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A numerical study of vegetation impact on reducing storm surge by wetlands in a semi-enclosed estuary

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ABSTRACT

Coastal wetlands play a unique role in extreme hurricane events. The impact of wetlands on storm surge depends on multiple factors including vegetation, landscape, and storm characteristics. The Delft3D model, in which vegetation effects on flow and turbulence are explicitly incorporated, was applied to the semi-enclosed Breton Sound (BS) estuary in coastal Louisiana to investigate the wetland impact. Guided by extensive field observations, a series of numerical experiments were conducted based on variations of actual vegetation properties and storm parameters from Hurricane Isaac in 2012. Both the vegetation-induced maximum surge reduction (MSR) and maximum surge reduction rate (MSRR) increased with stem height and stem density, and were more sensitive to stem height. The MSR and MSRR decreased significantly with increasing wind intensity. The MSRR was the highest with a fast-moving weak storm. It was also found that the MSRR varied proportionally to the expression involving the maximum bulk velocity and surge over the area of interest, and was more dependent on the maximum bulk surge. Both MSR and MSRR appeared to increase when the area of interest decreased from the whole BS estuary to the upper estuary. Within the range of the numerical experiments, the maximum simulated MSR and MSRR over the upper estuary were 0.7 m and 37%, respectively.

1. Introduction

Coastal wetlands play a unique role in extreme events such as tropical storms and hurricanes. They act as a buffer to protect coastal communities by attenuating strong winds, waves and storm surges. On the other hand, they may enhance surges seaward of the wetlands as storm tides are blocked by them, especially at the beginning of a flooding process (Chen et al., 2012). In southern Louisiana, wetland restoration and protection in the Mississippi Delta become more challenging with the aftermath of Hurricanes Katrina and Rita in 2005 (Day et al., 2007; Stokstad, 2005). It is of importance to understand and predict the effect of vegetation during extreme events. This study focused on quantifying the role of coastal wetland vegetation in reducing storm surge under realistic field conditions. Often, a constant storm surge attenuation rate, such as 1 m per 14.5 km has been used to demonstrate the reduction of storm surge by coastal wetlands (USACE, 1963). However, such a constant attenuation rate is not accurate as pointed out by Resio and Westerink (2008). In fact, the impact of coastal wetlands on storm surge depends on many factors, including vegetation biomechanical properties (e.g., stem height, diameter, density, and coverage), landscape characteristics (e.g., land/water configuration, bathymetry, topography, local geometry, levee, channels and other features), and storm parameters (e.g., storm track, storm size, duration, forward speed, and wind intensity) as well as the interaction of these factors (Chen et al., 2008; Rego and Li, 2009; Resio and Westerink, 2008; Sheng et al., 2012; Wamsley et al., 2010; Zhao and Chen, 2013).

Numerical models can be an effective tool for examining the impact of coastal wetlands on storm surge under complicated configurations of vegetation, landscape, and storm characteristics. There are numerous models that have been applied to storm surge modeling, including the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) (Jelesnianski et al., 1992) and the ADvanced CIRCulation model (ADCIRC) (Dietrich et al., 2011; Luettich et al., 1992), and general process-based hydrodynamic and transport models such as the Finite-Volume Community Ocean Model (FVCOM) (Chen et al., 2003; Rego and Li, 2010), the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005; Wang et al., 2008), the Curvilinear-grid Hydrodynamics three-dimensional model (CH3D) (Sheng et al., 2010), DHI Software (Madsen and Jakobsen, 2004; Warren and Bach, 1992), and Delft3D by Deltares (Hu et al., 2009; Lesser et al., 2004). Vegetation effects are commonly taken into account in the bottom friction term in operational models. For instance, the Manning's n friction coefficient can be assigned according to the specific land cover class, e.g., provided by the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD). With this representation, Wamsley et al. (2010) studied the

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potential of wetlands in southern Louisiana in reducing storm surge and waves under two landscape configurations through a few representative hurricanes. Liu et al. (2013) studied the effects of mangroves on reducing storm surge and flooding in southern Florida by changing hurricane characteristics. In this method, the drag of vegetation stems acting on the flow is treated as a bottom friction and may cause an overestimation of bottom shear stress that is used to suspend sediments from bed in the modeling of sediment transport. By contrast, another method treats vegetation directly as a series of rigid cylindrical structures, which adds extra terms of drag force in the momentum equations and turbulence equations, such as those implemented in CH3D (Sheng et al., 2012) and Delft3D (Temmerman et al., 2005). This method is suitable for simulating three-dimensional flows with vertical variations in vegetation characteristics. Temmerman et al. (2007) took into account the growth and mortality of vegetation by coupling the Delft3D model with an external plant routine, which is applicable to long-term simulations of morphological change.

Few studies have been carried out to investigate the impact of vegetation on storm surge under combined realistic conditions of vegetation, landscape, and storm properties. Most of the existing studies have focused on evaluating storm surges with varying storm parameters (e.g., Nielsen, 2009; Rego and Li, 2009). Due to multiple factors influencing the effect of vegetation on storm surge and their interaction, more comprehensive numerical experiments are needed to simultaneously account for the influences of various vegetation, landscape, and storm features. Conclusions from studies using an idealized domain with simple coverage of vegetation (e.g., Sheng et al., 2012) may not be applicable to real wetlands where landscape characteristics, such as land and water configuration, topography and bathymetry, levees, and channel systems, could vary even at a local scale. In this study, we applied the Delft3D model, in which vegetation effects on flow and turbulence are explicitly taken into account, to the Breton Sound (BS) estuary in southeastern Louisiana. We investigated the impact of vegetation on storm surge by examining the effects of changing stem height, density, wind intensity and storm forward speed through a series of numerical experiments based on extensive field observations collected during Hurricane Isaac in 2012.

2. Study area and Hurricane Isaac (2012)

The BS estuary is a semi-enclosed estuary in southeastern Louisiana. As shown in Fig. 1, it is bounded on the south and on the west by the levees of the Mississippi River, and on the north in part by the ridges of the Mississippi River Gulf Outlet that was closed in 2009. It is open to the Gulf of Mexico on the southeast. The estuary encompasses approximately 2740 km^2, of which 750 km^2 are wetlands. Bathymetries are very complicated with numerous bays, lakes, bayous, canals and marshes. The BS estuary is economically important because it is the home to several of the largest public oyster seed grounds and private leases for the Gulf coast (LDWF, 2012; Soniat et al., 2013). Storm surges could cause salt water intrusion and result in increased estuarine salinity, thus affecting oyster growth and production. The major vegetation types in the estuary are fresh, intermediate, brackish, and saline marshes (Sasser et al., 2008; Visser et al., 2003). Their distributions based on a coast-wide aerial survey in 2007 (Sasser et al., 2008) are shown in Fig. 1. Dominant species are *Panicum hemitomon*, *Polygonum punctatum Elliot*, and *Sagittaria lancifolia* for fresh marsh; *S. lancifolia*, *Eleocharis albida*,

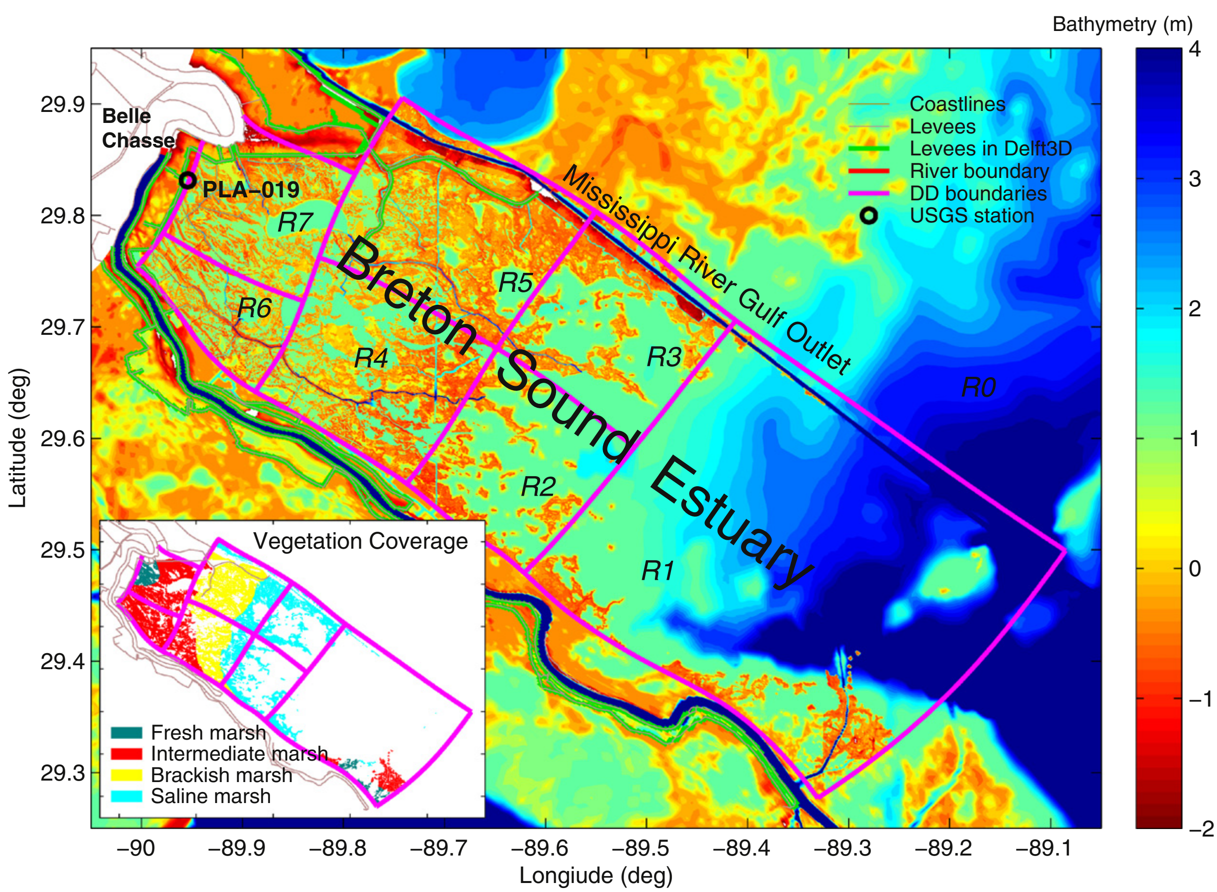

Fig. 1. Bathymetry and vegetation coverage (subfigure) in the Breton Sound estuary. R0–R7 denote eight sub-domains in the regional domain, respectively, which are connected by domain-decomposition (DD) boundaries (pink lines). See legends for other symbols.

and *Spartina patens* for intermediate and brackish marshes; and *Spartina alterniflora* and *Juncus roemerianus* for saline marsh, respectively (Sasser et al., 2008; Visser et al., 2003). The biophysical features of these vegetation types used in this study are listed in Table 1.

Hurricane Isaac originated from a tropical wave that moved off the coast of Africa on 16 August, 2012, and entered the southeastern Gulf of Mexico early on 27 August. It gradually strengthened while moving across the Gulf of Mexico and became a Category I hurricane when located 140 km southeast of the mouth of the Mississippi River around 1200 UTC 28 August. It slowed down considerably to about 10 km/h while it approached the coast of Louisiana with winds of 130 km/h and lowest pressure of 965 mb, which prolonged the strong winds, dangerous storm surge, and heavy rains along the northern Gulf coast. According to the measurements by the USGS, the storm surge at the upper BS estuary reached over 4 m (see http://ga.water.usgs.gov/flood/hurricane/isaac/sites/charts/SSS-LA-PLA-019WL.html). Isaac made two landfalls along the coast of Louisiana, the first one at Southwest Pass on the mouth of the Mississippi River around 0000 UTC 29 August and the second one at just west of Port Fourchon around 0800 UTC 29 August. Isaac then gradually weakened and dissipated inland. Refer to the National Hurricane Center's report on Isaac (Berg, 2013) for details.

3. Methods

An asymmetric parametric hurricane wind model (Hu et al., 2012a, 2012b), which is integrated with background winds, was employed to generate surface wind fields. The hurricane wind model has the ability to maintain the consistency of the input and output (e.g., maximum wind speeds and wind radii for 34-, 50- and 64-knot thresholds in each quadrant). Changing the hurricane parameters (e.g., forward speed and wind intensity) in our numerical experiments is straightforward using this wind model. We can adjust the interval of hurricane best track data to get different forward speeds, and scale inputs of maximum wind speed and specified wind speeds to change wind intensity while keeping its wind structure.

We applied the Delft3D model, which has been used widely for studies of coastal processes (e.g., Dykes et al., 2003; Hu et al., 2009), to examine the effect of coastal vegetation on reducing storm surge. Nested computational domains were designed and set up in Fig. 2. The Gulf-scale domain, which covered the Gulf of Mexico, Caribbean Sea and part of North Atlantic Ocean, provided boundary conditions (water levels and currents) for the regional domain. These two boundary conditions were applied to the major open boundaries at the southeast and southwest, respectively, in the nested domain to avoid stability issues that the use of the same boundary type may induce. In order to resolve the complex bathymetry/topography in the BS estuary, a domain decomposition technique in Delft3D, which allows local refinement, was adopted in the nested domain. There were eight sub-domains (R0 to R7) in the regional domain (Figs. 1 and 2b). They were connected by internal domain decomposition (DD) boundaries with the capability of two-way communication of water level and current. Our area of interest, the BS estuary, was covered by R1 to R7 with ~50 m grid resolution. The highest resolution reached 20 m in the upper BS (R6 and R7). This high grid resolution ensured the representation of small channels/bayous in the model domain. The Mississippi River levee system was represented by the sub-grid structure of local weirs in Delft3D. From a tidal constituent database (Mukai et al., 2002), seven dominant constituents (O_1, K_1, Q_1, M_2, N_2, S_2 and K_2) were considered to determine tidal levels at the open-sea boundary in the Gulf-scale domain. Observed Mississippi River discharges at Belle Chasse from the USGS (http://waterdata.usgs.gov/usa/nwis/uv?07374525) were added in sub-domain R0 (see Fig. 1). In addition, two Neumann boundaries were set to let storm surge freely flow out of the regional domain (see Fig. 2b). Vertically, seven sigma layers, of which thicknesses were 5, 10, 20, 30, 20, 10 and 5% of total water depth, respectively, were selected for 3D modeling with high resolution both at the bottom and at the surface. We obtained the bathymetric data and Manning's n coefficients for bottom friction from the Louisiana Coastal Protection and Restoration Authority (CPRA). Topography in the BS estuary was updated based on the 5 m-resolution National Elevation Dataset in 2011 from the USGS (http://ned.usgs.gov/). Note that waves were not coupled with the storm surge model in this study because numerical tests and wave measurements showed that the gradient of radiation stresses was small in wetlands and wave setup was less than 5% of the storm surge in the BS estuary during Hurricane Isaac.

The effect of vegetation on hydrodynamics in areas other than the BS estuary was represented by an increased Manning's coefficient in the quadratic bottom friction term. In the BS area (R1–R7), Manning's n coefficient was set to 0.025 to represent the friction of an unvegetated bottom, and the vegetation-induced drag was explicitly taken into account by the 3D influence of rigid cylindrical structures on drag and turbulence. Based on the work of Uittenbogaard (2003), three extra terms were added into the model: a source term of drag force that represents the influence of vegetation in the momentum equations, a source term of turbulent kinetic energy (k), and a source term of turbulent energy dissipation (ε), which represent the influence of vegetation on turbulences in the $k-\varepsilon$ equations (e.g., Rodi, 1993), respectively. Detailed expressions of those terms can be found in Uittenbogaard (2003) and Temmerman et al. (2005). This vegetation module has been validated extensively against laboratory flume experiments (e.g., Baptist, 2003; Borsje et al., 2009), and against field data on flow patterns in salt marshes (Temmerman et al., 2005), and intertidal flats and sandy sites (Bouma et al., 2007). The main limitation of this module is the assumption that vegetation is rigid. In vegetated areas, some vegetation types, such as marsh plants, will substantially bend due to the force of the flow or high wind. Zhao and Chen (2013) determined the deflected vegetation stem height by iteration for modeling the attenuation of storm surge in wetlands. Similar to other studies (Kuiper, 2010; Monden, 2010), the flexibility of vegetation is taken into account through reducing the stem height, in this study, by 60% according to the values in Table 1. The sensitivity of stem height will be discussed in the next section.

We set up two groups of numerical experiments: vegetation-varying and hurricane-varying, to study the impact of vegetation on storm surge. In the vegetation-varying experiments, stem density and stem height were changed from 50% of their values in the base case to 200% with an interval of 25%. Note that the vegetation module uses stem height and the product of stem density and stem diameter, and therefore the variation of stem density is equivalent to the same relative variation of stem diameter in this study if the density is kept unchanged. In the hurricane-varying experiments, a series of "Isaac-like" hurricanes were generated through changing the wind intensity (maximum wind speed and specified wind speed) and forward speed. The wind intensity was changed from 75% of the values in the base case to 175% with an interval of 25%, that is, from a tropical storm to a Category 4 Hurricane according to the Saffir–Simpson Hurricane Wind Scale. By setting the time interval to 8, 6, 5 and 4 h, respectively, the forward speed was

Table 1
The biophysical characteristics of various vegetation types.

Vegetation type	Average stem height (m)	Average stem diameter (mm)[e]	Average stem density (m^{-2})[e]
Fresh marsh	0.76[a]	5.59	578
Intermediate marsh	0.50[b]	2.03	2095
Brackish marsh	0.50[c]	1.50	740
Saline marsh	0.40[d]	3.67	341

[a] United States Department of Agriculture (USDA) natural Resources Conservation Services (NRCS) herbaceous plant online database (http://plants.usda.gov/java/factSheet).
[b] No data for Intermediate marsh, assumed the same as Brackish marsh.
[c] Randall and Foote (2005).
[d] McKee et al. (2006).
[e] Visser (2007).

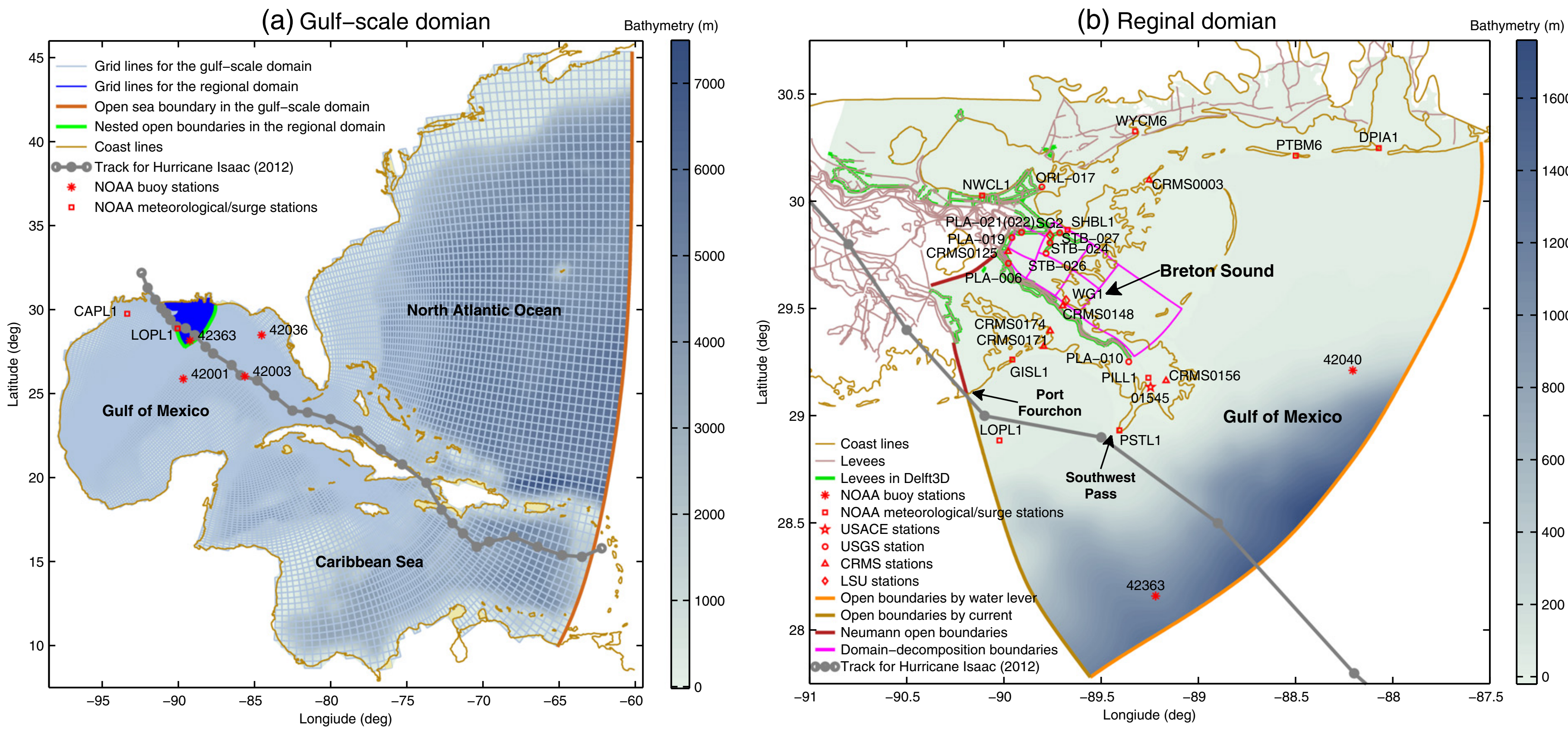

Fig. 2. Model settings in (a) Gulf-scale domain and (b) Regional domain, and observed stations from NOAA, USGS, USACE, CRMS and LSU. See legends for details. Note that in (b), USGS stations PLA-021 and PLA-022 are located very close to each other, but on different sides of a levee, that is, the east (open) side and the west (enclosed) side, respectively.

changed from 75% of the values in the base case to 150%, that is, about from 2.5 m/s to 5.0 m/s near the Louisiana coast.

In order to quantify the vegetation impact on storm surge, we introduce the maximum surge reduction (MSR) and the corresponding maximum surge reduction rate (MSRR) in terms of water volume for a specific area (i.e., area of interest or AOI) during an event, as follows:

$$S_{nv,max} = \frac{\left(\iint_{AOI} L_{nv}(x,y,t)dxdy\right)_{max} - \iint_{AOI} L_{nv}(x,y,0)dxdy}{\iint_{AOI} dxdy} \quad (1)$$

$$S_{v,max} = \frac{\left(\iint_{AOI} L_{v}(x,y,t)dxdy\right)_{max} - \iint_{AOI} L_{v}(x,y,0)dxdy}{\iint_{AOI} dxdy} \quad (2)$$

$$\text{MSR} = S_{nv,max} - S_{v,max} \quad (3)$$

$$\text{MSRR} = \frac{\text{MSR}}{S_{nv,max}} = \frac{S_{nv,max} - S_{v,max}}{S_{nv,max}} \quad (4)$$

where $L(x,y,t)$ is the water level for a specific location and time, S is the bulk surge for the AOI, the subscripts nv and v indicate the absence and the presence of vegetation, respectively, and the subscript max denotes the maximum value of water volume or bulk surge over the whole event. This kind of definition is similar to that used in Sheng et al. (2012). Both are area-based instead of single-location-based, which avoids the spiky spatial variation in the definition for a single location.

4. Model validation

Within our study region, there exist permanent meteorological and tide stations from the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.S. Army Corps of Engineers (USACE) and the Louisiana Coastwide Reference Monitoring System (CRMS, http://lacoast.gov/crms2/). In addition, the USGS deployed a number of temporary surge gages for Hurricane Isaac. Our research team at Louisiana State University (LSU) deployed several wave and surge gages in BS as well prior to Hurricane Isaac landfall. In this study, multiple sources of observed data (see Fig. 2 for the locations of observed stations) were used for Hurricane Isaac's wind and surge validation.

Comparisons of wind speed/wind direction with measurements at 15 stations are shown in Fig. 3. It is seen that the modeled winds are in good agreement with the observed data. At Buoy 42040, wind model captured the highest wind speed, near 30 m/s. At Stations LOPL1 and PSTL1, the significant changes of wind speed were reproduced very well when Hurricane Isaac passed by closely. Statistically, the root-mean-square error (RMSE) of wind speed at all stations is 2.8 m/s with a correlation coefficient (r) of 0.8694.

Water level comparisons are shown in Fig. 4. It can be seen from both measurements and model results that Hurricane Isaac induced over 4 m of storm surge at the upper BS estuary (see Stations PLA-019, PLA-021 and PLA-022). Model results present the different retreating patterns of surge processes at Stations PLA-021 and PLA-022 which are located very close to each other but on different sides of the levee. The RMSE of water levels at 20 stations is 0.3 m with $r = 0.9528$. In all, model results agree well with the field observations, especially at stations in the BS.

5. Results of numerical experiments and discussion

Fig. 5a shows the distribution of maximum water levels in the BS induced by Hurricane Isaac. Hurricane Isaac passed through to the south and southwest of the BS area, and maintained southeasterly and easterly winds blowing over the BS for about one day, which forced water from the Gulf of Mexico continuously into this area. The semi-closed geometry and man-made levees sufficiently kept and blocked water from flowing over to the west of the Mississippi River. There were two regions with high storm surges. One was located at the middle estuary. At that time, easterly winds pushed water into this region. The southwest side of the BS was blocked by the levees. Simultaneously, wetlands prevented surge flooding further upstream. As time went on, the wind direction changed to southeasterly. The wetlands in the upper BS were finally flooded, and the surge in the uppermost estuary, blocked by levees, kept rising up to more than 4 m (see Figs. 4 and 5a).

In order to understand how multiple factors would affect storm surge in the BS, we conducted a few tests prior to the detailed investigation of vegetation impacts. Fig. 5b shows the time series of water level at Station PLA-019 for field measurements and six modeled scenarios. The modeled scenarios were base case, cases with no vegetation, slow moving (by 25% comparing to base case), fast moving (by 20%), weak intensity (by 25%) and strong intensity (by 25%), Isaac-like hurricanes, respectively. We expected higher storm surge in BS with the conditions of: 1) no vegetation and/or 2) strong wind intensity and/or 3) a slow-moving hurricane; and lower storm surge with the conditions of 1) weak wind intensity and/or 2) a fast-moving hurricane. Simulations showed that not only the wind intensity, but also the duration of wind forcing, contributed to the final surge height, especially in a semi-closed estuary. Among those factors, the wind intensity was the most determinative one that controls the maximum surge height in the upper BS. The effect of wind intensity in this study was consistent with numerical experiment results of Rego and Li (2009) based on Hurricane Rita (2005) in southwestern Louisiana.

The distributions of the maximum surge (MS) with vegetation ($S_{v,max}$), MSR and MSRR by numerical experiments for the upper BS (R6–R7) are shown in Fig. 6. In the vegetation-varying experiments, the MS without vegetation ($S_{nv,max}$) is invariable, about 3.7 m (Fig. 6a–c). It is clear that the MS with vegetation decreases with higher stem heights and densities, and the resultant MSR (or MSRR) has an inverse distribution. The change of MS or MSR with different vegetation parameters is about 0.45 m, while the change of MSRR is about 12.4% from 6.4% to 18.8%. In the hurricane-varying experiments, the MS increases with higher wind intensities and lower forward speeds (Fig. 6d). When the relative forward speed is fixed to 1, the MS significantly increases from less than 1.5 m to more than 7.5 m as the relative wind intensity varies from 0.75 to 1.75. When the relative wind intensity is fixed to 1, the MS decreases from 3.8 m to 2.4 m as the relative forward speed varies from 0.75 to 1.5. A faster forward speed means a shorter duration of a hurricane that induces a lower storm surge in the BS. The distributions of MSR and MSRR show that the effect of height-limited vegetation is more significant with a smaller inundation depth (Fig. 6e and f). For instance, when the MS is less than 3 m, the MSR and MSRR are larger than 0.4 m and 12%, respectively. The MSRR reaches its maximum value (38%) when the MS is extremely low (less than 1 m), while the absolute surge reduction does not reach its maximum simultaneously. When wind intensity is increased, storm surge increases quickly, which dramatically weakens the effect of vegetation, to less than 0.1 m and 2% in regard to MSR and MSRR, respectively. Comparing the vegetation-varying cases and the hurricane-varying cases, it can be seen that the range of MS by changing hurricane winds is dramatically wider than that by changing vegetation. In other words, hurricane parameters control the maximum surge. Regarding vegetation effects on reducing storm surge, the extreme value of MSR in the vegetation-varying cases is larger than that in the hurricane-varying cases, but with the MSRR the opposite occurs.

Our result of the trend of MSRR changing with the forward speed of a hurricane is consistent with the findings of Sheng et al. (2012) and Liu et al. (2013). With regard to the MSRR changing with the wind intensity, our result is also consistent with Liu et al. (2013), but

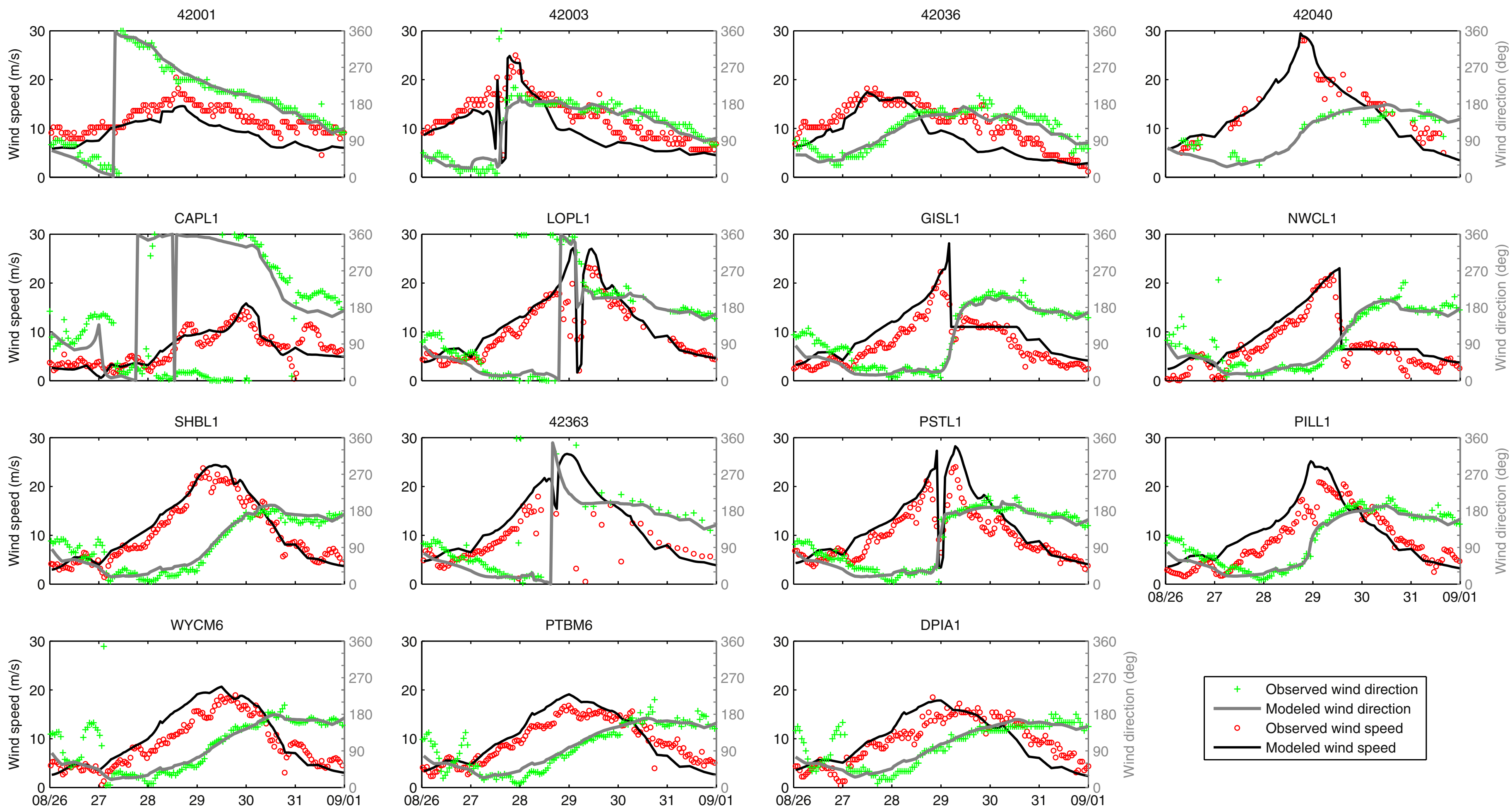

Fig. 3. Comparisons of wind speed and wind direction with observed data at 15 stations during Hurricane Isaac. Pluses, circles, light solid lines and solid lines denote observed wind direction, observed wind speed, modeled wind direction and modeled wind speed, respectively.

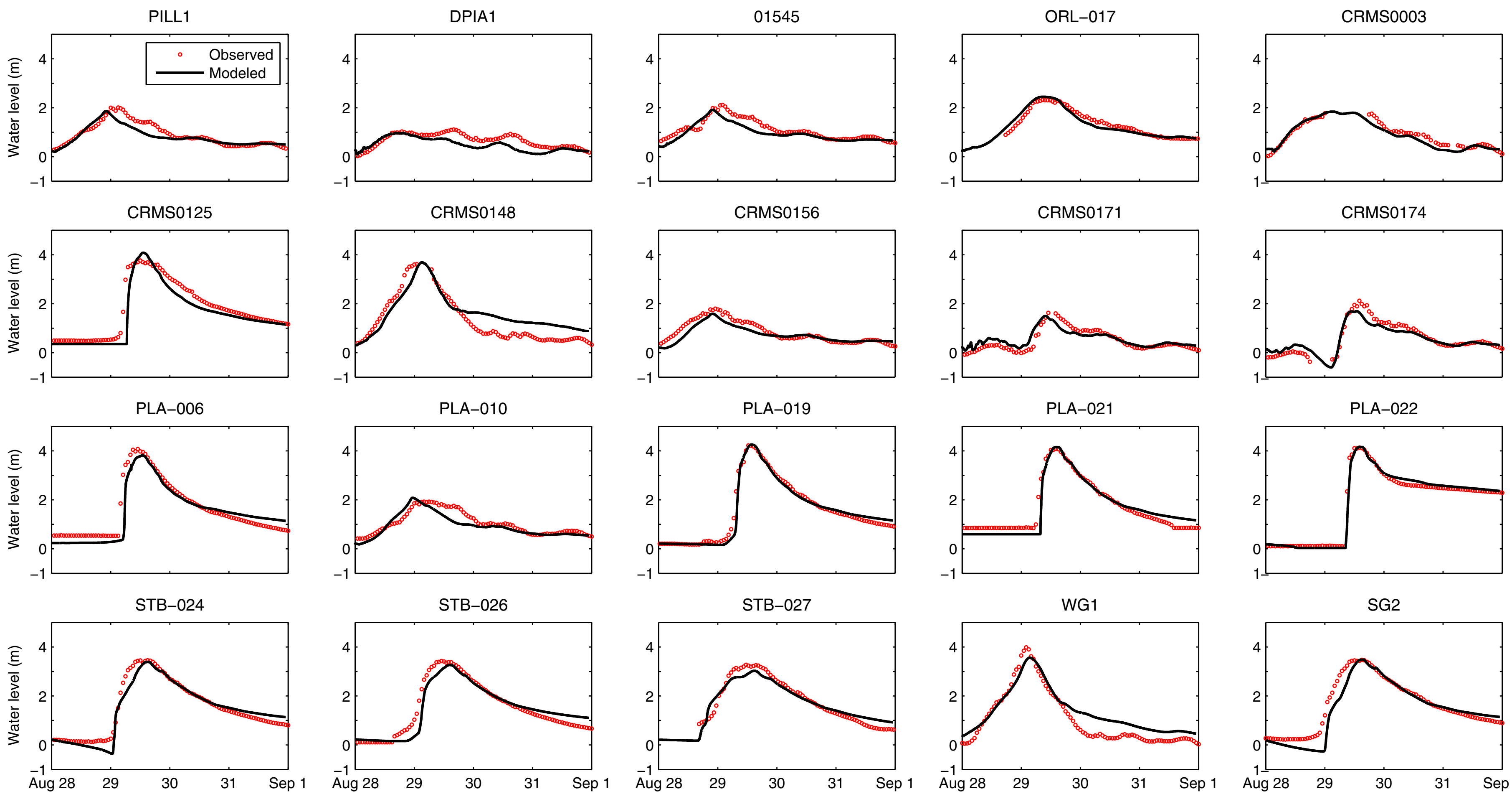

Fig. 4. Comparison of water level (m, NAVD88) with observed data at 20 stations during Hurricane Isaac. Circles and solid lines denote observed water level and modeled water level, respectively.

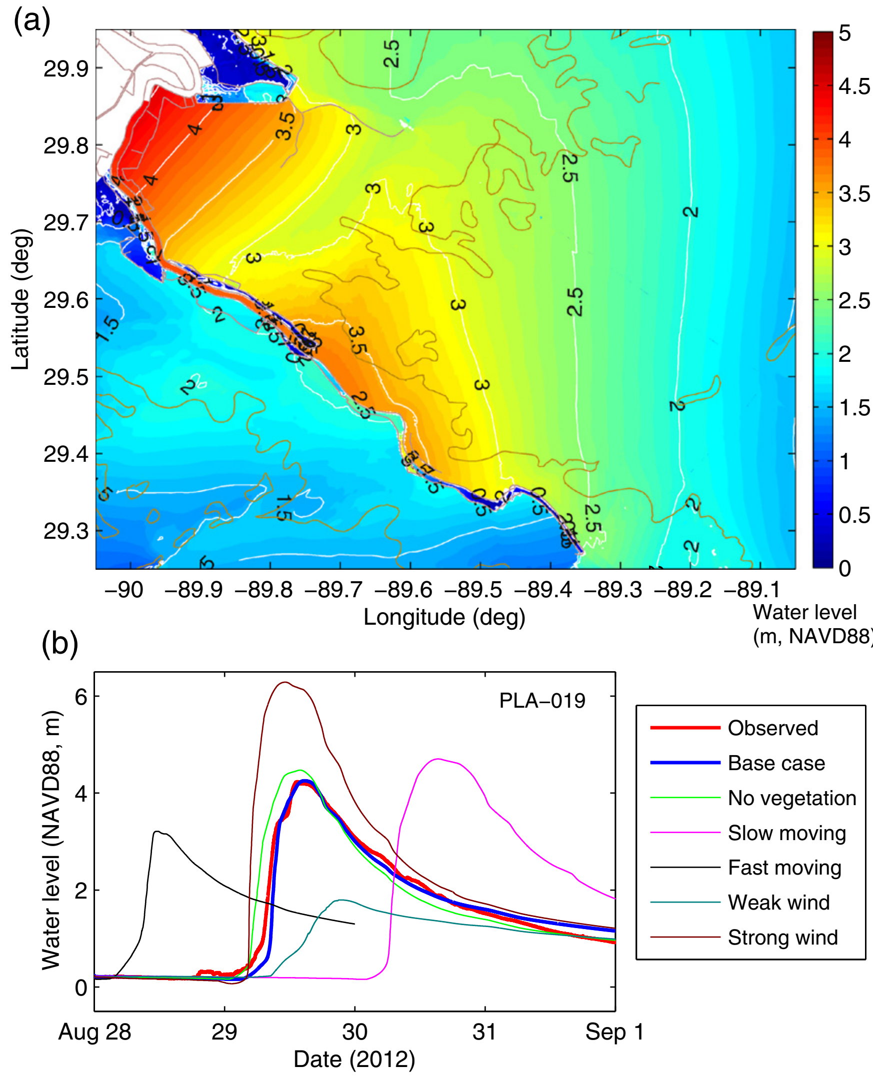

Fig. 5. (a) Distribution of maximum water levels (m, NAVD88) during Hurricane Isaac (2012) in the Breton Sound estuary. (b) Simulated time series of water levels (m, NAVD88) at USGS Station PLA-019 for six different cases (see legends for details) and field measurements (thick red line).

contradicts Sheng et al. (2012). There are two major differences between our study and Sheng et al.'s (2012). Our study area is a real semi-enclosed estuary with distributions of four marsh types rather than their idealized, mild-slope, open coast with a strip distribution of one *Spartina*-like marsh type. Additionally, in calculations of MSRR in this study or Vegetation Dissipation Potential in Sheng et al. (2012), our integral area is fixed, while they used 'landward area', which varies with the surge height.

It is generally acknowledged that the impact of vegetation on storm surge reduction tends to be greater under the conditions of higher flow velocity and lower water depth. By using the results in the hurricane-varying experiments, we further examined the relationship between MSRR and maximum bulk velocity ($V_{v,max}$, defined as the square root of total kinematic energy divided by half of the total mass) and maximum bulk surge (i.e., $S_{v,max}$, defined as total potential energy divided by half of the product of total mass and gravitational acceleration) of the AOI with vegetation. The following relationship was found:

$$\text{MSRR} \propto \frac{V_{v,max}^2}{S_{v,max}^{\alpha}} \tag{5}$$

where the power α indicates the contribution of $S_{v,max}$ to MSRR. The optimized α value is achieved when the correlation coefficient (r) is closest to 1 (exact linear relationship). As shown in Fig. 7, we obtained $\alpha = 4$ with $r = 0.9762$. The high value of r verifies the proportionality of Eq. (5). A higher order of $S_{v,max}$ than that of $V_{v,max}$ (i.e., $\alpha > 2$) in Eq. (5) implies that the maximum surge height for the AOI is a significant indicator of MSRR. For instance, an increase in the wind intensity causes an increased surge height (see Fig. 6d), and results in a decreased MSRR (see Fig. 6f); on the other hand, a speedup of a hurricane causes a decreased surge height, and results in an increased MSRR. Note that Eq. (5) is a general expression. The specific linear relationship changes with different AOIs, estuaries and landscapes.

Vegetation properties were shown to affect MSRR substantially; therefore, Eq. (5) was applied to the vegetation-varying experiments as well. An extra coefficient determined by the relative stem density (Rd) and relative stem height (Rh) was added into the right side of Eq. (5). After optimization with r, we obtained the expression of $Rh \bullet Rd^{0.15}$ for the extra coefficient, along with $r = 0.9834$ (Fig. 7). The smaller power of 0.15 for Rd, compared to the power of 1 for Rh, suggests that MSRR is much more sensitive to the change of stem height than that of stem density. In other words, the variation of stem density is less important to the surge reduction rate. This is consistent with the experiment of Leonard and Croft (2006) in which *S. alterniflora* was used to examine the effect of standing biomass on flow velocity and turbulence. Leonard and Croft (2006) found that the mean velocity within

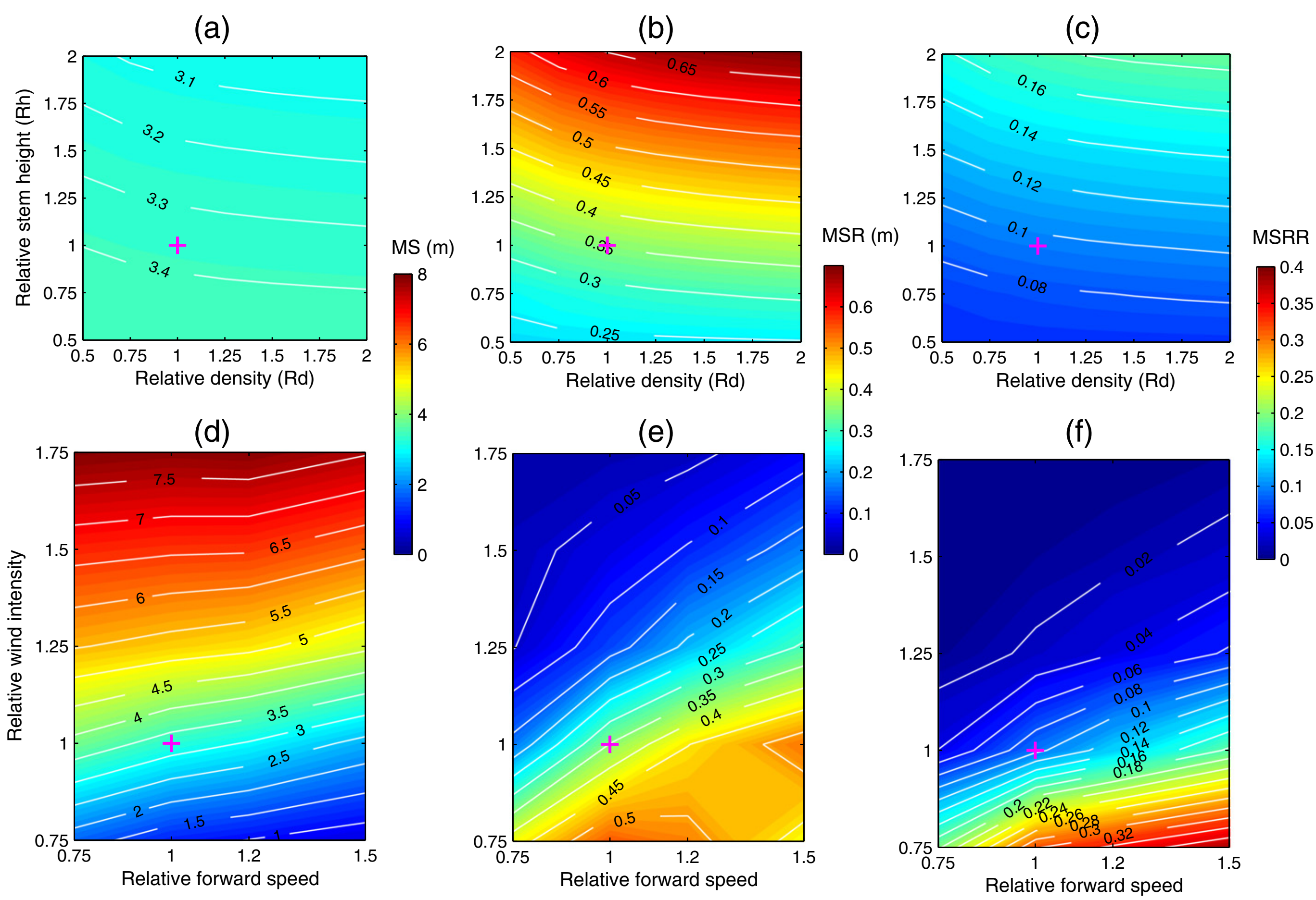

Fig. 6. Distributions of the maximum surge (MS), vegetation-induced maximum surge reduction (MSR) and maximum surge reduction rate (MSRR) for the upper Breton Sound (R6–R7) in numerical experiments. (a), (b) and (c) show distributions of MS, MSR and MSRR, respectively, for vegetation varying cases. (d), (e) and (f) show distributions of MS, MSR and MSRR, respectively, for hurricane varying cases. Pink plus symbol denotes base case.

the vegetated canopy was reduced to approximately 50%, and this ratio changed little when 1/3 or 2/3 of original biomass was removed.

Previous discussion focused on the vegetation impact on the storm surge reduction rate for the upper BS estuary. The vegetation effects in other regions of BS (Fig. 8) were reflected by the ranges of MSR and MSRR for four areal extents within the BS estuary. Because the wetland vegetation was mainly distributed in the middle and upper BS, both MSR and MSRR for the whole estuary (R1–R7) were very small (less than 0.2 m and 10%, respectively). Among all cases, the maximum surge reduction was 0.7 m in the upper BS estuary (R6–R7) for the vegetation-varying cases, while the maximum reduction rate was 38%

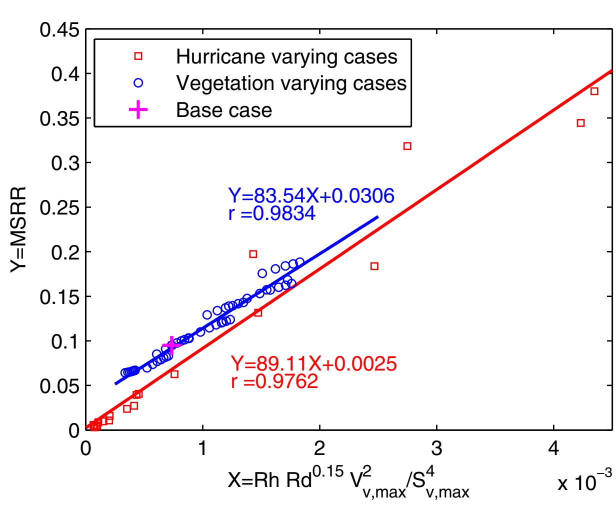

Fig. 7. Proportional relationships between MSRR and the expression by relative stem height (Rh), relative stem density (Rd), maximum bulk velocity ($V_{v,\,max}$) and bulk surge ($S_{v,\,max}$) with vegetation for the upper Breton Sound in numerical experiments (see legends for details).

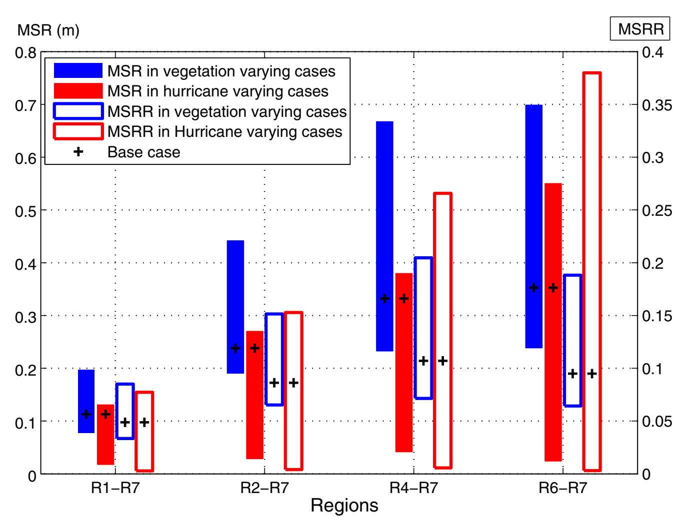

Fig. 8. Ranges of MSR (m) and MSRR for four different regions of the Breton Sound estuary (i.e., R1–R7, R2–R7, R4–R7 and R6–R7) in numerical experiments (see legends for details).

for the hurricane-varying cases in the same region. There is a trend that the maximum values of both MSR and MSRR increase as the AOI decreases and moves toward the upper estuary, except that in the vegetation-varying cases, where the maximum MSRR in R4–R7 is slightly greater than that in R6–R7. Comparing between two groups, the maximum value of MSRR in the hurricane-varying experiments is larger than that in the vegetation-varying experiments for most regions except R1–R7. On the contrary, the maximum value of MSR in the vegetation-varying experiments is larger than that in the hurricane-varying experiments for all regions, which shows the importance of vegetation parameters on absolute surge reduction and implies that wetland restoration in the lower BS estuary could enhance wetland's role in protecting a coastal community from storm surge.

6. Summary and conclusions

The impact of vegetation on reducing storm surge by wetlands was investigated in the BS estuary by applying a 3D hydrodynamic model where vegetation was represented by cylindrical structures. After the validation of storm surge generated by Hurricane Isaac (2012), a series of numerical experiments were carried out based on variations of realistic vegetation properties and hurricane parameters within four areal extents in the BS estuary. Effects of vegetation stem height, stem density, wind intensity and forward speed of a hurricane were studied. All four factors affect the maximum storm surge, vegetation-induced maximum surge reduction and reduction rate in the area of interest. In the vegetation-varying cases for the upper BS, the maximum surge changed slightly (less than 0.5 m) with different vegetation parameters; the vegetation-induced reduction and reduction rate increased with the stem height and stem density, and were more sensitive to the stem height. In the hurricane-varying cases for the upper BS, the maximum surge changed significantly from less than 1 m to more than 7.5 m with different hurricane parameters. The vegetation-induced reduction and reduction rate decreased remarkably with an increase in the wind intensity; and the reduction rate increased with an increase in the forward speed or a decrease in the wind intensity. It was found that the vegetation-induced maximum surge reduction rate varied proportionally to the expression involving the maximum bulk velocity and surge over the area of interest with vegetation, and was more dependent on the maximum bulk surge. Vegetation-induced reduction and reduction rate have an increasing trend when the area of interest shrinks from the whole BS estuary to the upper estuary. Among all experiments, the maximum values of vegetation-induced maximum surge reduction and reduction rate were 0.7 m in the vegetation-varying cases and 37% in the hurricane-varying cases, respectively, for the upper BS.

It should be noted that only limited factors were discussed in this paper. The main limitation of this study is that the flexibility of vegetation is not taken into account explicitly in the model. Moreover, according to the CRMS monitoring data, the vegetation type in a specific site in the BS estuary can change periodically from one marsh type to another (Visser et al., 2013), thus resulting in changes of spatial distribution of these vegetation types. In terms of hurricane parameters, we fixed the track of Hurricane Isaac and studied Isaac-like hurricanes or tropical storms with different wind intensities and forward speeds. Landfall locations and approaching directions, however, would also play an important role (e.g., Rego and Li, 2009; Wamsley et al., 2010). As such, more comprehensive and accurate studies are required for further understanding of vegetation impact on storm surge in estuarine and coastal areas.

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