WLD. A) base case; and **B)** vegetation-included scenario (EX3), showing the vegetation reduces the progragation of flood waters, leading to a high water level on the high-elevated wetlands at the northwest of the WLD. **C)** shows the differences in significant wave heights between the base case and vegetation-included scenario (EX3), demonstrating that vegetation decreases wave heights on islands. DOI: https://doi.org/10.1525/elementa.125.f11

was set up to compare with results from the original settings of Hurricane Rita. The magnitude of winds was kept similar for the base case and the direct landfall scenario (EX4), with a maximum speed of 30 m s^{-1} on the WLD area. However, the major wind direction during the storm surge changed significantly from southeast to northwest (**Figure 7A, 7B**), leading to dramatic differences in flow pattern and consequently morphological changes. Compare to the base case, the direct landfall scenario (EX4) generated smaller storm surges both on the islands (1.1 m vs. 2.0 m) and in the channels (0.3 m vs. 1.6 m) because the study area was dominated by strong offshore-directed winds, leading to less water and sediment transport towards the inland (**Figures 7B, 8F** and **9F**). Changes in the wind and flow fields resulted in weaker residual currents in the direct landfall scenario (EX4) (0.1–0.4 m s^{-1} vs. 0.3–0.6 m s^{-1} in the base case), which directed towards the southeast with high values occurring on the western banks of the islands. Sediment transport was significantly weakened too, for both erosion and deposition. Erosion occurred on the western side of the delta with a maximum value of 0.05 m (vs. 0.3 m for the base case) and deposition occurred occasionally on the eastern side of the islands (maximum 0.1 m vs. more than 0.2 m for the base case) (**Figures 7B, 9A** and **9F**). The total amount of sediment erosion and deposition was reduced to 50% and 47% of the base case, respectively. This analysis demonstrates the importance of the trajectory of hurricane tracks on morphological changes of coastal wetlands. From morphology point of view, a hurricane that has its track 120 km on the west side of WLD caused more sediment erosion to the deltaic system comparing to a hurricane with the same setting that made direct landfall on the WLD.

4.3. Uncertainty analysis of the modeled morphological changes

Using the Dakota software, the uncertainties of sediment properties (grain size and critical shear stress) result in the modeled morphological changes to vary from 200,000 to 3,800,000 m^3 within 100 hours in the study area (1600 UTC, September 21th 370 to 1900 UTC, September 25th). Simulation results indicate that critical shear stress for clay erosion was the predominant factor determining the net sediment balance in the study area. Variations of critical shear stress from 0.50 N m^{-1} to 1 N m^{-1} led to a model uncertainty of 332,000 m^3 (standard deviation), with the mean value of 889,000 m^3. The areas having the most significant morphological changes also had the highest uncertainty (**Figures 9A** and **12A**) for the reason that variations in critical shear stress greatly influenced areas that encountered strong flow and wave shear stress. The uncertainty of the model over time was also explored by computing model uncertainty over time during Hurricane Rita, demonstrating that the model uncertainty varied significantly with changes in hydrodynamics. The uncertainty of the model was much higher under intensive coastal hydrodynamics, such as hurricanes, compared to calm weather periods (**Figure 7A** (see wind speeds) and **Figure 12B** (see the standard deviation)). The intensity of storm event plays a significant role in determining the model uncertainty, as shown through the significant rise when surge water started to flood the WLD area. On the other hand, the parameters grain size (silt) and critical shear stress for deposition were more important during calm weather periods, rather than during the intensive events. Our study demonstrates that uncertainties in input parameters significantly influence model results, and need to be evaluated for specific environmental settings. The spatial and temporal variations of model uncertainty require careful explanations of modeled results.

4.4. Morphological responses of deltas to hurricane events

The morphological responses of deltas to hurricanes vary depending on delta's geometric properties, receiving basin properties and hurricane properties (Fan et al., 2006; Turner et al., 2006; Barras, 2009; Tweel and Turner, 2012; Brownell, 2013). The WLD, which is predominantly

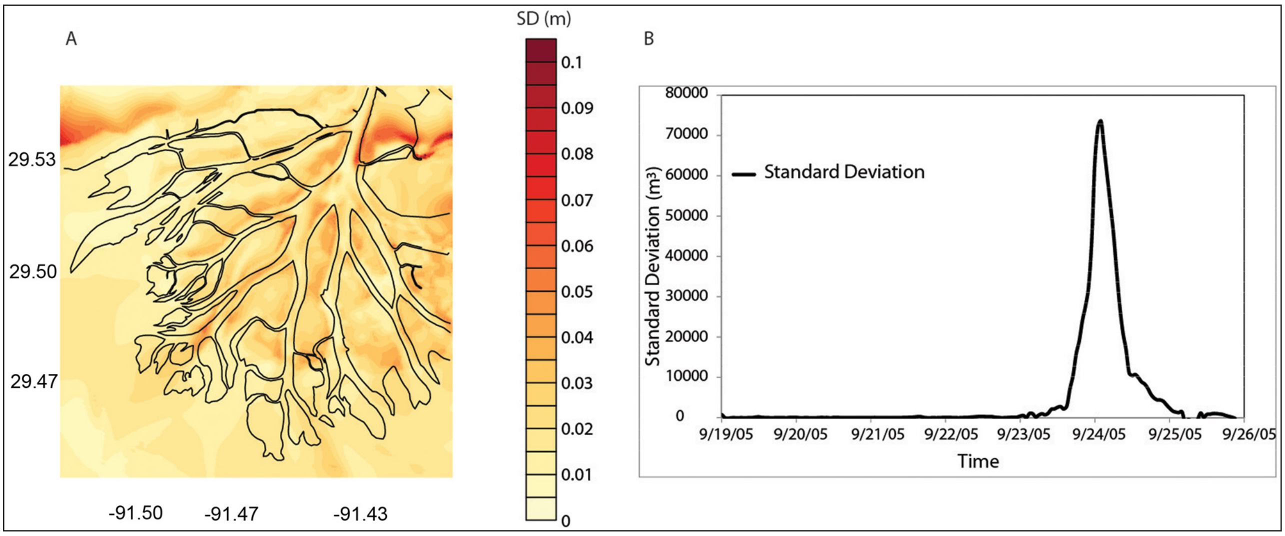

Figure 12: Simulated spatial uncertainty (A) and temporal uncertainty (B) for the WLD during Hurricane Rita. Fig. 12 shows that the areas with large morphological changes also have large uncertainty (Figures. 3, 8), and that model uncertainty is highly correlated to the magnitude of an event. DOI: https://doi.org/10.1525/elementa.125.f12

controlled by fluvial forces, and located in a shallow bay area protected by barrier islands, may response differently to hurricanes compared with other river-dominated deltas. For example, the Mississippi River Delta experiences wide spread land loss during hurricanes (Barras, 2009), attributed to the strong waves and surges caused by hurricanes, and the deep receiving basin that favors wave progragation. Due to high percentage of organic matter compared to the WLD system, the mature vegetation and solid soil layer of the Mississippi River Delta, may reduce the sediment movement during hurricane events. The large magnitude of deltaic area of the Mississippi River Delta could cause some unique features of morphological changes compared with the WLD during hurricanes. For instance, there could be a transition pattern from coast to inland wetlands, and the spatial varied vegetation types may cause different spatial morphological responses to hurricane events (Howes et al., 2010); while the morphological changes pattern would be more uniform on a small delta, such as the WLD. Most former studies are based on observed morphological changes of deltas due to hurricanes (Turner et al., 2006; Barras, 2009; Tweel and Turner, 2012), but the mechanism on how hurricanes cause these changes has been difficult to deduce.

The study of the WLD offers significant insights to explain the mechanism how river-dominated deltas respond to hurricanes. Our model results indicate that the area located on the right side of hurricane track experiences more significant morphological changes due to strong wind and wave forces, and barrier islands are subjected to erosion in support of previous observations (Coch, 1994; Weisberg and Zheng, 2006; Horton et al., 2009; Williams, 2009; Guidroz et al., 2006). Our results demonstrate the roles of waves, fluvial discharge, and vegetation on determining morphological changes of the WLD during Hurricane Rita, and provide important insights on how these factors would influence the delta's morphology during hurricane events.

5. Conclusions

The numerical simulation of the WLD during Hurricane Rita (2005) demonstrated that Hurricane Rita significantly influence the hydrodynamics and cause tremendous morphological changes on coastal wetlands in a relative short period. Hurricane Rita that made landfall 120 km west of the WLD as a Category 3 hurricane induced widely distributed erosion on the continental shelf and coastal areas when the hurricane system passed to proceed onshore. The areas located on the right side of hurricane track experienced more significant erosion than the areas located on the left side of hurricane track due to the wind-wave and surge fields. The recession of storm water from inland to offshore caused deposition in the inland wetlands and a band of deposition on the offshore side of barrier islands. As to the WLD area, the maximum storm surges was 2.5 m and maximum significant wave heights was 1.4 m on the delta, which was 3 and 5 times higher than that under normal conditions, respectively. Due to the dominant southeastern winds, the simulated residual currents directed towards the northwest, with maximum values occurring on the eastern banks of the islands (0.3–0.6 m s^{-1}). Combined with higher wave shear stresses in shallow areas, high erosion occurred on the eastern banks of the islands (0.3 m), accompanied by high deposition in the channels located on the west of these islands (0.1–0.2 m). This was caused by a significant decrease in shear stress moving from the islands to the channels during the northwestern flow. In total, 500,000 m^3 of sediment was removed from the WLD area during Hurricane Rita (base case).

Local topography and the flow field determined the main patterns of residual current and sediment transport, while waves significantly intensified erosion in the shallow areas, increasing the amount of erosion by 48%. Dense vegetation decreased the flow propagation as well as flow velocities on the island tops, leading to flow amplification in the channels. Both erosion on the islands and deposition in the channels was reduced by half when vegetation was included in the simulation. Fluvial force, although determining the local flow and morphology during normal condition, did not significantly change the sediment transport pattern during hurricane condition. The hurricane that made direct landfall on the WLD induced a smaller storm surge and less sediment erosion compared to Hurricane Rita that made landfall 120 km west of the WLD. The magnitude of residual currents decreased from 0.3–0.6 m s^{-1} to 0.1–0.3 m s^{-1} on the islands, and the amount of sediment that was eroded from the WLD area

Table 5: Summary of waves, fluvial forces, vegetation and hurricane track on determining hydrodynamics and morphodynamics of the deltaic systems during hurricane events based on the study of Hurricane Rita on the WLD system. DOI: https://doi.org/10.1525/elementa.125.t5

	Hydrodynamics	Morphodynamics
Waves	Cause wave-induced current; increase bottom shear stress	Significantly increase the amount of erosion on wetlands
Fluvial forces	Highly control flow dynamics in upstream channels; less influence on wetland areas	No significant changes on sediment transport pattern on wetlands
Aboveground Vegetation	Reduce inundation; increase drag and turbulence	Reduce both erosion and deposition on wetlands; significantly attenuate morphological changes
Hurricane track	Change wind field and local flow and wave dynamics	More morphological changes on the right side of hurricane track comparing to the direct landfall area

reduced to 56% of the original value. The influences of waves, fluvial forces, vegetation and hurricane track on hydrodynamics and morphodynamics of the WLD, all based on the study of Hurricane Rita are summarized in **Table 5**.

Sediment grain sizes, critical shear stress for clay deposition and erosion were selected for model uncertainty analysis. The results indicated that among the selected sediment properties, critical shear stress for clay erosion is the major factor contributing to high model uncertainty for the WLD during Hurricane Rita simulation. Model uncertainty under dramatic changes in hydrodynamic condition (like a hurricane event) is larger than that under comparatively calm weather conditions. Model uncertainty varies spatially i.e. areas on the island boundaries that encounter the strongest currents have the largest uncertainty, and also temporarily as the hydrodynamic conditions change.

Data Accessibility Statement
All data are provided in full in the results section of this paper.

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Competing interests
The authors have no competing interests to declare.

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- Contributed to conception and design: FX, JPMS, AJK
- Contributed to acquisition of data: FX, JPMS, JHA, EAM, AKK
- Contributed to analysis and interpretation of data: FX, JPMS, AJK
- Drafted and/or revised the article: FX, JPMS, AJK, JHA, EAM, AKK
- Approved the submitted version for publication: FX, JPMS, AJK, JHA, EAM, AKK

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