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Sensitivity considerations and the impact of spatial scaling for storm surge modeling in wetlands of the Mid-Atlantic region

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ABSTRACT

Among the many activities in the recent efforts to evaluate coastal resiliency is the study of the capacity of wetlands and coastal marshes to attenuate storm surge. The development of an acceptable index or attenuation rate for coastal flooding is complicated by the many factors that contribute to maximum surge elevation, inundation extent and duration, including storm characteristics (e.g. track, size, forward speed, duration, central low pressure) and local features including topo-bathymetry, land-cover, barrier islands, channels, lagoons and inlets. For this study, we investigated the impact of spatial scaling, mesh resolution, storm characteristics and bottom friction on storm surge in wetland areas in the barrier island system of the Delmarva Peninsula using the coupled hydrodynamic-wave model (ADCIRC + SWAN). Synthetic storms derived from hindcasts of historical storms affecting this region were used for model forcing through multi resolution meshes recreating the complex wetland areas exposed to varying degrees of ocean surge through natural breaks in the barrier islands. Sensitivity to mesh resolution and bottom friction were evaluated for regional attributes and storm characteristics, confirming the results of previous studies. Results suggest inlet configuration and exposure to ocean surge are dominant factors for surge propagation through small scale wetlands and barrier island systems for weak to moderate storms. Attenuation rates observed for weaker storms, were influenced secondarily by the complex geometry of channels, lagoons and the presence and continuity of marshes. Results evaluating greater surge produced by stronger storms, even of less than a meter of storm surge increase, indicate that the mitigating impacts of local features are greatly diminished. Our results indicate that although the back bays systems in the Delmarva Peninsula and similar ecosystems in the US East Coast could provide storm surge attenuation for annual storm events, its use in coastal engineering protection may require a case by case analysis due to the high dependence on local characteristics.

1. Introduction

Recent attention to coastal hazards and infrastructure vulnerability has renewed interest in evaluating the effectiveness of the defensive properties of coastal wetlands to storm surge resulting from tropical and extra tropical storms (Costanza et al., 2008; Gedan et al., 2011; Shepard et al., 2011). The potential to replace traditional hard structures such as sea-walls and levees with soft structures such as wetlands, Barrier Island/Back Bay Systems (BIBBS) or hybrid solutions has also received recent attention given the ecological importance of coastal estuarine environments (Feagin et al., 2010; Browne and Chapman, 2011; USACE, 2013; Luo et al., 2015). An improved understanding of the discretized function of the constituent parts of BIBBS and the combined resultant reduction of storm surge and inland flooding is needed however, before the viability of incorporating natural systems into design considerations can be properly determined. Much of the difficulty in quantifying the defensive capabilities of such systems is the role played by the multiple contributing physical processes resulting from the distinct meteorological, geophysical and hydrodynamic interactions.

Early efforts by the United States Army Corps of Engineers (USACE) to develop a metric relating the attenuation of inland storm surge through wetland dominated terrain were conducted using statistical analysis based on high water marks from historic storms along coastal areas of Louisiana. The report suggested a simplified rule of thumb, stating that storm surge is attenuated by approximately 1 m for each 14.5 km of marsh as surge propagates

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inland (USACE, 1963). The viability of such a rule of thumb has been challenged, however, due to the high level of statistical uncertainty upon which the metric was based, and the unsuitability of applying a linear relationship to the complex phenomenon which is dependent upon numerous variables including storm characteristics (e.g. track, size, forward speed), topo-bathymetric features, wetland configuration, local surface roughness, momentum balance and wave action (Loder et al., 2009; Resio and Westerink, 2008; Wamsley et al., 2010).

More recent efforts have benefitted from the availability of sophisticated hydrodynamic models operating in High Performance Computing (HPC) environments. Advances in mesh refinement and the availability of computational resources have advanced efforts to more accurately understand storm surge flow through wetland environments, enabling studies at multiple scales and the inclusion of geospatial properties as model inputs (Dietrich et al., 2011; Luettich et al., 1992). In wetland areas commonly found in BIBBS, increased resolution improves the performance of hydrodynamic models, as water is conveyed through an often extensive network of channels and lagoons. In 2013, Kerr et al. conducted an extensive study evaluating the sensitivity of mesh resolution to storm surge response along the Louisiana-Texas coastal region. This study found that as water propagates inland through shallow areas, increased mesh resolution is critical to accurately simulate conveyance and attenuation of storm surge, concluding that appropriate mesh resolution for that study area ranged from 30 to 80 m for rivers and 80–500 m for inland areas (Kerr et al., 2013).

Capitalizing on the improvements of hydrodynamic modeling through areas requiring increased resolution and utilizing modern computational power, Wamsley et al. (2010) evaluated the role of physical processes involved in the dissipation of energy and resultant attenuation of surge through wetland areas, also along the Louisiana Coast. Using a suite of storms over varied topographies, Wamsley et al. (2010)confirmed earlier hypotheses that surge propagation is highly dependent not only on meteorological forcing but on the interaction between the surrounding landscape and storm characteristics. In another study Zhang et al. (2011) conducted an analysis of flow dynamics through a constructed wetland in the Florida everglades, evaluating the impact of topography, finding that topographic variation plays a heightened role in attenuation during low flow conditions.

Also modeling surge along the Louisiana Coast, Loder et al. (2009) developed an idealized grid to evaluate the sensitivity of models to wetland characteristics including marsh continuity, topography and friction, finding that these parameters have an effect on peak surge levels. Sheng et al. (2012) investigated the reduction of storm surge by vegetation canopies in an idealized domain using three-dimensional modeling (incorporating drag, shear and Reynolds stress) to demonstrate the importance of accurately representing the role of vegetation numerically for simulating flow resistance by wetlands. The frictional role that vegetation plays in the forcing and dissipation mechanisms of storm surge in coastal bays has also seen recent attention in the modeling community in both 2-D and 3-D analyses (Hu et al., 2015; Westerink et al., 2008; Zhang et al., 2012).

To date, most studies assessing the role wetlands play in attenuating storm surge or providing coastal protection have been conducted on large scale marshes in tropical or semi-tropical areas. Indicative of wetlands found throughout the Gulf Coast region, geospatial scales for the Wamsley et al. (2010), Loder et al. (2009) and Zhang et al. (2011) study, varied from 20 to 60 km. Smaller scale wetlands and BIBBS, present in varying degrees and spatial scales along the Mid-Atlantic coast of the United States, provide the first line of defense to storm induced flooding, yet have been underrepresented in wetland storm surge research. The objective of this study is to explore the interaction of storm surge and BIBBS typical of the mid-Atlantic to identify dominant features driving surge inundation and evaluate results derived from use in large scale systems typical of the Gulf Coast, for applicability in smaller scale BIBBS of the Mid-Atlantic region. To perform this analysis, recent historical and synthetic storms were used to force storm surge through a BIBBS wherein topography, bathymetry and land cover were synthesized as faithfully as possible using available datasets. Sensitivity analyses for mesh resolution, storm characteristics, friction parameterization and spatial scaling were conducted in this region.

2. Study areas

2.1. Geographical context

Bounded by the Chesapeake Bay along its western edge and the Atlantic Ocean and Delaware Bay to the east, the Delmarva Peninsula extends approximately 274 km from north to south, with land in Delaware, Maryland and Virginia from whence its name is derived (Fig. 1). Protected by a BIBBS on the eastern coastal areas facing the Atlantic, wetland areas throughout the Delmarva provide protection to inland infrastructure and communities in the form of coastal flood defense while offering a vibrant landscape for ecological activity. Northampton County and Accomack County, situated on the southernmost part of the Virginia portion of the peninsula, combined have approximately 46,452 acres of salt marsh separated by large shallow lagoons protected by a series of barrier islands extending north and south along the Atlantic Coast. (Moore, 1977).

2.2. Sampling areas and transects

Along ~40 km of the Delmarva Peninsula's Atlantic coastline, three contiguous marsh regions were selected for this study; in large part due to the following favorable features 1) uniformly low topographic relief to minimize the impact of steep elevation changes in the hydrodynamic response; 2) exposure to surge through discrete barrier island inlets to evaluate water levels at different locations relative to a shared initial value; and 3) relative homogeneity of vegetative cover to minimize potential influence of frictional variance. With an average ground elevation of 0.5 m throughout the study area, overland areas lying beyond the sandy barrier islands are dominated by Saltmarsh Cod grass (*Spartina alterniflora*) (Silberhorn and Zacherle, 1987).

Region 1 (R1) extends ~12 km north from Hog Island Bay to the southern edge of Metomkin Bay. Characterized by discontinuous marsh islands with numerous lagoons and channels, water is conveyed through Quinby and Wachapreague Inlets on the south and north, respectively, of Paramore Island. From the inlets shoreward, this region spans ~8 km with an average above ground elevation of ~0.5 m and waterway depth of −2.5 m.

Region 2 (R2) bordered on the south by Burtons Bay and on the north by Metomkin Bay with inlets north and south of Cedar Island extends ~14 km longitudinally. With 3 distinct channels cutting through a more continuous marsh than R1, this section narrows to ~ half its width along its northern face.

Region 3 (R3) is the most continuous marsh included in this study, extending ~14 km from its southern inlet to just below Wallops Island. Shoreward of the barrier islands, 2 shallow lagoons (Gargathy and Kegontank Bay) are connected by well-defined channels running longitudinally, with an average ground elevation of 0.5 m and bathymetric depth of −1.5 m for channels and lagoons. The barrier Islands of this region are closer to the coast than R1 and R2, with emergent marsh connected directly to the sand dunes.