MODELED CHANGES IN FOREDUNE MORPHOLOGY INFLUENCED BY VARIABLE STORM INTENSITY AND SEA-LEVEL RISE

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Abstract: Coastal foredunes can mitigate the impacts of intensifying hurricanes and extratropical storms on vulnerable, low-lying communities. However, the degree of foredune resilience to climate change remains largely unquantified. Here, we use the numerical AeoLiS model to project annual-scale patterns of accretion and erosion of coastal foredunes for a range of beach and dune morphologies representative of the Outer Banks, North Carolina, USA. The model is subsequently used to explore how sea-level rise and changes in storminess may modify future dune volumes across beach morphologies. Model outcomes suggest that even modest rates of sea-level rise have the potential to greatly exacerbate dune erosion; whereas increased storminess may lead to accretion due to increased wind speeds or exacerbate erosion due to increased total water levels. The precise nature of these future impacts on coupled dune-beach systems is highly dependent on the degree of climate change and the pre-existing beach morphology. Climate change is therefore unlikely to impact coastal foredunes uniformly, posing a challenge for communities relying on these features for protective services into the future in the context of both increasing sea level and changing storm properties.

Introduction

Storms pose substantial risks to coastal communities through flooding and beach erosion. These coastal hazards will likely be exacerbated by climate change and sea-level rise (SLR), which will impact millions of people living in vulnerable low-lying coastal areas. There is poor consensus on the magnitude of potential SLR over the coming century, with estimates for increases in global water level for 2100 ranging between 0.3 and 2.0 m (Sweet et al. 2022). Simultaneously, warming sea-surface temperatures are likely to result in stronger, more intense tropical cyclones and hurricanes, which will bring increased coastal flooding and storm surge. Although the frequency of these events is expected to decrease (Knutson et al. 2021), their impacts will be exacerbated by higher background water levels due to SLR. This is likely to result in an increase in the number of events that cause damage to valuable infrastructure in coastal regions (Tebaldi et al. 2012).

In response to these increasing threats from climate change, communities often maintain natural and nature-based features (commonly dunes) to protect landward infrastructure (Elko et al. 2016). However, both natural and constructed dunes have been shown to be highly vulnerable to erosion, breaching, and overwashing (*e.g.*, Santos et al. 2019; Morton and Sallenger 2003), which reduces the protective services that they provide. Both the frequency and magnitude of storms mediate the number of waves that reach the dune face and the resulting potential magnitude of dune erosion (*e.g.*, Larson et al. 2004; Palmsten and Holman 2012). Higher background water levels associated with SLR and storm surge will therefore amplify volumetric dune erosion through increased frequency of wave collision (Walsh et al. 2019). However, storms are not necessarily fully erosive agents (Cohn et al. 2019): changes in storminess could also alter the speed and direction of winds responsible for dune growth (Knutson et al. 2021), thereby increasing sediment fluxes to the dunes, and partially counteracting wave-driven erosion. The dynamic erosive/accretive balance associated with these countervailing impacts of climate change increases the uncertainty in projecting future dune behavior (Yan and Baas 2015; Walsh et al. 2019), and in applying best practices for optimizing dune management strategies. Specifically, additional investigation is required to quantify the range of likely shifts in dune erosion/accretion thresholds under concurrently evolving climatic conditions.

The objective of this study is to quantify how potential climatic changes associated with alterations to windiness, wave climates, and rising still water levels, may lead to changes in dune stability (*i.e.*, the balance between wave-driven erosion and wind-driven accretion). Specifically, we use the numerical, process-based model, AeoLiS (Hoonhout and de Vries 2016) to assess how potential shifts in these environmental forcings from present-day conditions may affect sediment volume changes to adjacent dunes.

Methods

Study Site

We parameterize our model based on morphologic conditions present along the 35-km stretch of the northern Outer Banks. This microtidal (tidal range ~ 1 m) barrier-island chain is frequently impacted by tropical storms (*i.e.*, hurricanes) in the late summer and fall and extratropical nor'easters during the winter (Brodie et al. 2019). Storms passing through the Outer Banks are often distinguished by onshore oblique winds from the north-northeast (Brodie et al. 2019). Average significant wave height (H_s) is about 1 m (Cohn et al. 2021). These islands are net erosional over multi-decadal timescales (*e.g.*, Kratzmann et al. 2017), a behavior that continually threatens landward-situated coastal infrastructure.

Baseline Model

We apply the AeoLis model to predict coastal profile changes resulting from variable environmental forcings through time. AeoLis is a process-based numerical model that simulates aeolian sediment transport in supply-limited systems (Hoonhout and de Vries 2016). An analytical dune erosion model (Palmsten and Holman 2012) has recently been added into AeoLiS to additionally account for volumetric dune volume losses and associated profile change due to wave collision. These erosional and accretional capabilities are used to forecast the future morphological evolution of coastal dune landforms at our study site in response to changing environmental conditions.

Table 1. Intervals of Methodology Parameters

Dune-Toe Elevations (m)	Beach Slopes (m/m)	Sea-Level Rise Scenarios (m)	Storminess Scenarios (% inc.)	Combined Climate Conditions
2.5	0.05	0.3	5	0.5 m SLR w/ 5% inc. (Low-Risk Climate)
3	0.075	0.5	25	1.5 m SLR w/ 5% inc. (High-Risk Climate)
3.5	0.10	1.0	50	N/A
4	0.15	1.5	N/A	N/A

A one-year (1 January 2019 to 31 December 2019) record of wind, wave, and tide data measured at the US Army Corps of Engineers Field Research Facility (FRF; Duck, North Carolina) was used to develop a baseline environmental time series with which to force the model. These data are publicly available on the CHL THREDDS data server (https://chlthredds.erdc.dren.mil/thredds/catalog/frf/catalog.html). Numerous storm events impacted the study area over this time period, including Hurricane Dorian (6 September 2019). Sets of AeoLiS simulations were run using 16 combinations of dune-toe elevations and beach slopes representing the range of beach and dune morphologies present along the northern Outer Banks (Table 1). For each simulation, one-dimensional model grids were set up with grid resolution of 0.5 m with a one-hour time step and vegetation processes activated to simulate sediment trapping. For each morphologic condition, both the baseline environmental case and modified environmental forcings (described below) were implemented to evaluate present and future risk for dune stability. The net volume change is per meter in the alongshore for each set of dune morphologic conditions calculated from the net profile change in the model across the one-year period. As the model is used to predict both aeolian-driven dune growth and wave-driven dune erosion, these results are specifically used to identify the erosion threshold (erosion > accretion) associated with varying beach morphologies and for different environmental scenarios.

Environmental Exploration

The impact of rising sea levels on dune accretion and erosion was tested by comparing the changes in dune volume for 16 combinations of dune-toe elevations and beach slopes under modern conditions to those modeled under the range of SLR scenarios for 2100 predicted by Sweet et al. (2022). Specifically, we tested a SLR of 0.3 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m. These increases in sea level were incorporated into the model by modifying tidal forcing through the addition of a uniform value across the tide-level time series. Each suite of morphologic configurations was assessed for these additional SLR scenarios.

The impact of potential storm intensification on coastal foredunes was also assessed with the AeoLiS model. Quantitative predictions of increased storminess vary according to the type of climate model used and the climatology parameters considered (*e.g.*, Bacmeister et al. 2018; Bender et al. 2010; Knutson et al. 2015; Morim et al. 2019; Oderiz et al. 2021). However, the most common prediction for the end of the 21st century is for an ~5% increase in storm intensity (Knutson et al. 2021). Changes in storm climatology were modeled by modifying the environmental time series from 2019. We used the “triangular method” described in Santos et al. (2019) to amplify storm intensity after confirming the common “triangular” geometric pattern on hydrographs for all hurricanes to strike the Outer Banks in the past two decades. To “intensify” storminess, the maximum value of wind speed, wave height, and water levels for the top ten storm events in the 2019 time series (Hurricane Dorian included) were identified and amplified by varying percentages (5–50%) (Santos et al. 2019). This approach is meant to be illustrative of potential climate change effects on storms and their response, as storms in the future will not all change in the same way. The baseline cases were re-run for each intensification scenarios (Table 1) to gain insights into the potential future increases in dune growth and/or erosion.

Realistic future environmental conditions are likely a combination of SLR and changes in other environmental variables, such as increasing storm intensity. Thus, we also test combined forcings. Specifically, we paired a 5% storm intensity increase (the most common forecast) with the intermediate-low SLR scenario (0.5 m) and the intermediate-high SLR scenario (1.5 m) to create "low-risk" and "high-risk" climate simulations.

Results

Baseline (Modern Day) Scenarios

The 16 different combinations of dune-toe elevations and beach slopes showed a range of volume change from +3.7 m^3/m to -58.1 m^3/m over the year-long simulation (Fig. 1). The model was used to simulate profile evolution at annual scale, with morphologic responses being dependent on both the environmental conditions and initial morphology. More accretion was generally simulated on dunes with higher toe elevations and gentler beach slopes, while more erosion occurred on dunes with lower toe elevations and steeper beach slopes (Figs. 1 and 2a). Under simulated modern conditions, most accretion occurred on dunes with

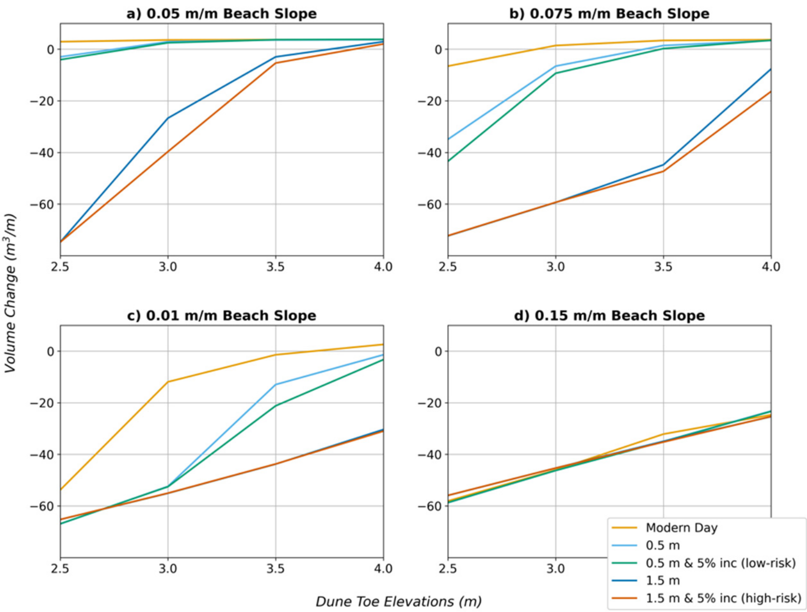

Fig. 1. Line plots depicting dune volume changes associated with various sea-level rise and storminess scenarios for different combinations of beach slope (panels a–d) and dune-toe elevations.

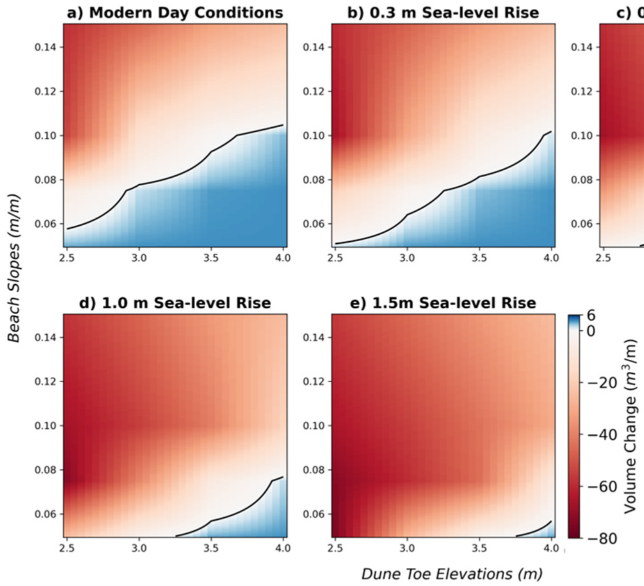

Fig. 2. Simulated annual dune volume changes for various dune-toe elevations and beach slopes for (a) modern baseline conditions, and for a (b) 0.3 m, (c) 0.5 m, (d) 1 m, and (e) 1.5 m rise in sea level.

a toe elevation of 4 m and fronting a beach slope of 0.05 m/m; the most erosion occurred with a 2.5 m toe elevation and 0.15 m/m beach slope. Dunes experiencing net accretion exhibited a range of morphologic responses. Some cases experienced scarping near the dune toe, which was offset by wind-blown sediment accumulating at higher elevations. Dunes experiencing net erosion often sustained large scarping and dune-toe retreat.

Sea-Level Rise

Volume change for the SLR scenarios ranged from +3.7 m^3/m to -74.8 m^3/m (Fig. 2b–e). This does not include the highest SLR scenario (2.0 m), which was omitted from analysis due to the near-total dune erosion predicted based on the shift of erosion/accretion threshold from 0.3 m SLR to 1.5 m SLR (Fig. 2e). The net volume change to the dune for the lowest SLR scenario (0.3 m) ranged from +3.7 m^3/m to -66.2 m^3/m while net volume change during the highest SLR scenario (1.5 m) ranged from +2.9 m^3/m to -74.8 m^3/m (Fig. 2b and 2e). Like the baseline runs, the most accretion for the 0.3 m of SLR scenario occurred on dunes with a toe elevation of 4.0 m and 0.05 m/m beach slope. The greatest net erosion occurred on dunes with a toe elevation of 2.5 m and 0.1 m/m beach slope for the

1.5 m SLR scenario. For lower amounts of SLR (0.3 m and 0.5 m), most erosion occurred at the dune toe in the form of scarps, with some accretion observed at the crest of the dune. For higher amounts of SLR (1.0 m and 1.5 m), 50% and 69% of the simulated dunes were completely eroded, respectively.

Storm Intensification

Volume change for cases with increased storm intensity ranged from +5.2 m^3/m to -72.6 m^3/m (Fig. 3b-d). The net sediment volume change to the dune ranged from +3.8 m^3/m to -64.1 m^3/m for a 5% increase in storminess, while a 50% increase led to +5.2 m^3/m to -72.6 m^3/m change. The greatest net accretion occurred on dunes with a toe elevation of 3.5 m and 0.05 m/m beach slope, while the greatest net erosion occurred on dunes with a toe elevation of 2.5 m and 0.1 m/m beach slope. With a 5% increase in storm intensity, dunes with higher toe elevation and gentler fronting beach slopes experienced an increase in net accretion compared to modern conditions. However, larger increases in storm intensity generally resulted in net erosion across more beach morphologies relative to present-day conditions.

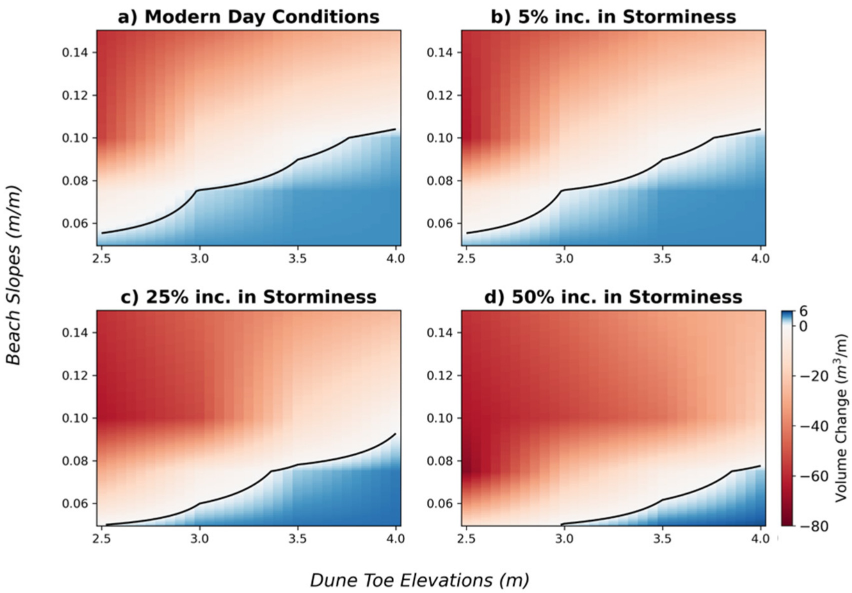

Fig. 3. Net annual simulated dune volume changes for various dune-toe elevations and beach slopes for (a) modern conditions and increases in storm intensity by (b) 5%, (c) 25%, and (d) 50%.

Combined Climate Conditions

Sediment volume change to the dune for the low-risk climate scenario (Table 1) ranges from +3.7 m^3/m to -66.9 m^3/m; the high-risk climate scenario ranges from +2.0 m^3/m to -74.8 m^3/m. For some morphologies (*e.g.*, 3.5–4.0 m dune-toe elevation and 0.05 m/m beach slope), the enhancement of storminess in conjunction with a 0.5 m increase in sea level led to more vertical accretion as compared to the scenario of SLR alone. The combination of a 5% increase in storm intensity and 1.5 m of SLR (high-risk scenario) largely led to more net erosion, including additional retreat of the dune scarp (Fig. 4). The high-risk climate conditions almost doubled the increase in dune erosion compared to the low-risk climate conditions (Fig. 5).

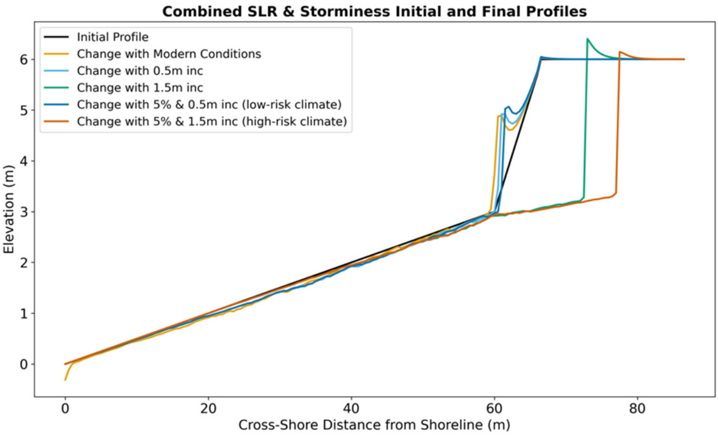

Fig. 4. Example model simulated beach and dune profiles (3 m dune-toe elevation, 0.05 m/m beach slope) after 1 year with varying increases in sea level and storminess.

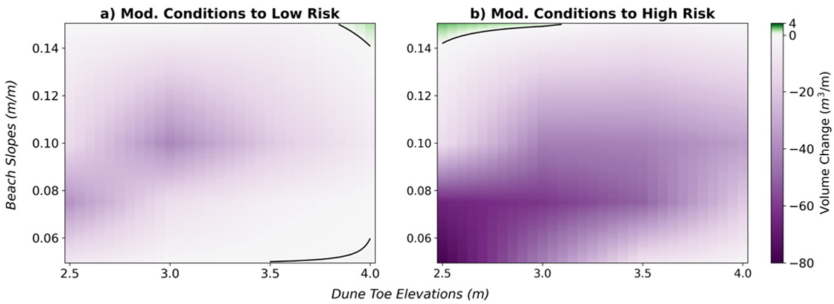

Fig. 5. Difference in net annual dune volume change between the baseline case and (a) the moderate conditions/low-risk climate scenario; and (b) the extreme conditions/high-risk climate scenario.

Discussion

Future Changes in Environmental Forcing

Model results indicate that both the degree of environmental forcings and the initial morphology of the dune and beach can influence the style and magnitude of dune evolution at annual timescales. Unsurprisingly, the alteration of environmental forcings has important implications on subsequent dune evolution. According to the model, any increase in sea level from present elevations will reduce volume gains to the dune and/or enhance dune erosion (Fig. 2). Higher total water levels decrease aeolian transport of beach sand by reducing both the fetch across the beach and the area of dry, exposed sediment available for transport; this ultimately reduces wind-driven sediment inputs to the dune (Davidson-Arnott and Bauer 2009). Additionally, under conditions of higher sea level, wave swash can reach the dune toe more frequently, leading to an increase in the duration and magnitude of wave-driven dune erosion (Theuerkauf et al. 2014). We find that these trends are highly dependent on the initial morphology of the dune and beach (Fig. 1): modeled dunes with lower toe elevations experienced greater erosion, reflecting the higher frequency of wave collision against the dune toe. Increases in both sea level and storminess led to greater variation in beach-to-dune sediment fluxes for those dunes fronted by gentler-sloping beaches as compared with those fronted by steeper beaches; notably, the latter showed little change between modern-day conditions and the high-risk climate scenario (Fig. 5). This unexpected result may reflect the predisposed vulnerability of dunes fronted by steeper dunes to overtopping under modern-day conditions, or the lessened opportunity for wave-energy dissipation while traveling up steeper beaches.

It is unclear how climate change will alter long-term wind and wave patterns (Morim et al. 2019; Oderiz et al. 2021) or storm tracks and extreme precipitation events (Bacmeister et al. 2018). Thus, we assess only the impact on dune dynamics of fixed increases in peak wind speeds, wave heights, and surge for major storm events. We find that the effect of increased storm intensity on a dune is strongly dependent on the *a priori* morphology of that dune and its fronting beach (Fig. 3). As would generally be expected, higher storm intensity increased net erosion for dunes fronted by steeper beaches. However, not all increases in storminess led to enhanced dune erosion: specifically, modeled dunes fronted by gentler beach slopes with higher dune-toe elevations experienced net accretion under conditions of greater storm intensity. This is attributed to sequencing of high wind speeds during these events with a wide exposed beach during low tidal stages that allows for higher rates of aeolian sediment transport to the dune (Davidson-Arnott and Bauer 2009). In the (highly unlikely) absence of additional

SLR in the future, these results may indicate a possibility of future dune growth for the lowest-sloping beaches under future storminess changes.

Our results demonstrate that, between SLR and storminess, SLR is the dominant environmental forcing in the coming century, leading to decreased modeled dune growth rates (or accelerated erosion) along beach-dune systems with attributes similar to those in the northern North Carolina Outer Banks. Additional work is needed to understand the long-term combined effects of changing static (sea level) and dynamic (winds, waves, surge) environmental conditions on dune processes on the multidecadal to centennial timescale. This is especially true because the specific combination of pre-existing morphology, SLR, and changing storminess plays a fundamental role in the future evolution of dunes (Figs. 2 and 3).

Finally, it is important to note this model application considers only one-dimensional effects, whereas real-world dunes and beaches are two-dimensional features and not always defined by an initial planar morphology. Furthermore, our methodology assumes a stationary beach slope, and that dune collision always results in erosion (following the framework of Palmsten and Holman 2012), thus neglecting the possible role of swash deposition at the base of the dune (*e.g.*, Cohn et al., 2022). Our approach to modifying meteorological and oceanographic forcings by fixed percentages for 10 storm events is also unlikely to account for the true future changes, however it is illustrative of potential changes to the state of the dune system. These assumptions, along with inherent limitations in process-based morphodynamic models in representing the full suite of real-world physical processes acting on dune-beach systems, should be considered when interpreting the model results. Nonetheless, we stress that the primary aeolian and marine drivers of coastal foredune change are included in AeoLiS, and that these results can therefore provide valuable insights into the potential morphodynamic controls on present and future dune evolution.

Implications

Dunes are increasingly relied upon as a critical line of defense against both storm- and SLR-induced flooding, particularly when applied in conjunction with beach nourishment projects (Elko et al. 2016). However, there is limited guidance for optimizing dune construction in a manner that considers the impacts of non-stationary environmental conditions. The lack of numerical frameworks that account for both marine and aeolian processes—at least ones that do not require complex model coupling (*e.g.*, Cohn et al. 2019; Roelvink and Costas 2019)—has largely hampered the ability to optimize site-specific dune design and management. This study shows that a single, modified numerical modeling framework that includes both accretionary and erosive processes relevant to coastal foredunes can be used to explore dune stability, growth, and erosion in the context of variable morphology and changing environmental forcings. Although limited by the implementation of uniform increases in sea level and uncertainty in likely future changes in storminess, the framework presented here could be used to more holistically identify and assess sites most vulnerable to an evolving climate, and to improve dune design to enhance resilience. Future modeling work could also include the incorporation of specific dune-management strategies, such as sand fencing and vegetation planting—parameterizations for which are already incorporated into the AeoLiS modeling framework—to further guide management.

Conclusions

This study used exploratory numerical modeling to investigate potential shifts in erosional versus accretional behavior of dunes in response to changing climate conditions. When decoupling climate forcings, we found SLR to be a greater threat to dune stability than storm intensity. Specifically, higher SLR led to more extreme total water level events that increased dune erosion and, in some cases, resulted in total dune destruction. Increases in storm intensity resulted in more variable responses: future small increases in wind speeds have the potential to generate dune growth (even with simultaneous increases in storm wave and surge properties), though larger increases in storm intensity are likely to lead to net erosion. These specific dynamics are highly dependent on the preexisting morphology of the beach and dune, with dunes with low toe elevations fronted by gentle sloping beaches being most vulnerable to changes in SLR. Climate change is therefore unlikely to impact coastal foredunes uniformly, posing a challenge for communities relying on these features for protective services into the future in the context of both increasing sea level and changing storm properties.

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