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Key Points:
- Decadal barrier island behaviors shift in response to changes in sea level and storminess
- Increased sea levels and storminess may cause island deflation and increase vulnerability to breaching
- Barrier island drowning may occur in a duration of only 10 years under high storminess and sea level rise

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The Roles of Storminess and Sea Level Rise in Decadal Barrier Island Evolution

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Abstract Models of alongshore sediment transport during quiescent conditions, storm-driven barrier island morphology, and poststorm dune recovery are integrated to assess decadal barrier island evolution under scenarios of increased sea levels and variability in storminess (intensity and frequency). Model results indicate barrier island response regimes of keeping pace, narrowing, flattening, deflation (narrowing and flattening), and aggradation. Under lower storminess scenarios, more areas of the island experienced narrowing due to collision. Under higher storminess scenarios, more areas experienced flattening due to overwash and inundation. Both increased sea levels and increased storminess resulted in breaching when the majority of the island was not keeping pace and deflation was the dominant regime due to increased overtopping. Under the highest storminess scenario, the island was unable to recover elevation after storms and drowned in just 10 years.

Plain Language Summary Barrier islands protect mainland coastal communities during storms. In the future, the effects of storms and sea level rise (SLR) threaten barrier islands with increased inundation and loss of land. Barrier islands can keep pace with SLR by moving sand across the island during storm events to maintain height and width. However, if storms are too intense or sea levels are too high, the island may drown. This study uses computational models to assess the future response of a barrier island to higher sea levels and changes in frequency and intensity of storms (storminess). We found that the barrier island exhibits five behaviors in response to storms and SLR: keeping pace by maintaining height and width, losing width but maintaining height, losing height but maintaining width, losing height and width, and gaining height and width. These behaviors shifted based on the amount of SLR and storminess. Both increased SLR and increased storminess resulted in less of the island keeping pace and more of the island losing height and width; in some cases, this caused channels to be cut through the island. Under the most frequent and intense storm scenarios, the island lost significant amounts of land and was unable to recover.

1. Introduction

Hydrodynamic processes such as tides, waves, and hurricane storm surge can reshape barrier islands over time scales ranging from hours to days. During extreme storm events, water levels interact with coastal morphology resulting in swash erosion (minor sand loss on the beach), collision (erosion of the dune face with sand transported offshore), overwash (overtopping of the dune crest with sand transported landward and deposited on the backside of the island), and inundation (which can result in breaches) (Sallenger, 2000; Stockdon et al., 2007, 2012). Over decadal time scales, the combination of short-term perturbations such as storms and long-term drivers such as sea level rise (SLR) can result in geomorphic threshold crossings that may be irreversible (Moore et al., 2010). Barrier islands can keep pace with SLR through landward migration (rollover) due to overwash deposition while maintaining geometry. If barrier islands are unable to keep pace with SLR, they may drown by flattening (height drowning) if the island is unable to maintain the subaerial height or by narrowing (width drowning) if the island undergoes rapid shoreline retreat and narrowing (Ciarletta et al., 2019; Lorenzo-Trueba & Ashton, 2014; Miselis & Lorenzo-Trueba, 2017).

Most studies of long-term barrier island evolution focus on time scales ranging from decades to millennia and rely on idealized models with simplified processes (e.g., Lorenzo-Trueba & Ashton, 2014) or behavior-oriented cross-shore models (e.g., Moore et al., 2010). High-resolution, two-dimensional modeling of decadal barrier island evolution that accounts for the effects of multiple storm events, poststorm recovery, and fair-weather conditions is complex due to computational demands and the lack of a single model capable of describing multiple processes that occur over varying time scales. Further, detailed modeling assessments of decadal-scale morphologic evolution in the context of a changing climate are limited. This study assesses the roles of increased SLR and storminess on decadal barrier island evolution through use of high-resolution modeling and realistic climatologic scenarios. A novel framework for integrating models of alongshore sediment transport during quiescent conditions, storm-driven morphology, and poststorm recovery is developed for simulations of decadal island evolution under scenarios of increased sea levels and variability in storm intensity and frequency. The model results are used to examine how the barrier island responds to a range of climate scenarios.

2. Study Area

Dauphin Island is a 25-km long, low-lying barrier island located offshore of the Alabama coast between the Gulf of Mexico and Mississippi Sound. Most of the island is a narrow (minimum width of 169 m) Holocene sand spit backed by marshes; on the wider (2 km width) eastern end, high dunes are backed by maritime forest. Longshore currents supply sand to the western end, resulting in lateral spit growth (Morton, 2008). The island has been severely impacted by extreme storm events including Hurricane Ivan (2004) which caused extensive overwash and Hurricane Katrina (2005) which breached the middle of the island. Following the Deepwater Horizon oil spill in 2010, a rubble mound structure was constructed to close the Katrina Cut. Due to its low elevation with dune heights on the order of 1.5 to 3 m, future hazards such as SLR and storms threaten the island with increased inundation, overwash, and loss of land (Bilskie et al., 2016; Passeri et al., 2016, 2018).

3. Modeling Approach

3.1. Description of Models

An integrated modeling approach was developed to understand how Dauphin Island may evolve in the future, accounting for the effects of quiescent conditions, storms, and poststorm recovery. A two-dimensional depth-averaged Delft3D model (Lesser et al., 2004) was used to simulate tides, waves, alongshore sediment transport, and resulting shoreline and subaqueous bed level change during quiescent conditions. The model was operated using the mormerge approach (Roelvink, 2006), which allows for simultaneous simulations of tides, waves, and sediment transport to achieve computationally efficient long-term morphologic simulations. Details on grid development, elevation sources, and model validation can be found in Jenkins et al. (2020). A two-dimensional depth-averaged XBeach model (Roelvink et al., 2009) was used to simulate storm-driven waves, water levels, and morphologic change on Dauphin Island. Details on the grid development, model parameterization, and validation can be found in Passeri et al. (2018). To account for poststorm dune recovery on the island, an empirical dune growth (EDGR) model was developed. EDGR models the cross-shore profile of the island as a sum of Gaussian function curves that represent the subaerial island platform, dunes, and berms. The model evolves the foredune of each profile based on empirical growth curves parameterized with information on the terminal dune height and dune location. Dune growth rates were calculated based on the Houser et al. (2015) sigmoid growth curves using lidar data sets from 2004 to 2015. Further information on EDGR development and validation can be found in Mickey et al. (2019).

3.2. Model Integration and Verification

The Delft3D, XBeach, and EDGR models were operated sequentially to simulate decadal barrier island evolution. To assess the coupled model performance, a hindcast of island evolution was performed for the time period of 2004 to 2015, during which there were seven tropical cyclones that made landfall within 200 km of Dauphin Island. In the sequential model operation, Delft3D was run to simulate alongshore sediment transport and resultant shoreline and bed level change occurring during time periods without storms. The model was forced with a tide and wave climatology representative of average fair-weather conditions (significant wave height <2.18 m) for the region, which was derived from tide gauge data and the European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis-Interim (ERA) model. Over the same time period, EDGR was run to simulate dune growth using the output elevations from Delft3D. In years when storms occurred, subaerial elevations from EDGR and subaqueous elevations from Delft3D were passed to XBeach, which was used to simulate storm-induced morphologic change. XBeach was forced with water levels and waves representative of each storm using a best match of the historic event to a synthetic storm from the FEMA coastal flood insurance study for the Florida Panhandle and Alabama (Lettis Consultants International, 2012). The poststorm XBeach elevations were passed back to Delft3D and EDGR, which were run until the time of the next storm. Observed elevations from 14 lidar surveys were compared with modeled island dune heights and shoreline locations at the time within the simulation when each lidar survey was taken. Over the hindcast period, the average root-mean-square error (RMSE) for the Gulf shoreline location was 59 m and the average RMSE for dune heights was 0.75 m. Additional details on the model integration, forcing, and verification can be found in Mickey et al. (2019).

3.3. Future SLR and Storm Climatology

The integrated models were used to simulate the effects of plausible scenarios of future SLR and storms on island evolution over an arbitrary 10-year period. Projections of future sea levels were derived from the U.S. Army Corps of Engineers (USACE) sea level curve calculator version 2017.55 (http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html) at Dauphin Island gauge station 8735180. The selected low (0.3 m), intermediate (0.5 m), and high (0.96 m) scenarios (herein referred to as SL1, SL2, and SL3, respectively) are not meant to represent a specific year but rather correspond to different future times for different projected rates of SLR. In addition to SLR, variability in storm occurrence accounting for both frequency and intensity (herein referred to as storminess) was considered. Storm sequences over a 10-year time period were generated using the FEMA synthetic storms and a Monte Carlo sampling method developed by USACE in which random selection from a Poisson distribution was used to identify 1,000 sequences of storms (realizations). These realizations were run through a 1-D proxy model that includes processes of storm erosion and dune recovery. Realizations were binned by the number of storms for which the runup exceeded the dune crest (corresponding to overwash and inundation regimes; Sallenger, 2000), resulting in four storminess scenarios (ST1, ST2, ST3, ST4). This method simultaneously accounts for the effects of storm intensity and frequency in categorizing storminess; because dune crest exceedance is calculated using a dune height that evolves in time, it includes the influence of prior storm frequency and intensity. Further details on the development of the storm climatology can be found in Mickey et al. (2020). Between the three SLR scenarios and the four storminess conditions, a total of 12 climate scenarios were considered. The integrated model inputs and outputs can be found in Mickey et al. (2020).

4. Results

For each of the 12 climate scenarios, the modeled island elevations at the end of the 10-year simulation period are shown in Figure 1 and the differences between the initial (Year 0) and final (Year 10) island elevations are shown in Figure 2. Under the lowest storminess scenario (ST1), the island remains intact and elevation changes are confined mostly to the berm and foreshore. Increased SLR results in higher magnitudes of shoreline erosion and nearshore deposition. This is also seen in ST2-SL1 and ST2-SL2. In ST2-SL3, there is erosion across the foredunes with deposition on the backbarrier indicating overwash and breaches in the areas immediately east and west of the rubble mound structure with sand deposition in the Mississippi Sound. In the ST3 scenarios, there is overwash of the foredunes with deposition on the backbarrier shoreline. Similar to ST2-SL3, in ST3-SL3 there are breaches immediately east and west of the rubble mound structure. The highest storminess scenarios (ST4) have the most notable changes in island elevation. There is widespread erosion across the island due to significant breaching with deposition landward of the initial island footprint in shallow subaqueous fans within the Mississippi Sound. The widths of the breaches increase with higher SLR and the majority of the island is submerged in the ST4-SL3 scenario.

To assess the island's response to increased SLR and storminess, the change in the subaerial island width and the change in the maximum island height from Year 1 to Year 10 are calculated at cross-shore transects spanning every 25 m across the island. Additionally, the frequency (hours) that each transect is overtopped during storms over the 10-year period is calculated and shown in Figure 3. The wide eastern end is excluded

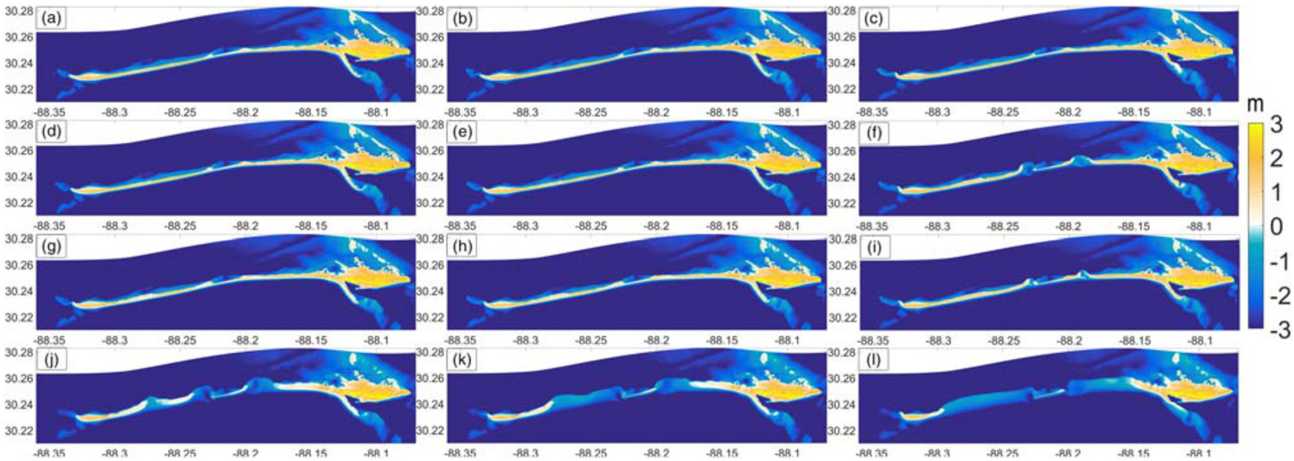

Figure 1. Modeled elevations at the end of the 10-year simulation period for ST1 (a–c), ST2 (d–f), ST3 (g–i), ST4 (j–l), and SL1 (a, d, g, j), SL2 (b, e, h, k), and SL3 (c, f, i, l).

from this analysis since this area is relatively stable due to its high Pleistocene core (Morton, 2008; Rosati & Stone, 2009). At the end of the 10-year period, the transects exhibit the following five response regimes, which are shown spatially in Figure 4:

1. Maintained height and width (keeping pace).
2. Lost width but maintained/gained height (narrowing, which leads to width drowning).
3. Lost height but maintained/gained width (flattening, which leads to height drowning).
4. Lost height and lost width (herein referred to as deflation).
5. Gained height and gained width (aggradation),

Transects keep pace when the geometric configuration is maintained; for this study, this is defined as a change in island height less than or equal to ±0.12 m (the calculated bias of the XBeach model from Passeri, Long, et al., 2018) and a change in island width of ±10 m (following Gutierrez et al., 2011, which defines a stable shoreline change of ±1 m/year). Narrowing typically occurs at transects that are not overtopped, indicating that this response regime is driven by collision. During storms, collision erodes the berm and dune face and sand is transported offshore, thereby decreasing the subaerial island width. Flattening typically occurs at transects that are overtopped during storms, indicating that overwash and/or inundation are dominant. Overwash causes dune erosion with sand deposition on the backbarrier, which increases island width. Deflation is a combination of narrowing and flattening and occurs at some transects that experience collision and others that are overtopped. In this response regime, dunes are lowered during

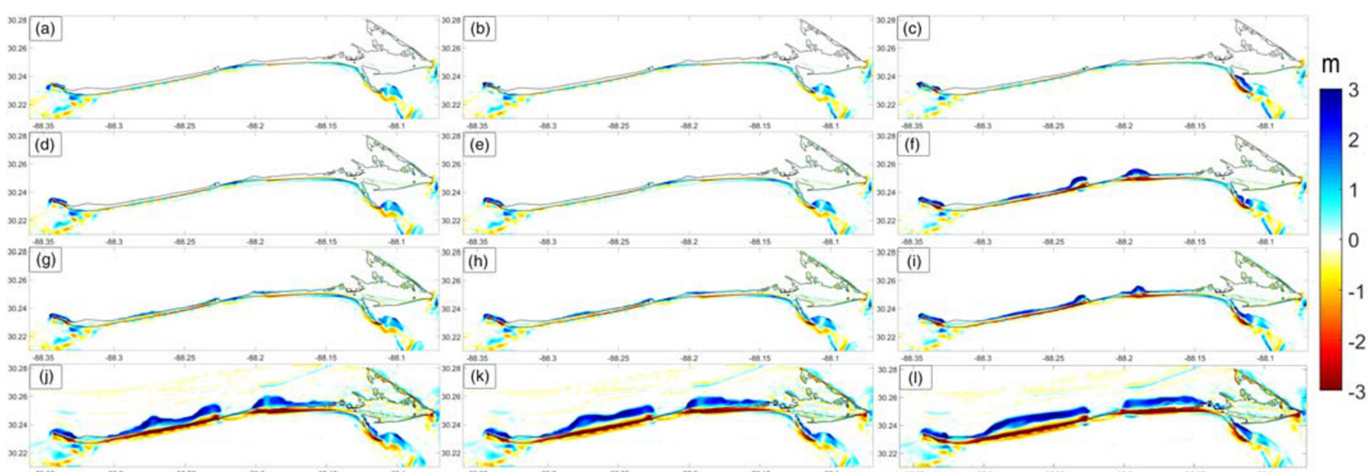

Figure 2. Difference between final (Year 10) and initial (Year 0) modeled elevations for ST1 (a–c), ST2 (d–f), ST3 (g–i), ST4 (j–l), and SL1 (a, d, g, j), SL2 (b, e, h, k), and SL3 (c, f, i, l). Warmer colors indicate erosion, cooler colors indicate accretion.

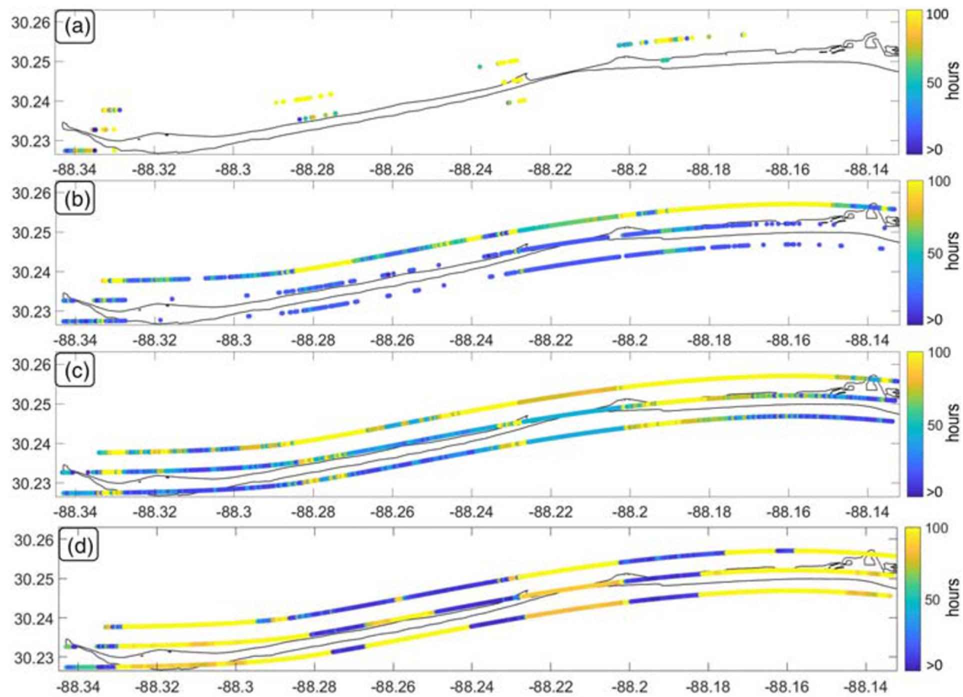

Figure 3. Overtopping frequency in hours during storm events for (a) ST1, (b) ST2, (c) ST3, and (d) ST4; lower band (SL1), middle band (SL2), upper band (SL3).

storms either through collision or overwash and eroded sand is lost to the system (i.e., deposited in the nearshore or in the back-bay). In the lower storminess scenarios (ST1 and ST2) when dunes are not overtopped during storms, deflation occurs primarily because of collision, which causes dune avalanching and shoreline erosion with sand deposited in the nearshore. In the higher storminess scenarios (ST3 and ST4) when there is overtopping, dunes are overwashed and sand is transported and deposited in the Mississippi Sound. Lastly, aggradation occurs when dune heights increase and the island widens either due to overwash or alongshore transport deposition.

Table 1 shows the percent of transects that experience each of the five barrier island response regimes for the 12 climate scenarios. Under the lower storminess scenarios (ST1 and ST2), most transects on the island keep pace, followed by either deflation or narrowing; there are minimal areas that experience flattening (<0.5% in ST1 and <2.1% in ST2). Under the higher storminess scenarios (ST3 and ST4), the majority of the island either keeps pace, experiences deflation, or experiences flattening. In the ST3 scenarios, less than 5.6% of

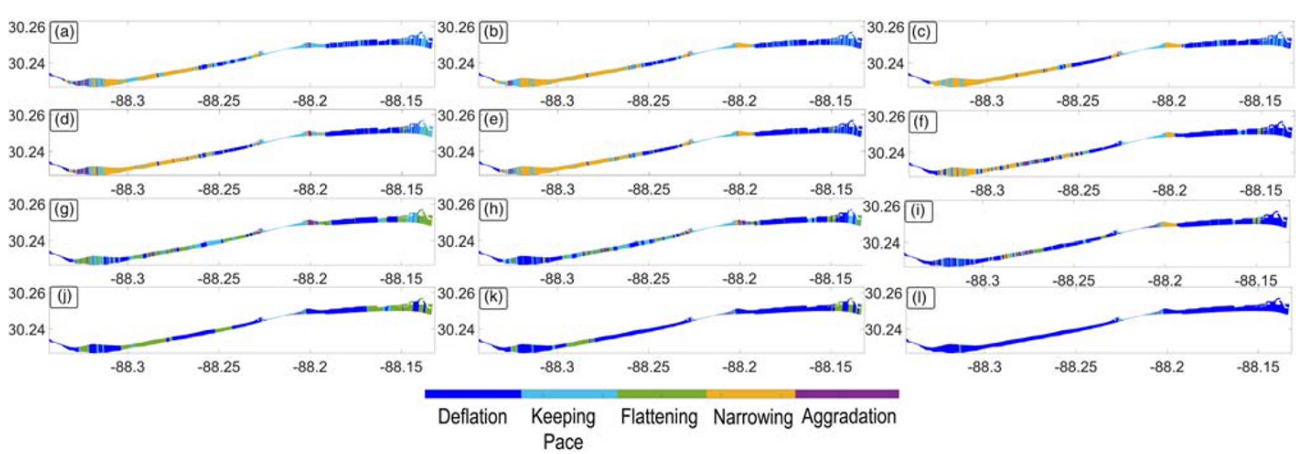

Figure 4. Barrier island response regimes for ST1 (a–c), ST2 (d–f), ST3 (g–i), ST4 (j–l), and SL1 (a, d, g, j), SL2 (b, e, h, k), and SL3 (c, f, i, l).

Table 1
Percent of Cross-Shore Transects That Exhibit Each of the Five Barrier Island Response Regimes Across the 12 Climate Scenarios of Increased Storminess and SLR

Scenario	Aggradation (%)	Narrowing (%)	Flattening (%)	Deflation (%)	Keeping pace (%)
ST1_SL1	3.5	18.6	0.5	24.0	53.4
ST1_SL2	1.2	28.5	0.0	25.9	44.4
ST1_SL3	0.5	29.2	0.0	31.6	38.7
ST2_SL1	3.5	23.1	1.2	29.7	42.5
ST2_SL2	1.1	27.8	0.6	32.7	37.8
ST2_SL3	2.6	16.5	2.1	41.6	37.3
ST3_SL1	4.5	1.1	22.7	25.8	45.9
ST3_SL2	4.3	1.6	11.9	37.2	45.0
ST3_SL3	5.1	5.6	4.7	52.2	32.3
ST4_SL1	2.6	0.0	25.8	44.3	27.3
ST4_SL2	2.4	0.0	10.2	61.3	26.1
ST4_SL3	2.0	0.0	0.4	73.1	24.5

transects experience narrowing and in the ST4 scenarios, there are no transects that experience narrowing. In the scenarios where deflation is the dominant response regime across the transects, breaches occur in the island (ST2-SL3, ST3-SL3, ST4-SL1, ST4-SL2, ST4-SL3). In all scenarios, less than 5.1% of transects experience aggradation; these transects are located either on the western spit of the island or in close proximity to the rubble mound structure, which are dynamic areas that have sand deposition from alongshore transport. ST3 results in the most aggradation as a result of overwash increasing island widths and heights at these low-lying transects.

For each storminess scenario, increased SLR results in less transects that keep pace. In ST1, higher sea levels increase the amount of transects that experience narrowing and deflation. This is also seen in the ST2 scenarios, except in ST2-SL3 due to the island breaching. In the scenarios where overtopping does not occur, higher water levels allow waves to act further on the beach profile which increases shoreline erosion and, in some cases, lowers dune heights due to avalanching. In the ST3 and ST4 scenarios, higher sea levels decrease the amount of transects that experience flattening and increase the amount of transects that experience deflation. Higher water levels cause sand to be transported further landward and deposited in the Mississippi Sound, especially in the scenarios where the island breaches.

5. Discussion

Keeping pace, narrowing, and flattening align with the long-term barrier island responses to SLR described by the Lorenzo-Trueba and Ashton (2014) morphodynamic model. In that model, barrier island response to SLR is predicted based on idealized island geometry and sediment flux parameters (Ciarletta et al., 2019; Miselis & Lorenzo-Trueba, 2017). This study uses predictive process-based modeling to define the barrier island response regime based on changes in island geometry while accounting for the effects of alongshore sediment transport, multiple storm events, and poststorm dune recovery, which are not incorporated into the Lorenzo-Trueba and Ashton (2014) model. Additionally, seaward-directed sediment fluxes driven by wave collision, which enhance subaerial deflation over decadal time scales, are also captured. Results illustrate that barrier island drowning can occur over shorter time scales (decades) than predicted by the Lorenzo-Trueba and Ashton (2014) model under realistic scenarios of increased storminess and SLR.

Deflation is characterized as a novel response regime since it is the only regime where breaching occurs. Previous research has shown that although breaching only occurs during inundation, it does not always occur (Long et al., 2014). For ST3, the island is overtopped in all scenarios but only breaches in ST3-SL3. The ST3 scenario has four storms that occur in Years 2, 4, 6, and 7. Comparison of prestorm and poststorm elevations shows that island breaches during the third storm (Year 6). Breaches are observed at the transects immediately to the east and west of the rubble mound structure, corresponding with the lowest elevations of the initial (Year 0) island geometry; this follows Long et al. (2014), which found that breaches on Dauphin Island occurred at locations with low prestorm dune heights. Prior to the Year-6 storm, the transects that were breached were experiencing deflation as a result of subsequent overtopping during storm events.

This indicates that areas that continuously lose height and width due to storm inundation are vulnerable to breaching. Once breaching occurs, the island may not be able to recover and may lose additional land in subsequent storms, resulting in drowning. In the ST4 scenarios, the island breaches during the first storm event which occurs in Year 3 and sand is deposited landward in the Mississippi Sound. The island is unable to rebuild elevation before the occurrence of the next storm and subaqueous sand is transported further landward in shallow fans as storms continue.

In all 12 of the climate scenarios, the island in its entirety is unable to keep pace and loses subaerial volume over the 10-year simulation period. Shifts in the response regimes between scenarios illustrate the relative impacts of storminess and SLR on loss of land. As seen in the ST2 and ST3 scenarios, increased sea levels can result in breaching when the majority of the island is no longer keeping pace and more locations experience deflation due to increased overtopping during storm events. Similarly, increased storminess can result in breaching due to higher storm-induced water levels causing overwash and inundation. Both increased storminess and increased SLR result in less collision and more overwash and inundation during storm events. Compared to collision, overwash leads to a larger reduction in dune heights, which increases vulnerability for future storms (Long et al., 2014). This was seen in the highest storminess scenario which resulted in catastrophic land loss and drowning when the island was unable to recover after the first storm.

Although the response regimes may vary through time (e.g., a transect may narrow completely before losing height), characterizing the response based on the total change over the 10-year simulation period provides a more holistic understanding of how the island is failing over coastal engineering design time scales and can inform restoration strategies based on coastal management risk tolerance. For example, considering a lower storminess scenario (and therefore higher risk tolerance), the island is less likely to be overtopped and more likely to experience narrowing. Restoration scenarios such as beach nourishment may be beneficial for restoring island widths. Considering a higher storminess scenario (and therefore lower risk tolerance), the island is more likely to be overtopped during storms and experience flattening. These areas may benefit from dune rebuilding to elevate the island. For areas that are susceptible to deflation, a combination of beach and dune nourishment may be advisable. Additionally, since areas that experience deflation are vulnerable to breaching, monitoring shoreline positions and island elevations can aid in identifying areas that may breach prior to future storms.

6. Conclusions

Decadal simulations of barrier island evolution were conducted using a novel integrated modeling framework to simulate alongshore sediment transport during quiescent conditions, storm-driven barrier island morphology, and poststorm dune recovery under 12 climate scenarios. Model results confirmed the barrier island responses of keeping pace, narrowing, flattening, and aggradation as found in previous studies, and introduced deflation as a novel response. Both increased storminess and increased SLR caused less of the island to keep pace and more of the island to experience deflation. Lower storminess resulted in more of the island experiencing narrowing whereas higher storminess resulted in more of the island experiencing flattening. In scenarios where deflation was the dominant response regime, breaching occurred. Under the highest storminess scenario, the island was unable to recover elevation after the first storm and became vulnerable to increased loss of land in subsequent storms. The study illustrated that barrier island drowning can occur over shorter time scales (10 years) as opposed to centennial scales as observed in previous studies. The results of this study provide a better understanding of the decadal response of barrier island to storms and SLR.

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