TROPICAL CYCLONE IMPACTS TO BEACH AND DUNE RESTORATIONS WITH BACKBARRIER MARSH CREATIONS

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Abstract: A numerical modeling system is developed to simulate the event scale (days) impact of tropical cyclones to the Caminada Headlands, Louisiana, USA. The model is used to investigate storm impacts to an actual beach and dune restoration of the Caminada Headlands, as well as, a hypothetical marsh creation. Three restoration scenario are forced with Hurricane Gustav's (2008) waves and water levels and a synthetic 100-year return period storm. The presence of a restored backbarrier marsh reduced dune lowering and subaerial volume losses compared to the scenario without a marsh creation component or with open water backing the beach and dune restoration. The simulated results suggest that backbarrier marsh creation, which provides vegetated land cover and increased elevation to reduce landward washover sediment transport, may enhance the resiliency of coastal restorations of low-lying barrier systems impacted by tropical cyclones.

Introduction

Vulnerable coastlines are often restored and fortified by renourishing the main barrier sand body to offset natural shoreline erosion and protect against future storm impacts. For many mid- and low-latitude coastlines, the major driver of loss rates are tropical cyclone (TC) impacts (Morton and Sallenger Jr., 2003). Understanding the sediment transport mechanisms and their interaction with the natural features during a TC event is central to assessing the sustainability of restoration projects and developing techniques to improve their resiliency.

Sediment transport driven by TC events is, to the first order, controlled by the event's maximum water level elevation relative to the barrier's dune crest elevation (Sallenger, 2000). However, backbarrier elevation and its land cover also influence event-scale sediment transport. This is primarily due to vegetated land cover and increased elevation which promotes deposition and reduces landward sediment transport (Morton and Sallenger Jr., 2003; Johnson et al., 2019).

The objective of this study is to test the effect of the backbarrier elevation and land cover on the sediment retainment capacity of barrier systems that experience overwash under TC forcing. To address this question, a physics-based numerical model is employed to investigate the morphological response of three different coastal restoration scenarios subject to two different TC forcing regimes.

Methodology

Restoration Scenarios

The Caminada Headlands (CH) Beach and Dune Restoration Project placed approximately 2.38 × 105 m^3 of sand along 21.3 km of the CH's shoreline (see the green polygon in Figure 1). The design template had a beach elevation of 1.37 m NAVD88 that is 20 m-wide and a dune crest elevation of 2.13 m NAVD88, see Figure 2 from Coastal Engineering Consultants (2015). A subsequent marsh creation project (see purple polygon in Figure 1) was designed to create approximately 5.6 km^2 of marshland at an elevation of 0.76 m NAVD88 (Ardaman & Associates, 2018). The three post-construction scenarios used in the numerical experiments are directly based on these designs.

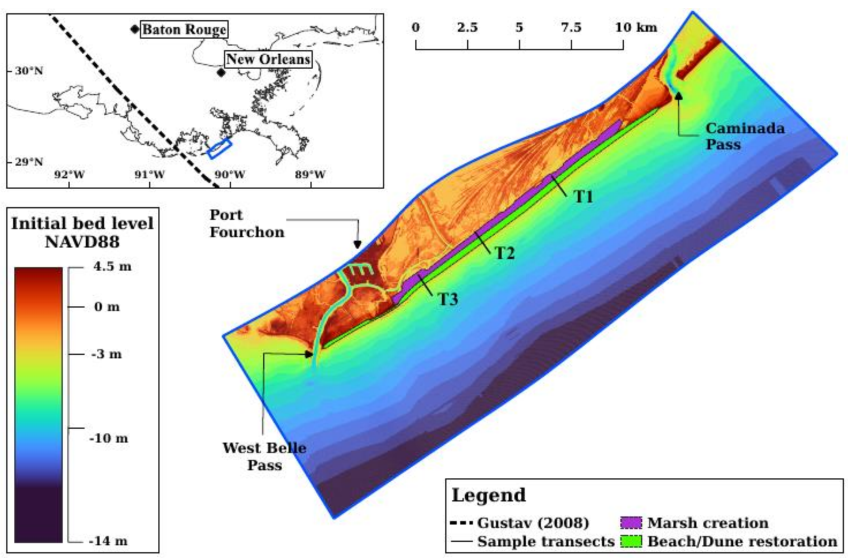

Fig. 1. The CH model grid and initial bed level. The inset shows the CH domain relative to Louisiana (LA) and Hurricane Gustav's storm track. The marsh creation and beach/dune footprints are displayed as purple and green polygons, respectively. Sample transects T1, T2, and T3 are shown with black lines.

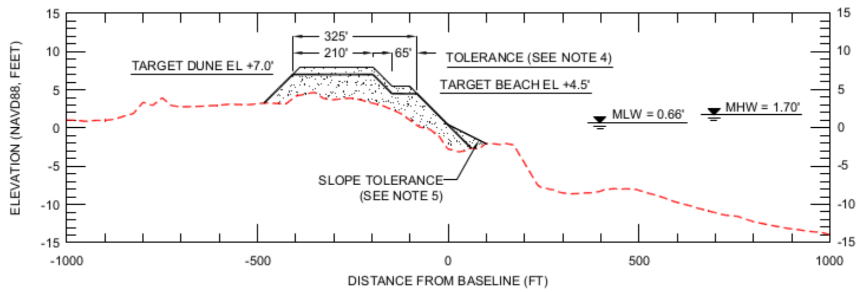

Fig. 2. Typical design profile for the Caminada Beach and Dune Restoration.

The first restoration scenario (BD scenario) is the as-built morphology of the beach and dune restoration and was set up by incorporating the post-construction survey of the CH restoration. The second scenario (MC scenario) includes the beach and dune restoration but further incorporates the backbarrier marsh creation project. The final scenario models the complete deterioration of the backbarrier wetland (WD scenario). Figure 3 shows the initial topo-bathymetry for the BD, MC, and WD scenarios at sample transects T1, T2, and T3.

Modeling Set up

A coupled hydrodynamic-wave model (Delft3D-Flow version 64519 and SWAN version 4072ABCDE) covering the eastern Atlantic Ocean basin and the Gulf of Mexico, which has been verified for Hurricane Gustav (2008) (Liu et al., 2018; Johnson et al., 2020), was used to generate water level and wave boundary conditions for a morphodynamic-sediment transport model of the CH (CH model) (XBeach-X release, version 5526). The CH model was previously calibrated and verified to hindcast Hurricane Gustav's impact using wave gage, water level and lidar data (Johnson et al., 2020). The same CH model (see Figure 1) is used here, but its topo-bathymetric and land cover/land class based surface roughness inputs are modified to reflect the post-construction CH and other scenarios.

The new topo-bathymetric data, incorporated to model the CH model, were comprised of terrestrial (RTK-GPS) and hydrographic (single-beam sonar) survey data. The RTK-GPS and hydrographic data were collected in December 12th, 2014 and May 25th, 2016 during the post-construction phases of the BA-45 and BA-143 restoration projects, respectively. An additional single-beam sonar hydrographic survey was conducted between October 29th and November 10th, 2015 as part of the Louisiana Barrier Island Comprehensive Monitoring (BICM) Project Phase 2 which extended out to approximately -14 m NAVD88 (Byrnes et al., 2015). To set up the post-construction scenarios, these survey data sets were triangularly interpolated to the CH model's grid and the remaining grid points were sampled from the Coastal National Elevation Database (CoNED) digital terrain model (DTM) of Thatcher et al. (2016). To update the LULC-based surface roughness distribution to post-construction conditions following the restoration's construction, Landsat 8 (TM) imagery from December 10th, 2016 was acquired. The remotely sensed data were classified following the methodology in Johnson et al. (2020).

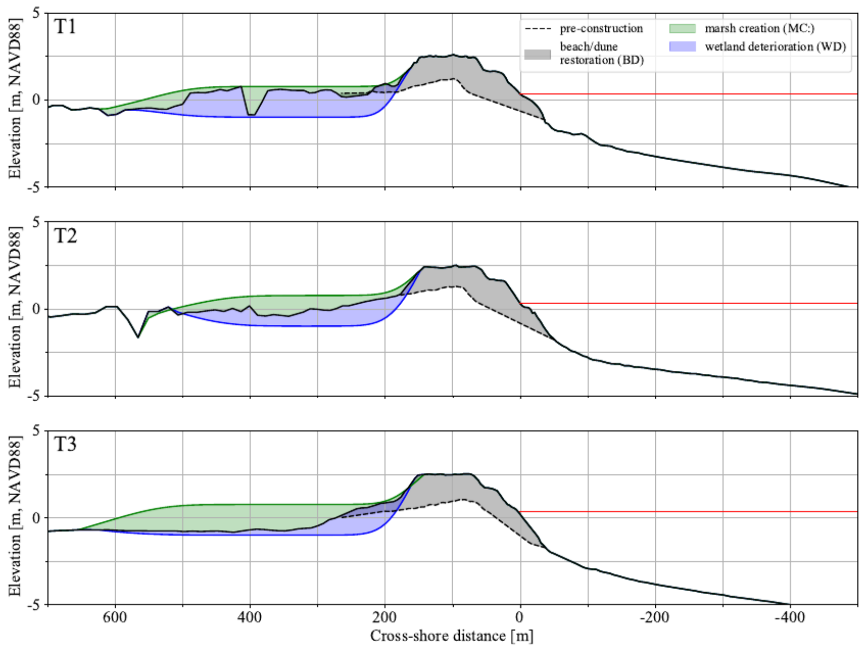

Fig. 3. Initial topo-bathymetric inputs for the BD (black), MC (green) and WD (blue) restoration scenarios at sample transects T1, T2, and T3. The pre-restoration profile is shown as a dashed line. The gray, green, and blue shaded areas are the difference between the restoration scenario profiles and pre-restoration profile, respectively.

For the restoration scenarios, the input topo-bathymetry and roughness fields were generated based on restoration design documents and post-construction data (Coastal Engineering Consultants, 2015; Ardaman & Associates, 2018). The backbarrier marsh creation was set up in the model by uniformly setting the elevation of the grid points within the marsh creation footprint to the design elevation of 0.76 m NAVD88 (Ardaman & Associates, 2018). The created marshland is assumed to have a uniform land use/land cover class and Manning's n value (0.034) corresponding to backbarrier vegetation in Johnson et al. (2020).

Storm Conditions

Two storm conditions were used to force the CH model. Forcing was imposed as water levels on all boundaries and 2D spectra on the offshore boundary. One set of conditions (see Figure 4a, c, and e) were identical to those produced by Hurricane Gustav (2008) (HG conditions) and have previously been verified within the CH model (Johnson et al., 2020). An additional set of conditions (see Figure 4b, d, and f) were synthesized to simulate 100-year return period storm forcing along a track identical to Hurricane Gustav's (see inset in Figure 1). To generate the conditions for 100-year return period, the HG boundary conditions were scaled by ramp functions, where peak values equal the 100 year return period storm conditions.

Peak water level was estimated as 2.13 m MSL for a 100-year return-period water level, which was acquired from the National Oceanographic and Atmospheric Administration (NOAA) Grand Isle tidal station (CO-OPS id: 8761724), approximately 15 km to the northeast of the CH. The 100-year H_{m0} of 7.64 m was obtained from the Wave Information Studies (WIS) station 73129.

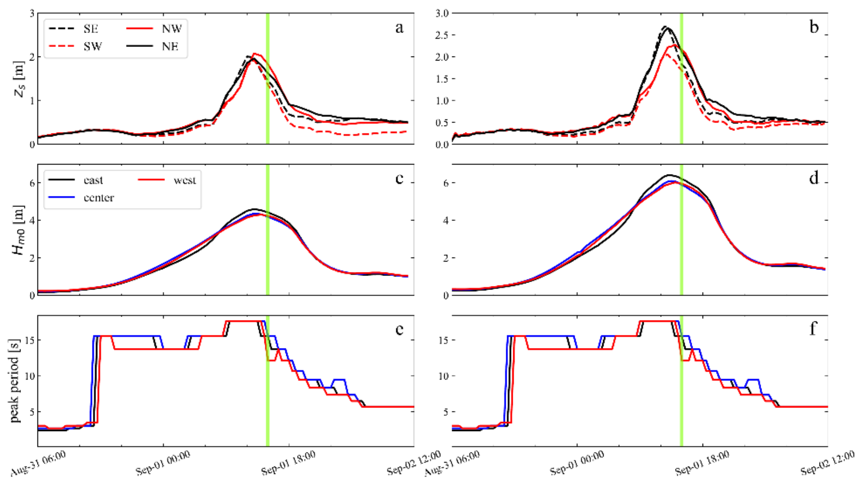

Fig. 4. Water level and surface wave boundary conditions. (a) Hurricane Gustav water levels at the CH model's boundary. (b) Water levels in the 100 year conditions. (c) Offshore zero-moment wave height for Hurricane Gustav. (d) Offshore zero-moment wave height for the 100 year conditions. (e) Peak period for Hurricane Gustav conditions. (f) Peak period for the 100 year conditions. The tropical cyclone's landfall is shown as a vertical green line.

Results

Morphodynamics

Figure 5 shows the pre- and post-storm profiles at T1, T2, and T3 for each restoration scenario under the HG storm conditions along with the maximum mean water levels. The backbarrier mean water levels approached the dune crest elevation (approximately 2.35 m NAVD88), but never establish a connection with the ocean. Therefore, the HG storm conditions never initiated the inundation regime from Sallenger (2000) due to the CH's restored dune elevation.

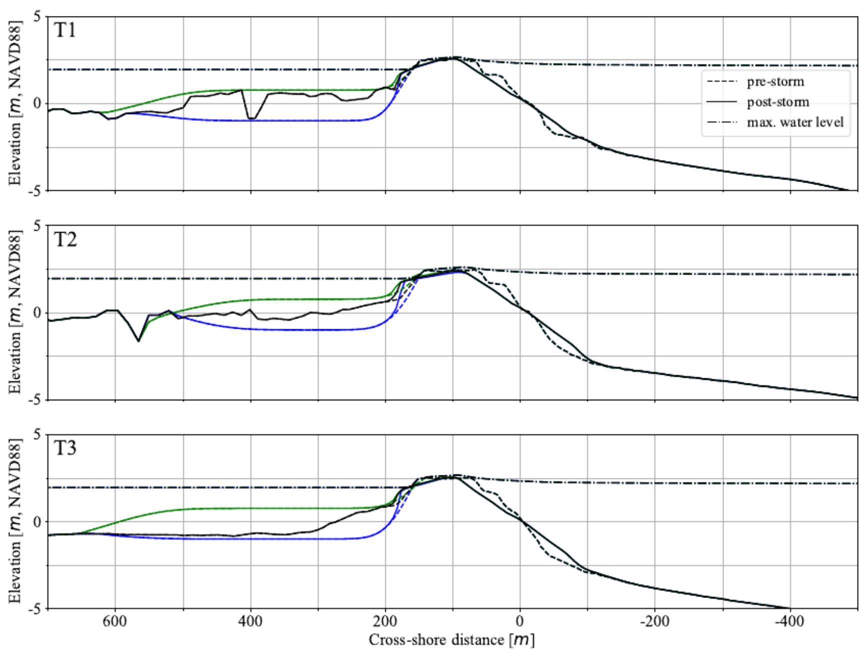

Fig. 5. Pre- and post-storm profiles for the HG storm conditions shown as dashed and solid lines, respectively. The BD restoration is shown as black, the MC as green, and the WD as bluelines. Maximum water levels over the entire event are shown as dash-dot lines.

The 100-year storm conditions produced inundation regime forcing at transects T1, T2, and T3 as indicated by the maximum mean water levels in Figure 6. The result of the inundation regime forcing is landward transport of beach and dune sediment. The profiles' net change indicate that dune lowering between each scenario is morphologically similar, but there are quantitative differences.

The presence of a restored backbarrier marsh (scenario MC) decreases the amount of lowering compared to scenarios BD and WD. The post-storm dune crest elevation decreases with decreasing backbarrier elevation at every transect. Comparing the profiles from scenario MC to WD reveals a difference in that the horizontal landward excursion of washover increases when the backbarrier marsh is present (MC scenario) compared to the WD scenario with open-water landward of the dune.

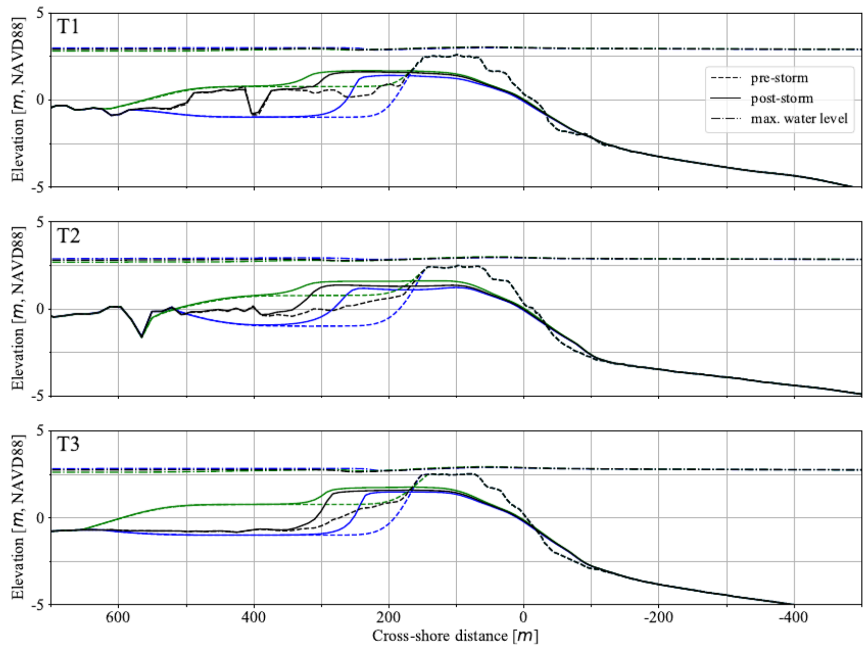

Fig. 6. Pre- and post-storm profiles for the 100 year storm conditions shown as dashed and solid lines, respectively. The BD restoration is shown as black, the MC as green, and the WD as blue lines. Maximum water levels over the entire event are shown as dash-dot lines.

Figure 7 shows the displacements of eroded beach and dune sediment onto the backbarrier at the sample transects from the 100-year return period storm conditions. The displacement between the eroded pre-storm volume and post-storm deposition volume centroids shows the trajectory of net sediment transport. The pre- and post-storm profiles were alongshore-averaged over a one-kilometer shoreline stretch centered at T1, T2, and T3. These transects highlight deposition patterns along the CH.

Landward sediment migration in the MC scenario is more emphasized as opposed to those in BD and WD scenarios. However, the opposite is the case of the sediment's vertical displacement (Δz) which is deposited at a higher elevation in the MC scenario than in the BD and WD scenarios. This suggests that the volume of sediment eroded is similar in all the cases, and the landward migration determines the vertical displacement of the dune crest. The results also indicate that approximately half of the post-storm sediment transport in the WD scenario is deposited below MHW.

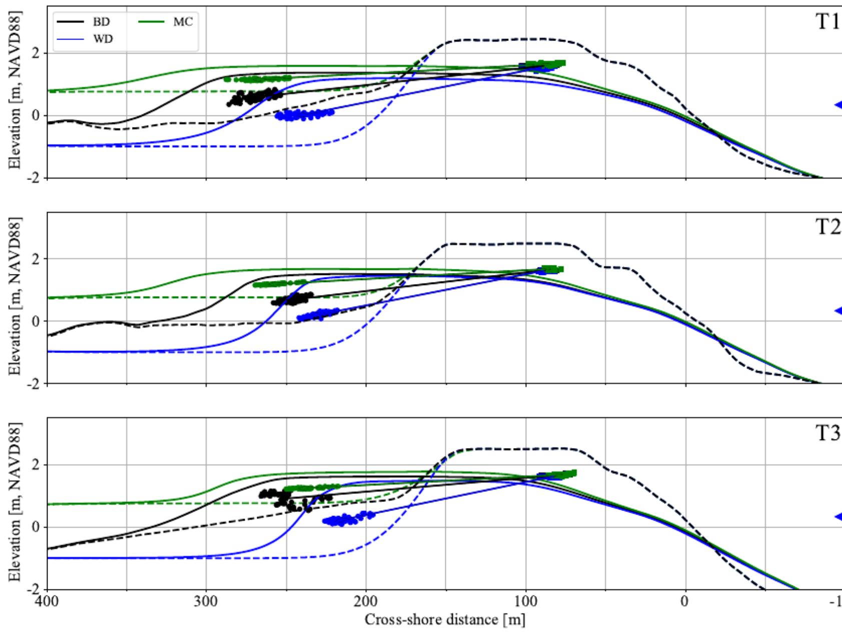

Fig. 7. Alongshore averaged transport of dune volume at sample transects T1, T2, and T3. The BD, MC, and WD restoration scenarios are represented with black, green, and blue lines. The pre- and post-storm profiles are shown as dashed and solid lines respectively. Centroids of the pre-storm dune volume and post-storm deposition are indicated with squares and circles, respectively. The displacement between the two is indicated with an arrow.

Impact Regimes

Figures 8 is a timestack showing the morphological and forcing evolution at profile T1 under the 100 year storm conditions within the BD scenario. Panel a shows the profiles after each impact regime with cross-sectional area changes during different impact regimes, where yellow, orange and red colors indicate the profiles after collision, overwash and inundation regimes from Sallenger (2000), respectively. Panel b shows the mean water level and dune crest elevation time series. Panel c in the same figure shows time series of cross-shore velocity at MHW, and panel d presents the time stack of bed level changes.

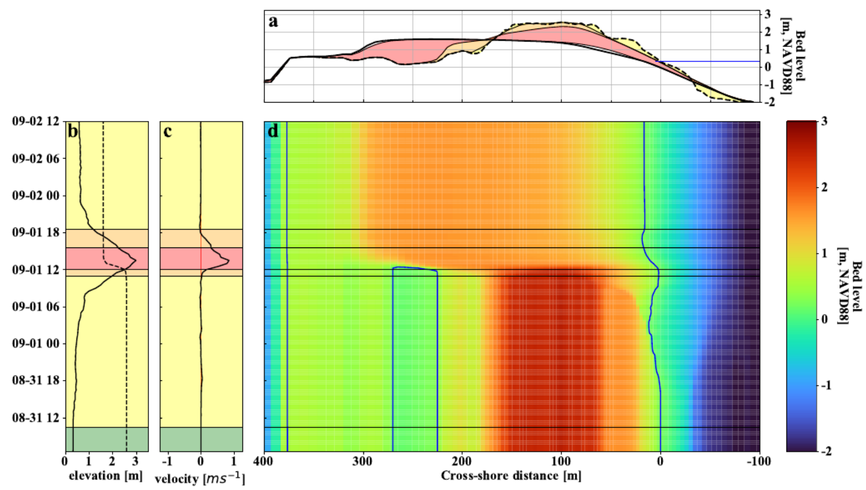

Fig. 8. Cross-shore bed level evolution at T1 for the BD scenario under 100 year stormconditions. (a) Cross-shore profiles and MHW (blue line). The dashed and solid black lines are the initial and final bed levels, respectively. The yellow, orange, and red areas indicate profile change over the first collision, overwash, and inundation regimes, respectively. (b) Time-series of water level (solid) and zdc elevations (dashed). (c) Time-series of cross-shore current velocity at the shoreline in (a). The green, yellow, orange, and red shaded areas in (b) and (c) indicate the swash, collision, overwash, and inundation regimes, respectively. (d) Time-stack of bed levels showing the profile's evolution with the MHW contour (blue line) for reference.

During the 100-year return period storm, profile T1 is within the collision regime for approximately 24 hours before a two-hour long overwash regime. Cross-shore velocity at the MHW contour of the initial profile, starts increasing during the overwash regime, and accelerates sharply once the dune is inundated (red shaded area). Most of the sediment transport occurs during the inundation regime which lasts approximately 4 hours. The eroded dune sediment forms a washover deposit landward of the pre-storm dune. No significant flow reversal occurs in the 100 year storm conditions. Overall, most of the sediment transport occurs during the inundation regime, and the deposition pattern is linked to the accommodation space in the backbarrier, which depends on the backbarrier's pre-storm topography.

Domain-Wide Morphodynamics

To holistically assess the effect of the different restoration scenarios on the CH, change in the pre- and post-storm subaerial sediment volume is plotted along the CH's shoreline in Figure 9. Subaerial volume calculations were limited to grid cells with elevations above MHW which were contiguous with the main barrier sand body. The net change in subaerial volume was calculated at cross-shore grid lines between the input and output topography.

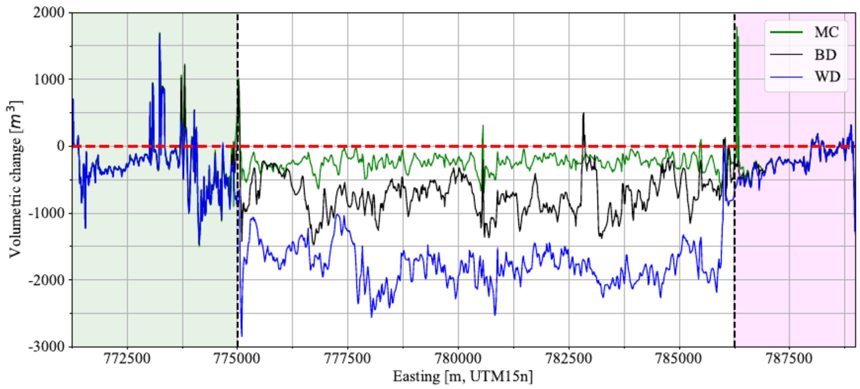

Fig. 9. Net volumetric change over the 100 year storm event as a function of alongshore distance. The BD, MC, and WD restoration scenarios are shown as black, green, and blue lines, respectively. The green shared area indicates a protected stretch of the CH and the magenta area indicates an area affected by inlet processes.

The green and magenta areas indicate the shoreline sections that are protected by structural defenses and involved with inlet/spit processes, respectively. Volumetric change in the central CH exhibited distinct morphological responses to the restoration scenarios. The MC restoration uniformly sustained relatively small volumetric change; volumetric decreases rarely exceed 500 m^3. On the other hand, sediment loss from the dunes in the WD scenario ranges between 1500 m^3 and 2250 m^3. Volumetric sediment loss in BD falls between those of the MC and WD scenarios with most of the central shoreline exhibiting volumetric changes between -500 m^3 and -1000 m^3.

The net change in dune crest elevation along the CH shoreline, shown in Figure 10, is similar to that of the volumetric change. Similar to the alongshore variation of the volumetric change, WD shows the greatest impact, followed by BD with MC being the least impacted. However, the relative differences between scenarios are smaller compared to the volumetric change. Throughout most of the central CH, dune crest elevation in the MC scenario was lowered by at least 0.75 m. The WD scenario sustained large dune lowering with net changes on the order of a meter, while the BD restoration typically varied between -0.75 m and -1.0 m. In addition, there appears to be a trend in which the difference between the MC and WD scenarios increases along the eastern part of CH's shoreline. Dune crest lowering increases for the WD scenario and decreases for the MC, which conceivably indicates that marsh creation is more important in this part of the domain.

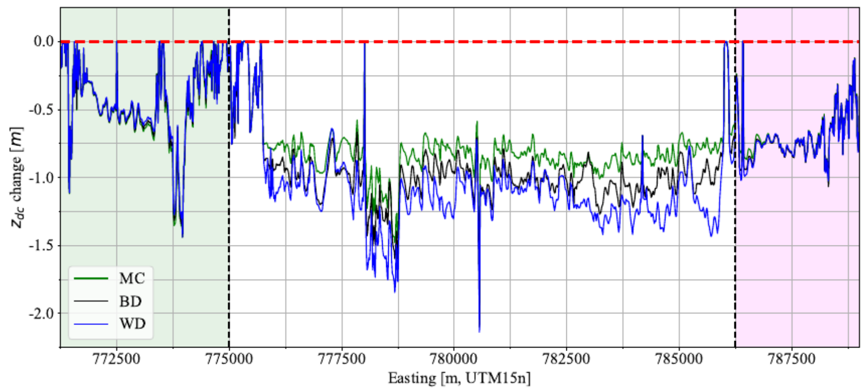

Fig. 10. Net dune crest elevation change over the 100 year storm event as a function of alongshore distance. The BD, MC, and WD restoration scenarios are shown as black, green, and blue lines, respectively. The green shared area indicates a protected stretch of the CH and the magenta area indicates an area affected by inlet processes.

Discussion

The sediment transport results from the 100-year storm conditions clearly demonstrate the benefit of restoring/creating backbarrier marshes in barrier systems that are likely to experience inundation and/or overwash regimes during a storm. Figures 9 and 10 show that the presence of a backbarrier marsh systematically reduces storm impacts. The benefits of reducing dune lowering across the domain are obvious as a higher post-storm dune crest elevation is less vulnerable to subsequent impacts.

Barrier island restoration projects typically set a specific barrier elevation at the end of its design lifetime. If, in the project design, it is assumed that overwash and inundation events are probable, it can be expected that the backbarrier wetlands will help mitigate dune crest lowering during those events. The target elevation at the end of its design lifetime can then be accomplished with a lower initial beach and dune template. In addition, the design lifetime of the restoration could be extended (e.g., from 20 years to 25 years) adding value to the cost of the project's construction.

Sub-aerial volumetric change is less negative in scenario MC and Figure 7 indicates that washover sediment is deposited at a higher elevation relative to the pre-storm dune. This situation is advantageous to achieve long-term resilience of restored barrier against storm-induced erosion. Since washover deposition is kept at a higher elevation in the tidal frame, i.e., higher relative to MSL, eroded sediment deposits will readily be available for natural and anthropogenic post-storm recovery processes. The subaerial sediment can then be used to rebuild the target dune elevation or can serve as a source for aeolian recovery processes.

Conclusions

A physics-based sediment transport-morphodynamic model was used to simulate the event-scale morphodynamic changes under real and synthetic tropical cyclone conditions at the Caminada Headlands, Louisiana after a large-scale beach and dune restoration. Two tropical cyclone conditions were simulated: (1) forcing identical to those of Hurricane Gustav (2008); (2) storm conditions for 100-year return period along Hurricane Gustav's storm track. In addition to the actual post-restoration scenario, two hypothetical scenarios were considered. These alternative scenarios assess the influence of the backbarrier's land cover and elevation on landward sediment transport. The first incorporated a marsh creation and the second considers a marsh which has completely deteriorated and converted into open water.

The results indicate that the Caminada Headlands Beach and Dune Restoration could sustain the impact of a Hurricane Gustav-like storm, regardless of backbarrier restoration. The morphodynamics of the 100-year storm conditions, which produced overwash and inundation regimes, show considerable differences depending on the restoration scenario. In general, the presence of a restored backbarrier marsh reduced the subaerial volume loss and dune crest elevation lowering compared to those with an un-restored marsh and open-water backed beach and dune creation. These results suggest that incorporating backbarrier marsh creation into beach and dune restoration projects at low-lying barriers which experience frequent overwash may increase the barrier system's resiliency to storm impacts.

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