2017

Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise

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MSU Digital Commons Citation
Miselis, Jennifer and Lorenzo Trueba, Jorge, "Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise" (2017). *Department of Earth and Environmental Studies Faculty Scholarship and Creative Works*. 33.
https://digitalcommons.montclair.edu/earth-environ-studies-facpubs/33

Published Citation
Miselis, J. L., & Lorenzo-Trueba, J. (2017). Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise. Geophysical Research Letters, 44(23), 11922-11931. doi:10.1002/2017gl074811

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL074811

Key Points:
- Observations combined with a morphodynamic model forecast barrier island response to sea level rise (SLR)
- For a moderate SLR rate, 28% of the barrier island is forecast to be vulnerable to SLR
- Human alterations to barrier-estuary geomorphology and sediment fluxes increase vulnerability to SLR and may accelerate drowning

Supporting Information:
- Supporting Information S1

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Citation:
Miselis, J. L., & Lorenzo-Trueba, J. (2017). Natural and human-induced variability in barrier-island response to sea level rise. *Geophysical Research Letters*, *44*, 11,922–11,931. https://doi.org/10.1002/2017GL074811

Received 31 JUL 2017
Accepted 17 NOV 2017
Accepted article online 20 NOV 2017
Published online 11 DEC 2017

Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise

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Abstract Storm-driven sediment fluxes onto and behind barrier islands help coastal barrier systems keep pace with sea level rise (SLR). Understanding what controls cross-shore sediment flux magnitudes is critical for making accurate forecasts of barrier response to increased SLR rates. Here, using an existing morphodynamic model for barrier island evolution, observations are used to constrain model parameters and explore potential variability in future barrier behavior. Using modeled drowning outcomes as a proxy for vulnerability to SLR, 0%, 28%, and 100% of the barrier is vulnerable to SLR rates of 4, 7, and 10 mm/yr, respectively. When only overwash fluxes are increased in the model, drowning vulnerability increases for the same rates of SLR, suggesting that future increases in storminess may increase island vulnerability particularly where sediment resources are limited. Developed sites are more vulnerable to SLR, indicating that anthropogenic changes to overwash fluxes and estuary depths could profoundly affect future barrier response to SLR.

Plain Language Summary Barrier islands, thin strings of islands offshore of mainland coasts, are the first line of defense for protecting estuaries and mainland population centers from storms. They are also important for tourism that drives many coastal economies. Sand movement to the top of and across barrier islands is how they keep pace with sea level rise (SLR), so restrictions to those processes may make barrier islands more vulnerable to SLR effects. In our study, we used observations from New Jersey, USA, as inputs to a model that forecasts barrier island changes in response to SLR. This is particularly important for New Jersey, which is expected to experience rates of relative SLR that are higher than average. We found that 28% of the barrier island was vulnerable to a moderate rate of SLR and 100% of the barrier island was vulnerable to a high rate of SLR. Furthermore, we found that barrier island vulnerability increased in heavily populated locations relative to less populated locations. This suggests that human changes to coastal systems likely impact the lifespan of barrier islands. If some barrier islands degrade faster than others, their ability to protect mainland coasts and sustain coastal communities and economies could be compromised.

1. Introduction

Most barrier islands formed and evolved during the last 6,000 years (McBride et al., 2013) when rates of sea level rise (SLR) were lower compared to the early Holocene (Fleming et al., 1998; Kemp et al., 2011; Khan et al., 2015; Milne et al., 2005). Given increased SLR rates forecast for the future (Church et al., 2013; Jevrejeva et al., 2014; Kopp et al., 2014; Miller et al., 2013), there is interest in predicting how these highly dynamic landforms will respond (Lentz et al., 2016). This is a challenging problem because it requires the integration of episodic, cross-shore processes (e.g., storms; Plant & Stockdon, 2012) with long-term processes (e.g., SLR; Lentz et al., 2016) that are often addressed separately (Roelvink, 2015). Perhaps more important, however, is the recognition that humans interact with these coastal landscapes (Lazarus et al., 2016; McNamara et al., 2011; McNamara & Werner, 2008a, 2008b; Nordstrom, 2000), ultimately altering coastal morphology and sediment fluxes (Miselis et al., 2016; Rogers et al., 2015). This suggests that barrier islands may not evolve as they have over observable geological and historical time scales, further complicating forecasts of future behavior.

In response to these challenges, simplified morphodynamic models have been used to evaluate sensitivity of barrier island response to SLR to controlling factors, such as coastal geology and morphology (Moore et al., 2010; Wolinsky & Murray, 2009), coastal development (McNamara & Werner, 2008a, 2008b; Rogers et al., 2015), and cross-shore sediment fluxes (Lorenzo-Trueba & Ashton, 2014). Simplification of coastal systems is achieved through various assumptions, such as alongshore-uniform morphology, idealized or geometric cross-shore morphology, and/or assuming the dominance of either cross-shore or alongshore sediment transport. These steps may allow for identification of primary influences on rates of barrier retreat (Moore et al., 2010) and exploration of a range of possible response outcomes (Lorenzo-Trueba & Ashton, 2014) and how they change due to land-use-related reductions in overwash flux (Rogers et al., 2015). However, they can also make it difficult to determine the extent to which model results have real-world relevance, particularly for areas with significant spatial variability in coastal development, morphology, and geology.

In this paper, we attempt to bridge the gap between exploratory modeling results (Murray, 2003) and possible real-world outcomes by combining site-specific geomorphological and storm-response observations with a simple, long-term morphodynamic model. In doing so, we are able to explore how alongshore variability in island-estuary geomorphology and sediment fluxes influences modeled barrier response to SLR. The model forecasts millennial-scale (~2,000 years) barrier island behavior given cross-shore fluxes, barrier-estuary morphology, and rates of SLR, and we constrain these values based on empirical pre- and post-Hurricane Sandy observations from coastal New Jersey, USA. Because observations span both natural and developed environments, we evaluate the impact of human alterations to the coastal system on possible long-term barrier behavior. Though the integration of short-term observations and long-term, highly simplified modeling cannot provide explicit outcomes for any location, this exercise explores how varying combinations of coastal geometry, overwash fluxes, and development may contribute to future barrier island vulnerability to SLR.

2. Data and Methods

2.1. Study Area and Observational Data

The study area is located in New Jersey in the Mid-Atlantic Bight on the eastern coast of the U.S. (Figures 1a and 1b). It includes Barnegat Bay, a back-barrier estuary, and Island Beach, a barrier spit, which ends at Barnegat Inlet. Island Beach State Park occupies the southernmost 15 km of Island Beach and represents an undeveloped barrier system relative to the highly developed coast north of the park (Figure 1c). This transition allowed for exploration of spatial differences in island-estuary characteristics and modeled barrier island response regimes between developed and undeveloped coastlines.

Estuarine bathymetry data targeting water depths less than 1.5 m were collected over 4 days between 18 and 26 October 2012, the last survey occurring 3 days before Hurricane Sandy made landfall south of Atlantic City, NJ, on 29 October 2012 (Wright, Troche, Klipp, et al., 2014). Post-Sandy estuarine bathymetry data were collected between 1 November 2012 and 10 January 2013 (Wright, Troche, Kranenburg, et al., 2014). Estuarine depths greater than 1.5 m were mapped during three boat-based surveys from November 2011 to March 2013 (Andrews et al., 2016). In combination, these data sets were used to calculate magnitudes of estuarine deposition resulting from Sandy's impacts to the barrier. Coastal topographic data were collected 3 days prior to and 1–5 days after landfall to estimate beach and dune volume change every 10 m alongshore (Sopkin et al., 2014). Geomorphological characteristics of the coastal system were extracted from a topobathymetric terrain model (Andrews et al., 2015, Figure 1b) along 50 m spaced ocean shoreline-perpendicular transects, which were also used to extract storm-related estuarine deposition and beach and dune volume losses.

2.2. Morphodynamic Model

The morphodynamic model focuses on three coastal components: the active shoreface on the ocean side, the subaerial barrier island, and the back-barrier lagoon on the terrestrial side, where infrequent overwash processes control landward mass fluxes between these different components (Lorenzo-Trueba & Ashton, 2014 or LTA, 2014). Long-term barrier behaviors captured by the model include width drowning, height drowning, and keeping pace with sea level (i.e., rollover). Width drowning occurs when overwash fluxes largely exceed onshore-directed fluxes at the shoreface, which results in rapid shoreline retreat and unsustainable island narrowing. Height drowning occurs when overwash fluxes are insufficient to maintain the subaerial portion of the barrier and the height eventually goes to zero. To keep pace with SLR, overwash and shoreface fluxes are balanced and sufficiently high to maintain barrier geometry as it migrates landward. We modified the model approach presented by LTA (2014) to account for an averaged maximum depth instead of a linear lagoon slope (Figure S2 in the supporting information). In this way, lagoon depth is expressed as a function of the lagoon sedimentation rate γ and the SLR rate $\dot{z}$:

$$D_B = D_{B,0} + (\dot{z} - \gamma) \cdot t, \quad (1)$$

where $D_{B,0} = D_B(t = 0)$ is the initial lagoon depth and t is time.

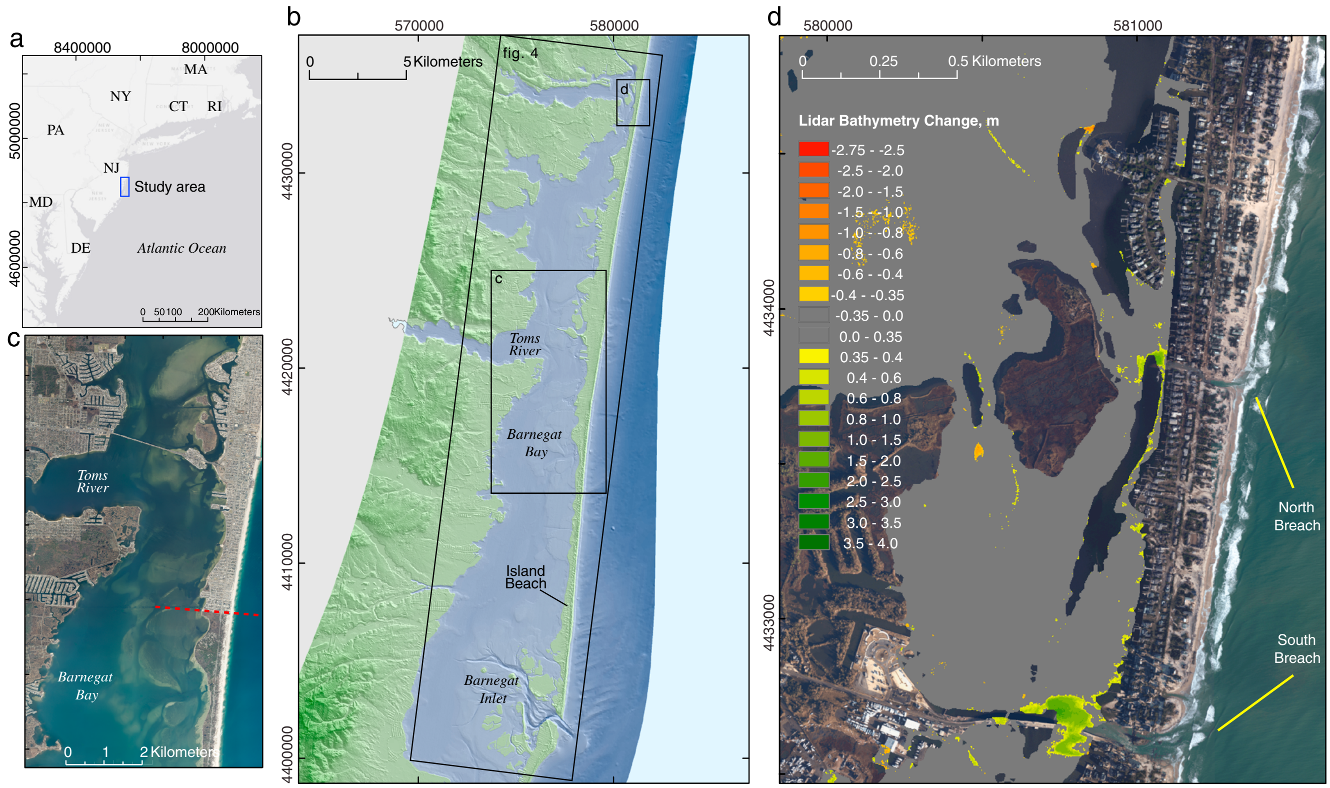

Figure 1. (a) Location of the study area in central New Jersey, spanning the inner shelf, Island Beach (barrier island), and Barnegat Bay (estuary) as shown in a (b) terrain model. (c) Note the distinct transition (red dashed line) from a highly developed barrier to the north to relatively undeveloped barrier to the south. (d) Hurricane Sandy caused erosion of beaches and dunes along the barrier island and the formation of two breaches. Storm-related overwash resulted in barrier-adjacent deposition in the estuary.

2.3. Parameter Estimation From Geomorphological and Storm-Response Observations

Geomorphology and storm response of the study area were spatially variable and influenced by barrier island development (Figure 2). Back-barrier depths were shallow with regional, undeveloped, and developed averages of 1.7, 1.4, and 1.8 m, respectively. On average, developed barrier island segments were wider and lower than undeveloped segments (Figure 2). Storm-related estuarine gains and barrier island losses also varied with barrier island development. Estuarine deposition adjacent to undeveloped barrier island was less than the regional average, whereas deposition adjacent to developed barrier was greater than the regional average. The opposite was true for beach and dune volume losses; developed regions lost less than the regional average, whereas undeveloped regions lost more. Both of these trends persist when volumes associated with breaches in the barrier island are removed from the analysis though the magnitude of the difference between developed and undeveloped regions decreases. The cause of the difference in trends is unknown; previous work suggests that the presence of back-barrier marshes in the undeveloped region allows the barrier to retain more sediment subaerially via frictional dissipation of cross-barrier flow (Miselis et al., 2016) relative to developed regions in which roads and sidewalks can serve as sediment transport conduits across the island (Miselis et al., 2016; Rogers et al., 2015).

Detailed descriptions of observational parameterizations are provided in Table S2 in the supporting information. Observed island widths, island heights, maximum estuarine depths, and overwash volumes ranged from 225 to 1,650 m, 2.8 to 9.7 m, 0.25 to 9 m, and 50 to 3,000 m^3/m (not including breaches), respectively (Figure 2). To calculate overwash fluxes, we estimated the recurrence interval for large storm events. Scileppi and Donnelly (2007) used geologic evidence of historical storm events on Long Island, NY, and identified preserved overwash deposits for four historical hurricanes since 1693. Assuming these storms had surge comparable to that measured during Hurricane Sandy and that equivalent storm surges occurred 5 times in 319 years, the return interval is 64 years. For simplicity, we divide observed overwash volumes by

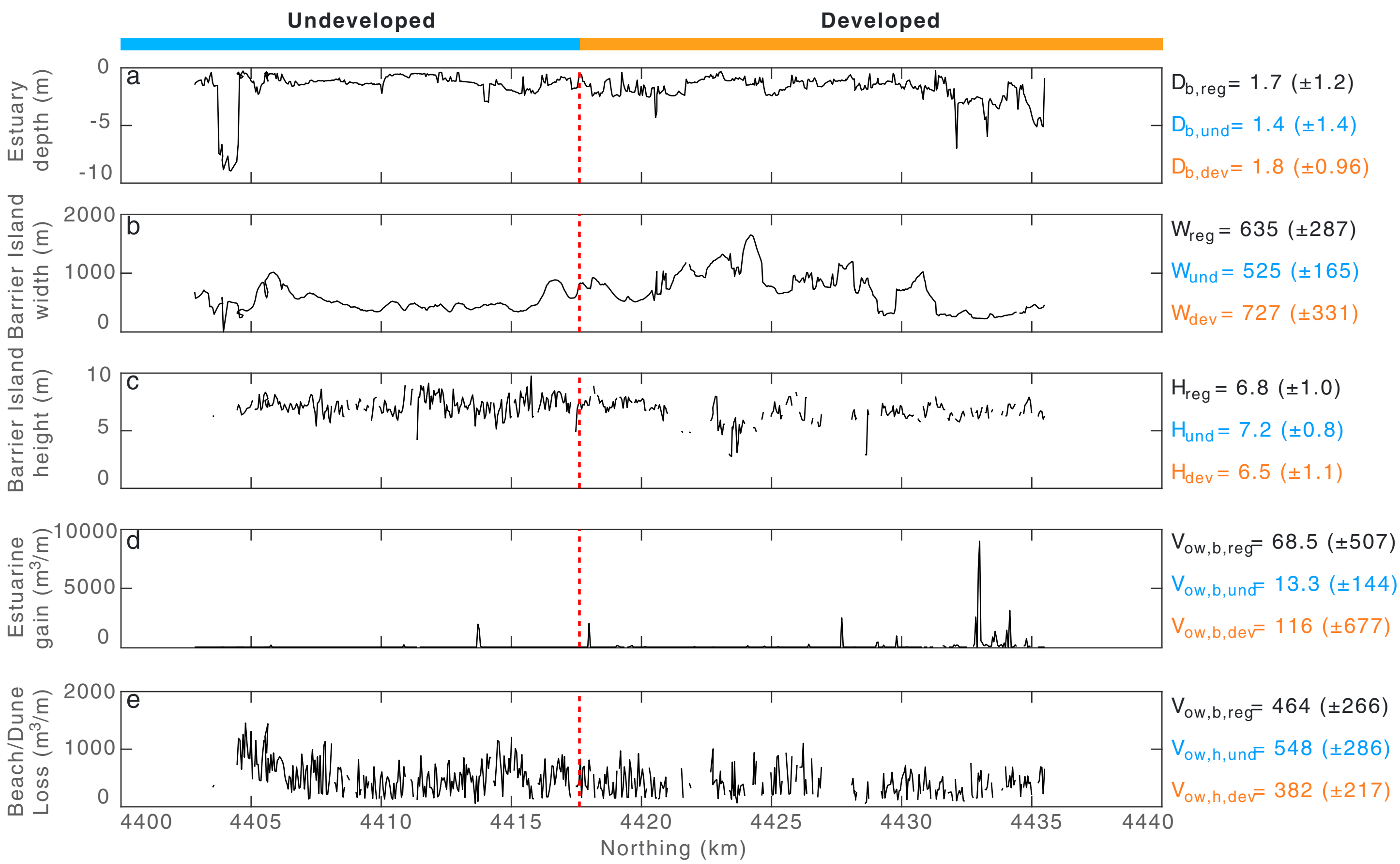

Figure 2. (a–c) Geomorphologic and (d and e) storm response observations parameterized for this analysis. Regional, undeveloped, and developed averages are reported at the right.

a return interval of 50 years, which yields maximum overwash flux rates within the range used by LTA (2014). Additionally, we simulate an increase in the frequency and intensity of tropical storms (Emanuel, 2013) by assuming a return interval of 1 year, which we consider an upper limit.

3. Results

3.1. Modeled Responses to Sea Level Rise

Modeled barrier responses to three SLR rates (4, 7, and 10 mm/yr; bases for these rates are described in the supporting information) are shown in regime diagrams and are overlain with overwash flux and estuary depth observations from developed and undeveloped sites (Figures 3a–3c). For a modeled SLR rate of 4 mm/yr, all of the sites keep pace with SLR. As the SLR rate increases to 7 mm/yr, 13% of the sites experience width drowning and 15% of the sites experience height drowning. Due to a combination of deeper back-barrier depths and lower overwash fluxes for developed compared to undeveloped areas, width and height drowning outcomes were predominantly associated with developed locations; 87% of the width drowning predictions and 62% of the height drowning predictions were associated with developed sites. When the SLR rate is increased to 10 mm/yr, all sites are unable to keep up with sea level and experience either width (78%) or height (22%) drowning, though developed areas are more likely to experience height drowning. Since model input parameters correspond to specific locations, spatial variability in modeled barrier island response regime can be shown for the study site (Figures 4a and 4b). We interpret either height or width drowning as indicators of vulnerability to SLR, particularly when the same modeled behavior is consistent alongshore (e.g., spans several transects).

To explore how increases in storm-driven, cross-shore fluxes alter modeled response regimes, we increased overwash fluxes in the model (e.g., return interval = 1 year; Figures 3d–3f), leaving all other parameters the

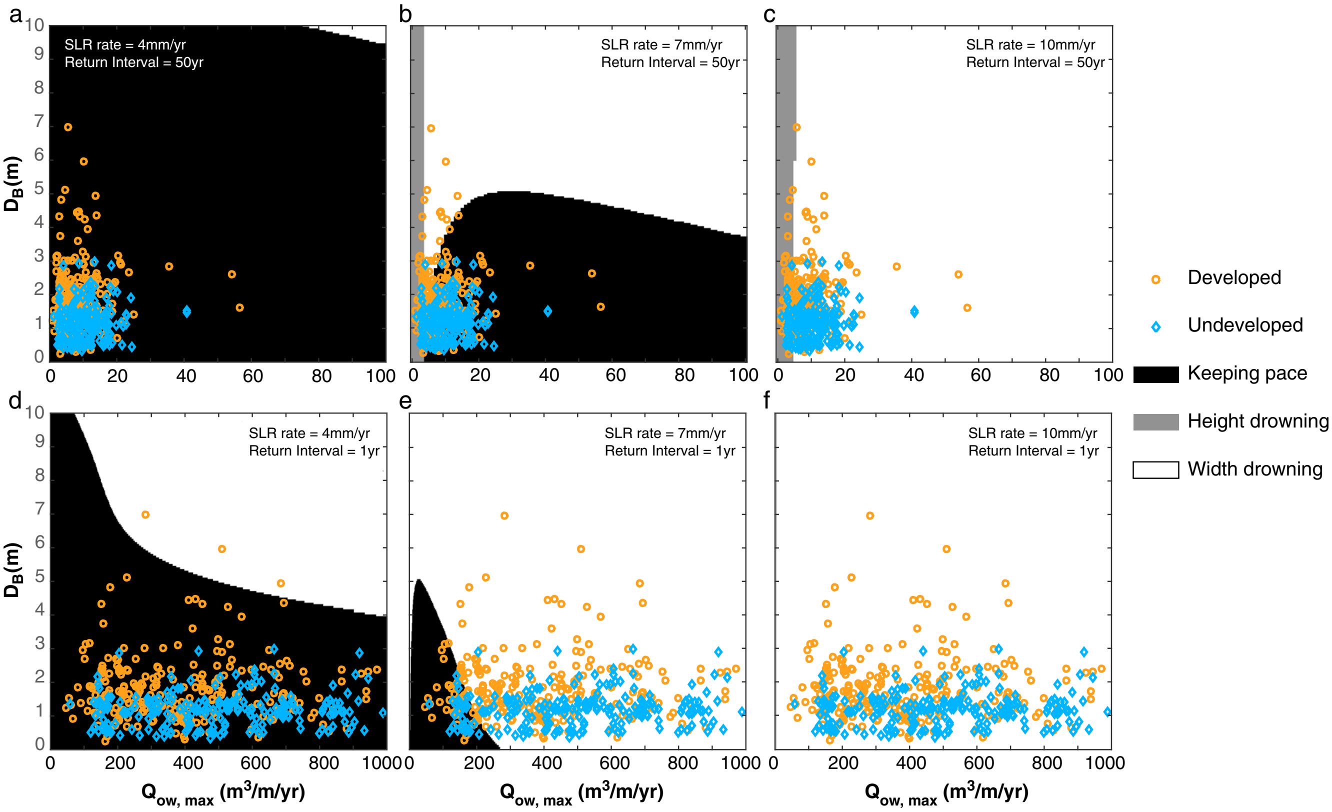

Figure 3. Modeled barrier island response to SLR given variations in maximum overwash flux, $Q_{ow,max}$ (*x* axis), and lagoon depth (D_B; *y* axis) for SLR rates of 4, 7, and 10 mm/yr for a storm return interval of (a–c) 50 years and (d–f) 1 year. The background colors indicate modeled barrier response modes: keeping pace = black; height drowning = gray; width drowning = white. Observations from undeveloped (blue diamonds) and developed (orange circles) locations are overlain on the modeled responses in order to determine barrier response for each observation pair.

same. Modeled outcomes included keeping pace and width drowning. For a SLR rate of 4 mm/yr, only extreme back-barrier depths (>regional average + 3 standard deviations or ~5 m) experience width drowning and all are developed sites. With a modeled SLR rate of 7 mm/yr, only the lowest fluxes and shallowest back-barrier depths result in the barrier keeping pace with SLR (15%), whereas the other sites undergo width drowning (85%). When the SLR rate is increased to 10 mm/yr, all sites succumb to width drowning regardless of magnitudes of overwash flux or back-barrier depth.

3.2. Human Impacts on Barrier Response to Sea Level Rise

Using regional averages for initial barrier geometry (Figure 2) and development-based input parameters (Table S3), we model long-term effects of human alterations on barrier island response to SLR. In one scenario, we assume that human modifications to the system stop at $t = 0$, and therefore, development-specific overwash rates are applied and barrier geometry evolves. Though average developed island width is greater than average undeveloped width (Figure 2), the developed barrier narrows and drowns faster than the undeveloped barrier (Figure 5a). In a second scenario, we assume that human alterations continue in the developed region for some time, T_A. During this time, the barrier is fixed in place (ocean and back-barrier shorelines are static) and the barrier does not aggrade vertically ($Q_{ow,max} = 0$). Here we assume the ocean shoreline is fixed by protection measures, such as beach nourishment and/or hard structures, and the barrier does not aggrade because whatever subaerial overwash that occurs is moved back to the beach, consistent with observations from the study area (Miselis et al., 2016; Rogers et al., 2015). We find that the longer coastal geometry is fixed (a higher T_A), the earlier width drowning occurs (Figure 5b). However, drowning is the end result of a variety of human interventions and island adjustments over ~2,000 years; the model forecasts developed ocean shoreline retreat by a distance equal to 6–45% of modern island width after ~275 years (Figures 5c and 5d; ~3–14% for undeveloped).

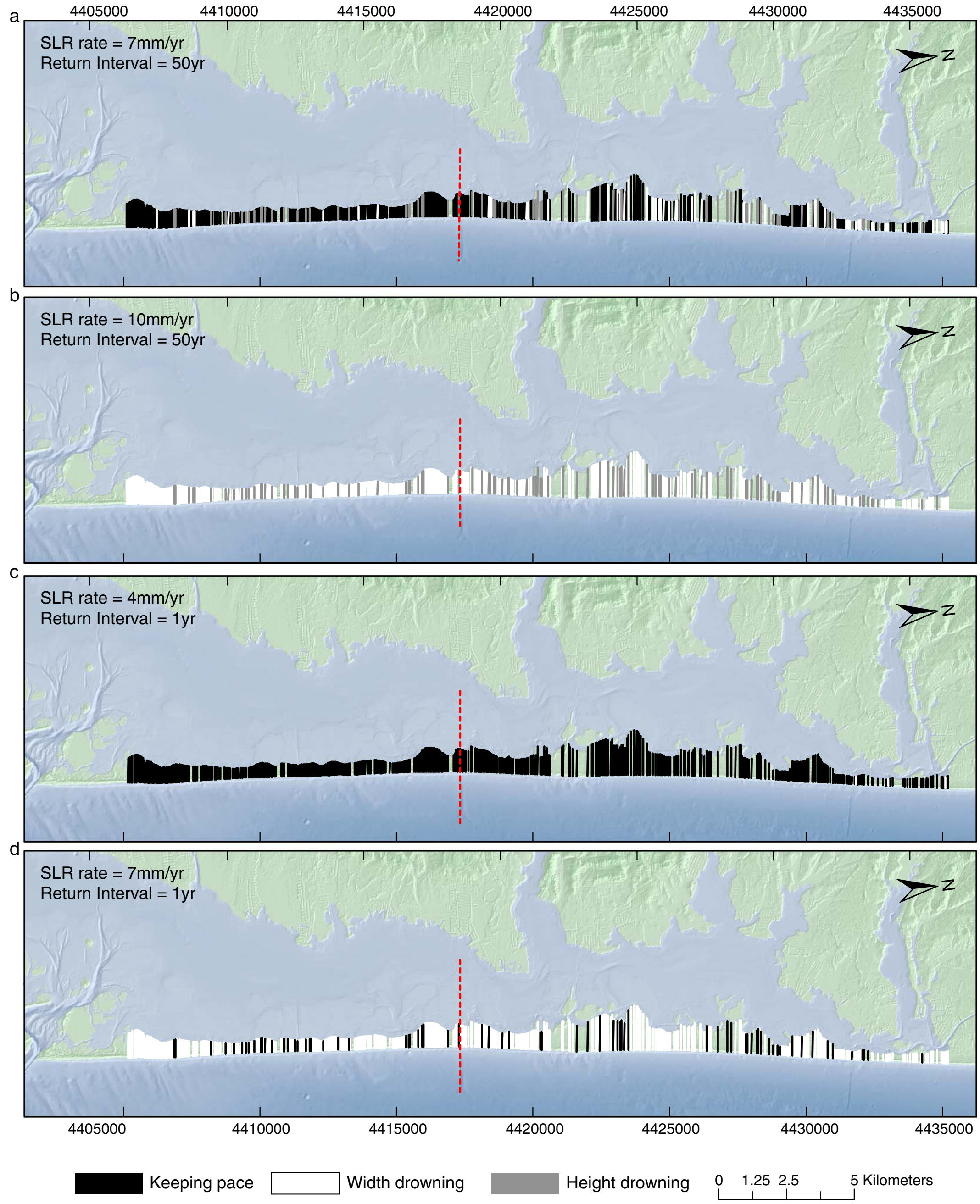

Figure 4. Alongshore-varying forecasts of barrier island response to SLR for storm return intervals of (a and b) 50 years and (c and d) 1 year and for SLR rates of 4 (Figure 4c), 7 (Figures 4a and 4d), and 10 mm/yr (Figure 4b). The dashed red line indicates the (right) developed and (left) undeveloped transition. The lines spanning the barrier indicate location of cross-shore transects; the colors indicate modeled barrier island response: keeping pace = black; height drowning = gray; width drowning = white. No color indicates no data.

4. Discussion

This study utilized geomorphic and storm-response observations as morphodynamic model inputs in order to model barrier island response to varying rates of SLR and explore the impact of human alterations to the island-estuary system on long-term barrier behavior. Though we believe the model results are more informative when constrained by observations, the intent of this effort is not to predict the location and timing of a specific response. Instead, we suggest that observation-based model output allows us to explore how

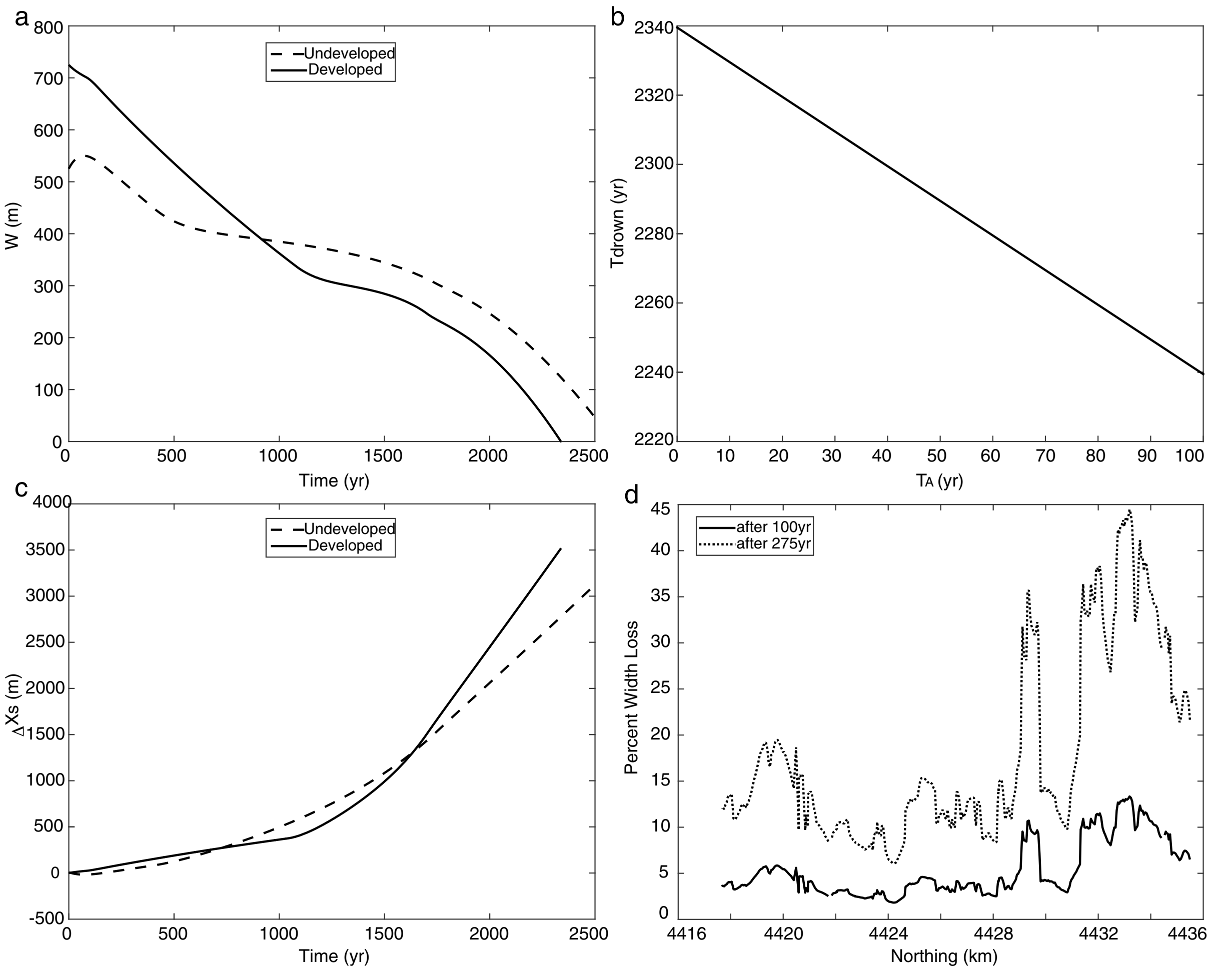

Figure 5. Modeled human impacts on (a) barrier island width and (b) time to drowning for an SLR rate of 7 mm/yr. Developed barrier drowns faster than the undeveloped barrier (Figure 5a). Drowning occurs faster if the time period of human alterations (T_A) is longer (Figure 5b). (c) The model forecasts that developed shoreline will retreat by 100 m after ~275 years. Over the same period, undeveloped barrier shoreline retreats by ~35 m (Δx_s on the *y* axis represents change in shoreline position). (d) For developed barriers, this retreat represents 6%–45% of modern barrier island width for the 275 year estimate.

reduced cross-shore sediment fluxes and variable island-estuary morphology may interact to increase barrier island vulnerability to SLR on this island and in general. By integrating storm-response fluxes with coastal geomorphology, this approach marries shorter and longer time scales to deliver a forecast for island vulnerability beyond storm time scales (Sallenger, 2000; Stockdon et al., 2007). Furthermore, this is an improvement over SLR vulnerability assessments that rely on inundation of existing coastal topography (Strauss et al., 2012), since the model allows the barrier island to dynamically adjust and, in this case, uses observations that accurately represent both natural and human-altered systems. This approach supports recent research that demonstrates that dynamic adjustment of coastal landscapes changes the likelihood of inundation (Lentz et al., 2016) by driving dynamic behavior with spatially varying cross-shore fluxes from both developed and undeveloped environments.

Despite these advantages, the model does not capture a range of processes and complexities known to influence barrier evolution. Alongshore sediment transport, for example, can diffuse the effects of cross-shore processes over time scales of months and years (Lazarus et al., 2011; List et al., 2006) to millennia (Ashton & Lorenzo-Trueba, 2015) and might reduce or eliminate localized vulnerabilities forecast by the model. However, this benefit may be diminished if alongshore sediment fluxes along engineered coastlines are restricted, such as by groins or jetties, resulting in barrier islands that are more vulnerable to cross-shore sediment flux imbalances simulated here. Furthermore, by assuming uniform sediment distribution, the model homogenizes barrier island geology, whereas natural barriers are composed of a mix of coarse and fine sediments. Any reduction in coarse sediment volume could significantly enhance barrier drowning (Brenner et al., 2015). Notwithstanding these simplifications, this initial step of bounding an exploratory model with empirical parameters is a critical one, because it allows us to explore in general ways how island-estuary geometry, overwash fluxes, and coastal development interact to drive spatial variations in barrier island vulnerability over long time scales.

Interpretation of model results shows that natural and human-induced variability in island-estuary geomorphology and cross-shore sediment fluxes result in spatially variable barrier vulnerability to SLR. At low, moderate, and high SLR rates, 0%, 28%, and 100% of the barrier is predicted to be vulnerable, respectively. Different modeled behaviors for similar island-estuary geometries underscore the importance of sediment fluxes in contributing to future barrier island evolution. Though dune/island height is a good predictor of coastal response to storms (Plant et al., 2010; Sallenger, 2000; Stockdon et al., 2007), this work demonstrates that island-estuary geomorphology alone is not sufficient for understanding future coastal response to SLR and that quantifying sediment budgets and associated fluxes is essential (Roelvink, 2015).

Increasing only overwash fluxes in the model to simulate increased storminess did not lead to fewer SLR vulnerabilities along the island as might be expected. Instead, the imbalance between overwash and shoreface fluxes (e.g., material loss from increased overwash was not replenished at the same rate by shoreface fluxes) leads to elevated barrier vulnerability to SLR. As above, this effect is likely to be more pronounced in sediment-limited coastal systems and/or where diffusive alongshore fluxes are restricted. Also, because modeled shoreface flux is highly theoretical, quantifying existing imbalances in cross-shore fluxes from detailed morphological (Brenner et al., 2017), geological (Locker et al., 2017; Miselis & McNinch, 2006), and physical (Limber et al., 2008) observations and deriving more representative shoreface flux values would result in more realistic forecasts of the influence of increased storminess on barrier vulnerability to SLR.

Human modification of the island-estuary system contributes to differences in modeled barrier island behavior. First, model results indicate that development makes barrier drowning more likely (consistent with the nonlocation-based modeling results of Rogers et al. (2015)); developed locations in the study area were ~6 times as vulnerable to SLR due to loss of island width and almost 2 times as vulnerable due to loss of island height compared to undeveloped sites. This disparity was driven by the coupling of deeper estuarine depths due to dredged navigation channels (Kennish, 2001; Miselis et al., 2016) and reduced overwash fluxes due to interactions with infrastructure (Rogers et al., 2015) common to developed locations. Second, in model results, developed barriers narrow and drown faster than undeveloped barriers, though modeled time-to-drowning could decrease with increasing sediment limitation (Brenner et al., 2015). Moreover, it is important to note that drowning is only an end result. Given that model results also show significant ocean shoreline retreat over <300 years, it is likely that decreases in island area available for infrastructure and habitat will occur long before the island is completely submerged. Finally, model simulations indicate that the longer humans intervene in the coastal system by fixing the barrier in place laterally and vertically, the faster drowning occurs, even if natural barrier island morphodynamics are restored after human intervention. This suggests that coastal management techniques that seek to maintain barrier position and redistribute overwash deposits may result in more resilient coastlines initially but that increased vulnerability resulting from existing human alterations may not be reversible over longer time scales.

5. Conclusions

Integration of observations extracted from remotely sensed data and a morphodynamic model could be a powerful tool for forecasting barrier island vulnerabilities to SLR over large spatial domains. Natural and human-induced spatial variability in island-estuary geometry and sediment fluxes tends to result in nonuniform barrier island response to SLR and an increase in vulnerable locations from 28% to 100% with an increase in SLR rates from moderate to high. For the same rate of SLR, percent vulnerability increases as overwash fluxes are increased in the model, suggesting that enhanced storminess will exacerbate SLR effects, particularly along sediment-limited coasts. Human influence is apparent in modeled response to SLR, and spatial associations between barrier island vulnerability and coastal development suggest that human modification of island-estuary geometry and cross-shore sediment fluxes will influence future barrier island retreat trajectories.

Acknowledgments

Observational data are published and available online as cited in the text. This work was funded by the New Jersey Department of Environmental Protection and the USGS Coastal and Marine Geology Program and a National Science Foundation grant CNH-1518503 to Lorenzo-Trueba. Brian Andrews provided GIS support for spatial analysis. Noreen Buster assisted with drafting of figures. Thoughtful reviews by Eli Lazarus, A. Brad Murray, and an anonymous reviewer improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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