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.

Key words: Storm surge, coastal flooding, inlets, back bays, coastal protection

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 meter for each 14.5 km of marsh as surge propagates inland. 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 30-80m for rivers and 80-500m 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 modelling 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 20-60km. 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. 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)

Figure 1: Geographic context showing the study area and regions evaluated.

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 Cord grass (*Spartina alterniflora*) (Silberhorn and Harris, 1977).

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 ~8km 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.

Figure 2: Detailed figure of the regions, sampling areas and transects.

3. METHODS

3.1 Computational Methods

For this study a coupled version of the hydrodynamic ADvanced CIRCulation (ADCIRC) model and the wave model Simulating WAVes Nearshore (SWAN) (Dietrich *et al.*, 2011) was used to simulate hurricane storm surge inundation along the coast of the Delmarva Peninsula. ADCIRC is a finite-element hydrodynamic model that generates water levels and current velocities, and is widely used for storm surge modeling in the east coast of United States and Gulf of Mexico (e.g., Bunya *et al.*, 2010; Ferreira *et al.*, 2014; Westerink *et al.*, 2008). We used the two dimensional, depth-integrated version of ADCIRC (Luettich and Westerink, 2004) that solves the vertically integrated Generalized Wave Continuity Equation (GWCE) and the momentum equations (eq. 1 and 2), respectively:

$$\frac{\partial h}{\partial t} + \nabla_h(\vec{U}h) = 0 \quad (1)$$

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla_h) \vec{U} = -g \nabla_h \left(\zeta + \frac{p(x, y)}{g\rho} \right) + f \hat{k} \times \vec{U} + \frac{\vec{\tau}_s}{h\rho} - \frac{\vec{\tau}_b}{h\rho} \quad (2)$$

where h [L] is bathymetric depth, t [T] is the time, ζ [L] is surge elevation above mean sea-level, $\vec{U}$ [L/T] is depth averaged horizontal velocity vector, p [M/LT²] is barometric pressure, f [1/T] is the Coriolis force coefficient, $\hat{k}$ is a vertical unit vector, τ_s [M/LT²] is the free surface shear stress, τ_b [M/LT²] is the bottom shear stress, and ρ [M/L³] is the water density, g [L/T²] is gravitational acceleration. The wave model SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters (Zijlema, 2010). SWAN computes the wave action density spectrum $N(x, t, \sigma, \theta)$ in geographical space x [L] and time t [T], with σ [rad/T] the relative frequency and θ [rad] the wave direction, as governed by the action balance equation (Booij *et al.*, 1999):

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} [(\vec{C}_g + \vec{U})N] + \frac{\partial C_{\sigma} N}{\partial \theta} + \frac{\partial C_{\theta} N}{\partial \sigma} = \frac{S_{tot}}{\sigma} \quad (3)$$

where, N [M/T] is the wave action density spectrum, $\vec{C}_g$ [L/T] is the wave group velocity, $\vec{U}$ [L/T] is ambient current vector, C_{σ} [L/T] is the propagation velocity, C_{θ} [rad/T] is the wave propagation velocity. The source term, S_{tot} [M/T³] represents wave growth by wind. More detailed information regarding governing equations related to ADCIRC and SWAN can be found in Luetich and Westerink (2004) and Booij *et al.* (1999) respectively and information regarding applications of the coupled SWAN-ADCIRC model can be found in Dietrich *et al.* 2011.

Simulations were performed on the High Performance Computing (HPC) Stampede cluster at the University of Texas, provided by the Extreme Science and Engineering Discovery Environment (XSEDE) (Towns *et al.*, 2014).

3.2 Numerical Mesh

A Low Resolution Mesh (LRM) and a High Resolution Mesh (HRM) were developed from the FEMA Region III East Coast mesh (FR3) for use in this study (Forte *et al.*, 2012). Developed by FEMA, FR3 is a 1.8 million node unstructured grid that includes increased resolution at inlets and geomorphologically sensitive regions, and extends inland to the 15 m contour line to enable modeling of coastal flooding well inland of the shore. The LRM was created by removing ~300,000 nodes from the Delaware Bay region of the FR3 to reduce computational costs, leaving all other areas unchanged. Resolution in study areas for the LRM range from 50-2500 m in our study area. For the HRM, Surface water Modeling System (SMS) was used in combination with data from the United States Geological Survey (USGS) 10 m resolution National Elevation Dataset (NED) Digital Elevation Models (DEM) to add ~300,000 nodes to the LRM within the study area, increasing resolution to ~10-100 m. Due to limited bathymetric data availability, lagoons and channels in most of R1 and all of R2 and R3 were assigned a uniform depth of -1.5 m. Nodal attributes were parametrized using data from the National Land Cover Database (NLCD) and incorporated into the model (Mattocks and Forbes, 2008).

Figure 3: Example of numerical HRM and LRM images and details at the inlet of R3: A) LRM terrain visualization ; B) HRM terrain visualization ; C) Frictionalized LRM nodes; D)

Frictionalized HRM nodes; E) Close up of LRM nodes at Gargathy inlet; F) Close up of HRM nodes at Gargathy inlet

3.3 Meteorological & Tidal Forcing

The wind fields for all storm simulations were generated internally within ADCIRC using a dynamic asymmetric Holland gradient wind model (Holland, 1980). Inputs to this wind model were generated based on meteorological data extracted from the National Hurricane Center (NHC) Best Track database. The parametric wind model is embedded in ADCIRC, and is internally coupled to the SWAN wave model (Dietrich *et al.*, 2013; Mattocks and Forbes, 2008; Xie *et al.*, 2006). The NHC best track database contains hurricane track and intensity information at 6 hour intervals, and ADCIRC interpolates the wind input to 15 minute intervals to generate meteorological forcing through the model mesh. Tidal forcing was propagated through the model domain from the ocean boundary, using seven tidal constituents extracted from the LeProvost database (Le Provost *et al.*, 1994).

Wind forcing for Hurricane Isabel (2003) was generated based on the Extended Best Track dataset (Demuth *et al.*, 2006), supplemented with an estimation of radius to maximum winds (Rmax). The maximum radial extents for Hurricane Floyd (1999) were estimated based on simple calibration using observed water levels at NOAA stations in the study area. Two synthetic storms were simulated based on modifications to the Hurricane Floyd wind forcing data. Storms F1 and F2 reduce the forward speed and the central pressure, respectively, as the storm passes over the study area. Wind forcing for Hurricane Sandy (2012) was extracted from the NHC Best Track dataset, which includes complete radial extent information for all storms beginning in 2004. See Fig. 4 and Appendix A for storm data.

Table 1: Meteorological forcing: Rmax value simulated as the storm passes through the study area, and the mean forward speed, and mean central pressure

Figure 4: Meteorological Forcing: storm tracks passing by the study area. F-1 and F-2, not listed, followed the Floyd track.

3.4 Bottom Friction

In ADCIRC, the influence of coastal vegetation on wind stress and the corresponding effects on momentum transfer to the water column is accounted for by a wind reduction coefficient due to the frictional drag caused by the land cover surface and a complete blocking effect of momentum transfer in areas with dense canopy. The frictional resistance at the sea bottom is accounted for by using a non-linear bottom drag coefficient related to land cover surface roughness. Here, we calculate the dimensionless friction coefficient (C_f) based on the Manning's n (n) parameter using (Eq. 4):

$$C_f = g * \frac{n^2}{h^{(1/3)}} \quad (4)$$

where g [m^2/s] is the acceleration due to gravity and h [m] is water depth. The friction coefficient is incorporated into the bottom shear stress $\vec{\tau}_b$ formulation by (Eq. 5)

$$\vec{\tau}_b = \frac{C_f \vec{U} |\vec{U}|}{h} \quad (5)$$

where $\vec{U}$ is the depth-averaged horizontal velocity vector [m/s]. To specify the spatially variable land cover parameters, we used the methods of (Atkinson *et al.*, 2011), which have been

employed and validated in a number of surge modeling studies (Dietrich *et al.*, 2011; Luettich and Westerink, 2004; Tsihrintzis and Madiedo, 2000).

To assess the impact of friction in our study area using a high resolution grid over a small geospatial scale, we conducted simulations using a ‘normal’ case and a ‘high friction’ case. For the normal case, each node was assigned a Manning’s n value based on the NLCD classification for that point. As noted above, uniformity of vegetative cover was key to selecting this region, and at nearly all overland points in the study area between the barrier island and the shore, a value of $n=0.045$ was applied for the normal case. For the high friction simulations a uniform value of $n=0.15$ was used for overland areas, leaving wet nodal values unchanged. The high friction value was chosen due to its use in previous studies. It should be noted that although this value may be unrealistic for the study, it was selected as an upper threshold and for use as a basis of comparison to results from studies conducted over more extensive wetlands (Zhang 2012, Xu *et al.*, 2010).

3.5 Analysis Metrics

Water levels used for this study were taken from representative Sampling Areas (SA) and Transects within the BIBBS. From each of the 3 regions, 7-10 SA’s (Fig. 2), each $\sim 1 \text{ km}^2$, were established in lagoons, continuous and discontinuous sections of the marsh. To evaluate sensitivity of model output due to changes in mesh resolution and bottom friction, the following metrics were used:

$$\bar{\zeta}_{SA,r} = \frac{1}{n} \sum_{i=1}^n \zeta_i \quad (6)$$

$$\Delta_{SA} = \frac{(\bar{\zeta}_{SA,r1} - \bar{\zeta}_{SA,r2})}{\bar{\zeta}_{SA,r1}} (100\%) \quad (7)$$

where ζ_i is the peak surge or surface elevation (WSE) above mean sea level at a given node, SA is the sampling area, n is the node and r is the simulation. For analysis of sensitivity to mesh resolution, r_1 is the result from the LRM and r_2 is the result from simulations performed on the HRM. For analysis of sensitivity to bottom friction, r_1 is the result from the ‘normal’ case and r_2 is the result from simulations using the high friction parameterization. Spatial analysis of attenuation was calculated as a pure difference, using the following metric:

$$\delta_{n,r} = (\zeta_{n,r} - \zeta_{n,r}) \quad (8)$$

where δ is attenuation at the transect node for a given run. Due to the adoption of the ADCIRC wetting and drying algorithm, taking average WSE values using metrics 6 and 7, may in some cases overstate the difference between two runs in a given SA. In order to account for this phenomenon, we considered a second method for averaging WSE values, whereby only nodes that were wetted in both simulations were compared. After evaluating the results using both methods, we decided not to include both metrics, as results did not vary appreciably in most cases. See Appendix B for tabular results.

4 RESULTS AND DISCUSSION

Simulations of recent historical and synthetic storms were conducted to evaluate the interaction of storm surge propagating through the wetland marsh areas composing a selected study area within the BIBBS of the Delmarva Peninsula. WSE’s were recorded at mesh nodes within 25 SA’s and 7 transects across 3 loosely defined regions. Average values for SA’s were

computed for WSE's at nodes within SAs at all simulations, with peak levels ranging from 0.94-2.06 m. Sensitivity analyses were conducted to evaluate model performance for the SA's within the study area and over the regional subsections due to changes in mesh resolution, meteorological forcing and bottom friction parameterization. The impact of geospatial scaling was evaluated at transects in Region 3.

4.1 Hydrodynamic response in the sampling areas

R1 was subjected to flooding through Wachapreague and Quinby Inlets at its northern and southern edges, respectively. With the exception of sporadic breaches, the barrier islands were not overtopped for the storms included in this study, limiting the propagation of surge through discrete inlets. Consistent in all simulations, WSE's at the narrower Wachapreague inlet, which is partially obstructed by a small island at its center, were lower than those at the Quinby Inlet. Surge entering through Quinby Inlet propagated through the channel and into the surrounding bays. From there, surge propagated over emergent marsh and into Swash Bay (SA-6) and Bradford Bay (SA-8). WSE's for all storms ranged from 1.30-1.86 m in these interior lagoons. WSE values for overland areas ranged from 1.08-1.42 m at Clubhouse Marsh (SA-10) just beyond the Wachapreague Inlet to higher levels of 1.24 and 2.01 m at the interior-most marsh area (SA-4).

Hydrodynamic response in R2 differed from R1 in range and location of maximum WSE's, showing greater sensitivity to storm characteristics. Entering through Metomkin and Wachapreague Inlets at its northern and southern edges, surge propagated through Burtons (SA-11) and Metomkin Bay (SA-18). Steep topographic and frictional resistance along the land-sea interface forced water away from inland areas, resulting in surge propagating along the

longitudinal extents of this marsh system. With the exception of Sandy, water was conveyed overland in all directions through this region, with maximum WSE's recorded in Burtons and Metompkin Bays.

R3 was subjected to ocean surge through Gargathy Inlet from the east and local surge propagating northward from Metompkin Bay. Flowing over an area of relatively continuous marsh, ocean surge was conveyed through two main channels south toward Gargathy Bay (SA-20) and flowing through a single channel north into Kegotank Bay (SA-23) and the marsh beyond. Minimal overtopping of the barrier island occurred in this region, where maximum WSE's were recorded in Gargathy Bay and overland in SA-21.

4.2 Sensitivity to Resolution

Previous studies have demonstrated the importance of mesh resolution and accurate topo-bathymetric representation for surge response in rivers and floodplains. Kerr *et al.* (2013) tested a mesh with resolution ranging from 80-500 m, and Bilskie *et al.* (2013) considered mesh resolution ranging from 20-160 m. Xu *et al.* (2010) provided a multi-scale framework to simulate storm surge in the Chesapeake Bay and demonstrated the importance of incorporating accurate representation of topo-bathymetric data with resolution up to 30 m. For our study, simulations were conducted for Hurricanes Floyd and Isabel on the LRM (resolution from 100~2500 m) and the HRM, which increased resolutions to a range of 10-100 m, to evaluate the storm surge response in each of the selected regions due to more accurate representation of topo-bathymetric data and improved conveyance through channels and uneven terrain. Note that the detail level of the HRM is greater than the previous studies (Kerr *et al.* 2013: 80~500 m; Bilskie *et al.* 2013: 20~160 m; and Xu *et al.* 2012: 30 m). As demonstrated in Fig. 3, the increased resolution

allowed for a significantly enhanced representation of the geometric wetland features, principally channels and lagoons in the BIBBS. On average, the SA's in the HRM contained ~15 nodes for every node in the LRM.

Our results demonstrated that the impact of mesh resolution on the surge response inside the BIBBS is highly dependent on the ocean surge magnitude resulting from meteorological forcing, the geometric characteristics of the marsh system and presence or absence of inlets. For example, R1 is significantly more susceptible to ocean surge due to the conveyance capacity of Quinby and Wachapreague inlets than R3, which is protected more extensively by the barrier islands, limiting surge propagation through a central inlet. Therefore, WSE's in R1 were fairly consistent for both simulations, showing a decrease of < 10% for Floyd and almost no difference for Isabel, as demonstrated in Fig. 5. In R2 and R3 surge response showed a higher degree of sensitivity; particularly for Floyd where WSE's were up to 30% lower on the HRM, a decrease of ~0.5 m. Results from Isabel also showed higher sensitivity in R2 with values decreasing ~5-20% or ~0.4 m. These simulations support the importance of enhanced resolution and more accurate representation of topo-bathymetric features in BIBBS is more pronounced in areas or more continuous overland wetland areas benefiting from a lower exposure to ocean surge.

Fig. 5: WSE and percent difference plots at SA's for Isabel and Floyd simulations on the LRM and the HRM.

4.3 Sensitivity to Meteorological Forcing

Three simulations were conducted on the HRM to evaluate surge response to storm characteristics. Results for surge response to synthetic versions of Floyd with a reduced forward

speed (F-1) and a lowered central pressure (F-2) are plotted in Fig. 6. As expected based on previously examined impacts of intensity and wind speed on storm surge, the simulations with lower central pressure (F-2) yielded higher peak surges in all SA's. In general, we observed an increase in peak surge in the range of 15-25%, with an average of ~17% throughout the study area. The impact of lowered central pressure on the storm surge response was nearly uniform across all regions (Fig. 6) with greater differences in SA's 2 and 4. This may be attributed largely to water piling up as resistance and elevation increase drastically in this region, which lies at the land sea interface and is surrounded by three lagoons.

The impacts of the slower forward speed storm (F-1) on the surge response were lower as compared to the more intense storm but still produced differences in the range of 4-23% in the study area. As expected, the slower storm produced higher peak surges in all study areas, a phenomenon supported by previous studies (Irish *et al.*, 2008; Wamsley *et al.*, 2010). However, the surge response due to F-1 was more dependent on spatial location compared to the stronger storm response of F-2. The impact of the slower storm on the surge response was much greater in R1, most likely due to greater exposure to the open ocean provided by the inlets. Impacts on R3 could be considered negligible, with differences lower than 7% in all SA's. The impacts on R2 were on the order of ~10% surge increase in all SAs. With the greatest increase in surge response measured in SA 4 for both storms, F-2 produced more consistently greater WSE's throughout all SA's than the slower moving F-1.

Fig. 6: Absolute (left) and percent (right) difference plots of WSE's from F-1 (Synthetic Floyd with a slower forward speed) and F-2 (synthetic Floyd with a lower central pressure) simulations normalized to Floyd.

4.4 Sensitivity to Friction

A central finding of efforts to evaluate the frictional resistance of vegetation on storm surge in wetland areas is the interrelatedness of dampening due to friction storm characteristics. Findings of this study support these results, as demonstrated in the Fig. 7 (Alongi, 2008; Hu *et al.*, 2015; Liu *et al.*, 2013; Loder, 2008; Sheng *et al.*, 2012; Zhang *et al.*, 2012). In R1, increased friction resulted in drastic differences among SA's and by storm. In this region, Isabel simulations showed a near uniform 5-10% reduction in WSE's, while Sandy simulations saw a slight increase in several SA's. Floyd, F1 and F2 results differed drastically among SA's, ranging from almost no change at the inlet to ~55% reduction in WSE's in SA4. This wide disparity in WSE's makes it difficult to differentiate the role of friction from the hydrodynamic response resulting from the unique characteristics of meteorological forcing, local marsh geometry, and the total combined interaction. One possible explanation for these phenomena could be ocean wave setup. As noted by Irish *et al.* (2008), while ocean surge and local wind setup constitute the major contributors of peak surge, ocean wave setup can play a significant role in flooding of back bays and lagoons sheltered by barrier islands, particularly when overtopping is not widespread and surge is forced through tidal inlets. In this case, elevated water levels within the BIBBS over an extended period of time, as in those produced by Sandy, could result in inundation scenarios made possible due to a unique combination of geometry and forcing.

Generalizing for all regions and all storms, results indicate that applying increased friction has a greater impact at SA's furthest from the inlet. This suggests a gradient similar to the Vegetation Dissipation Potential developed in a 3-D study of the interaction between storm surge and vegetation canopies discussed by Sheng *et al.* (2012). While Sheng evaluated density

of vegetative cover and not the spatial scale of water through a BIBBS, the uniformly high friction values at closely-spaced nodes for this study could be treated as a dense canopy, with similar results. Furthermore, Loder *et al.* (2009) concluded that increased friction has a greater impact on the reduction of peak WSE's when surge is less than 2 m, which is consistent with our findings. The Floyd run, and to a lesser extent the F- runs, produced WSE between 0.25 and 0.5 m lower than the Sandy or Isabel runs, and correspondingly experienced generally greater reduction in all SA's. With the exception of SA's 23-25 which lie in at the outermost edge of the study area, friction sensitivity in the Isabel simulation was consistent with Sandy, showing a difference of ~10% or less from most SA's.

Fig. 7: WSE and percent difference plots of high and expected friction for all storms on the HRM.

4.5 Spatial Scales

The impact of spatial scales on surge reduction was implicitly addressed in both analyses of resolution (section 4.2) and friction (section 4.3) sensitivity. The difficulty with assessing surge reduction at a given spatial scale explicitly is due in large part to our inability to separate and quantify the various constituent forces that are at play on a per storm basis. Further complicating this subject in a BIBBS is the complex geometry, topographic and land cover features, and the source and direction of flow (e.g. an inlet, an overtopped dune, a channel). Loder *et al.* (2009), found that marsh continuity plays a significant role in surge levels for storms of low surge potential, due in part to the conveyance of water into and out of the marsh through discrete paths. For this analysis, R3 was singled out for evaluating spatial scales based on the

following criteria: 1) aforementioned surge studies have evaluated larger spatial scales; 2) due to the lack of consistent overtopping, surge enters this region through a central inlet and therefore WSE's can be traced back to a central point for consistent comparison; and 3) of the regions included in this study, R3 has the most continuous marsh areas extending north and south beyond the inlet.

Passing beyond Gargathy inlet, surge enters this system and is conveyed through three main channels into the marsh system. Containing two central lagoons, and with a near uniform ground surface elevation of 0.5 m above MSL, surge from simulations propagated overland, flowing in all directions North, East and South upon entering the marsh. The impact of spatial scales was analyzed at 7 transects, where a node in the center of the inlet was used as the reference point. WSE's were then recorded at nodes ~250 m intervals extending from 1.75- 5 km into the marsh and compared to the initial condition. Average attenuation rates are generated using Equation 8, and are plotted in Fig. 8. Although WSE's were similar for all storms, ranging from 1.56-1.78 m at the inlet, the behavior of flow and subsequent attenuation for the Floyd runs differed markedly from the Sandy and Isabel simulations. Consistent for all simulations, WSE's were impacted within 250 m of the inlet. Sandy and Isabel, whose surge was slightly higher overall, experienced less attenuation at all transects. After an initial decrease upon entering the marsh, WSE's leveled off and in some cases increased as water was forced over lagoons or the relatively level surface of the marsh itself.

Fig. 8: Surge attenuation plots for all storms at 7 transects in R3 on the HRM.

Fig. 9, a spatial representation of surge attenuation at each point along the transect created using ArcStormSurge (Ferreira *et al.*, 2014b), further demonstrates the difficulty with assigning attenuation rates within such a marsh system. Unlike R1 and R2, surge enters this area through a central inlet and a path can be drawn directly from the point of entry to delineate attenuation along a direct path. Wamsley *et al.* (2009) evaluated attenuation across extensive marsh (~60 km) areas, concluding that while highly sensitive to storm characteristics, attenuation rates from that study ranged from 1m per 60 km to 1m per 4 km. Our study evaluated attenuation on a much smaller scale, with the largest transects measuring 5 km. Results of this study confirm that establishing attenuation rates based on a spatial scale is not practical based on current understanding of the physical processes simulated by the model and inconsistent statistical results produced.

Fig. 9: ArcStormSurge visualization of surge attenuation at nodes over transects in R3.

5. CONCLUSIONS

As tropical and extra-tropical storms threaten communities and infrastructure in coastal communities, reliable coastal defenses are becoming increasingly important to provide protection and increase resilience to coastal areas. Improved understanding and awareness of the ecological importance of wetlands has contributed to the discussion of integrating soft structures such as replenished or revitalized wetland systems into coastal engineering design considerations, presenting an attractive alternative to more traditional hard structures. Quantifying the properties of these defenses for design purposes is complicated by multiple factors, however, not all of which are well understood. The purpose of this study was to explore the interaction of storm

surge and BIBBS typical of the mid-Atlantic to identify dominant features driving inundation extent and attenuation.

Our results confirm prior studies that increased resolution is important when modeling complicated geometries, but may be sacrificed in larger areas depending on geometric and topographic details. This is true to an even greater extent when stronger storms produce greater surge, as demonstrated by the results of the Isabel simulation. Due to the lack of continuity in R1 and greater exposure to surge through inlets, results suggest this area did not benefit from increased resolution, as water levels remained consistent for both simulations. Conversely, the more remote, protected R3 saw a sharp improvement to mesh refinement for both the stronger Isabel and the weaker Floyd. Sensitivity to storm characteristics was evaluated by altering Floyd using methods applied in previous studies, and yielding similar results. Of note here, however, is that an evaluation of sensitivity to forcing for this region is not limited to the results of the Floyd runs, but can be improved through the inclusion of Isabel and Sandy. Incorporating these storms into the sensitivity to meteorological forcing, it is clear that storm characteristics play an overwhelming role in surge response in this region. As mentioned, sensitivity to mesh resolution was diminished for the stronger storm, as was sensitivity to friction and attenuation. This suggests that for small scale wetlands, the dominance of greater surge produced by stronger storms, even of less than a meter increase, may overwhelm the mitigating impacts of other factors.

One of these factors evaluated in this study was sensitivity to friction, wherein simulations were conducted using a normal case (NLCD) and an upper threshold considered unreasonably high for the native land cover native to the study area. Although consistent with prior studies, the decrease in peak WSE's resulting from the drastic increase in friction,

particularly for the stronger storms, indicates that the sensitivity to friction, as applied to this study, is minimal. However, greater disparities on peak levels recorded in R3 should not be overlooked. Future studies are needed to evaluate the relationship and the implications it has for assessing attenuation, which was evaluated at 7 transects in this region. Results from the attenuation study are consistent with the other analyses conducted in this study, principally that there exists a water level threshold which, when reached, renders frictional and subtle topographic differences inconsequential. Attenuation is achieved principally due to the barrier islands, where surge forced through the inlet is immediately attenuate, however the rate of attenuation is not changed in a consistent fashion for all storms.

While not within the scope of this paper, ongoing geomorphic activity, particularly at barrier islands, increases the complexity of the phenomena discussed here and offers potential for future studies. At times, strong storms accelerate the geomorphic process through the creation of inlets as storm energy reshapes barrier islands and creates new inlets. Future work in this area may include multiple simulations of storm surge in a small spatial scale through a complex geometry, such as found in the system evaluated here, with an emphasis on inlet size, quantity and geospatial distribution. Our results also demonstrated that although wetlands and BIBBS representative of the US East Coast can offer storm surge protection, application to engineering design may need to be evaluated on a case by case basis due to significant dependence on local characteristics as discussed in this study We expect that these results will provide guidance and insight for coastal engineers and coastal community planners interested in evaluating coastal ecosystems with respect to storm surge protection, as well as to stimulate future research in investigating the optimal framework to provide coastal protection in similar areas.

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