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Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina Outer Banks

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[1] Using a morphological-behavior model to conduct sensitivity experiments, we investigate the sea level rise response of a complex coastal environment to changes in a variety of factors. Experiments reveal that substrate composition, followed in rank order by substrate slope, sea level rise rate, and sediment supply rate, are the most important factors in determining barrier island response to sea level rise. We find that geomorphic threshold crossing, defined as a change in state (e.g., from landward migrating to drowning) that is irreversible over decadal to millennial time scales, is most likely to occur in muddy coastal systems where the combination of substrate composition, depth-dependent limitations on shoreface response rates, and substrate erodibility may prevent sand from being liberated rapidly enough, or in sufficient quantity, to maintain a subaerial barrier. Analyses indicate that factors affecting sediment availability such as low substrate sand proportions and high sediment loss rates cause a barrier to migrate landward along a trajectory having a lower slope than average barrier island slope, thereby defining an "effective" barrier island slope. Other factors being equal, such barriers will tend to be smaller and associated with a more deeply incised shoreface, thereby requiring less migration per sea level rise increment to liberate sufficient sand to maintain subaerial exposure than larger, less incised barriers. As a result, the evolution of larger/less incised barriers is more likely to be limited by shoreface erosion rates or substrate erodibility making them more prone to disintegration related to increasing sea level rise rates than smaller/more incised barriers. Thus, the small/deeply incised North Carolina barriers are likely to persist in the near term (although their long-term fate is less certain because of the low substrate slopes that will soon be encountered). In aggregate, results point to the importance of system history (e.g., previous slopes, sediment budgets, etc.) in determining migration trajectories and therefore how a barrier island will respond to sea level rise. Although simple analytical calculations may predict barrier response in simplified coastal environments (e.g., constant slope, constant sea level rise rate, etc.), our model experiments demonstrate that morphological-behavior modeling is necessary to provide critical insights regarding changes that may occur in environments having complex geometries, especially when multiple parameters change simultaneously.

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1. Introduction

[2] Barrier islands occur throughout the world and are dynamic over a range of temporal and spatial scales. Because they are low-lying features, these landforms are especially vulnerable to sea level rise and fall, changes in sediment supply/loss rates and coastal storms. As sea level rises or sediment supply rates decrease, a barrier island will respond by (1) migrating landward across the underlying substrate to higher elevations, (2) disintegrating if there is no longer sufficient sand volume and relief above sea level to prevent inundation during storms, or (3) drowning in place and transforming into a marine sand body. If we apply the geomorphic threshold concept [e.g., *Schumm*, 1980; *Ritter et al.*, 1999] to barrier island evolution, a change from one of these three equilibrium states to another represents a geomorphic threshold crossing if the change is irreversible over time scales of decades to millennia. Factors such as rising sea level or decreasing sediment supply rate may ultimately result in background conditions that are sufficiently different

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from previously existing conditions to promote a shift in equilibrium state. A permanent, abrupt shift to a new equilibrium is likely be catalyzed by system perturbations resulting from a disruptive event, such as a hurricane or extratropical storm that cannot be recovered from prior to the occurrence of the next disruptive event.

[3] Because barrier island threshold crossings have the potential to be extremely disruptive to human activities, an understanding of how barrier islands will evolve in the future under conditions of rising sea level [e.g., *Intergovernmental Panel on Climate Change (IPCC)*, 2001; *Church et al.*, 2004; *Church and White*, 2006; *Overpeck et al.*, 2006; *IPCC*, 2007; *Nicholls et al.*, 2007] and potentially more frequent hurricanes of greater intensity [e.g., *Emanuel*, 2005; *Trenberth*, 2005; *Emanuel*, 2008] is vital to the development of wise coastal management practices [*FitzGerald et al.*, 2008], yet predictions of future barrier island evolution to date have been based largely upon geologic inference [e.g., *Riggs and Ames*, 2003]. Quantitative assessments of the range of potential future barrier island evolution are also needed. Simplified barrier translation models [e.g., *Bruun*, 1962; *Masetti et al.*, 2008; *McNamara and Werner*, 2008] and morphological-behavior models, also known as stratigraphic models [e.g., *Cowell et al.*, 1992, 1995; *Storms et al.*, 2002; *Stolper et al.*, 2005; *Moore et al.*, 2007], which simulate barrier island evolution over decadal to millennial time scales, currently provide the only quantitative method available for testing hypotheses regarding the large-scale evolution of barrier islands under changing conditions. The development of numerical experiments to explore potential future barrier island evolution, however, requires an improved understanding of how barrier islands have evolved throughout the Holocene and an assessment of the relative importance of factors critical to barrier island evolution over a range of time scales and in realistically complex scenarios where multiple parameters are changing at the same time.

[4] To advance the understanding of Holocene barrier island evolution, we apply the morphological-behavior model GEOMBEST [*Stolper et al.*, 2005; *Moore et al.*, 2007] to a field site in the North Carolina Outer Banks. We select this location because it is one of the largest and most thoroughly investigated barrier island chains in the world. This effort is complimentary to three model experiments presented by *Stolper et al.* [2005] which explored the Currituck region of the North Carolina Outer Banks, 100 km north of our study area. *Stolper et al.* [2005] demonstrated that estuarine sedimentation reduces barrier migration rates and that the presence of a lithified substrate increases migration rates (factors which are not important in our study area). Through a series of over thirty model experiments, we assess the relative importance of sea level rise rate, sediment supply rate, shoreface depth, substrate composition, substrate erodibility and maximum shoreface erosion rate in determining how barrier islands evolve. By extending the range of input parameters beyond the range of values expected for the North Carolina Outer Banks, we yield broadly applicable, unforeseen and counterintuitive insights into the complexities of barrier island evolution. (Of course, reproducing the details of barrier island evolution in locations having morphologies and stratigraphies that are significantly different than the Outer Banks would require additional site-specific simulations, which are not within the scope of our present work.) Using constraints from the geologic and modern record, we then develop a refined simulation that represents a geologically plausible scenario for barrier island evolution in the North Carolina Outer Banks throughout the Holocene.

2. Morphological-Behavior Modeling

2.1. GEOMBEST

[5] Sediment transport models, driven by hydrodynamics, cannot yet address questions of large-scale coastal behavior such as the evolution of barrier islands over length scales of kilometers and time scales of decades to centuries and millennia. Morphological-behavior models, which are driven by changes in sediment supply, sea level rise, and shoreface geometry [e.g., *Cowell et al.*, 1992; *Roy et al.*, 1994; *Cowell et al.*, 1995; *Storms et al.*, 2002; *Stolper et al.*, 2005; *Moore et al.*, 2007], without simulating the detailed physical processes of sediment transport, currently provide the only means for testing the geometric validity of hypotheses regarding barrier island evolution. Though these models do not simulate barrier island evolution at the scale of individual storm events, and therefore cannot directly simulate changes from one equilibrium state to another, they are a valuable tool for assessing the vulnerability of a landward migrating barrier to a change in state.

[6] Geomorphic Model of Barrier, Estuarine and Shoreface Translations (GEOMBEST), as first described by *Stolper et al.* [2005], is a 2-D, cross-shore, numerical morphological-behavior model that simulates the evolution of barrier island morphology and stratigraphy over time scales ranging from decades to millennia. Basic model formulation and model inputs are described here but the reader is referred to *Stolper et al.* [2005] for an additional discussion of the model.

[7] In an approach similar to that of *Cowell et al.* [1995], model formulation in GEOMBEST is based on sediment conservation principles expressed in the continuity equation and behavior rules originating from the concept that, given appropriate conditions and sufficiently long time scales, the shoreface and barrier profile will tend to remain invariant. For example, the shoreface in a particular location will tend to attain a profile shape that is related to decreases in nearbed wave energy with offshore distance. Similarly, model formulation is based on the assumption that storm characteristics, and therefore integrated barrier island response to storms (i.e., subaerial and back-barrier morphologies), remains approximately constant over sufficiently long times scales. Thus, a user-specified equilibrium morphology, determined using the best available bathymetry and topography for an area of interest, extends from the base of the shoreface across the subaerial barrier to the back-barrier environment. For a simplified set of conditions under which the sediment budget is balanced, the substrate is sandy and the assumption of a constant profile shape is valid, the geometric relationships and sediment conservation specified in GEOMBEST are essentially identical to those applied to the shoreface profile by *Bruun* [1962] and extended to the combined shoreface and island profile by *Wolinsky and Murray* [2009]. In this case, the degree of landward migration is simply a function of the average slope of the profile and the amount of sea level rise.

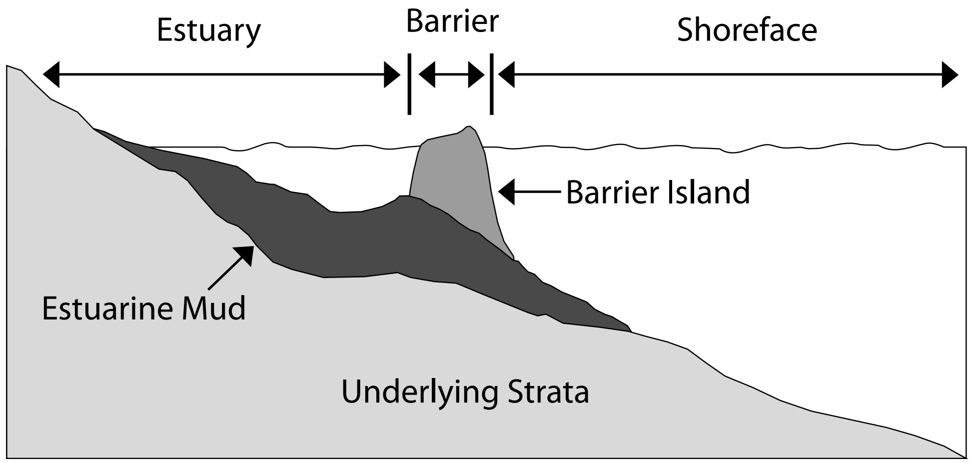

Figure 1. Cross-shore schematization of coastal morphology for a low-gradient barrier island coast. The three functional realms in GEOMBEST (shoreface, barrier, and estuary) are distinct stratigraphic units that comprise the coastal tract. After *Stolper et al.* [2005].

[8] The model domain consists of a cross-shore grid of user-specified cell size in the horizontal and vertical dimensions (typically hundreds of m horizontal and less than 1 m vertical) extending from the base of the shoreface (or deeper) to the mainland and encompassing the shoreface, barrier and estuarine realms (i.e., the coastal tract) (Figure 1). Morphological evolution in GEOMBEST is driven by differences between this coastal tract surface and the user-specified equilibrium morphology. The equilibrium morphology maintains its vertical position relative to sea level throughout a simulation. With each time step (typically 10–50 years) it shifts vertically as sea level rises or falls and then moves horizontally to the cross-shore position that conserves sand (in the case of a balanced sediment budget for the tract). In the cross-shore dimension sand needs to be added to the coastal tract where the equilibrium morphology arrives above or seaward of the previous coastal tract surface (resulting in a sediment sink) and, if the underlying substrate contains sand, sand is liberated where the equilibrium morphology arrives below or landward of the previous coastal tract surface (providing a sediment source). Adjustments to the sediment budget that occur due to sand gains and losses associated with gradients in alongshore sediment transport can be specified by the user at each time step and are also taken into account when determining the new position of the coastal tract surface. A sand loss from alongshore transport gradients tends to make the coastal tract surface move landward (which produces sediment from shoreface erosion to feed this loss) and vice versa. Achieving sediment conservation within the existing geometric and stratigraphic framework may also require adjustments to the morphology and underlying barrier stratigraphy. For example, barrier island height (relative to the estuary) and barrier island volume may increase or decrease with each new position of the coastal tract surface.

[9] GEOMBEST allows the user to define multiple stratigraphic units in the substrate and to define input parameters that describe both how quickly each stratigraphic unit erodes (i.e., erodibility) and what proportion of the sediment in each stratigraphic layer is sand as opposed to mud (i.e., the substrate composition); features that are not currently available in other morphological-behavior models. These stratigraphic characteristics are expressed as indices between 0 and 1. For example, a substrate having an erodibility of 1 will erode quickly, representing a loose sediment for which the erosion rate is determined only by sediment transport gradients rather than by any other factors (e.g., cohesion, lithification, weathering, etc.). Since this parameter is expressed as an index, a substrate having an erodibility of 0.5 will erode half as quickly as a substrate having an erodibility of 1. Likewise, a substrate consisting of 100% sand and no mud has a substrate composition index of 1.0, while a substrate composed of 50% sand and 50% mud has an index of 0.5 [*Stolper et al.*, 2005].

[10] An additional parameter, the depth-dependent response rate (DDRR), also allows specification of the rate at which the shoreface can erode (or accrete) vertically as a function of depth, i.e., the shoreface erosion rate. As wave energy decreases with offshore distance so does the DDRR. This depth-defined parameter works in concert with the stratigraphic unit-specific erodibility parameter to determine the maximum amount of sediment that can be eroded or deposited within each grid cell at each time step.

[11] The erodibility, substrate composition and DDRR parameters are important because they constrain the volume of sand liberated at each time step (for example, from shoreface erosion), thereby altering the position of the tract surface, the associated morphology and the underlying barrier stratigraphy (e.g., barrier island height and volume) that achieve sediment conservation. Specification of these parameters also allows simulation of more complex geological scenarios for which the assumption of an equilibrium profile is essentially relaxed, addressing previously expressed concerns about this assumption [e.g., *Pilkey and Cooper*, 2004]. For example, a geologic framework consisting of nonerodible substrate (or partially nonerodible substrate, in the case of multiple stratigraphic layers) that will not attain a shape that is in equilibrium with wave conditions, such as those occasionally encountered along the North Carolina coast [e.g., *Riggs et al.*, 1995] can be specified in the model domain. Although the model tends toward attainment of the equilibrium morphology at each

time step, full development of the specified barrier and shoreface morphology is not forced in the model solution. For example, the specified morphology will not be attained if the substrate is nonerodible or if sea level rises too rapidly for the substrate to achieve the specified shape in the allotted time. In these situations, other geometric adjustments (e.g., increases landward migration rate or decreases in barrier island volume) will occur to create a coastal tract surface, and underlying barrier stratigraphy, that achieves sediment conservation.

2.2. Comparison With Shoreline Translation Model (STM)

[12] A series of model simulations carried out in the Shoreline Translation Model (STM) [*Cowell et al.*, 1992; *Roy et al.*, 1994; *Cowell et al.*, 1995] and described by *Roy et al.* [1994] explores the effect of variations in alongshore sediment transport gradients on transgressive barrier evolution for a low-gradient (less than 1 degree) coastal tract consisting of fully erodible, 100% sand substrate where the shoreface of the landward-migrating barrier is steeper than the underlying substrate of constant slope and the relative sea level rise rate is constant. These simulations are millennial in scale and provide plausible scenarios for the evolution of ravinement surfaces and sand sheets often observed on barrier coastlines. To demonstrate that GEOMBEST results are consistent with those produced by the well-established morphological-behavior model, STM, we develop a series of GEOMBEST simulations (Figure 2) having the same initial conditions and parameter variations as those reported by *Roy et al.* [1994].

[13] Under the boundary conditions described above, *Roy et al.* [1994] demonstrate that, in the case of a balanced sediment budget, barrier migration rate and barrier dimensions remain constant and the barrier neither erodes into the substrate nor deposits a trailing edge sand sheet as it translates landward (compare with Figure 2a). As discussed in section 2.1, under these conditions, the geometric relationships specified in STM and GEOMBEST are consistent with those presented and applied to the shoreface by *Bruun* [1962] and applied to the combined shoreface and island profile by *Wolinsky and Murray* [2009]. As a result, output from STM and GEOMBEST, under these conditions, is consistent with a Bruun-type approach to modeling profile response to sea level rise. A negative sediment budget under the same boundary conditions causes the barrier to erode the underlying substrate as it migrates landward creating a ravinement surface below the initial surface. The resulting sand excavated from the shoreface is then available to supply the barrier. In this simulation, the final barrier is smaller (by 40% in STM and by 35% in GEOMBEST), moves farther landward and is associated with a smaller estuary than the barrier in the balanced sediment budget simulation (compare with Figure 2b). Under the same boundary conditions but in the case of a positive sediment budget, simulation modeling by *Roy et al.* [1994] predicts the deposition of a thin sand sheet across the shelf and shoreface. In this case, the final barrier is larger (by 55% in STM and by 50% in GEOMBEST), the barrier migrates landward more slowly throughout the simulation due to the increased sand supply and is associated with a larger estuary than the barrier in the balanced sediment budget simulation (compare with Figure 2c). The rate of coastline retreat across the three scenarios changes by ±10% for the STM simulations [*Roy et al.*, 1994] and by ± 13% for the GEOMBEST simulations.

3. North Carolina Outer Banks

3.1. Geological and Oceanographic Setting

[14] The North Carolina Outer Banks is a 320 km long barrier island chain extending south from the Virginia-North Carolina border to Bogue Inlet. Although the Outer Banks includes sections of transgressive and regressive barrier islands as well as sections of barrier composed primarily of inlet channel fill [*Moslow and Heron.*, 1994; *Riggs et al.*, 1995], transgressive barriers comprise approximately 80% of the shoreline [*Moslow and Heron*, 1994]. The Outer Banks is a wave dominated, microtidal environment having an average wave height of 1.7 m [*Moslow and Heron*, 1994] and a mean tidal range of 0.91 m [*Dolan and Lins*, 1986]. The barriers of the Outer Banks are separated from the mainland by shallow bays and estuaries having widths of up to 45 km. The islands themselves exhibit considerable regional and local variability in width and height and overall morphology, having widths ranging from approximately 0.20 to 3.0 km and berm and dune heights of 0.5 to 12 m. Barrier elevations along Cape Hatteras National Seashore are fairly constant at 3 m [*Elko et al.*, 2002]. In the 1930s, linear foredunes were constructed along much of the Outer Banks as part of a large-scale stabilization project, carried out by the U.S. Civilian Conservation Corps [*Dolan and Lins*, 1986]. Remnants of these dunes are now discontinuous and degraded, although they tend to be maintained in locations where the road is threatened. Along northern parts of the Outer banks, complex natural dune ridges (e.g., Jockey's Ridge) reach heights of up to 40 m [*Morris*, 1993].

[15] Barrier island formation occurred sometime between the last sea level low stand 18,000−12,000 years ago and the decrease in sea level rise rate 4000 years ago [e.g., *Dolan and Lins*, 1986; *Inman and Dolan*, 1989; *Moslow and Heron*, 1994; *Pierce*, 1969]. Because there is a lack of remaining geologic evidence that can be used to determine more specifically when barrier islands formed, a consensus regarding the timing of barrier island inception has not emerged. *Moslow and Heron* [1994] suggest the Outer Banks began migrating landward between 9000 and 4000 years ago. Based on barrier island stratigraphy, they estimate landward migration rates of 50–100 m century^{-1} between 7000 and 4000 years ago [*Moslow and Heron*, 1979] followed by a decrease in migration rate 4000 years ago commensurate with a decline in sea level rise rates. For comparison, historical shoreline change rates in the North Carolina Outer Banks (mid-1800s–1990s), which are the best proxy for historical migration rates, range from −6 m yr^{-1} to + 4 m yr^{-1} [*Morton et al.*, 2005].

[16] Though the timing of barrier island formation is unclear, the presence and across-shelf extent of shoals associated with Cape Lookout and Cape Hatteras provide evidence for the origination of barrier islands near the shelf edge and provide further evidence for the landward migration of the Outer Banks throughout the Holocene [*Pierce*, 1969; *Inman and Dolan*, 1989; *McNinch and Wells*, 1999; *McNinch and Luettich*, 2000]. Diamond Shoals and Lookout

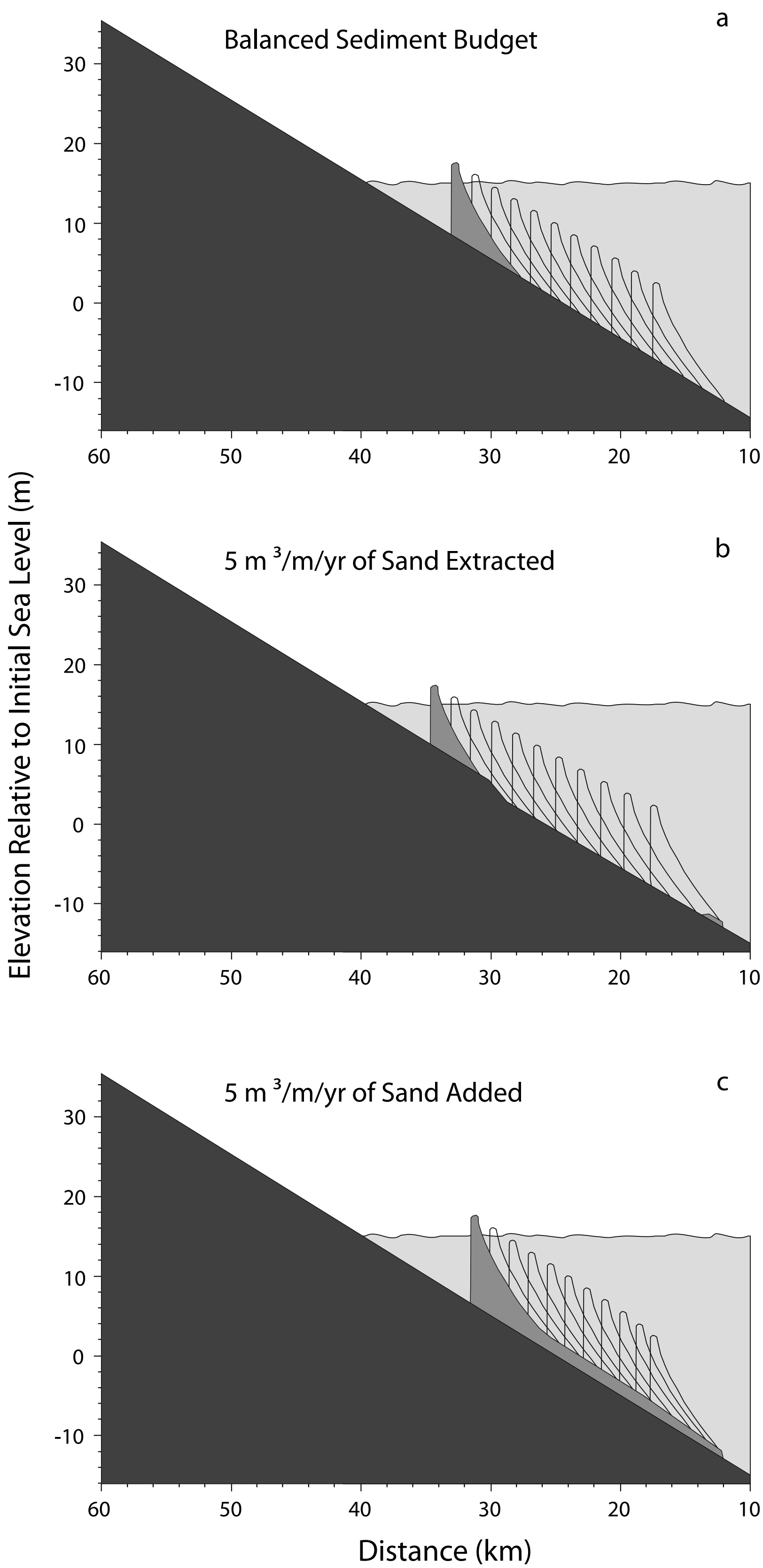

Figure 2. Simulations for a highly simplified coastal tract with a shoreface depth of 12 m and (a) a balanced sediment budget, (b) a negative sediment budget, and (c) a positive sediment budget.

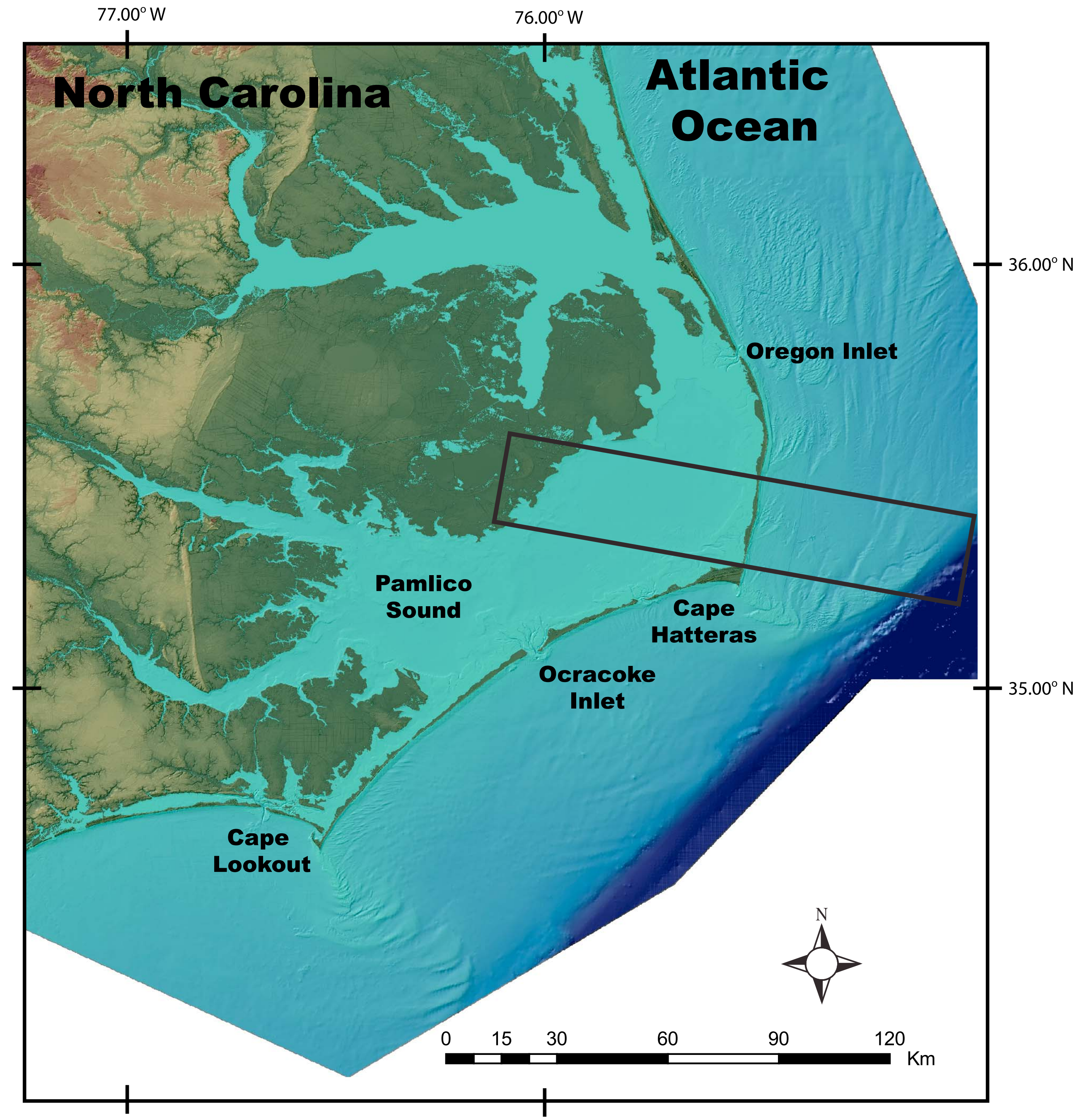

Figure 3. The study area covers 25 km of barrier coast between Rodanthe and Cape Hatteras, North Carolina, and extends from the western edge of Pamlico Sound to the shelf edge as outlined above.

Shoals are sediment trails formed as a result of alongshore sediment transport gradients at the southern end of littoral compartments and thus represent a major sediment sink in the littoral system [*McNinch and Wells*, 1999; *McNinch and Luettich*, 2000]. Evidence for offshore sediment transport along the axis of Cape Lookout Shoal and historical changes in shoal volume suggest that observed growth drops off rapidly beyond a distance of 13 km from the modern barrier island sediment source [*McNinch and Luettich*, 2000]. Thus, given the seaward extent of the shoal complexes (e.g., Diamond Shoals extends nearly to the shelf edge, see Figure 3), the initial barrier islands likely formed considerably seaward of the modern Outer Banks, at minimum of 13 km from the shelf edge, and the sediment budget must have been negative at least since the time when the barrier was located 13 km from the shelf edge. Evidence for the expected corresponding shoreface erosion of Pleistocene sediments during barrier island migration has been documented [*Riggs et al.*, 1995] and is further indicated by the presence of Pleistocene shells within the Holocene barrier island sands [*Wehmiller et al.*, 1995].

Table 1. Summary of Sources and Input Parameters for the Base Case and Exploratory Holocene Simulations

Input Parameter	Basis for Parameter Estimate	Base Case Simulation	Exploratory Holocene Simulation
Estuarine infilling rate (mm yr^{-1})	*Folger* [1972]; *Wells and Kim* [1989]	0	0
Sea level rise rate (m (100 years)$^{-1}$)	E. R. Thieler, personal communication (2005); *Horton et al.* [2009]	0.5/0.24/0.15	0.5/0.24/0.15
Sediment supply rate (m^3 m^{-1} yr^{-1})	*Inman and Dolan* [1989]	−25	0/−30/−25
Shoreface depth (m)	Determined based on shelf morphology and consistent with *Everts* [1978]	20	20
Erodibility index	E. R. Thieler and D. J. Mallinson, personal communication (2006); *Meisburger and Williams* [1987]; *Mallinson et al.* [2010]	1 (for barrier island and substrate)	1 (for barrier island and substrate)
Sand/mud ratio	E. R. Thieler and D. J. Mallinson, personal communication (2006); *Meisburger and Williams* [1987]; *Mallinson et al.* [2010]	1 (for barrier island and substrate)	1 (for barrier island and substrate)
DDRR (m yr^{-1} at 0 m)	Unknown	1	1
Initial shelf morphology and stratigraphy	E. R. Thieler and D. J. Mallinson, personal communication (2006); *Meisburger and Williams* [1987]; *McNinch et al.* [1999]; *Mallinson et al.* [2010]	Modern plus average of 5 m of substrate added	Modern plus average of 5 m of substrate added
Initial barrier island volume	Unknown	approximately 1/2 of modern volume	approximately 1/4 of modern volume

3.2. Study Site

[17] The study area encompasses 25 km of barrier coast between Rodanthe and Cape Hatteras, NC (Figure 3), extending from the mainland to the shelf edge over 50 km offshore. The area is largely undeveloped including 17.5 km of National Seashore and the small towns of Avon and Salvo. The barrier island is narrow, ranging in width from 0.5 to 1.5 km, and a discontinuous frontal dune provides only moderate relief of less than 1–2 m. Net alongshore sediment transport is to the south and transport gradients result in an estimated volume of 5.9×10^5 m^3 yr^{-1} lost between Oregon Inlet and Cape Hatteras [*Inman and Dolan*, 1989]. Average long-term shoreline change rates for the mid-1800s to 1997 range from −4 to +2 m yr^{-1} [*Morton et al.*, 2005].

4. Model Inputs, Assumptions, and Constraints

[18] GEOMBEST allows exploration of average coastal behavior for a stretch of coast having similar characteristics. For this reason, boundary conditions and input parameters must provide a reasonable approximation of average conditions and characteristics across the study area. We use available information from the Outer Banks barrier island literature and interpretations of geologic data to develop the best possible estimates of constraints and input parameters. For a discussion of how errors in parameter estimation may impact model output we refer the reader to section 5.1 and section 6.1. All experiments presented herein are conducted using a 50 year time step in combination with a horizontal and vertical grid spacing of 250 m and 0.2 m, respectively. A summary of input parameters and their sources, as described below, appears in Table 1.

4.1. Morphology and Stratigraphy

[19] Using available bathymetric and topographic data, we develop an average modern morphology for the study area. It is this morphology that we attempt to reproduce in simulations to investigate the relative importance of a range of factors in determining how barrier islands evolve and to explore the Holocene evolution of the Outer Banks. Additionally, the modern morphology, and underlying stratigraphy, provide the basis for synthesis of an initial morphology and stratigraphy for input into GEOMBEST. Arising from the initial morphology and stratigraphy is a geometric relationship (see Figure 4) between average barrier island slope (represented by the slope of a line between the intersection of the back barrier with the underlying substrate and the base of the shoreface) and substrate slope (represented by the slope of the substrate immediately behind the barrier). As further demonstrated in section 4, this geometric relationship is a critical factor in determining how barrier islands evolve [*Wolinsky and Murray*, 2009].

[20] To calculate an average modern barrier and shelf morphology, we extract, along 18 shore-perpendicular transects with an alongshore spacing of 1.5 km, elevations from a grid constructed by combining bathymetric data from the National Geophysical Data Center Coastal Relief Model and topographic lidar data collected by the United States Geological Survey (USGS) in partnership with the National Oceanic and Atmospheric Association (NOAA) and the National Aeronautics and Space Administration (NASA). These profiles are used to calculate an average elevation profile from the mainland shoreline to the middle of the continental slope. All 18 profiles are used to calculate an average shoreface and shelf profile out to a depth of about 30 m at a distance of 34 km from the shoreline. Because the width of Pamlico Sound varies across the study area, using all 18 profiles for an averaged back-barrier and sound region would result in an unrealistic profile with over-flattened seabed slopes near the mainland and back-barrier shorelines. Therefore, we only average the six central transects for the mainland to back-barrier part of the profile, which results in profile that still approximates the average width of Pamlico Sound for all 18 profiles, but preserves the steeper seabed slopes near the shorelines. Similarly, because the distance from the shoreline to the shelf break increases from south to

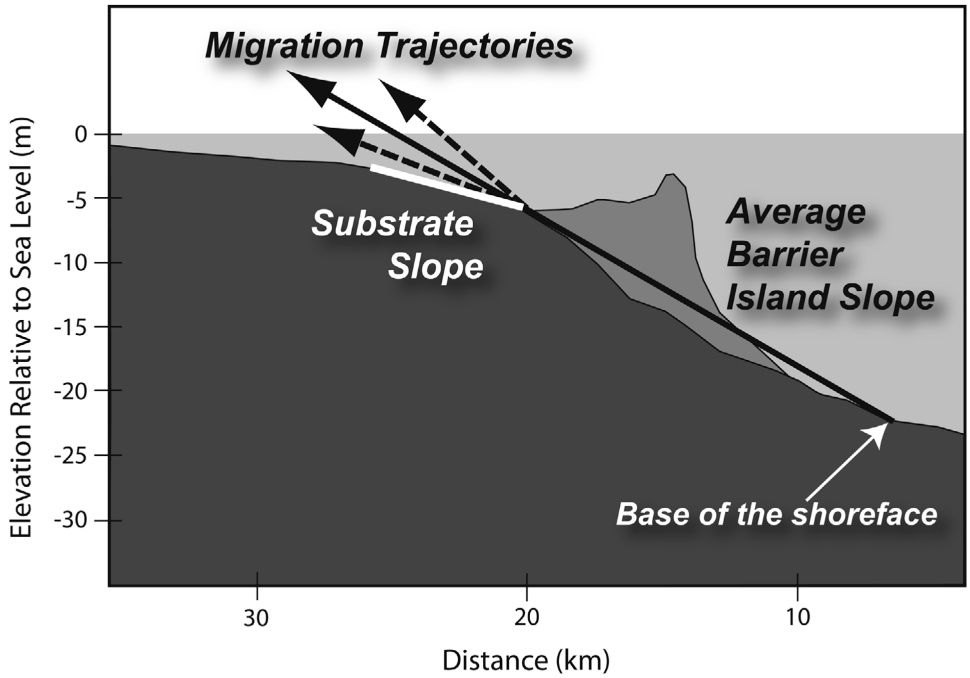

Figure 4. Average barrier island slope (black line) and substrate slope (white line) are defined. If substrate slope is constant and the sediment budget is balanced, the trajectory for landward migration (solid black line with arrow) will be defined by the average barrier island slope and barrier island volume will increase until average barrier island slope is equal to substrate slope. The top dashed black line represents a steeper migration trajectory, which defines a steeper effective barrier island slope (e.g., resulting from a positive sediment supply rate), whereas the bottom dashed black line represents a shallower migration trajectory that defines a shallower effective barrier island slope (e.g., resulting from a negative sediment supply rate or low substrate sand proportions).

north through the study area, we again only average the six central transects in this area to preserve the sharpness of the shelf break while still approximating the average shelf width for all 18 profiles. This resulting "hybrid average" cross-shore profile, extending from the coastal mainland to the continental slope, represents the average, modern, study area morphology that we seek to reproduce through Holocene simulations (Figure 5). We note that neither the width of Pamlico Sound nor the exact location of the shelf break influence the simulations presented here.

[21] A generalized stratigraphy, characterized for the study area using core descriptions and ground penetrating radar transects collected on the barrier, and seismic data (collected in Pamlico Sound and offshore to a distance of ~13 km) as part of the USGS North Carolina Regional Study, consists of four primary Pleistocene stratigraphic units separated by subsurface reflectors, a Holocene silt unit deposited within Pamlico Sound, and a Holocene barrier island up to 10 m thick [*Mallinson et al.*, 2010; E. R. Thieler and D. J. Mallinson, personal communication, 2006] (Figure 5). This stratigraphy is generally consistent with stratigraphic sections presented by *Meisburger and Williams* [1987] for a location in Duck, NC and average barrier island thickness reported in an along-strike cross section from Cape Hatteras to just north of Oregon Inlet from *Pierce and Colquhoun* [1970]. Cores indicate that the barrier island in the study area and the units underlying identified reflectors Rx and R25 (Figure 5) consist primarily of unconsolidated sand. In the absence of more precise information with which to constrain composition and erodibility, we designate these layers in the model domain as fully erodible (erodibility index = 1) and 100% sand (substrate composition index = 1). Though setting these indices to 1 is very likely an overestimation of actual characteristics, as we demonstrate later through sensitivity analyses, there is little effect on barrier evolution (i.e., migration rate, substrate erosion depth and final barrier island volume) as long as the erodibility index remains above 0.001 and substrate composition remains above 50% sand; reasonable estimates for the layers in question fall well above these lower limits.

[22] The composition of sediments underlying reflection R38 is undetermined, but due to its depth this layer does not intersect the shoreface and is therefore not relevant to Holocene barrier island evolution. An earlier study [*Pierce and Colquhoun*, 1970] suggests that lagoonal deposits are found below barrier sands in our study area. However, core logs and sediment descriptions are not provided to substantiate this conclusion. More recent studies [*Meisburger and Williams*, 1987; *Mallinson et al.*, 2010; E. R. Thieler and D. J. Mallinson, personal communication, 2006] have concluded that lagoonal deposits in the study area are either absent, localized or relatively limited in areal extent on the shoreface. Further, we infer from studies of surficial sediment distributions that true estuarine sedimentation is restricted to the central Pamlico basin [*Folger*, 1972; *Wells and Kim*, 1989]. For these reasons, and in the absence of

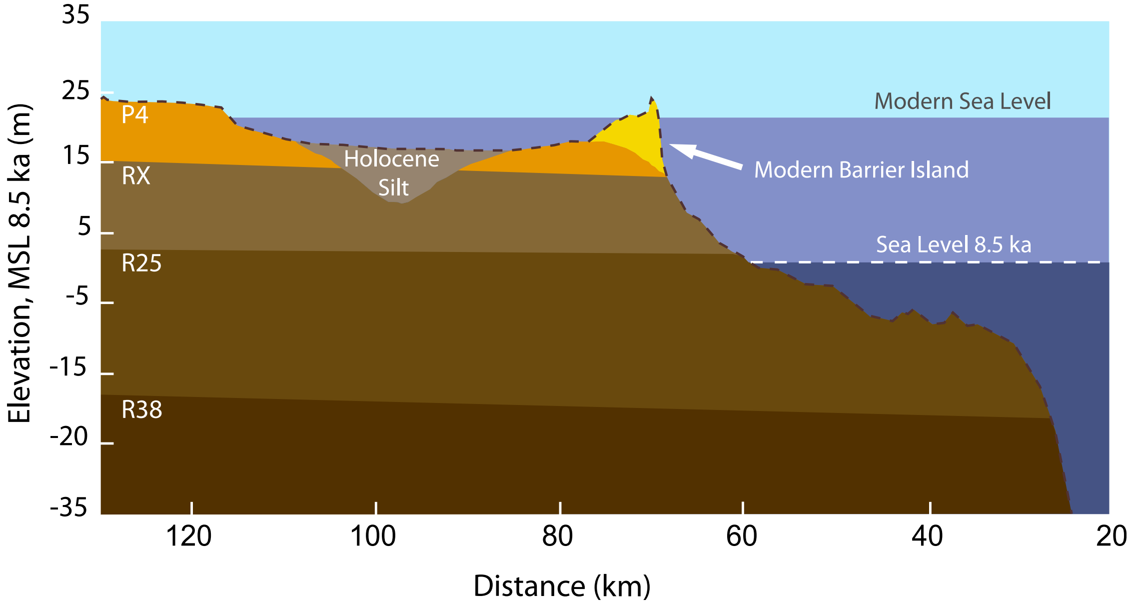

Figure 5. The average modern surface profile, or the modern morphology, for the study area appears as a dashed black line, while an average modern stratigraphy for the study appears in solid shades of brown color. The modern barrier island appears as a yellow stratigraphic unit. Elevations are plotted relative to mean sea level (MSL) 8500 years ago, which is equivalent to −22.5 m modern MSL. The modern morphology and stratigraphy shown represent the "goal" morphology and stratigraphy for simulations of Holocene barrier island evolution for the study area.

data to suggest conditions were different in the past, we assume that lagoonal and estuarine sedimentation are not sufficiently widespread to provide a significant platform onto which the barrier migrates.

[23] We develop an initial morphology and stratigraphy by increasing the thickness of exposed shelf sediments vertically by an average of 5 m (Figure 6) based on estimates by *McNinch et al.* [1999] that a 5 m thick swath of shelf sediments must have been eroded during barrier island migration to account for present-day barrier island and shoal volumes. Though the extent and sediment composition of the estuary 8500 years ago is not known, the current relatively steep slope of the Pleistocene shelf surface suggests the initial estuary would have been limited in area. Given this, and the lack of significant estuarine deposits in the modern record, the configuration of the initial estuary is likely of limited consequence to barrier evolution at the time scales of interest. Further, the lack of significant estuarine deposits in the modern record indicates that what early estuarine sedimentation was present has been eroded.

[24] In the absence of estimates regarding initial barrier island volume and to account for the likelihood that barrier islands were smaller immediately following inception, we begin the simulation with an island that is approximately half the volume of the modern barrier. Positioning the initial barrier on the adjusted shelf surface, near the shelf edge as suggested by the analysis of *McNinch et al.* [1999] provided in section 3.1, places it at an elevation 22.5 m below modern mean sea level (MSL). This elevation corresponds to MSL 8500 years ago and is consistent with several estimates for the timing of barrier island formation [e.g., *Pierce*, 1969; *Dolan and Lins*, 1986; *Moslow and Heron*, 1994]. Based on these constraints, the adjusted shelf surface, combined with the surface of the initial barrier island (Figure 6), provides a likely representation of shelf and barrier morphology 8500 years ago. Below this morphology, surfaces of stratigraphic units are extrapolated to meet the adjusted shelf surface. Holocene sedimentation in Pamlico Sound appears in both the initial stratigraphy and the modern stratigraphy because GEOMBEST is not designed to simulate deposition restricted to the central portion of basins behind barrier islands and because the contemporaneous deposition of this layer does not affect island evolution since the barrier does not migrate across it. The deposit is included both to provide an accurate representation and because its presence becomes important when the sand body migrates landward of its modern position as it does in some of the sensitivity analyses. During model simulation, the initial barrier island moves landward across the initial substrate morphology eroding into the initial stratigraphy and liberating sediment creating the modern morphology as sea level rises.

4.2. Shoreface Depth and Equilibrium Morphology

[25] To account for decreases in near-bed wave energy with depth, we define a depth, herein called the shoreface depth, beyond which sediment transport is deemed to be insignificant. Shoreface depth increases with longer time scales [*Nicholls et al.*, 1998] because larger, less-frequent storms are more likely to occur as time scales lengthen. Fortunately, as we demonstrate in section 4.3, GEOMBEST simulations for the North Carolina Outer Banks are relatively insensitive to changes in shoreface depth. This makes selection of the "correct" shoreface depth, which cannot

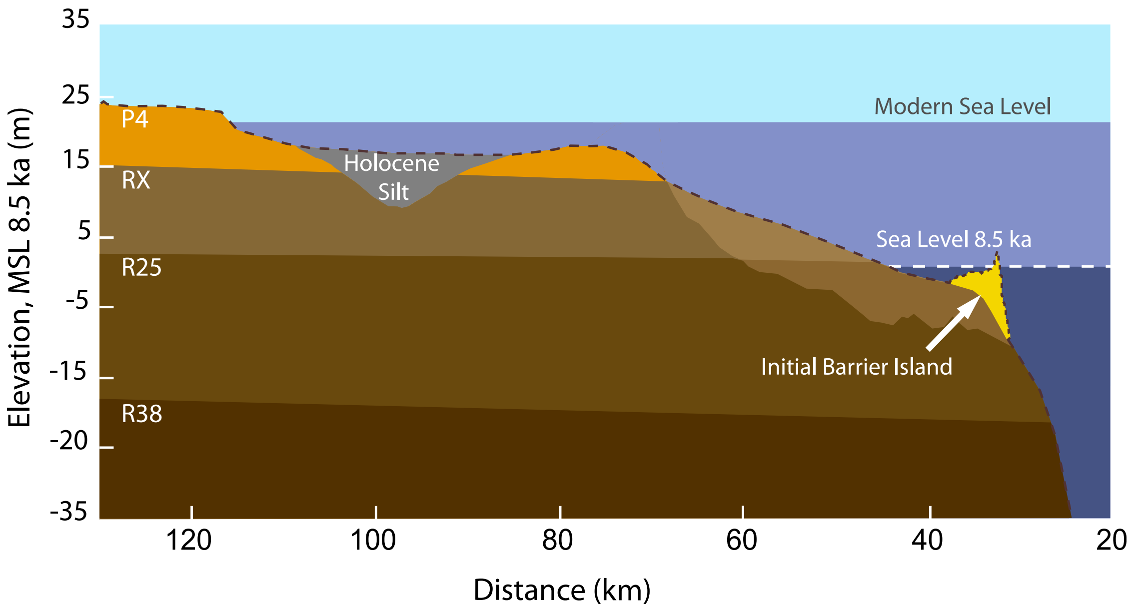

Figure 6. Modifications to the modern morphology and stratigraphy are made to synthesize an initial morphology and stratigraphy for use in a simplified 8500 year base case Holocene simulation and sensitivity analyses. To create the initial morphology, approximately 5 m of sediment thickness is added to the modern surface profile as represented by the more transparent brown shades appearing below the initial surface behind the initial barrier. Elevations are plotted relative MSL 8500 years ago, which is equivalent to −22.5 m modern MSL.

truly be known for time scales of thousands of years, less critical.

[26] Examination of the hybrid average modern profile for the study area (Figure 5) reveals a relatively smooth shoreface down to a depth of 20 m below modern sea level where bathymetric undulations begin to occur. *Everts* [1978] suggests that such changes in offshore morphology are indicative of long-term limits to significant cross-shore transport. Based on this argument, we use 20 m as a reasonable approximation of shoreface depth for the purpose of modeling barrier island evolution. This value agrees well with shoreface depths of 18.6 m and 21.6 m estimated by *Everts* [1978] based on morphology for Nags Head and Cape Hatteras, located to the north and south of the study area, respectively. For comparison, these depths are considerably, and appropriately, deeper than the short-term shoreface depth estimate for Nags Head of 7.95 m calculated using local significant wave height and wave period [*Hallermeier*, 1980].

[27] In addition to determining the depth of the shoreface, decreases in near-bed wave energy with offshore distance also influence the shape of the shoreface, tending to produce a characteristic concave upward profile, given sufficiently long time scales. Depending on the geologic framework, however, a shoreface may or may not develop a characteristic concave upward profile even if the time scale is long [e.g., *Pilkey et al.*, 1993; *Riggs et al.*, 1995]. Thus, to provide a reasonable morphology that model simulations can drive toward, but that may not be attained during simulation due to geologic framework and/or time scale constraints, we define an equilibrium morphology consisting of the modern hybrid average profile as it extends from the barrier to a water depth of 20 m (Figure 5).

4.3. Depth-Dependent Response Rate (DDRR) and Substrate Erodibility

[28] Depth-dependent response rates of natural coastal systems at millennial time scales are currently unquantified leaving us to make approximations that allow us to assess how sensitive barrier island evolution is to changes in this parameter. We find that both linear and exponential functions for DDRR produce similar results. For this reason, we use a linear function for simplicity and initially set the DDRR to 1 m yr^{-1} at the shoreline (0 m water depth) with a linear decrease to 0 m yr^{-1} at the shoreface depth of 20 m.

4.4. Sea Level Rise Rates

[29] The rate of sea level rise in North Carolina has decreased over the last 10,000 years. Sea level rise throughout the simulation follows the best available published Holocene sea level rise curve for North Carolina with rates of 0.5 m $(100 \text{ years})^{-1}$ from 8500–6800 years ago, 0.24 m $(100 \text{ years})^{-1}$ from 6800–4200 years ago, and 0.15 m $(100 \text{ years})^{-1}$ from 4200–0 years ago (E. R. Thieler, personal communication, 2005). This sea level curve for North Carolina is generally consistent with changes in Holocene sea level recently documented by *Horton et al.* [2009].

4.5. Sediment Supply Rates

[30] Although GEOMBEST is a cross-shore model, gradients in alongshore sediment transport for the study area are accounted for by varying the amount of sand added to or removed from the model domain at each time step. A sim-

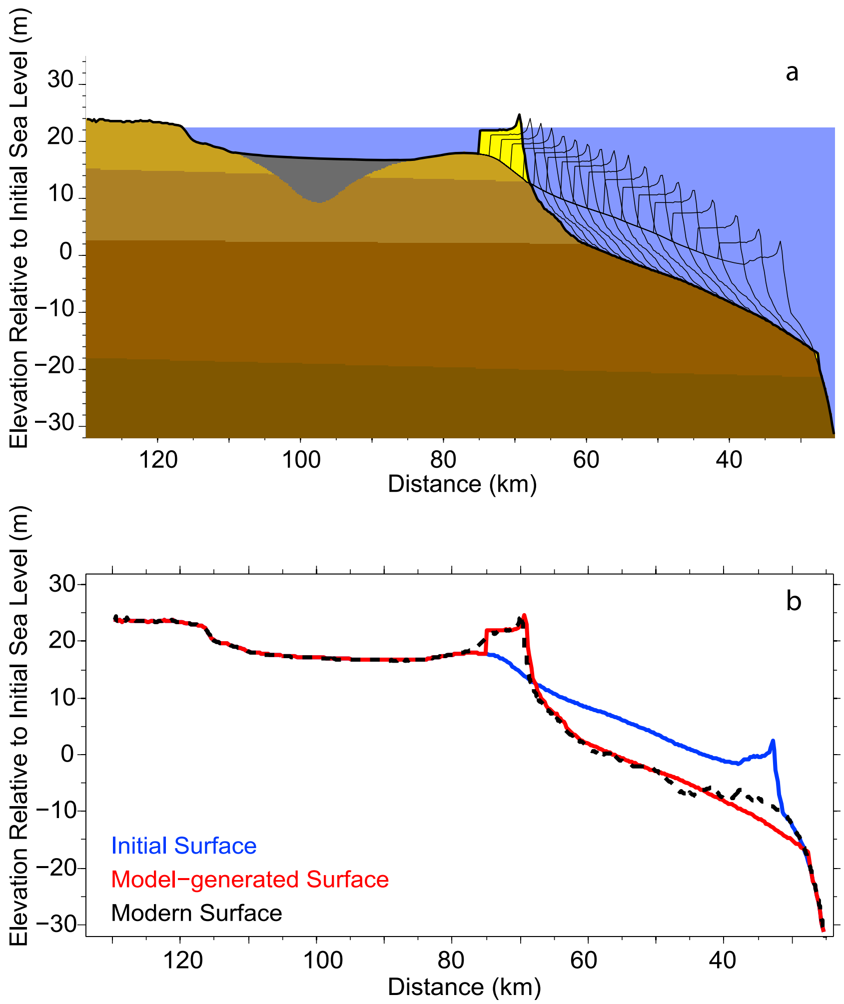

Figure 7. (a) The final time step in the 8500 year base case Holocene simulation used for sensitivity analyses. Each trace represents a 500 year time increment and the modern barrier island appears in yellow. The initial surface is shown as a thin black line above the bold black line, which represents the modern shelf surface. (b) Comparisons between the initial, model-generated, and modern morphology and stratigraphy.

plified 8500 year simulation that approximately reproduces the modern morphology and stratigraphy for use as a base case simulation in sensitivity experiments requires the removal of 25 m^3 m^{-1} of sand per year to bring the barrier island to its modern position by the end of the simulation. (This removal can be thought of as the sediment transport gradient, i.e., difference between sediment input and output to our study area.) This is equivalent to 625,000 m^3 yr^{-1}, resulting in the total removal of 5.3×10^9 m^3 across the 25 km study area over the past 8500 years. The total volume of sand removed per year during this simulation is of the same order as estimates for the net loss of 590,000 m^3 yr^{-1} reported for recent decades between Oregon Inlet and Cape Hatteras [*Inman and Dolan*, 1989]. Although this section of coast (Figure 3) is approximately twice as long as our study area, this order of magnitude agreement in sediment budget estimates is encouraging considering the large uncertainty in any sediment budget estimate.

4.6. Estuarine Infilling Rates

[31] Sedimentation of estuarine silt and clay in Pamlico Sound is limited to the central basin [*Folger*, 1972; *Wells and Kim*, 1989] and is therefore located too far behind the barrier to provide a platform for barrier island migration. For this reason, estuarine sedimentation rates are set to 0 mm yr^{-1} in GEOMBEST for all simulations reported here.

5. Results

5.1. Sensitivity Experiments

[32] Using GEOMBEST, we simulate the response of a complex coastal environment to a variety of factors as sea level rises. Here, we explore the relative importance of sea level rise rate, sediment supply or loss rate, shoreface depth, substrate erodibility, substrate composition and depth-dependent response rate in determining barrier island

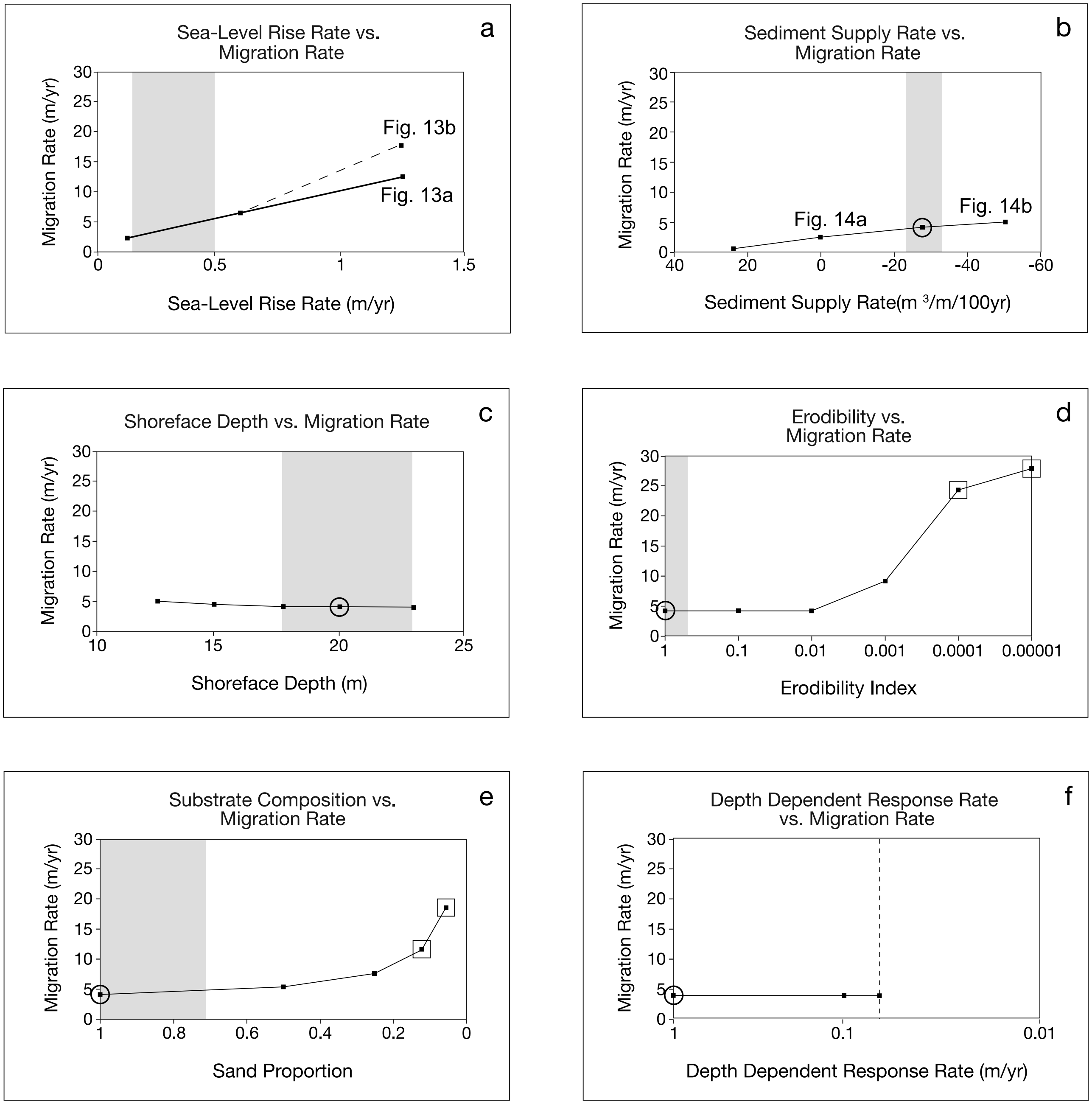

Figure 8. Results of sensitivity analyses showing the effect of changes in six different input parameters on barrier island migration rate. Gray bars indicate best estimates for the range of most likely Holocene values in the North Carolina Outer Banks. Because DDRR cannot be constrained, an estimate is not provided for this parameter. In Figure 8a, a solid line denotes results of constant total sea level rise simulations while a dashed line denotes results of constant duration simulations. Base case simulation values are indicated by an open circle. Simulations which do not run to completion, because the barrier island cannot be maintained above sea level, are indicated by an open square.

response to sea level rise. (We note that these analyses can also be thought of as providing an assessment of how model output changes in response to possible errors in input parameters). Our base case is a simplified Holocene simulation, having input parameters as described in section 4 and summarized in Table 1, which simulates a possible scenario for the evolution of the area between Rodanthe and Cape Hatteras over the last 8500 years (Figure 7). Varying one parameter at a time around the actual or best estimated value, we determine the degree to which changes in each parameter produce changes in the following three measures of barrier island evolution: (1) average landward barrier island migration rate, (2) average depth of substrate erosion, and (3) final barrier island volume (Figures 8–10). Due to space limitations we cannot provide graphical output for each of the simulations presented, however, we note that

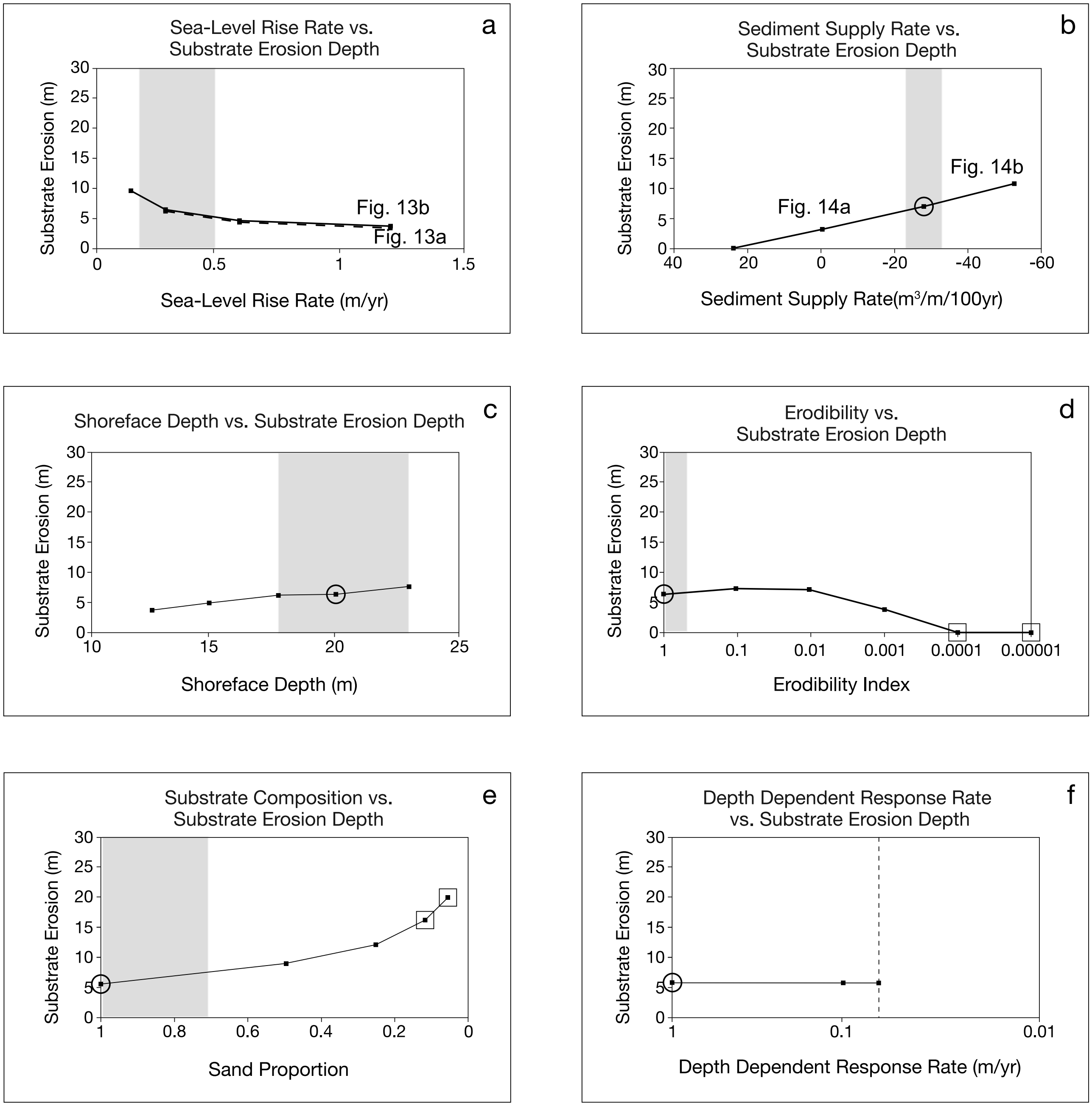

Figure 9. Results of sensitivity analyses showing the effect of changes in six different input parameters on substrate erosion depth. Gray bars indicate best estimates for the range of most likely Holocene values in the North Carolina Outer Banks. Because DDRR cannot be constrained, an estimate is not provided for this parameter. In Figure 9a, a solid line denotes results of constant total sea level rise simulations while a dashed line denotes results of constant duration simulations. Base case simulation values are indicated by an open circle. Simulations which do not run to completion, because the barrier island cannot be maintained above sea level, are indicated by an open square.

Figures 12 and 13 (the details of which are discussed in sections 5.1.1 and 5.1.2 on sea level rise rate and sediment supply rate, respectively) provide examples of how morphology and stratigraphy vary with changes in input parameter values.

[33] Average barrier island migration rate is determined by finding the slope of the linear regression between shoreline position and time for the length of the simulation. Average substrate erosion depth is calculated by averaging the vertical difference between the initial surface and the final surface between the cross-shore position (x) where the back edge of the initial barrier intersects the initial substrate (38 km in the model grid) and the cross-shore position where the barrier/substrate contact on the shoreface intersects the final surface. Average barrier island volume is calculated by integrating to determine the area of this

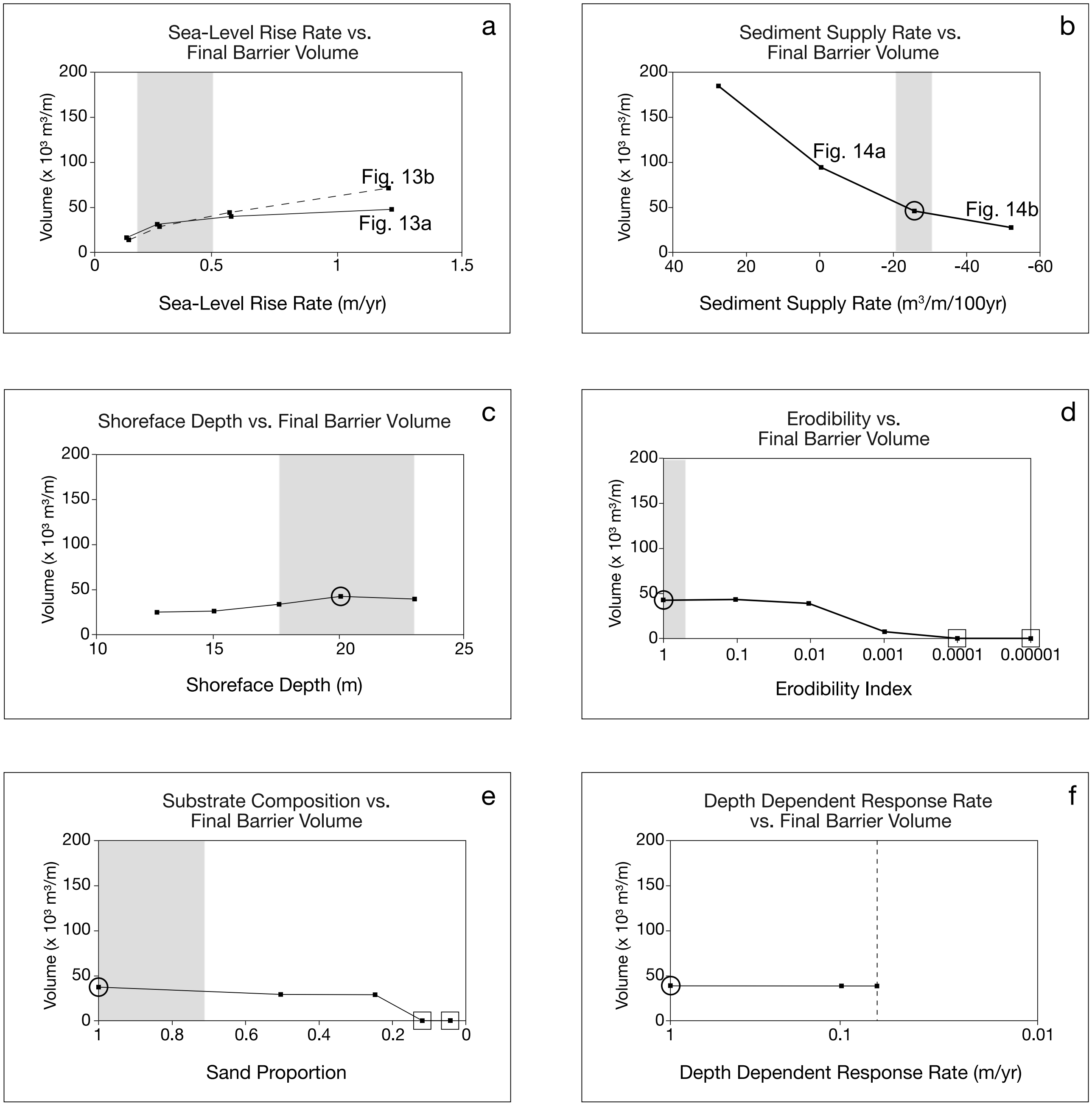

Figure 10. Results of sensitivity analyses showing the effect of changes in six different input parameters on barrier island volume. Gray bars indicate best estimates for the range of most likely Holocene values in the North Carolina Outer Banks. Because DDRR cannot be constrained, an estimate is not provided for this parameter. In Figure 10a, a solid line denotes results of constant total sea level rise simulations while a dashed line denotes results of constant duration simulations. Base case simulation values are indicated by an open circle. Simulations which do not run to completion, because the barrier island cannot be maintained above sea level, are indicated by an open square.

stratigraphic unit under the final surface between the cross-shore position where the final barrier intersects the shoreface and the cross-shore position where the final back barrier intersects the initial surface (e.g., the area shown in yellow/lightest gray in Figure 7), resulting in volume units of m^3 m^{-1}. For reference, the base case simulation, to which all results are compared, produces an average barrier island migration rate of 4.2 m yr^{-1}, an average depth of substrate erosion of 5.9 m and a final barrier volume of approximately 40×10^3 m^3 m^{-1}. For reference, the actual position of the modern shoreline lies at 69.5 km within our model grid and the final position of the present-day shoreline in the base case simulation lies at 70.3 km.

5.1.1. Sea Level Rise Rate

[34] To test the sensitivity of barrier island evolution to the rate of sea level rise, we run two sets of simulations

in which the sea level rise rate increases from 0.15 m (100 years)$^{-1}$ to 1.2 m (100 years)$^{-1}$ (Figures 8–10a) while remaining constant throughout any single run. Because the base case simulation is designed to simulate barrier island evolution throughout the Holocene, the rate of sea level rise throughout this simulation is inconstant, changing twice during the model run to follow the Holocene sea level rise curve (average rate of 0.26 m yr^{-1}). As will be demonstrated throughout the sensitivity analyses section, the timing with which a barrier encounters changing substrate geometries alters simulation outcomes. For this reason, in the case of the sea level rise rate sensitivity experiments only, the base case simulation results are not included in comparisons among different model runs.

[35] In the first set of simulation experiments, each simulation runs until sea level has risen 12 m (i.e., constant total sea level rise series, Figures 8–10a, solid line). As a result, each simulation runs for a different length of time ranging from 8000 years for a sea level rise rate of 0.15 m (100 years)$^{-1}$ to 1000 years for a sea level rise rate of 1.2 m (100 years)$^{-1}$. In the second set of simulations, each simulation runs for a total of 2500 years (i.e., constant duration series, Figures 8–10a, dashed line) but total sea level rise ranges from 3.75 m for a sea level rise rate of 0.15 m (100 years)$^{-1}$ to 30 m for a sea level rise rate of 1.2 m (100 years)$^{-1}$.

[36] As expected, when the sea level rise rate increases, the average landward migration rate increases significantly in order for the barrier island to maintain a position above sea level. The rate of increase is linear, increasing from 2.7 to 12.5 m yr^{-1}, or by a factor of approximately 4.5, when total sea level rise is held constant, while the rate of increase is nonlinear, increasing from 2.6 m to 16.5 m yr^{-1}, or by a factor of approximately 6.5, when the simulations run for the same length of time (Figure 8a).

[37] When the sediment budget is negative, as it is in all of the sea level rise simulations, less sand is lost per increment of sea level rise with higher sea level rise rates. In this case, less sand needs to be extracted from the substrate to balance losses due to the negative sediment budget and, as a result, average substrate erosion depth is inversely proportional to the sea level rise rate, with higher sea level rise rates leading to less substrate erosion. But, as shown in Figure 9a, this measure is less sensitive than migration rate, varying only between 3.5 to 6 m, or by a factor of close to 2, across all simulations for the range of parameter values plotted. Results are not shown for the 0.15 m (100 year)$^{-1}$ simulations because these runs are too short for comparable measurements of substrate erosion depth to be made.

[38] The range of final barrier island volume is smaller for the constant total sea level rise simulations, increasing from 23 to 48 × 10^3 m^3 m^{-1}, or by a factor of 2, compared to an increase of 19 to 68 × 10^3 m^3 m^{-1}, or by a factor of approximately 3.5, for the constant duration simulation. In both sets of simulations (Figure 10a), the relationship between sea level rise rate and final barrier island volume is slightly nonlinear with higher sea level rise rates leading to larger barrier island volumes. The increase in barrier island volume with sea level rise rate is related to the interplay between the negative sediment budget and the rate of sea level rise mentioned above, but it is also a function of the relationship between average barrier island slope and substrate slope (Figure 4) as explained in the paragraphs below.

[39] Substrate slope in the simulations is consistently shallower than average barrier island slope. As a result, barrier island volume will tend to increase during landward migration until the two slopes are equal. To understand this intuitively, let us first consider a simplified scenario in which the substrate slope is constant and the sediment budget is balanced. In this case, a small barrier island will be associated with a relatively deep incision of the shoreface into the underlying substrate (Figure 11a) while a large barrier island will be associated with a relatively shallow incision of the shoreface into the underlying substrate (Figure 11c). As a result, for the same increment of sea level rise, extraction of sufficient sand from the substrate to maintain a position above sea level requires less landward motion (and therefore a steeper trajectory) in the case of the small barrier and more landward motion (and therefore a relatively shallower trajectory) in the case of the large barrier island. Geometrically, the direction of the trajectory in this simplified case is defined by, and parallel to, the average barrier island slope [*Wolinsky and Murray*, 2009]. As long as the shoreface extends into the substrate, barrier island volume will tend to increase during landward migration, resulting in a decrease in average barrier island slope (Figures 11a–11c), a concomitant decrease in the extent to which the shoreface incises into the substrate and an increasingly shallower landward trajectory. Thus, with each increment of sea level rise, under these conditions, the barrier moves landward along a trajectory defined by the average barrier island slope. During landward migration, barrier island volume increases as average barrier island slope progressively approaches that of the substrate. When the two slopes become equal, the shoreface will no longer incise into the substrate, and average barrier island slope and barrier island volume will be in a steady state, (i.e., in equilibrium).

[40] Keeping substrate slope constant, but adding the complicating effect of a negative sediment budget increases the amount of landward motion that occurs during each increment of sea level rise (resulting in a shallower trajectory) because more sediment needs to be removed from the substrate at each sea level rise increment to counter the negative sediment budget. In this case, barrier island volume reaches a steady state while the shoreface still incises into the substrate somewhat and the landward trajectory the barrier follows is shallower than the geometrically defined average barrier island slope. This trajectory, which, in this case, is different from average barrier island slope, can now be thought of as equivalent to the "effective" barrier island slope. Increasingly negative sediment budgets will lead to effective barrier island slopes that are increasingly divergent from (i.e., increasingly shallower than) average barrier island slope (see Figure 4).

[41] In an even more realistic scenario, substrate slope is not constant. Instead, barriers will tend to encounter changing substrate slopes throughout landward migration. With continually changing substrate slopes that are always shallower than the effective barrier island slope, barrier island volume will still tend to increase, thus allowing the effective barrier island slope to approach substrate slope. However, equilibrium between the two slopes is unlikely to

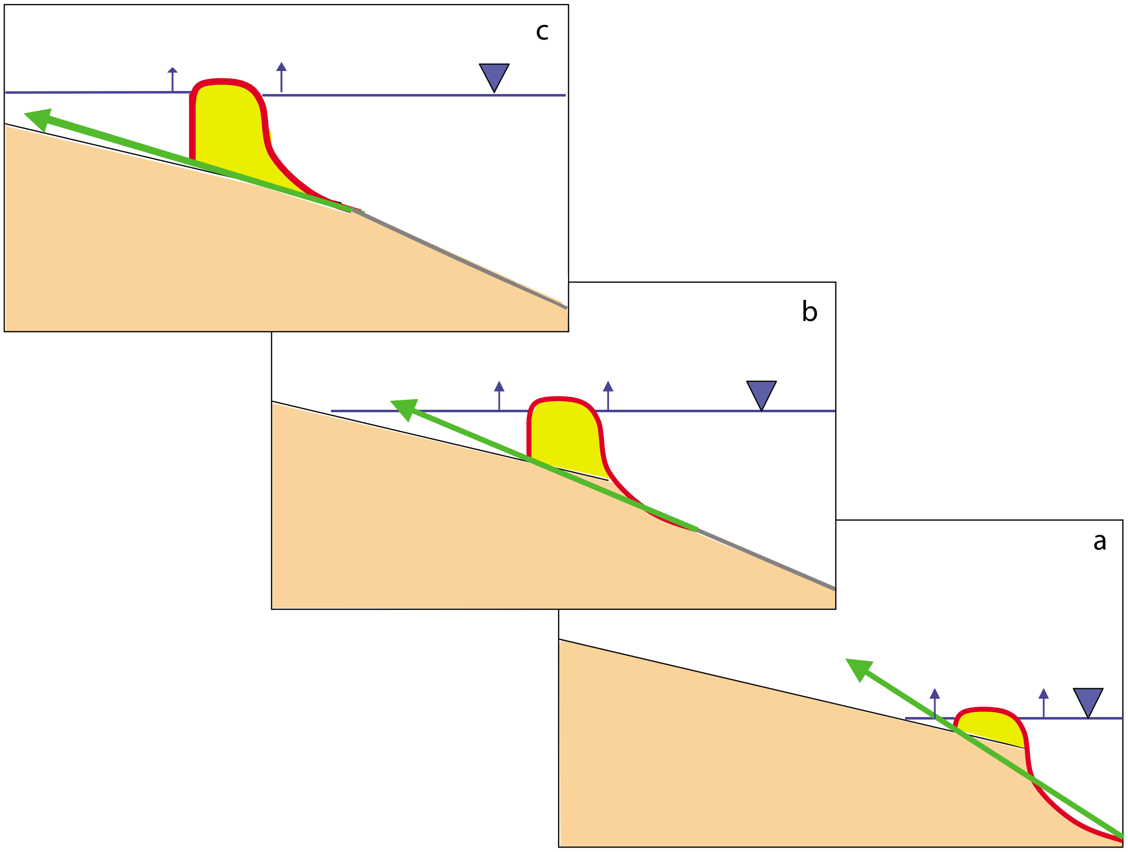

Figure 11. When the sediment budget is balanced and substrate slope is constant, at any instant, a barrier will move along a vector defined by the average barrier island slope [*Wolinsky and Murray*, 2009]. (a) A barrier island that is far from equilibrium will be smaller and associated with a shoreface that extends deeply into the underlying substrate. (b–c) A barrier island that is closer to being in equilibrium with the underlying substrate slope will be larger and will therefore be associated with a shoreface that does not extend very far into the substrate. In Figures 11a–11c a barrier will tend to increase in volume during landward migration until substrate slope and average barrier island slope are in equilibrium and as a result the trajectory (green arrow) the barrier follows will tend to become shallower resulting in faster migration rates as equilibrium is approached.

be attained because the substrate slope is continuously changing. As described for the constant slope case above, a barrier that is nearly in equilibrium with substrate slopes will also tend be large and associated with a shallow incision of the shoreface into the substrate. For the same volume of sand to be extracted from this smaller shoreface substrate thickness with each sea level rise increment, barrier island migration rate must continuously increase as effective barrier island slope approaches the substrate slope.

[42] The effect of this approach to equilibrium on migration rate is well illustrated by the 1.2 m (100 year)$^{-1}$ constant total sea level rise and constant duration simulations (Figure 12). The 1.2 m (100 year)$^{-1}$ constant total sea level rise simulation has a duration of only 1000 years and, in this limited time, for the given conditions, does not achieve a steady state in which average barrier island slope and substrate slope are equal. The 1.2 m (100 year)$^{-1}$ constant duration simulation, however, has a duration of 2500 years which, for the given conditions, allows the barrier island to more closely approach equilibrium with the underlying substrate slope, resulting in a larger barrier island associated with a less incised shoreface, and significantly higher migration rates. Further, because the constant total sea level rise simulations all have the same geometric endpoint, i.e., final sea level = 12 m above initial sea level, the barrier reaches the same pre–steady state condition in each simulation resulting in a linear increase in migration rate with sea level rise rate, i.e., at higher rates of sea level rise the barrier simply reaches the same cross-shelf position faster. In contrast, when the simulations run for the same length of time, the total amount of sea level rise is greater at higher sea level rise rates, which means the proportion of a simulation exhibiting higher migration rates becomes greater at higher sea level rise rates. In addition, when sea level rises 1.2 m (100 years)$^{-1}$ for 2500 years, the barrier in this simulation encounters significantly shallower substrate slopes toward the end of the simulation which has the effect of further increasing landward migration rates under these conditions. These two effects, both of which serve to increase migration rates at the end of long simulations having high sea level rise rates, account for the nonlinear increase in migration rates that occurs in the constant duration sea level rise rate experiments.

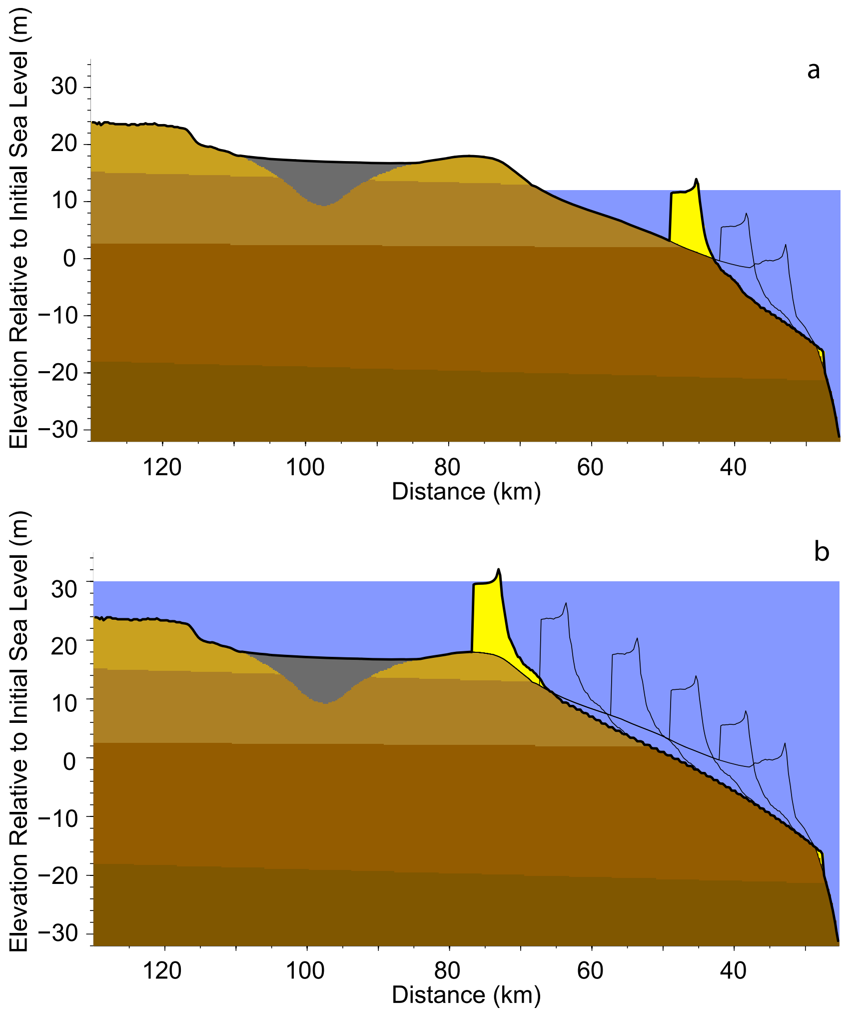

Figure 12. (a) Constant total sea level rise (duration = 1000 years) and (b) constant duration (duration = 2500 years) simulations having a sea level rise rate of 1.2 m century^{-1}. The first 1000 years of each simulation are identical, but the barrier island in the constant duration simulation has a much higher average migration rate toward the end of the simulation because there is more time for average barrier island slope to approach equilibrium with the substrate slope.

5.1.2. Sediment Supply or Loss Rates

[43] We run four simulations having sediment budgets ranging from positive to negative with sand supply or loss rates from 25 m^3 m^{-1} yr^{-1} to −50 m^3 m^{-1} yr^{-1} (with −25 m^3 m^{-1} yr^{-1} being the base case value) (Figures 8–10b). When the sediment budget is 25 m^3 m^{-1} yr^{-1}, landward migration and substrate erosion are not necessary for the maintenance of a subaerial barrier island. Instead, the barrier responds to sea level rise primarily by aggrading in place and by depositing a thin sand sheet to bring the offshore slope closer to equilibrium. As the sediment budget becomes balanced and then more negative over the other three runs, migration rate and substrate erosion depth increase linearly by a factor of approximately 1.5 and 3.5, respectively (Figures 8b and 9b). In these simulations, increasingly more sand must be extracted from the substrate in order to maintain a subaerial barrier as the sand loss rate increases.

[44] Final barrier island volume decreases nonlinearly by a factor of approximately 2.5 between the balanced and base case simulations and by a factor of nearly 1.5 between the base case simulation and the simulation having a sand loss rate of −50 m^3 m^{-1} yr^{-1} (Figure 10b). The changes in final barrier island volume that result from changes in the sediment loss rate indicate that current conditions are not only a function of current parameters. Rather, the history of the system (i.e., previous sediment supply/loss rates, etc.) also plays a critical role by enhancing, or offsetting, the tendency for barrier island volume to increase during landward migration, as illustrated by the examples that follow. Because sand is not removed from the balanced sediment budget simulation, as the barrier migrates landward with a tendency to increase in volume until it is in equilibrium with the underlying substrate, only a small amount of sand needs to be extracted from the underlying substrate at each time step (relative to the negative sediment budget simulations) to maintain a position above sea level. The barrier in this simulation moves landward along a trajectory defined by average barrier island slope and although the final barrier island is located considerably seaward of the final barrier in the base case simulation (Figure 7), near equilibrium with

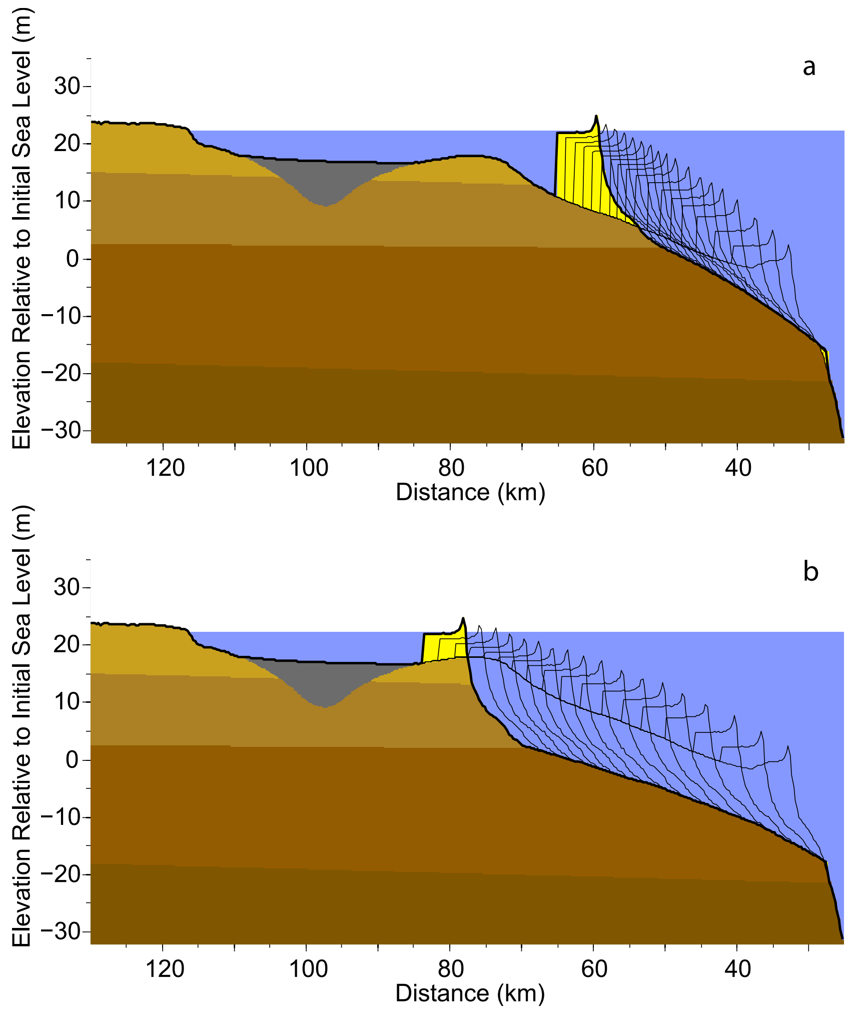

Figure 13. (a) Balanced and (b) $-50\ m^3\ m^{-1}\ yr^{-1}$ Holocene simulations. Comparison with base case simulation reveals that the history of the system (e.g., the history of sediment supply or loss) can offset or enhance the tendency for barrier island volume to increase during landward migration.

the substrate slope is attained by the end of the run (Figure 13a), i.e., equilibrium is approached more rapidly.

[45] In contrast, the $-50\ m^3\ m^{-1}\ yr^{-1}$ sediment budget simulation demonstrates that a high sediment loss rate can offset the tendency for barrier island volume to increase during landward migration. Because the sediment loss rate in this simulation is even greater than the sediment loss rate in the base case simulation, the barrier follows an even shallower landward trajectory. As a result, barrier volume remains small, the shoreface incises deeply into the substrate and effective barrier island slope diverges even farther from average barrier island slope (i.e., it is even shallower). For each increment of sea level rise, then, more sediment will be extracted from the shoreface in the case of the small barrier with a history of large sediment losses (Figure 13b), than in the case of a large barrier with a more balanced sediment budget perched in the same location (Figure 13a). For this reason, the small barrier that has experienced sediment loss in the past is better poised to survive increases in sea level rise rates than a larger barrier having a history of a more balanced sediment budget (Figures 13a and 13b).

[46] Differences between the balanced sediment budget simulation presented in this section and the schematic balanced sediment budget simulation presented in section 2.2 are also indicative of the combined importance of the relationship between average barrier island slope and substrate slope, and system history. Instead of simple translation without substrate erosion, the substrate erodes an average of approximately 3 m throughout the balanced sediment budget Outer Banks simulation (Figure 13a). In the schematic simulation (Figure 2b), initial average barrier island slope is equivalent to the substrate slope and as a result, barrier island volume is already in equilibrium with the substrate slope at the beginning of the simulation. For this reason, barrier island volume stays constant throughout the simulation. In contrast, average barrier island slope is steeper than the underlying substrate slope at the beginning of the North Carolina simulation resulting in incision of the shoreface into the underlying substrate and the tendency for barrier island volume to increase throughout the simulation.

5.1.3. Shoreface Depth

[47] To assess the sensitivity of barrier island evolution in the modeled coastal environment to shoreface depth, we

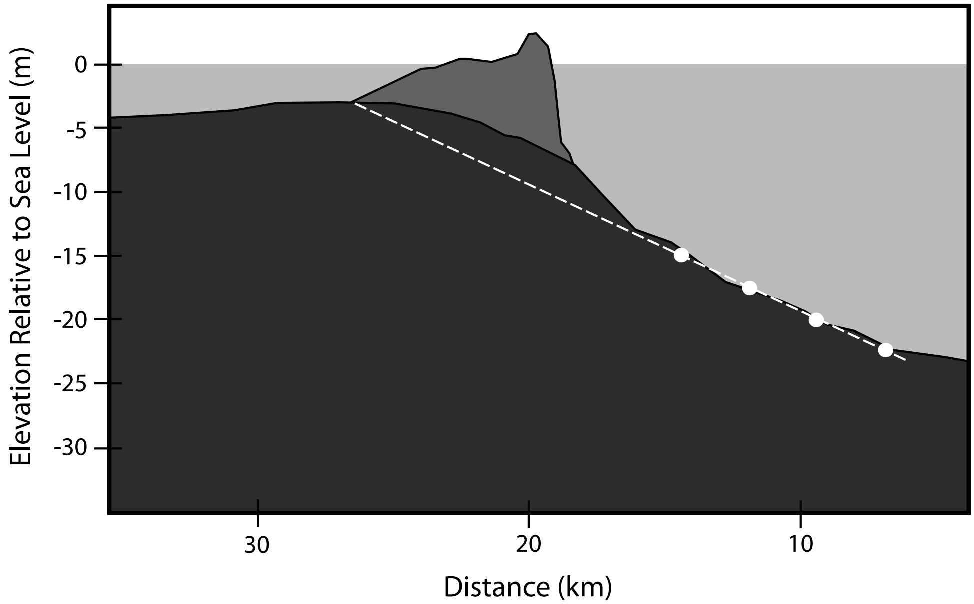

Figure 14. Average barrier island slope in the study area, represented by the slope of a line between the base of the barrier and the base of the shoreface, does not change as the shoreface depth changes from −15 m to −22.5 m.

run five simulations with shoreface depth varying between 12.5 m to 22.5 m in 2.5 m increments (with 20 m being the base case value) (Figures 8–10c). All three measures of barrier island evolution are fairly insensitive to this parameter. As shoreface depth increases, migration rates decrease slightly from 4.2 to 5 m yr^{-1} (Figure 8c), or by a factor of just over 1. Changes in substrate erosion depth (Figure 9c) display the opposite trend, increasing from 4.3 to 6.8 m, or by a factor of approximately 1.5, as the shoreface deepens. When the shoreface extends to greater depths, slightly more sediment is liberated at each time step resulting in more substrate erosion and less of a need for landward migration to extract sufficient sand to maintain a subaerial barrier island. As a result, barrier island volume increases slightly with shoreface depths, except for the 22.5 m simulation where a small amount of sedimentation occurs offshore early in the simulation (because the substrate slope is initially slightly steeper than average barrier island slope) accounting for a small decrease in final barrier island volume.

[48] The small degree to which changes in shoreface depth result in changes in barrier island evolution in the modeled Outer Banks environment is largely a function of the morphology and stratigraphy of the study area. Within the tested range of reasonable shoreface depths, average barrier island slope changes only slightly (Figure 14). For this reason, changing only the shoreface depth does not dramatically increase or decrease the volume of sediment that needs to be added to or removed from the barrier to approach equilibrium with the underlying substrate slope.

5.1.4. Substrate Erodibility

[49] Migration rates are particularly insensitive to the erodibility of the substrate showing essentially no change in the three measures of barrier island evolution until the substrate is 1/1000 as erodible as a fully erodible unconsolidated sediment (Figures 8–10d). When sediment erodibility is set to 0.001, migration rate increases by a factor of approximately 2, substrate erosion depth decreases by a factor of about 2, and barrier island volume decreases to approximately 7 m^3 m^{-1} or by a factor of approximately 5. In this simulation, substrate erosion depth is limited by erodibility and the barrier must migrate over a greater length of substrate to liberate a sufficient volume of sand to maintain subaerial exposure, effectively resulting in a shallowing of the shoreface. Though the barrier becomes progressively smaller throughout the simulation, it appears that the rates of sand production needed to maintain a subaerial barrier under modeled conditions are so low that even sediments having very low erodibility (but high sand proportions) can erode rapidly enough to produce the sand supply needed to counteract the negative sediment budget. In contrast, at erodibilities of 0.0001 and 0.00001, the substrate behaves as though it is nonerodible. Because the substrate does not erode, migration rates jump sharply bringing the barrier to higher elevations in an attempt to maintain a position above sea level. The increase in migration rates, however, is insufficient and barrier island volume decreases to zero within 800 years, simulating the disappearance of a barrier. This occurs because no new sediment is being supplied by substrate erosion to counter the negative sediment budget. Admittedly, in its current form GEOMBEST is not well suited to address the details of barrier evolution when system evolution becomes limited by the erodibility of the underlying substrate (because additional parameters describing rock weathering are needed to do this more appropriately) but we expect this general mode of behavior to be representative of the effect of a completely lithified substrate on barrier island evolution at this scale.

5.1.5. Substrate Composition

[50] Substrate composition affects barrier island evolution by determining the amount of sand-sized sediment that will be supplied to the barrier island system by erosion of a unit volume of substrate. To assess the effects of changing

Table 2. Model Output for the Base Case and Exploratory Holocene Simulations Compared With Geologic Constraints and Estimates

Measure of Barrier Island Evolution	Modern Constraints and Estimates	Base Case Simulation	Exploratory Holocene Simulation
Average migration rate (m yr^{-1})	Unknown	4.2	4.6
Modern shoreline change rate/migration rate (m yr^{-1})	Erosion rate = −4 to +2[a]	3.3	3.4
Substrate erosion depth (m)	5[b]	5.9	5.6
Depth of outer shelf relative to MSL 8.5 ka (m)	−10	−16.5	−11
Final barrier island volume (m^3 m^{-1})	36×10^3	40×10^3	35×10^3
Final shoreline position in model domain (km)	69.5	69	69.5
Sediment volume lost from study area (m^3 yr^{-1})	590,000[c]	625,000	625,000
Estimated Diamond Shoal volume/total volume removed (m^3)	1.3×10^9[d]	5.3×10^9	4.5×10^9

[a]*Morton et al.* [2005].
[b]*McNinch et al.* [1999].
[c]*Inman and Dolan* [1989].
[d]Calculated by dividing by three the total volume estimate from *McNinch et al.* [1999] which includes Frying Pan, Cape Lookout, and Diamond Shoals.

substrate composition, we run a series of simulations in which the sand proportion is decreased by half repeatedly from 1 to approximately 0.06 (Figures 8–10e). Across the first three simulations, barrier island migration rate and substrate erosion depth increase by a factor of just over 1 indicating that the barrier must move somewhat farther landward and erode somewhat more deeply at each time step in order to liberate enough sand-sized sediment to maintain barrier position above sea level. Decreasing sand proportions in the substrate, then, cause the barrier to follow a shallower landward trajectory (which therefore defines a shallower effective barrier island slope). Barrier island volume changes only slightly across the 100% to 25% sand simulations.

[51] When substrate composition is decreased to 12.5% sand and just over 6% sand, migration rate and substrate erosion depth both begin to increase nonlinearly. Neither increase, however, is sufficient to maintain a subaerial barrier throughout the entire simulation and barrier island volume decreases to zero after 8000 and 4500 simulation years, respectively. This series of simulations suggests that for the modeled environment barrier island evolution begins to be particularly sensitive to changes in substrate composition when the sand proportion falls within the range of 25%–12%. With slower rates of shoreface erosion and higher rates of sea level rise, barrier island evolution will become even more sensitive to substrate sand content.

5.1.6. Depth-Dependent Response Rate

[52] In GEOMBEST the maximum rate of net vertical erosion or accretion (i.e., shoreface erosion or accretion) that can occur within a specified period of time as a function of cross-shore distance is specified by the depth-dependent response rate (DDRR). The DDRR is specified at the shoreline (0 m depth) and decreases linearly to zero at the base of the shoreface (20 m depth in the base case simulation). A series of simulations having DDRR values ranging from 1 to 0.01 m yr^{-1} suggests that barrier island evolution responds to changes in vertical erosion rates differently than it responds to changes in the other parameters (Figure 8–10f). Here, migration rate, substrate erosion depth and final barrier island volume remain exactly or nearly the same with decreasing DDRR for DDRR values between 1 and 0.07 m yr^{-1}. When DDRR at the shoreline falls below 0.07 m yr^{-1} the simulations become unstable, running only for a few time steps before stopping because rates of vertical shoreface change are so slow that they inhibit barrier island migration and substrate erosion from occurring at rates that are fast enough to keep the barrier island above sea level. In these simulations barrier island volume does not decrease to zero, but rather, the barrier drowns in place (or begins to disintegrate) because the shoreface cannot evolve fast enough for the barrier/shoreface system to move landward as a unit. This series of simulations suggests there is a threshold beyond which evolution of a landward-migrating barrier responds dramatically (e.g., Figure 8–10f) to low depth-dependent response rates, or shoreface erosion rates, ultimately resulting in a geomorphic threshold crossing as a new equilibrium state (e.g., barrier island drowning or disintegration) becomes established.

5.2. Exploratory Holocene Simulation

[53] To explore possible scenarios for barrier island evolution on the Outer Banks of North Carolina, we apply insights from sensitivity analyses along with additional geologic constraints to develop a modified base case simulation, here referred to as the exploratory Holocene simulation, that more closely reproduces the modern morphology and stratigraphy in the study area while also conforming more closely to geologic constraints and estimates (see Table 2 for summary of comparisons between model output and geologic observations). In developing this exploratory simulation we do not seek to imply that our estimates and assumptions are highly precise. Rather, we suggest a possible long-term evolutionary scenario for barrier islands in the study area that will be reliable to the extent that the best available geologic information allows.

[54] Revising the base case simulation to more closely match the modern condition by the end of the simulation requires less substrate erosion overall, especially on the outer shelf, a more landward final shoreline position and a final barrier morphology and volume that more closely match that of the average modern barrier morphology and stratigraphy. As summarized in Table 1, we make a few adjustments to the base case simulation to produce these changes. First, to more closely reproduce the average modern barrier island morphology and volume, we extend the equilibrium morphology farther into the back-barrier region so that the morphology the barrier evolves toward more closely matches the modern morphology. Second, to decrease the need for substrate erosion during the earlier part of the simulation, we start the simulation with an initial barrier that is smaller and narrower than that of the base case

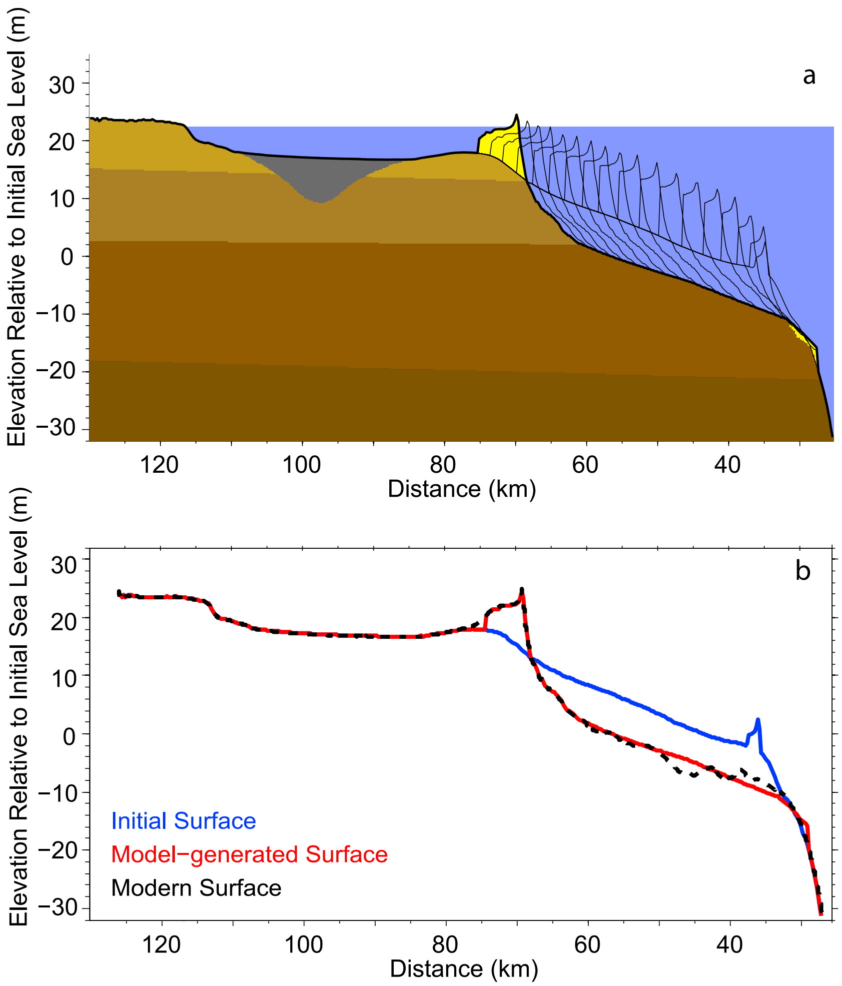

Figure 15. (a) The final time step in the 8500 year exploratory Holocene simulation. Each trace represents a 500 year time increment, and the modern barrier island appears in yellow. The initial surface is shown as a thin black line above the bold black line, which represents the modern shelf surface. (b) Comparisons between the initial, model-generated, and modern morphology and stratigraphy for the 8500 year exploratory Holocene simulation.

simulation having an approximate volume of one fourth that of the modern barrier island instead of approximately one half. The smaller barrier initially follows a steeper trajectory and therefore decreases the need for the liberation of sand early in the simulation, thereby improving the match between the initial and modern morphology. Field data to support the selection of an initial barrier island volume do not exist, but it is reasonable to assume that just after inception, the barrier was considerably smaller and narrower than the islands we see today.

[55] Sea level rise rate, estuarine infilling rate, shoreface depth, erodibility, and substrate composition are constrained by modern observations for the Outer Banks. For this reason, values for these parameters remain the same as in the base case simulation. Because the depth-dependent response rate appears unimportant, except at very low rates of response, we leave this parameter set to 1 m yr^{-1}, which essentially represents an instantaneous rate of response. Sediment supply/loss rate is the least well constrained of the parameters tested and changes in this parameter alter the depth of substrate erosion and the rate of landward migration as confirmed by sensitivity analyses. We find the best fit with modern morphology and stratigraphy (Figure 15) by adjusting the sediment budget to include three different periods of sand removal corresponding to the three time periods of varying sea level rise rate. The resulting sediment budget is balanced from 8500–6800 years ago with 0 m^3 m^{-1} yr^{-1} removed, negative from 6800 to 4200 years ago with 30 m^3 m^{-1} yr^{-1} removed and negative from 4200 to 0 years ago with 25 m^3 m^{-1} yr^{-1} removed, resulting in removal of 625,000 m^3 yr^{-1} during the latter part of the simulation and a total of 4.5×10^9 m^3 overall. Though there is no reason to expect the sediment budget and the sea level rise rate to covary directly in this way, it is reasonable to assume that the sediment budget has changed over time and selection of alternative time periods over which to vary the sediment budget would be even more arbitrary. A balanced sediment budget between 8500 and 6800 years ago results in an appropriate amount of substrate erosion along the outer shelf, thereby more closely reproducing the modern morphology (though, admittedly, geologic evidence to support

or refute a balanced sediment budget over this time period does not exist).

[56] Comparisons between the total volume of sediment removed over the course of the simulation and estimates for the volume of Diamond Shoals provide an independent measure of how well the simulation falls within the range of geologic constraints. If we make the simplifying assumption that Frying Pan Shoals, Cape Lookout Shoals, and Diamond Shoals are approximately equal in volume, then dividing by three the total shoal volume estimate provided by *McNinch et al.* [1999] results in an estimated 1.3×10^9 m^3 of sediment in Diamond Shoals alone. The total volume of sediment removed from the 25 km study area over the course of the exploratory Holocene simulation, 4.5×10^9 m^3, is the same order of magnitude as this estimated volume of Diamond Shoals. Although we have no reason to believe that the sediment stored in Diamond Shoals was derived exclusively from our study area, this order of magnitude agreement is encouraging considering the large uncertainty in using the *McNinch et al.* [1999] results in this manner. Comparison between historical shoreline change rates calculated for the study area and barrier island migration rates toward the end of the simulation provides another independent measure of how well the exploratory Holocene simulation fits modern constraints. Though shoreline change rates and migration rates may not be directly analogous, we would expect them to be the same order of magnitude given a sufficiently long time frame. Shoreline change rates for the study area reported by *Morton et al.* [2005] vary from an average of 4 m yr^{-1} of erosion to 2 m yr^{-1} of accretion between the late 1800s and the 1990s. The exploratory Holocene simulation yields an average landward migration rate of 3.4 m yr^{-1} which falls within the range of modern shoreline change rates suggesting that migration rates during the latter part of the simulation are reasonable compared to recent observations.

[57] Overall, the exploratory Holocene simulation closely reproduces the average modern morphology and stratigraphy and is consistent with estimates for the volume of Diamond Shoals and historical shoreline change rates while incorporating the best estimates for known geologic constraints and reasonable estimates for unknown parameters (see Table 2 for summary). The simulation still erodes approximately 1 m too deeply at the outer shelf edge and approximately 0.5 m too deeply across the entire shelf (Figure 15 and Table 2). However, making additional adjustments to the sediment budget and other parameters to achieve a more "perfect" fit is not warranted given the wide range of uncertainty in each of the parameter values to begin with.

6. Discussion

6.1. Model Limitations

[58] The morphological-behavior modeling approach, useful for providing insights into barrier island evolution, has some limitations that must be considered prior to discussing implications of the results presented here. For example, GEOMBEST is a cross-shore model and in this study it has been used to consider how a 25 km stretch of landward migrating barrier island coast evolves under different conditions. As such, we have necessarily collapsed 25 km of coast having similar characteristics to one cross-shore profile that provides a reasonable approximation of average conditions across the study area. For this reason, our results do not suggest quantitatively what may occur at any one location within the study area but rather provide a rough assessment of how the barrier system in this location may evolve on average. Additionally, as a cross-shore model, GEOMBEST can only address questions regarding the evolution of landward (or seaward) migrating barrier islands. Though effects of inlets and alongshore sediment transport gradients on sediment availability can be incorporated into GEOMBEST experiments using the sediment supply/loss rate parameter, the model does not directly address inlet processes or barrier island formation strictly by alongshore processes.

[59] Simplifying assumptions regarding barrier island behavior must also be made to implement the morphological-behavior modeling approach. For example, as a morphological-behavior model designed to assess barrier island response over decadal to millennial time scales, GEOMBEST does not simulate the short-term effects of individual storm events. In reality, storms of sufficient magnitude transport sand landward in the form of overwash thus providing a mechanism by which barrier islands migrate landward. The degree to which overwash deposition occurs during any single storm is a function of storm characteristics, local relative sea level change and barrier island morphology. In GEOMBEST, the volume of sand that is moved landward as overwash during any single time step is determined strictly by geometric relationships between the morphology, sea level, and sand availability rather than by a direct representation of storm activity/intensity over the time period represented. As a result, the long-term effects of storms are averaged throughout a simulation, which is appropriate and necessary for the development of useful simulations of coastal response at large spatial and temporal scales. Additionally, model formulation assumes that, over long time scales, the shoreface tends to evolve toward a profile shape that is in equilibrium with the wave climate. Numerous coastal models, along with all one-line coastal models, make this assumption [e.g., *Cowell et al.*, 1995; *Niedoroda et al.*, 1995; *Ashton et al.*, 2001; *Storms et al.*, 2002] and there is evidence to suggest that in some locations this is a valid assumption, especially along the open coast and away from inlets and the effects of coastal engineering [e.g., *Everts.*, 1985; *List et al.*, 1997; *Zhang et al.*, 2004]. To allow for the likelihood that some coastal locations do not evolve toward an equilibrium profile even over long time scales, GEOMBEST simulations drive toward an equilibrium morphology but do not require equilibrium to be attained.

[60] Another challenge that arises when modeling barrier islands over long time scales is that of defining initial conditions. In the case of the Outer Banks, despite a wealth of geophysical and geological data, several important initial conditions are poorly, if at all, constrained. For this reason, we are left to make best estimates based on available geologic evidence and geometric relationships represented in GEOMBEST. For example, though we can make estimates regarding the location of initial barrier island formation based on the presence, and modern behavior, of shoal complexes along the North Carolina coast, there is currently no available direct evidence to validate or invalidate such

estimates. Additionally, though an estimate for the timing of barrier island initiation can be determined based on estimates for the location of barrier island formation and geometric constraints implied by the relationship between the estimated cross-shore position of the initial barrier island and sea level history, there is no geologic record we can turn to in order to make this better than an educated best guess. Initial barrier island volume is another parameter that is unconstrained by geologic estimates, and for this reason, we must begin the simulation with a “best guess” for this parameter as well.

[61] Though geologic data (which are plentiful) for the North Carolina coast are limited in providing information necessary to determine initial conditions, which must be specified to develop model simulations, the simple geometric relationships that become apparent in preparing the initial morphology and stratigraphy for model input provide additional limits on viable combinations of initial conditions. For example, a larger initial barrier would require (1) a more seaward initial position (but this condition is already maximized), (2) a lower substrate surface than geologic estimates suggest, (3) a higher initial sea level than the sea level curve indicates for 8500 years ago, and/or (4) a younger incipient barrier (see Figure 6 for illustration of geometric relationships in the initial condition). A larger initial barrier island would be closer to equilibrium between average barrier island slope and substrate slope resulting in faster migration rates per sea level rise increment and less substrate erosion. Given the same initial sea level (i.e., changing 2 and/or 4 above, but not 3), such conditions would likely cause other factors (e.g., migration rates, substrate elevation) to fall outside the range of geologic estimates. In this way, inverse simulations provide a test of input parameters and scenarios for barrier island evolution [*Roy et al.*, 1994; *Cowell et al.*, 1995], thereby further restricting the range of reasonable estimates that allow us to closely reproduce modern conditions. Most importantly, because the sensitivity experiments presented in section 5.1 explore a wide range of parameter values (and therefore barrier island evolution under a range of migration rates, slope histories, barrier island volumes, etc.) uncertainty in initial conditions is unlikely to significantly impact the results and implications of these experiments.

[62] In addition to providing insights on barrier island evolution, the sensitivity experiments presented in section 5.1, also provide an assessment of the potential impact of uncertainties in parameter estimation on model output. We note again here, that within the range of reasonable estimates for the North Carolina Outer Banks (gray bars, Figures 8–10) model output is relatively insensitive to factors such as shoreface depth, substrate erodibility, substrate composition and DDRR while errors in substrate slope, sediment supply rates and sea level rise rates do result in changes to model output. An iterative combination of model experiments and additional field study in the future would ultimately improve the confidence with which we can estimate initial conditions and parameter values, thereby lending even further credence to model results.

[63] Last, our sensitivity experiments are limited, as are all sensitivity analyses, by an inability to consider the infinite number of possible combinations of initial conditions and input parameters. For this reason, we focus on a geologically plausible set of initial conditions and a range of possible values for input parameters, varying one parameter at a time to explore the effect on barrier island evolution.

[64] Though the uncertainties in geologic constraints and the alongshore-averaged nature of the model prevent us from applying this approach to provide absolute, quantitative predictions of expected coastal behavior at any specific point along a coastline, this approach does provide a valid means for testing the large-scale geometric feasibility of geologic hypotheses regarding barrier island evolution, allowing us to explore the factors most important in determining how barrier islands evolve and to make assessments of average barrier island behavior over stretches of coast having similar characteristics. Ultimately, we may not be able to ascertain some of the details of Holocene, and potential future, barrier island evolution, but in combination with geologic evidence, we can further constrain the range of possible behavior.

6.2. Implications

[65] Predictions of coastal response to sea level rise in simplified coastal environments (e.g., under conditions of constant slope, constant sea level rise rate, etc.) can be developed by making relatively simple calculations [e.g., *Bruun*, 1962; *Wolinsky and Murray*, 2009]. However, as the analyses presented here indicate, assessing barrier island response in more complex (and thus, more realistic) coastal environments such as the North Carolina Outer Banks, and in situations where interactions among multiple changing parameters are important, requires a morphological-behavior modeling approach. A number of qualitative insights, that improve our general understanding of barrier island evolution in complex coastal environments, as well as our understanding of barrier island evolution in the North Carolina Outer Banks specifically, arise from the sensitivity experiments and from the exploratory Holocene simulation. Within the range of parameter values considered here, sensitivity experiments suggest barrier island evolution is most sensitive to underlying substrate composition. When other parameters are held constant, migration rate and substrate erosion depth increase dramatically once underlying substrate sand proportions decrease to 25%; once sand proportions drop to 12% the barrier island can no longer maintain a subaerial profile. Increases in migration rate and substrate erosion depth occur to compensate for low substrate sand proportions, which require liberation of greater sediment volumes from the substrate to provide adequate sand supply, especially when the sediment budget is negative (though we note that there may be combinations of alongshore heterogeneities, to be explored in future investigations, which would serve to temper such cross-shore responses). Though the high proportion of sand in the substrate underlying the North Carolina Outer Banks prevents substrate composition from being a limiting factor in determining how these barrier islands evolve, results of sensitivity analyses suggest strongly that especially when sediment supply rates are negative, barrier island evolution in muddier coastal environments will be influenced greatly by the proportion of sand in the underlying substrate as well as the rate at which this sand is available to the island.

[66] In aggregate, the sensitivity experiments also demonstrate the critical importance of the relationship between

average barrier island slope and substrate slope. If the sediment budget is balanced, substrate slope is constant and average barrier island slope is out of equilibrium with substrate slope (i.e., the two slopes are not equal), changes in barrier island volume will occur with landward migration, over some time scale, until equilibrium is reached [*Wolinsky and Murray*, 2009]. At any instant in time under these conditions, then, a barrier island will move along a trajectory defined by the average barrier island slope [*Wolinsky and Murray*, 2009] (Figure 11). If the two slopes become equal (which is likely rare in complex natural environments because of continually changing geometries) barrier island volume will no longer change and simple translation of the barrier will occur (i.e., the shoreface will not be incised into the substrate).

[67] Along many barrier coasts, substrate slope is shallower than average barrier island slope and as a result barrier island volume and migration rate will tend to increase throughout landward migration (e.g., Figure 11) as average barrier island slope approaches substrate slope. The rate of barrier island volume change, and therefore the rate of average barrier island slope change, are proportional to the difference between average barrier island slope and substrate slope, and asymptotically approach zero as the two slopes become equal. Importantly, increases in sand loss rate, and/or decreases in substrate sand proportion will cause landward migration to occur along a shallower trajectory than the average barrier island slope would dictate (see Figure 4). The shallower trajectory defines an effective barrier island slope, which is the slope at any point in time that equals the direction of barrier island migration as a function of both average barrier island slope and sediment availability. As a result, equilibrium will be achieved when the effective barrier island slope, rather than the average barrier island slope, is equal to substrate slope.

[68] Even more realistically, continual changes in substrate slope will result in continual adjustments to barrier island volume and average, or effective, barrier island slope causing concomitant and complex changes in substrate erosion depth and migration rate during landward migration as evident in the GEOMBEST sensitivity experiments. The effect of changing substrate slope on barrier island volume introduces complexities to barrier island response to sea level rise that impact system response to changes in other parameters, with the degree of impact determined by the specifics of the system history (e.g., previous substrate slopes, sediment losses, etc.) encountered during migration. For example, the nonlinear increase in migration rate that occurs for sand proportions decreasing below 25% (Figure 8e) is a product of the convolution of sediment availability and substrate slope history as the following explanation illustrates: As sand proportions decrease, an increasingly landward migration trajectory is required to liberate sufficient sand from the substrate to counter the negative sediment budget (i.e., effective barrier island slope is shallower). At sand percentages below 25%, increasingly landward migration trajectories result in final barrier island positions that are increasingly landward of the present-day barrier and therefore substrate slope histories that increasingly include the very shallow slope of present-day Pamlico Sound. As substrate slopes become increasingly shallow toward the end of these simulations, the effective barrier island slope becomes shallower, thereby further increasing the landward component of the migration trajectory and leading to large additional increases in migration rate for simulations in which sand proportions fall below 25%. This is similar to the combined effect of increasing sea level rise rates and shallowing substrate slopes on migration rates demonstrated by the constant total sea level rise simulations presented and explained in section 5.1 (Figure 8a). These examples further illustrate that migrating barrier islands encountering a continually shallower substrate slope must increase their migration rates rapidly to allow sufficient removal of sand from the underlying substrate to keep up with sea level rise, especially if the barrier is close to equilibrium with the substrate slope. If such a situation occurs in a coastal system where the combination of substrate sand proportion, substrate erodibility and shoreface response rates is not sufficient to allow the necessary sand liberation rate to occur, the barrier island system will no longer be able to evolve as it has in the past and a new behavior will arise, i.e., a geomorphic threshold crossing (e.g., submergence or disintegration) will occur.

[69] The effects of system history also lead to a surprising conclusion regarding barrier island response to sea level rise, as the following argument illustrates: Other things being equal, a barrier island associated with a more deeply incised shoreface, and therefore having a smaller volume and benefitting from the liberation of more sediment from the substrate per sea level rise increment, will migrate landward less far with each sea level rise increment (i.e., the migration trajectory and therefore the average, or effective, barrier island slope will be steeper) than a barrier island associated with a less incised shoreface having a larger volume (e.g., Figure 11a versus Figure 11c). For a given sea level rise rate, then, other things being equal, smaller islands will have to migrate landward less rapidly to maintain subaerial exposure, which means they may be better poised to survive increasing sea level rise rates than larger islands. Sensitivity experiments indicate that barriers can become associated with a deeply incised shoreface through recent losses of sand to a negative sediment budget (as well as through slope history effects), therefore leading to the counterintuitive conclusion that, other things being equal, islands that have been experiencing a negative sediment budget in the past are likely to be less prone to imminent disintegration due to sea level rise.

[70] Though the sensitivity experiments suggest that barrier island evolution appears to be relatively insensitive to substrate erodibility until the substrate becomes nearly nonerodible, there appears to be a minimum rate of shoreface erosion as a function of depth (i.e., DDRR) that is required to maintain a subaerial barrier island. Within our study area, GEOMBEST simulations suggest the minimum shoreface response rate necessary to keep up with sea level rise rate over the Holocene has been on the order of 10 cm yr^{-1} at the shoreline with a linear decrease to 0 cm yr^{-1} at 20 m water depth. Estimates for the actual rate of net shoreface change, as a function of cross-shore depth, at this time scale do not exist, and thus we cannot ascertain how close actual shoreface response rates in different environments are to this critical threshold. However, factors that cause a barrier to migrate along a shallower trajectory, such as low sediment supply rates, low substrate sand proportions, or near approach

to steady state equilibrium between effective barrier island slope and substrate slope, will increase the shoreface erosion rate required to liberate enough sand to maintain subaerial exposure. If the required shoreface erosion rate exceeds the threshold shoreface response rate, then barrier island evolution will be altered and a previously landward-migrating barrier island may begin the process of drowning or disintegration.

[71] Though the base of the shoreface is important in determining the length of substrate from which sediment can be liberated to supply sand to a barrier, sensitivity experiments are surprisingly insensitive to changes in shoreface depth. This occurs due to the particular geometry of the North Carolina Outer Banks study area. Here, changing the shoreface depth from 15 to 22.5 m results in only minor changes in average barrier island slope (Figure 14) which, in turn, generate only minor changes in barrier island volume and landward barrier island migration rate. This result indicates that shoreface depth is only important to barrier island response to sea level rise for coastal environments in which average barrier island slope changes with shoreface depth. This result also highlights the importance of barrier island and shoreface geometries in determining the sensitivity of a barrier island system to changes in the depth of the shoreface. Further, for coastal geometries in which changing the shoreface depth does result in alterations to average barrier island slope, deeper shoreface depths will only impact barrier island evolution if the increase in shoreface depth results in erosion of a substrate containing sand.

[72] With respect to the North Carolina Outer Banks, development of the exploratory Holocene simulation allows us to limit the range of possible values for some of the unknown initial parameters. For example, geometric constraints suggest barrier island formation occurred prior to 6800 ka because the extent of Diamond Shoals and our understanding of their development suggest an initial position near the shelf edge which requires the high rate of sea level rise occurring 8500−6800 ka to move the barriers to their present location without extracting more sand from the underlying substrate than geologic studies indicate is reasonable. Additionally, geometric constraints imposed by the Holocene sea level curve and our understanding of shoal development, suggest that initial barrier island volume was approximately one quarter of the average barrier island volume observed in the study area today. Though we cannot provide temporally detailed estimates for sediment supply/loss rates throughout the Holocene, our exploratory Holocene simulation suggests that if the barriers originated 8500 years ago, the sediment budget in our study area was close to balanced for the first 1000–2000 years of barrier island migration and closer to an average of 25−30 m^3 m^{-1} yr^{-1} for the remainder of the time period.

[73] Finally, it is worth considering the results of our model experiments within the context of the potential for sea level rise rates to accelerate in the future. As sea level rises, a barrier island will respond either by migrating landward across the underlying substrate to higher elevations, by disintegrating if the rate of sediment supply is insufficient to offset sea level rise and to prevent inundation during storms, or by drowning in place. Disintegration of the Chandeleur Islands in southeast Louisiana during Hurricanes Katrina and Rita (2005) and Hurricanes Gustav and Ike (2008) [*Sallenger et al.*, 2009] (see also http://coastal.er.usgs.gov/hurricanes/coastal-change/) may represent this type of threshold response whereby rapid rates of relative sea level rise increase the vulnerability of migrating barriers causing a potentially irreversible change in barrier island behavior (i.e., from landward-migrating to disintegrating or submerging) following erosion and inundation by storms. *Culver et al.* [2007, 2008] suggest that a similar type of large-scale disintegration occurred for the southern portion of the Outer Banks around 1100 years ago. However, if a widespread perforation of the barrier chain did occur, it may not have been a true geomorphic threshold crossing because perforation must have been followed by recovery for the islands to appear in their modern form.

[74] Our sensitivity analyses suggest that some factors are more important than others in determining whether a barrier island will respond to sea level rise by continued transgression or by disintegration. As sea level rise rates increase into the future, substrate slope histories will change, and in the case of the North Carolina Outer Banks, average slope histories will become shallower resulting in an increase in barrier island migration rate. In the North Carolina Outer Banks, where the underlying substrate is largely composed of sand, and where the effective barrier island slope is such that the shoreface is incised significantly into the underlying substrate, more rapid landward migration rates will result in the liberation of additional sand to supply the barriers (at least until the barrier migrates across the Holocene silt layer in Pamlico Sound). In the near term (on the order of centuries) the current large-scale equilibrium condition consisting of landward migrating barrier islands should persist as long as coastal management practices allow barriers to migrate and as long as the shoreface response rate remains above the minimum threshold necessary to provide sufficient volumes of sand to maintain a subaerial barrier island in this environment. In the longer-term future, however, we note that the barrier island in our study area is approaching a stretch of landward-sloping substrate. True equilibration with this substrate slope is not possible because it would ultimately require a landward trajectory directed into the substrate, which, sustained over time, would result in disappearance of the barrier. If, however, the barrier remains sufficiently incised into the substrate prior to crossing the stretch of landward-sloping substrate, and if the shoreface extends deeply enough to penetrate sandy substrates below Pamlico Sound, sufficient sand could potentially be liberated per increment of sea level rise to maintain some form of subaerial barrier (though this would require extremely high rates of migration). In both the near- and long-term future, if shoreface response rates cannot keep up with sea level rise the lower shoreface would be abandoned and less sand would be liberated during migration leading to barrier island behavior that is different from what we observe today. A similar outcome would result if human interference with barrier island dynamics were to prevent landward migration and continued evolution of effective average barrier island slope toward substrate slope. Barring these circumstances, for the North Carolina Outer Banks, changes in substrate slope history, followed in rank order by sea level rise rate and net sediment supply or loss rate, will be most important

in determining future barrier island response to changing conditions.

[75] In contrast, landward migrating barrier islands underlain by substrates containing smaller proportions of sand and having lower erodibility will be most sensitive to changes in substrate composition that may be encountered with increased landward migration. Model experiments imply that islands in this type of environment will be more likely than their sandy counterparts to cross a geomorphic threshold in the future, changing their style of evolution and potentially disintegrating or submerging, as sea level rise rates increase.

7. Conclusions

[76] Model experiments presented here demonstrate that understanding barrier island evolution in realistically complex environments over long time scales requires a morphological-behavior modeling approach. Sensitivity experiments indicate that, in general, barrier island evolution is most sensitive to substrate composition followed in rank order by substrate slope, sea level rise rate and sediment supply, or loss, rates (see Figures 8–10 and section 5.1). Substrate composition will be most important for muddy coastlines while the remaining three factors can be expected to be most important in the North Carolina Outer Banks and other similar environments. We find that factors affecting sediment availability, such as low substrate sand proportions and high sediment loss rates, cause barriers to migrate landward along a trajectory defining an effective barrier island slope that is shallower than the average barrier island slope (Figures 4 and 13b). Continual changes in substrate slope occurring in natural environments cause continual adjustments to this trajectory such that barrier islands are unlikely to fully reach equilibrium between substrate slope and effective barrier island slope. Results further indicate that when landward motion occurs along a shallower trajectory, shoreface erosion rates and erodibility may become important in limiting the rate at which sand can be liberated from the underlying substrate.

[77] Analyses demonstrate that barrier island evolution is not sensitive to shoreface depth in the North Carolina Outer Banks (see Figure 14, sections 5.1.3 and 6.2), but that this may be an important factor in areas where system geometry is such that average barrier island slope changes with shoreface depth. Because system history determines the instantaneous and ultimate migration trajectories, and therefore the combination of barrier island volume and shoreface incision, it is of critical importance in determining whether or not a barrier island will persist in the face of future sea level rise (see section 6.2). Surprisingly, results indicate that larger barrier islands, associated with little incision into the substrate, and therefore having shallower migration trajectories requiring more landward movement per sea level rise increment, are more vulnerable to sea level rise, other things being equal, than smaller barriers that have been losing sand in the past. For this reason, in the near-term, barrier islands of the North Carolina Outer Banks are likely to persist as long as coastal management practices allow migration and shoreface response rates are fast enough to liberate sufficient sand. The longer-term future of the Outer Banks, however, is far less certain given the exceedingly high rates of landward migration that would be necessary to maintain a barrier during migration across the shallow substrate slopes of present-day Pamlico Sound (see section 6.2). Overall, our results suggest that barrier islands associated with muddy and/or less erodible substrates, and landward-migrating barriers approaching shallow substrate slopes, will be most vulnerable to geomorphic threshold crossing as sea level rise rates increase.

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