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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*,

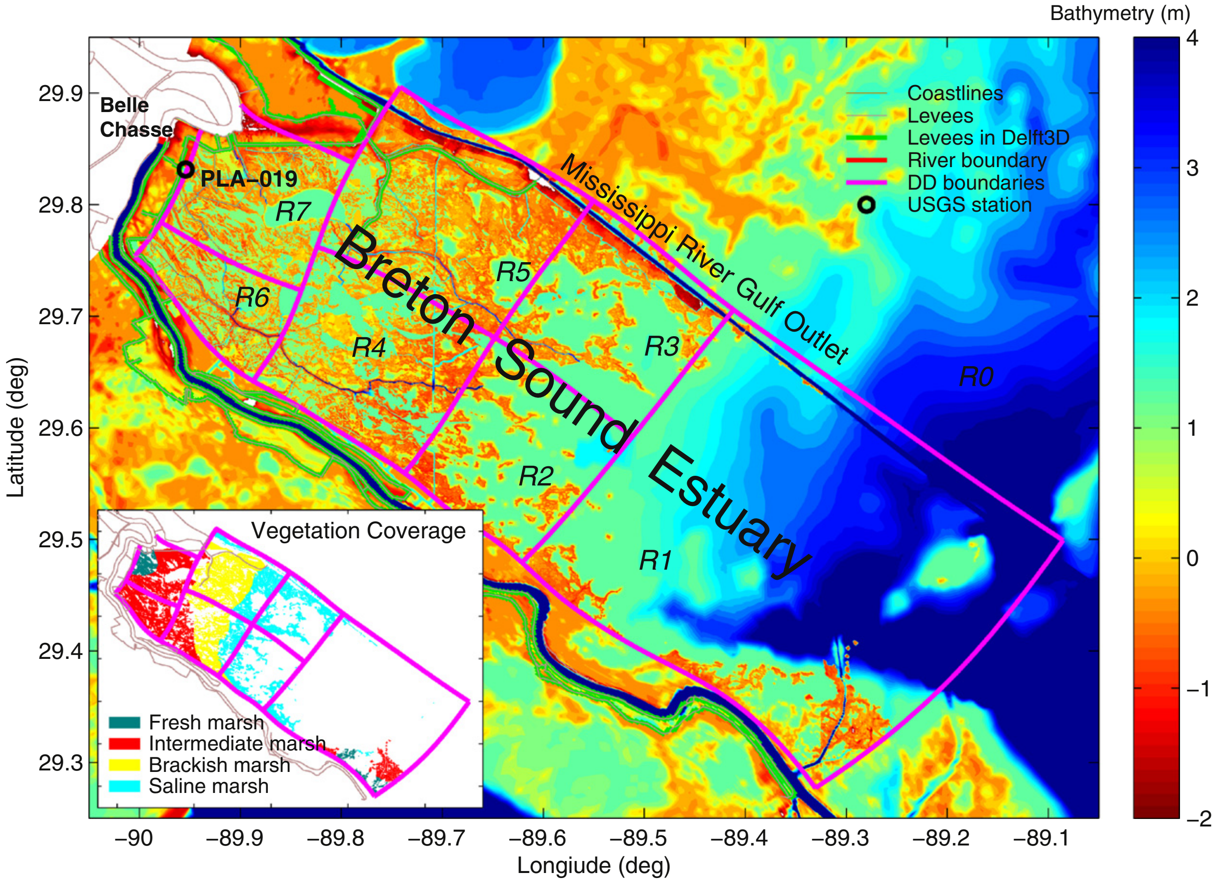

Fig. 1. Bathymetry and vegetation coverage (subfigure) in the Breton Sound estuary. R0–R7 denote eight sub-domains in the regional domain, respectively, which are connected by domain-decomposition (DD) boundaries (pink lines). See legends for other symbols.