The Complex Influences of Backbarrier Deposition, Substrate Slope and Underlying Stratigraphy in Barrier Island Response to Sea Level Rise: Insights from the Virginia Barrier Islands, Mid-Atlantic Bight, U.S.A.

Owen Thomas Brenner

Ringoes, NJ

B.A., Colgate University, 2008

A Thesis Presented to the Graduate Faculty
of the University of Virginia in Candidacy for the Degree
of Master of Science

Department of Environmental Sciences

University of Virginia

May 2012

ABSTRACT

In order to persist during periods of relative sea level rise (RSLR) a barrier island must migrate landward (primarily via storm related overwash processes) to maintain elevation above sea level. While rates of landward migration are largely determined by the rate of RSLR, island behavior (e.g., migration rates, island volume) is also influenced by numerous other physical processes and factors. To better understand the relative importance of contributing variables, I use GEOMBEST, a 2-D cross shore morphological-behavior model, to conduct a series of sensitivity experiments based on hindcast (late-Holocene) simulations of northern (marsh-backed) and southern (lagoon-backed) Metompkin Island along the Virginia Coast in the Mid-Atlantic Bight of the United States. I draw comparisons between these results and simulations of future (2000-2100 AD) island response to RSLR to disentangle the relative influences of backbarrier deposition, substrate slope, and underlying stratigraphy on barrier island behavior.

Results from late-Holocene sensitivity analyses indicate that Metompkin Island, as a whole, is highly sensitive to factors that reduce overall sand availability (i.e., high sand-loss rates and substrates that contain little sand). Southern Metompkin Island is even more sensitive to sand-deficient conditions than its northern counterpart (as evidenced by faster migration rates) due to a lower vertical position of the underlying backbarrier unit. During simulations in which island migration occurs along different portions of the substrate surface, variations in substrate slope alter the resulting backbarrier and island configuration, such that low substrate slopes (<1m/km) promote an expansion of the backbarrier region and a decrease in island volume, while higher (>1m/km) substrate slopes limit or reduce backbarrier width and account for volume

increases. I suggest that relatively rapid changes in the thickness of backbarrier deposits in response to substrate slope variability modulate barrier island response to RSLR allowing the barrier island migration trajectory, and therefore migration rates, to be more consistent through time. However, future simulations suggests that if backbarrier deposition rates—in both the salt marsh and open lagoon—do not sufficiently adjust to future RSLRR, changes in the extent and thickness of backbarrier deposits may not occur rapidly enough, thus requiring more drastic change in barrier island behavior in response to substrate slope variability. Results from future simulations also indicate that for all predicted future RSLR scenarios tested, Metompkin Island, if allowed to migrate freely, will likely avoid disintegration or submergence due to sufficient substrate sand content and landward elevation change.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Laura Moore, for her careful guidance and constant support throughout all stages of this project. I would also like to thank the members of my committee, Pat Wiberg, Alan Howard, and Brad Murray for all their helpful feedback and advice. I am very grateful to so many of my fellow graduate students and lab mates (Dana Oster, Amy Grady, Cat Wolner, Sean McLoughlin, Jenn Holm, Kiki Patsch, etc.) for their unrelenting assistance and encouragement. Lastly, I need to thank my family and friends for their ongoing support throughout my graduate career. Funding for this project was provided by the Virginia Coastal Reserve Long-Term Ecological Research (VCR LTER) site and the Department of Environmental Sciences at the University of Virginia.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. INTRODUCTION

1.1 Background

Barrier islands line the eastern margin of the United States and are found on most tectonically passive margins worldwide. The seaward position, low elevation, and unconsolidated nature of these landforms make them vulnerable to changing background conditions (e.g., rising sea level, changing sand-supply) and changes in driving forces (e.g., storm activity). With large percentages of the world's population concentrated in coastal regions, understanding how barrier islands evolve in response to changing conditions is critical to the management of private, public, and commercial interest.

Modern global temperature changes have been linked to high sea surface temperatures causing an expansion of sea water which contributes to eustatic sea level rise (RSLR) (IPCC, 2007), and an increase in tropical storm activity (Knutson et al., 2010), both of which are likely to impact barrier islands into the future. While immediate implications of single storm events may seem most pressing, the slow, continuous nature of human-induced climate change (and particularly relative sea level rise (RSLR)) will alter landscape evolution across longer time scales.

Understanding the impacts of climate change on barrier island behavior is of utmost importance to the management of coastal environments, and geomorphic models are a useful way to begin quantifying the range of possible future barrier island behaviors. Barrier island response to climate change is likely to be complex and variable, especially since changing background conditions (e.g., RSLR) and shifting small-scale driving forces (i.e., storm activity) vary spatially and temporally. Barrier island response to sea level rise is determined, in part, by the availability of sediment (e.g., Wolinsky & Murray, 2009, Moore et al., 2010). If incoming sand-supply is sufficient to maintain elevation during RSLR, a barrier island will remain in place or even prograde seaward. However, given that most modern barrier islands are sediment-starved, they generally must transgress landward to maintain subaerial exposure as sea level rises (e.g., Curray, 1964; Hayden et al., 1980).

Sediment deficiencies initiate island transgression via shoreface erosion and eventual destruction of the primary dune, leading to island narrowing. The resulting island morphology is increasingly susceptible to storm overwash, a process which mobilizes sediment from the shoreface and beach, transporting it landward beyond the dune crest, and depositing it on the back side of the island (e.g., Inman and Dolan, 1989). This cyclical transport regime, also called island rollover, results in a more landward island position through time (e.g., Hayden et al., 1980; Sallenger, 2003). If the resulting island position is sufficiently elevated (relative to sea level), the island may begin to stabilize through dune building processes, otherwise, storm overwash and migration will persist. While storm related overwash events drive island migration over short temporal scales, over long time periods the vertical position of the island relative to sea level dictates the need for landward migration via overwash processes, and therefore RSLR is the primary influence on long term island migration.

Barrier island response to RSLR is determined by complex interactions between the geologic framework, physical processes, sediment budget, and human activity (e.g., Pilkey et al., 2000; Gutierrez et al., 2007; Wolinsky & Murray 2009; Moore et al., 2010). For example, the amount of sand in near-surface geologic units influences sand-supply rates, (McBride & Moslow, 1991; Moore et al., 2010) while the presence of elevated marsh deposits provides a platform for barrier migration necessitating less landward migration and sediment input to preserve island elevation (e.g., Rice et al., 1976; Finkelstein, 1986; Stolper et.al, 2005; Oertel & Woo, 1995). Throughout the latter half of the Holocene, barrier islands have been able to persist during climate change, largely due to roll over processes. However, given uncertainties regarding the effects of anthropogenic climate change (e.g., on RSLR, storm activity, sand-supply), the effect future climate change will have on these dynamic landscapes is not yet clear. To better understand the likely effect of climate change on barrier islands, it is necessary to assess how specific physical characteristics (e.g., sand availability, stratigraphic relationships, morphologic inconsistencies) influence island migration as sea level rises.

While previous research within the VCR-LTER has described various aspects of barrier island morphologic change over the past 150 years, the majority of the geomorphic history of these islands (from island formation until earliest surveys) remains poorly understood, largely because indicators of historic island transgression are not well preserved. However, understanding mechanisms of barrier island response to sea level rise over long time scales is important in describing current island configuration and in assessing possible island response to future sea level rise. For this reason, my primary objectives are:

1. To simulate the late-Holocene (4600ybp-present) evolution of northern and southern Metompkin Island based on constraints on island evolution available in the scientific literature.
2. To evaluate the relative importance of physical parameters (particularly those involving interactions between the island and backbarrier environments) in determining island response to RSLR.
3. To assess the potential range of barrier island response to future RSLR scenarios.

To meet these objectives, I applied the cross-shore morphological-behavior model, GEOMBEST (Stolper et al., 2005; Moore et al., 2010), to a field site—Metompkin Island—along the Virginia Coast. Using sub-aerial and sub-aqueous elevation data and published core interpretations, I created a representative average modern coastal morphology and stratigraphy for north and south Metompkin Island. Using the modern configuration as a reference, along with available geologic constraints from the literature, I then constructed a plausible initial (4600ybp) island condition that successfully reproduces the modern morphology and stratigraphy. These calibrated simulations (of both north and south Metompkin), and the associated input values, are considered the “base” late-Holocene simulations from which I performed a series of systematic sensitivity analyses, varying one parameter at a time, to assess the relative importance of a range of factors in determining barrier island response to RSLR. The base-simulations also provide the basis for future simulations of barrier island response to different RSLR scenarios.

1.2 Study Site

The Virginia Coast Reserve (VCR) encompasses 12 barrier islands extending along 120km of the Virginia portion of the Delmarva Peninsula along the mid-Atlantic Bight of the U.S. East Coast (Figure 1). Virtually uninhabited since the 1930’s and devoid of large-scale human influences, the VCR represents one of the most naturally evolving barrier coastal systems in North America, and therefore provides an unparalleled opportunity to study barrier island evolution in the absence of direct human impacts.

The tide-dominated barrier islands found along the southern half of the VCR range in length from 4 to 12km, and are separated by stable tidal inlets. An approximate 20th century relative sea level rise rate (RSLRR) of 3.5mm/yr (Hicks et al., 1983; Inman & Dolan, 1989) and widespread sediment deficiencies (Demarest & Leatherman, 1985) contribute to high chain-wide landward migration rates averaging 5m/yr (Dolan et al., 1979). Exhibiting rapid shore-parallel shoreline retreat, the northernmost islands of the VCR (Wallops, Assawomen, Metompkin, and Cedar) form a 40km concave embayment dominated by erosion (Demarest & Leatherman, 1985) (Figure 1). Here, a scarcity of sediment has led to rapid landward migration of the barrier islands and relatively narrow backbarrier environments (Rice & Leatherman, 1983). Mechanisms to explain island behavior within this embayment include: limited longshore sediment input from Assateague Island (Rice & Leatherman, 1983); low paleo-topography caused by presence of the ancient Susquehanna or Potomac River valley (Mixon, 1985; Foyle & Oertel, 1995); and a combination of minimal cross-shore sediment input and topographic relief due to infilling of paleo-channels with fine mud (Oertel et al., 2008). The confined lagoonal environments in this area have promoted recent deposition and the accumulation of thick backbarrier deposits, facilitating the establishment of continuous salt marshes over the past thousand years throughout much of this area. (Newman & Munsart, 1965; Van de Plassche, 1990; Oertel & Woo, 1994).

Within the northern section of the VCR, Metompkin Island stretches 10.8 km from Gargathy Inlet south to Metompkin Inlet (Figure 2). The island has minimal topographic relief (maximum elevation ~3m) and a relatively constant width of ~200m. Consistent with the mean VCR migration rate, the island has been transgressing landward

~ 5 m/yr throughout much of the 20th century (Leatherman et al., 1982; Byrnes, 1988). Limited regional sand-supply and rapid transgression have led to minimal dune development and persistent overwash nearly island-wide (e.g., Wolner, 2011). Metompkin Island is divided into northern and southern halves by a mid-island shoreline offset, such that the shoreline of the southern half lies ~200 m west of the northern half (Figure 2). Following the opening of an ephemeral inlet in 1957, the southern half of Metompkin Island migrated at a rate approximately 2.5 times faster than the northern half, resulting in a maximum shoreline offset of 400 m in 1981 (Byrnes, 1988)(Figure 1.3). Following inlet closure in 1981, the pattern of dissimilar migration rates reversed and the shoreline has been actively straightening, although a significant offset still remains today.

The northern half of the island is devoid of significant dunes and is backed by a continuous marsh platform. Here, relic marsh deposits protrude into the swash zone providing evidence of active island transgression. The southern half of Metompkin is fronted by discontinuous dunes (max elevation ~ 3.5 m) interspersed with recent overwash deposits. A fringing marsh (maximum width ~50 m) is prevalent along the landward margin of the southern half of the island, and is best established in areas of recent overwash, likely due to higher sediment input (Figure 2).

Co-located with the offset on the beach and shoreface, is a transition in the backbarrier environment from platform marsh in the north to shallow open lagoon in the south (Figure 2 & 3). To explain this transition, Byrnes (1988) suggests the importance of underlying pre-Holocene fluvial topography, which slopes downward to the south. More elevated vertical positions along the northern half of the island are thought to have helped marsh vegetation remain subaerial during past RSLR. To the south, sediment deposition has not been sufficient to fill the larger void space created by lower initial topography; thus the backbarrier remains inundated and lagoonal conditions persist (Byrnes, 1988).

To improve our understanding of barrier island evolution I applied a cross-shore morphological-behavior model, GEOMBEST, to simulate the evolution of Metompkin Island. The apparent correlation between differences in backbarrier environment and historic migration behavior (i.e., migration rate, maintenance of island volume, and preservation of general backbarrier/island configuration) on Metompkin make it an ideal location for this study. Additionally, the rapid, shore-parallel migration of Metompkin Island increases the applicability of the 2-D cross-shore model and similar island-wide model constraints for the northern and southern halves of the island (e.g., sand-loss rate, RSLRR, shoreface depth, etc.), allow me to decipher the influence of differences between the two island halves, primarily in terms of stratigraphy and backbarrier environment, on island response.

2. SIMULATION DEVOLOPMENT

2.1 Morphological-behavior modeling with GEOMBEST

To model barrier island response to sea level rise within the VCR, I used the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations (GEOMBEST). Initially developed by Stolper et al. (2005), GEOMBEST is a two dimensional cross-shore morphological-behavior model that simulates the evolution of island morphology and stratigraphy in response to RSLR and sand availability across decadal to millennial time scales (Stolper et al., 2005; Moore et al., 2010) (Figure 4).

Despite seasonal and periodic variations in shoreface morphology (largely associated with storms), shoreface and barrier morphology is generally found to be invariant over long time scales (e.g., Larson, 1991). Thus, I defined (in GEOMBEST) an "equilibrium morphology," which is the shape of the modern surface profile extending from the backbarrier to the base of the shoreface. As sea level rises throughout model simulations, this equilibrium shoreface and barrier profile is shifted landward and upward (representing response to overwash processes) at each time step to the horizontal and vertical position that conserves sand. Throughout model simulations the shape of the barrier and shoreface profile will tend toward the shape of the equilibrium profile, however, maintenance of the equilibrium profile is not prescribed by the model and sufficiently low sand-supply rates, non-erodible substrates, and/or rapid RSLR rates will cause the simulated profile to deviate from the equilibrium profile. What makes GEOMBEST different from similar morphological-behavior models (Bruun 1962, Cowell et al., 1995) is that the shoreface and barrier morphology at each time step is influenced by physical characteristics of the underlying stratigraphy. While other models (e.g. Bruun 1962, Cowell, et al., 1995), assume the sediment below the barrier to be readily available unconsolidated sand, field data (cores, ground penetrating radar) typically indicate compositional heterogeneity. The amount of sand in the substrate (i.e. substrate composition), how easily the substrate can be eroded (i.e., substrate erodibility), and extent of shoreface exposure of each underlying unit influences how rapidly sand can be liberated from the shoreface. By including these physical constraints, GEOMBEST captures the influence of underlying geology on barrier island migration.

2.2 Development of late-Holocene Simulation Inputs

To apply GEOMBEST to Metompkin Island, I interpreted findings from the scientific literature to develop a set of plausible initial conditions and to provide estimates for model inputs. These include geometric constraints necessary to reproduce spatial geologic relationships of the landscape within the model (e.g., stratigraphic relationships), as well as local values for physical processes (RSLR, sediment-supply or loss rates, etc.) important to barrier island migration. GEOMBEST input parameters, and the development of estimates specific to Metompkin Island, are described below. For a summary of input parameters and sources see Table 1.

2.2.1 Initial Morphology and Stratigraphy

To assist in the development of a plausible set of initial conditions, I began by developing an average representation of modern morphology (i.e., surface profile, Figure 5) and underlying stratigraphy for the northern and southern halves of Metompkin Island. To construct a representative surface profile, I combined modern bathymetric data

(NOAA National Coastal Elevation Model), LIDAR elevations (NASA: Charts 2005), and mainland Delmarva Peninsula topography (USGS Seamless DEM) extending from the center of the peninsula, across the barrier island system to approximately 45 km offshore. Following methods of Moore et al., (2010) I extended ten shore-perpendicular transects at 1-km increments across the northern and southern halves of the model domain (5 transects on each) and extracted continuous surface elevation along each transect. To create a representative average surface profile for each half of the island, which also serves as the corresponding equilibrium morphology in GEOMBEST, I then calculated an average profile for each group of 5 transects.

Based on core data for Metompkin Island and the surrounding area, I positioned the top of each identified stratigraphic unit within the upper 20 m at its modern elevation below the surface profile (units include modern barrier island sands, lagoonal deposits and pre-Holocene material) (Finkelstein, 1986; Finkelstein & Ferland, 1987; Byrnes 1988; Wolner, 2011). The sand proportion (i.e., percent of the layer that is sand-sized sediment) and erodibility (i.e., an index relating to degree of consolidation) of each unit is specified in the input parameters based on estimates for each unit from core log data (Table 1). Due to compositional differences pre-Holocene material is divided into distinct units, with the lowermost unit being a late-Pleistocene fluvial deposit (dark tan unit in figure 5) composed primarily of fine to coarse unconsolidated fluvial sand. The upper surface of this unit has been heavily reworked by coastal and fluvial incision and slopes downward, from north to south, in the along-shore direction. Overlying this layer, is an early-Holocene lagoonal unit (tan unit in Figure 5) consisting of unconsolidated sandy-silt. The upper portion of this unit is greatly influenced by the position of the underlying late-Pleistocene layer, and therefore also dips to the south. Since this is the uppermost unit, modern erosional processes also impact this surface resulting in spatially varying topography (Finkelstein & Ferland, 1987; Byrnes 1988). Furthermore, because the barrier island and backbarrier units migrate across this topographic surface, the variations in topography impact island geometric relationships (e.g., relative size of backbarrier and island) during migration, ultimately influencing island migration. In addition to the deeper position of the late-Pleistocene fluvial unit in the southern Metompkin Island region, due to different depositional environments sediment characteristics of the backbarrier unit differ between island halves—the northern backbarrier unit consists of with silty marsh material while the southern unit is primarily fine, silty sand (Byrnes 1988).

Development of an initial mid-Holocene morphology and stratigraphy for northern and southern Metompkin Island (i.e., the two morphologies and stratigraphies used to represent a plausible starting point for island evolution in the model) also requires estimation of the cross-shore location of the barrier island at the start of the simulation. Basal peat found 6.6m below mean sea level (MSL) landward of Metompkin suggests initial submergence of a backbarrier environment during sea level rise 4650 ypb (Finkelstein, 1986; Finkelstein & Ferland, 1987). Finkelstein and Ferland (1987) use this evidence to suggest the island was located approximately 4km offshore and 6.6m below the modern position 4650 years ago. This change in elevation over the past 4650yr represents a RSLR rate of 1.44mm/yr, which is consistent with both local historic relative sea level curves (Newman & Munsart, 1965; Byrnes, 1988) and regional late-Holocene RSLRR estimates (Engelhart et al., 2009) further supporting the estimates of Finkelstein and Ferland (1987). In contrast, Byrnes (1988) estimates that approximately 4,600 years ago, when sea level was 6.6m below its modern position, Metompkin Island was 1.1km seaward of its current position (though the basis for this estimate was not provided). Pairing of geometric constraints imposed by the location of the modern surface profile with published estimates of mid-Holocene island position and estimated values from the literature for shoreface depth, indicates that the latter estimate for mid-Holocene island position is geometrically implausible. Based on the current location of the shoreface, island position 4600 BP must have been at least 2 km seaward of the current location, and likely significantly more, assuming any degree of shoreface incision during migration (Figures 5 & 6). Based on this analysis, I selected 4600 years ago as the starting point for simulations with the initial barrier island located 4 km offshore and 6.6 m below the modern barrier location. After positioning the barrier island in the model domain, I extended each stratigraphic unit seaward to meet the newly positioned initial surface profiles, resulting in initial island conditions for the late-Holocene simulations of northern and southern Metompkin Island (Figure 6).

2.2.2 Shoreface Depth & Depth Dependent Response Rate

The shoreface depth, dependent mostly on local wave climate and offshore bathymetry, defines the lower limit of the area across which wave energy moves sediment at long (centurial to millennial) time scales. Expressed in GEOMBEST as the lower limit of the equilibrium morphology and the depth at which shoreface erosion and accretion rates decrease to zero, this parameter limits the extent of actively eroding shoreface that can supply sand to the barrier island during transgression. Following

Evert's (1978) method of identifying the base of the shoreface as a subtle break in shoreface slope, I estimated a shoreface depth of 6.5m for Metompkin Island. The Depth Dependent Response Rate (DDRR) defines the maximum potential rate of shoreface erosion (or accretion) as a function of depth. This parameter accounts for the decrease in wave orbital velocity with depth, and the corresponding decrease in the ability of wave action to mobilize sediment. However, field studies do not provide guidance on a reasonable estimate for this relationship, and therefore, similar to previous studies (e.g., Moore et al., 2010), a linear rate of 1 m/yr was extrapolated from sea level (0 m) to a rate of 0 cm/yr at the shoreface depth (6.5 m).

2.2.3 Sand-Supply Rate

Unlike other morphological-behavior models (Bruun, 1965), GEOMBEST captures the general, time-averaged effects of shore-parallel (longshore) sediment transport processes via a sand-supply or -loss rate. Because GEOMBEST conserves sand in the cross-shore direction, the sand-supply or -loss rate reflects the addition or removal of sand (in m^3/m/yr) in the alongshore direction. To date there are no published estimates of longshore transport for Metompkin Island, and for this reason I estimated sand-supply rates based on alongshore sediment transport rates (assuming the majority of sediment transported is sand) for nearby islands (Wallops, Assawomen, and Cedar) (US ACE, 1973; Byrne et. al, 1974; Byrnes, 1988). Given the somewhat broad range of values (-13.6 − 1.4 m^3/m/yr), I used other geologic constraints to further refine the sand-supply rate to -0.5 m^3/m/yr during late-Holocene simulation calibrations (see section 2.3).

2.2.4 Backbarrier Deposition

To simulate evolution of the backbarrier region during island migration, the vertical position of the backbarrier depositional surface (relative to sea level) is determined by a combination of the backbarrier deposition rate and a maximum backbarrier elevation (formerly referred to in Stolper et al. (2005) as "resuspension depth"). Within GEOMBEST, backbarrier deposition rates represent the rate of vertical sediment accumulation upon the uppermost surface of the active backbarrier unit, regardless of whether the backbarrier environment is a marsh or a lagoon. For a particular backbarrier morphology to persist (both in the vertical and horizontal dimensions) over long time periods, this rate of deposition must be comparable to the RSLRR. When backbarrier sediment accumulates slowly, more sand, transported via overwash processes, will be needed to fill the area behind the barrier (sometimes referred to as backbarrier accommodation space), to maintain island elevation relative to sea level, as sea level rises. When backbarrier sedimentation is rapid, the backbarrier may fill in, allowing conversion of marsh to lagoon, for example. Acting to oppose such effects of rapid backbarrier deposition within the model, the elevation of the backbarrier region (relative to sea level) is limited by a maximum backbarrier elevation.

While backbarrier environments are variable throughout the VCR, the distribution of marsh platform and open lagoon has remained unchanged since the earliest recorded surveys (1852), suggesting the evolution of these backbarrier environments (i.e. infill rate) has paralleled RSLR. Additionally, over long time scales, vertical deposition rates of both subaerial marsh platforms (Van de Plassche, 1990; Oertel & Woo, 1994) and shallow open bays (Nichols, 1989) have been shown to mirror the rate of RSLR.

Therefore, during late-Holocene simulations, infill rates of both salt marsh and open lagoon are set to historic RSLRR (1.45mm/yr). A maximum backbarrier elevation of -0.4 m (average water depth of modern lagoon) for southern Metompkin Island maintains lagoon depth through time to avoid backbarrier infilling, and a value of +0.14 m (modern average marsh elevation) for northern Metompkin Island limits vertical marsh accretion to within 0.14 m of sea level at any given time. In this way, and as suggested by observations over the last 1.5 centuries, I do not allow salt marsh conversion to open water (or vice-versa).

2.3 Calibration of Late-Holocene Base Simulations

After gathering model input parameters and creating plausible initial conditions for northern and southern Metompkin Island, I calibrated the model by adjusting input parameters, within the range of values reported in the scientific literature, to successfully reproduce a backbarrier, barrier, and shoreface morphology similar to the modern configuration over the course of a 4600-year (late-Holocene) simulation (Figure 2.4). The resulting set of input values reflects estimated average rates and parameter values across both the late-Holocene period and each island half (Table 1). Because the two halves of the island are contiguous, therefore sharing similar values for parameters such as longshore sediment transport rate, shoreface depth, etc., the only parameters that vary between the northern and southern halves are those describing underlying stratigraphy and backbarrier conditions for which I have geologic and modern evidence to support differences. The 4600-year simulations (one for each island) resulting from this process (hereafter referred to as the “base” scenarios) are not intended to be singular and accurate portrayals of actual island evolution during the late-Holocene, but rather to provide a baseline for comparison with additional simulations designed to assess sensitivity to changes in input parameters. To provide a reference point for comparisons with sensitivity experiments—during base simulations northern Metompkin Island migrated slightly slower (at an average rate of 0.76 m/yr) than the southern half (0.78 m/yr), but had a slightly larger final barrier island volume (1280 m^3/m/yr vs. 1000 m^3/m/yr for the north and south, respectively.

3. RESULTS AND INTERPRETATIONS

To evaluate barrier island response to different input parameters and to compare behaviors across multiple simulations, the average migration rate and final barrier island volume are recorded for all simulation performed. Average island migration rate (m/yr) was found by calculating the slope of the linear regression of shoreline position through time. Barrier island volume, reported in m^3 /m, represents island volume at the final simulated time step and is calculated by integrating to find the cross-shore area under the portion of the surface profile representing the barrier island. In addition to migration rate and final island volume, to make for more detailed descriptions and comparisons of island and backbarrier evolution, supplementary measurements (e.g., backbarrier width, barrier island slope, and substrate slope) are recorded for certain simulations.

Many intrinsic differences (e.g., evolving backbarrier units, variability in backbarrier composition, highly inconsistent substrate slopes) between the VCR and the settings of earlier similar studies (e.g., Stolper et al., 2005; Moore et al., 2010; Moore et al., submitted) add additional complexities to my interpretations of island response. Unlike Moore et al. (2010), who describe the relationship between island migration trajectory (which is equivalent to average barrier island slope when the sand budget is balanced and equivalent to a less steep "effective" slope when sand-supply is negative) and the slope of the underlying substrate in the absence of a backbarrier unit, simulations of Metompkin Island include the evolution of backbarrier units. Here, base simulation values for sand-loss rate are only slightly negative (-0.5 m^3/m/yr) and therefore average 'barrier island slope' closely approximates effective barrier island slope—for this reason I refer only to average barrier island slope when using this quantity to make comparisons.

As in Moore et al. (2010), average barrier island slope is defined by the slope of a line extending from the base of the shoreface to the point where the island meets the backbarrier (Figure 4). Additionally, because over long timescales backbarrier deposition occurs increasingly landward on top of the underlying substrate as the island migrates, I used the term substrate slope to characterize the slope of the surface of the uppermost stratigraphic unit positioned beneath island and backbarrier deposits (rather than the slope of the backbarrier depositional surface).

3.1 Sensitivity Analyses

To evaluate the relative influence of individual input parameters (and the environmental factors they represent) in determining barrier island response to RSLR I conducted a series of sensitivity experiments, altering one model parameter at a time and assessing which factors most strongly influence measures of barrier island evolution. Specifically, I systematically adjusted sand-supply rate, back-barrier sedimentation rate, substrate composition, substrate erodibility, shoreface depth, DDRR, and RSLRR for north and south Metompkin simulations independently (Table 1) and evaluated the effect of changes in parameter values on final barrier island volume and average barrier island migration rate by comparing these outputs with those of the corresponding base simulation (average migration rate of 0.76 m/yr and final volume of 1280 m^3/m/yr in the north, and average migration rate of 0.78 m/yr and final volume of 1000 m^3/m/yr in the south) . To extend the application of these results to other similar coastal environments I varied input parameters not only within, but also just beyond, the range of published values for the VCR. To test the sensitivity of the overall barrier system and to look for possible thresholds that might induce changes in island state I also varied some parameters (e.g., RSLRR) beyond expected natural variation.

3.1.1 Backbarrier Sedimentation Rate

When rates of backbarrier sedimentation are low (0.5 mm/yr), a continuous backbarrier deposit (i.e., marsh and lagoonal) does not form, likely because RSLRR (1.44 mm/yr) outpaces deposition (Figures 8a & 9a). In the absence of persistent backbarrier deposits, island volume is larger and migration rates are high as the island moves farther inland and gains volume to maintain vertical elevations above sea level without the assistance of an underlying backbarrier unit. This is especially true for southern Metompkin Island due to lower substrate slopes (requiring more landward migration in response to given RSLR) and lower relative elevation of the underlying stratigraphic unit. When backbarrier sedimentation rates approach or slightly exceed RSLRR (1 – 1.5 mm/yr), marsh (north) and lagoonal (south) units become well-developed by the final simulation timestep and final island volumes decrease as backbarrier deposits, instead of island sand, fill the accommodation space behind the barrier (Figure 9a), thereby requiring less removal of sand from the shoreface and thus less landward migration to achieve a vertical elevation above sea level. When sedimentation rates exceed RSLRR (>1.5 mm/yr), vertical accumulation of backbarrier deposits is limited by the resuspension depth, and the horizontal extent of the backbarrier remains unchanged.

3.1.2 Sand-Supply Rate

As anticipated, as the rate of sand-supply increases (from sand removal to addition of sand) final barrier island volume rapidly increases and migration rates decline (Figures 8b & 9b). An increase in the sand-supply rate of 2m^3/m/yr (-1 – 1 m^3/m/yr) results in a ~100% increase in final island volume for both northern and southern Metompkin Island. While changes in overall barrier volume are nearly identical between the north and south, varying the sand-supply rate results in a greater disparity in migration rate fluctuation between the two island halves. Southern Metompkin Island migrates considerably more rapidly at lower sand-supply rates than northern Metompkin Island, suggesting that the migration of the southern half is relatively more sensitive to changes in barrier volume generated by lower sand-supply rates than northern Metompkin Island.

3.1.3 Substrate Sand Percentage

By assessing barrier island sensitivity to changes in the percentage of sand contained in each stratigraphic unit, I aim to describe the relative importance of individual units in supplying sand to the island. The effect of an individual stratigraphic unit on final barrier island volume or average migration rate is largely determined by the proportion of the total shoreface the unit covers, and how that proportion changes throughout the simulation. Differences in underlying stratigraphy and topography between island halves account for disproportionate amounts of exposure of each stratigraphic unit along the shoreface, and therefore the relative importance of each stratigraphic unit in island behavior varies between northern and southern Metompkin Island (Figure 10). Being the most prevalent along the shoreface during the late-

Holocene simulation, island behavior (evidenced by changes in volume and/or migration rates) is most sensitive to changes in the sand percentage of the early-Holocene lagoonal unit in the north and the backbarrier unit (although only slightly) in the south (Figure 10). Stratigraphic units that are less exposed along the shoreface, either because they are part of the shoreface for only a short period of time or because they are limited in spatial extent, have little effect on island behavior (i.e. northern backbarrier deposit, southern late-Pleistocene fluvial unit)

3.1.4 *Substrate Erodibility*

Consistent with Moore et al. (2010), substrate erodibility minimally affects island response to RSLR (Figures 11). Sensitivity analyses indicate island volume and migration rate are only affected when underlying stratigraphic units are 1000 times less erodible than fully unconsolidated material (erodibility values of .001; values of 1 being fully erodible). However, given the loosely consolidated silty muds and fine sands beneath the Virginia Barrier Islands (as opposed to lithified rock which might better represent erodibility values of .001) it is unlikely that the stratigraphic units here can resist erosion to a degree that would significantly impact large-scale island behavior. Therefore, it is assumed that wave energy along the shoreface can sufficiently break down the underlying substrate exposed along the shoreface readily supplying the island with sand contained in these units.

3.1.5 Depth Dependent Response Rate

Island behavior appears insensitive to DDRR given that only DDRR values less than 2 cm/yr impact barrier island response (Figures 8c & 9c). Given that average island migration rates over the past 25 years have averaged 4.6 m/yr I assume the morphology of the upper shoreface (i.e., equilibrium morphology) to remain nearly constant—thereby requiring island migration and shoreface erosion rates to be of the same order of magnitude. For this reason, it appears that actual response rates are likely to be far beyond the 2 cm/yr threshold indentified in sensitivity experiments.

3.1.6 Shoreface Depth

As anticipated, greater shoreface depths (4 −9 m) result in a trend of increasing island volumes and decreasing migration rates, because deeper shoreface depths allow extraction of sand from a greater portion of the bathymetric profile (Figures 8d & 9d) and therefore yield more sand per time step. Disparity in island behavior between northern and southern Metompkin Island throughout this range of shoreface depth values is most likely due to differences in underlying stratigraphy (i.e., a more vertically elevated sand rich late-Pleistocene fluvial deposit in the north) which allow the northern half to liberate more sand-rich sediment, particularly at shoreface depths >7.5 m. As reported above (in section 3.1.2), while shallow shoreface depths (<6 m) result in similar patterns of island volume decrease for both island halves, the migration rate of southern Metompkin Island appears to be more highly sensitive to this reduction in sand availability associated with a shorter active shoreface. While barrier island behavior appears sensitive to shoreface depths ranging from 4-9m, when considering only response to the range of depths reported in the literature (5.5 − 8m) volume and migration rate are fairly insensitive to changes in shoreface depth.

3.1.6 Relative Sea Level Rise Rate (RSLRR)

To assess the sensitivity of island behavior to RSLRR, I increase the RSLRR from 0.5 mm/yr to 4 mm/yr while keeping the total amount of RSLR constant at 6.5 m of total change across all simulations. Unlike simulations in which the duration of the simulation was held constant (i.e., the constant duration RSLRR simulations discussed below), in the constant total RSLR simulations the island traverses an identical substrate (slope and composition) throughout each model run, thereby eliminating the effects of variable substrate slopes on simulation results. This requires each simulation to run for a different length of time ranging from 1,600 years for the 4 mm/yr simulation to 13,200 yrs for the 0.5 mm/yr simulation.

As expected, the barrier migrates landward faster at higher SLRRR (Figures 8e). Interestingly and unexpectedly, at SLRRs ≤1 mm/yr, backbarrier environments struggle to stabilize within the model for both northern and southern Metompkin Island. In order to achieve a vertical position above sea level without the additional elevation provided by a backbarrier platform, northern Metompkin Island primarily experiences increases in island volume, whereas southern Metompkin Island experiences increases in landward migration rates (Figures 8e & 9e). This disparity is likely explained by differences in the position of underlying stratigraphy in the latter portion of the late-Holocene simulations (Figure 6).

When RSLRR are faster than 1 mm/yr, increases in migration rates are linear for both halves of Metompkin Island, final island volume changes little (Figures 8e & 9e), and the general coastal configuration (i.e., island shape, backbarrier width) remains unaffected. This suggests that final backbarrier, island, and shoreface morphology are minimally affected by changes in island migration rate—which is more directly controlled by RSLRR—when the length, composition, and slope of the underlying substrate surface the island traverses are held constant.

For the second portion of the RSLRR sensitivity experiment I again increase SLRRs from 0.5 – 4mm/yr in 0.5 mm/yr increments, however to assess the impact of substrate slope variability on final island configuration, these simulations span a constant 4600yrs requiring the barrier island to migrate progressively farther landward across mainland terrain of varying slope as RSLRR increase. Theoretically, increases in RSLRR should lead to increases in island volume over time since faster RSLRRs require the island to migrate across a larger portion of substrate allowing for a larger amount of sand to be liberated from the shoreface, According to Moore et al. (2010) island volume should increase until the barrier island slope (or "effective" barrier island slope in the case of a negative sand-supply rate) approaches equilibrium with substrate slope, however, the incorporation of a simultaneously evolving backbarrier unit limits the direct applicability of these general relationships, requiring additional examination of substrate slope, island, and backbarrier behavior at each individual RSLRR simulated.

At RSLRR less than 1.25mm/yr, both northern and southern Metompkin Island increase in volume (67% in the north and 18% in the south compared to initial volume at 1 mm/yr), with more rapid increases in the north likely due to a greater cumulative substrate sand percentage along the shoreface (Figure 9f). Sustained differences in cumulative substrate sand content, most notably due to differences in backbarrier unit composition, account for the general trends in volume change at SLRRs of 1 – 4 mm/yr, over which the northern volume decreases by 46% and southern volume increases 66%. Higher RSLRR cause a relatively steady increase in landward migration rates for both halves of Metompkin Island. Due to substrate slope variability, southern Metompkin Island migration rate decreases slightly (5-13% slower than north depending on RSLRR) when SLRRs are faster than 1.5mm/yr, creating a maximum north/south difference in total island migration distance of 0.9km at RSLRR of 4 mm/yr (Figure 8f).

A comparison of final backbarrier width and near-final substrate slope (specifically, the slope of the additional length of substrate traversed as compared to that of the next lowest RSLRR simulation) (Figure 12a) indicates that the horizontal width of the backbarrier region (in both the north and south) tends to increase when the island is migrating across a gently sloping substrate (i.e., slopes near or below 1 m/km). With higher cumulative RSLR, northern Metompkin Island migrates over a steep substrate allowing for only brief periods of rapid widening of the backbarrier. In contrast, the substrate encountered by southern Metompkin Island is more consistently gentle (<1 m/km) (Figure 12a) leading to nearly continual widening of the backbarrier. In general, when an island migrates across steep substrates backbarrier width remains constant (e.g., both islands) or even decrease (e.g., seen only in northern Metompkin Island. As described by Stolper et al. (2005), low substrate slopes (congruent with backbarrier widening) allow for the deposition of a more expansive backbarrier unit providing a more vertically elevated and seaward-protruding platform upon which future island migration can occur. Steeper slopes (which limit lateral backbarrier expansion) negate the potential for backbarrier units to supply an elevated landward surface for subsequent island migration (These relationships are perhaps best shown in comparing final timestep plots of various RSLRR for northern and southern Metompkin Island; see figure 13).

While, island volume tends to decrease for northern Metompkin Island and increase for southern Metompkin Island as RSLR increases, smaller fluctuations in volume are associated with changes in backbarrier width (and therefore substrate slope), such that increases in backbarrier width generally correspond to island volume decreases (Figure 12b). This implies that a more extensive backbarrier unit (associated with a low substrate slope) provides more vertical relief during island migration, thus requiring less island sand (i.e., smaller volume) to maintain island elevation above sea level.

3.2 Future Simulations

To explore the range of potential future barrier island response to RSLR, I conducted a suite of simulations extending from 2000 AD to 2100 AD in 5-year time steps. While these future simulations are based on the same values derived from the calibration of the late-Holocene simulation (Table 1), and incorporate well-supported estimates of future SLRRs, they are not intended to be accurate representations of future island evolution, but simply to capture the range of possible future response. Unlike the late-Holocene simulations, here, northern and southern Metompkin Island will migrate across known topographic surfaces which are far more variable (in slope) than the conceptualized initial condition (Figures 14 & 15).

Reported values for eustatic RSLR by the year 2100 AD range from 0.2m to 1.6m, (IPCC 2007; Grinsted et al., 2009; Jevrejeva et al., 2010). Local RSLRR are expected to be slightly faster than eustatic rates and therefore I choose to vary RSLR between 0.6 – 1.6m of total rise over 100 years. With uncertainty involving the amount of RSLR by 2100 and the nature of RSLR acceleration during that time, I simulated multiple accelerated RSLR scenarios, including constantly increasing RSLR rates, linearly increasing RSLRR, and RSLR rates that increase along a polynomial curve.

Various studies have shown that vertical accumulation rates within the backbarrier, particularly in salt marshes, have a finite upper limit considerably below some future RSLRR predictions (e.g. Craft et al., 2009). To explore how a backbarrier sedimentation rate that is lower than the RSLRR may influence island migration I performed additional simulations where back-barrier sedimentation rate is limited to 10mm/yr. This estimated rate is derived from model simulations of vertical marsh accumulation during accelerated RSLR by Kirwan et al. (2010), and is meant to represent a conservative upper limit to rates of back-barrier sedimentation. There is some evidence in the literature (e.g., Craft et al., 2009) to suggest that back-barrier sedimentation occurring in lagoonal environments may be unable to keep pace with future RSLR acceleration thereby resulting in a deepening of backbarrier bays in the future. For this reason, I applied a 10 mm/yr limit in simulations of southern Metompkin Island as well to consider the greatest range of potential impacts. Furthermore, to explore the effects of a possible lag period between accelerations in RSLRR and back-barrier sedimentation rate, as reported by Kirwan and Temmerman (2009), I included a series of simulations in which backbarrier sedimentation rates are offset from RSLRR by 20 years while still being limited to 10 mm/yr.

Island migration rate and final island volume remain fairly constant for a given amount of cumulative RSLR regardless of the rate of increase (Figure 16). This implies that the rate at which the RSLRR increases over time has less of an impact on migration rates than the cumulative amount of RSLR, and variations in substrate slope or composition. Substrate slope and composition are relatively constant between 2000-2100 for all RSLR scenarios (0.6-1.6m), but differ between northern and southern Metompkin Island (e.g., Figure 5). During the 100-year-long future simulations, northern Metompkin Island migrates faster and gains more volume than southern Metompkin Island, regardless of the RSLR scenario (Table 2 & Figure 16). Island migration rates during the first 20 years of the future simulations (7-8.6 m/yr in the north versus 4.5-6 m/yr in the south for a range of cumulative RSLR values) are in agreement with average observed shoreline change rates for 1985 – 2009 (7m/yr in the north vs. 2m/yr in the south calculated from shoreline position data from Wolner (2011)).

Consistent with the backbarrier sedimentation rate sensitivity experiments presented in the previous section (3.1.1), when the backbarrier sedimentation rate is less than the RSLRR (in future simulations with backbarrier sedimentation rate limited to 10mm/yr limits or lagging 20yr behind RSLRR) final volume of both island halves is affected(Figure 16b), however the migration rate of southern Metompkin Island is particularly sensitive to lower backbarrier sedimentation rates, particularly at high cumulative RSLR (Figure 16a) Differences in the behavior of northern and southern Metompkin are likely the result of distinct differences in landward substrate slope and substrate sand content. At the start of future simulations northern Metompkin Island is positioned atop a backbarrier unit containing limited sand (15%) and is backed by both subaerial marsh and steeply inclined mainland topography, while the backbarrier unit below southern Metompkin Island contains more sand (60%) and has a gently-sloped mainland topographic surface along its landward edge (Figure 14). Because the backbarrier units make up the bulk of the shoreface during future simulations (e.g., Figure 13), differences in the amount of sand in this unit affect overall sand availability, and therefore migration rate. Additionally, the slope of the landward substrate appears to influence the ability of the backbarrier to maintain its initial width during RSLR conditions. Similar to the previously described relationship (section 3.1.7), steep substrate slopes (i.e., behind northern Metompkin Island) do not allow for backbarrier widening, and may even reduce backbarrier width, but when landward substrate slope is gentle (<1 m/km) the area over which backbarrier deposition takes place increases resulting in a thicker backbarrier deposit.

Limitations to backbarrier sedimentation rate appear to amplify the effect of steep substrate slopes on backbarrier width. During future simulations when backbarrier sedimentation rate equals RSLRR the substrate slope landward of southern Metompkin Island is never sufficiently steep to cause backbarrier narrowing, regardless of the amount of cumulative RSLR by 2100. However when simulating the same RSLRR scenario with a limited backbarrier sedimentation rate, backbarrier width is constricted requiring faster landward migration (e.g., at cumulative RSLR ≥ 1 m on southern Metompkin Island) (Figure 16), suggesting that limitations on backbarrier deposition may influence future island behavior.

To briefly explore how Metompkin Island might respond to conditions more extreme than suggested by RSLR predictions, I ran additional simulations using combinations of more extreme rates of RSLRR and sand-loss. Independently, I simulate island response to 2 – 5 m total RSLR (at intervals of 0.5 m) by the year 2100 and sand-loss rates ranging from 0.5 – 35 m^3/m/yr (with progressively larger intervals), however both sets of simulations include SLRRs that increase polynomially and backbarrier sedimentation rate limits of 10 mm/yr to aid in simulation of most extreme conditions. Across all extreme RSLRR simulations increases in SLRR results in accelerated migration rates (ranging from 10 mm/yr to 33 mm/yr) for both halves of Metompkin Island, and never does the island appear unable to keep pace with RSLR. On both northern and southern Metompkin Island, migration rates increase linearly as sand-loss rates increase, and as in the future simulations involving more realistic representations of future conditions, northern Metompkin Island migrates much more rapidly than its southern counterpart. These simulations suggest that if island migration can occur freely in the future, Metompkin Island may respond, even to extreme conditions, via increases in migration rates rather than by disintegration submergence.

4. DISCUSSION

4.1 Model Limitations

When using a morphological-behavior modeling approach to simulate past and future island migration during RSLR, it is important to consider model limitations and assumptions prior to discussion of results and interpretation of model simulations. The morphological-behavior approach successfully elicits important mechanisms of island migration within the given study site and beyond, but generally restricts interpretations to theoretical and qualitative assessments of the range of potential island behavior. For example, here, I condense the long-term migration of an 11-km long barrier island to two sets (i.e., north and south) of 2-D cross-shore simulations each with < 12 input parameters such that the resulting island behaviors represent the average response to RSLR for that island segment. For this reason, model outputs are not meant to accurately portray island response at any one location along Metompkin Island, or to be predictive in a quantitative away.

To best assess on the role of variations in backbarrier environment and underlying stratigraphy in island migration, I chose a study site where these differ within a single island thereby reducing the number of dissimilar island characteristics influencing island response. However, by treating each island half as an independent island and ignoring the ability of longshore processes to redistribute sand and realign the beachface and shoreface, simulated differences in the behavior of northern and southern Metompkin Island are relative to actual island response. Thus, future island response to RSLR is more likely to fall somewhere between the simulated behaviors of the two island halves and only were the island to be breached would the island portions begin to migrate more independently from one another in the future. Additionally, some island behaviors (i.e., opening of ephemeral inlet along southern Metompkin Islands, development of shoreline offset, and subsequent closing of the inlet) are not included in my model simulations, but would be expected to play a role in past and future island behavior. It is important to note that despite giving extensive consideration to changes in sea level over long time periods, GEOMBEST does not simulate changes in island behavior due to variations in storm activity. Future deviations from time-averaged storm activity in the past (as suggested by Knutson et al. (2010) and others) may alter future island response beyond the range of potential future behavior simulated here.

Across all simulations of Metompkin Island, the accumulation of backbarrier deposits through time assumes a constant input of sediment to the backbarrier environment without accounting for where this sediment is derived from. In reality, much of the sand deposited in the backbarrier originates from the nearshore zone and is transported landward by overwash and/or inlet processes (particularly for southern Metompkin Island) and thus, backbarrier sedimentations is actually closely linked with alongshore sand supply. By simulating island response with backbarrier sedimentation acting independently from sand supply processes, I have not accounted for reductions in sand availability to the island due to this transfer of sand to the backbarrier. Future work exploring and simulating explicit coupling of sand supply rates and backbarrier sedimentations rates within GEOMEBST would be useful and allow more accurate depictions of the interactions between the nearshore and backbarrier environments.

4.2 Insights on Geologic Constraints

Interestingly, through development of an initial late-Holocene morphology and stratigraphy for northern and southern Metompkin Island and pairing of these configurations with estimated values from the literature for shoreface depth and historic island position it becomes evident that some published estimates of mid-Holocene island position are geometrically implausible. Based on the constraints listed above I find that island position 4600 BP must have been at least 2 km seaward of the current location, and likely was significantly more, assuming any degree of shoreface incision during migration (Figure 5). Just as preparations for conducting simulations sheds light on island position ~4600 years ago, the simulations themselves are consistent with and appear to corroborate published estimates for the timing of establishment of backbarrier deposition. For the first ~3500yrs of the late-Holocene base simulations both halves of Metompkin Island migrate landward with little to no accumulation of backbarrier sediment. Once the island reached a portion of more gently sloping substrate (near 40000 km on the x-axis in Figure 15) a continuous backbarrier unit began to form. The timing of initial backbarrier deposition, predicted by the simulations, matches well with reported ages of the formation of the modern lagoon and marsh system within the VCR (Van de Plassche, 1990).

4.3 Sand Availability

The sand composition within material exposed along the shoreface varies between northern and southern Metompkin Island due to differences in underlying stratigraphy (primarily position of the late-Pleistocene fluvial deposit) and the sand content of backbarrier deposits. Additionally, the sand composition fluctuates throughout the simulations as the island traverses across different substrate units. Because underlying stratigraphic units exposed along the shoreface are critical in supplying the island with sand and therefore in maintaining vertical island position during migration, these differences in substrate sand composition have a substantial impact on island behavior.

Figure 17 shows that the average sand content of units exposed along the shoreface (i.e., cumulative sand %), varies between island halves and changes over the course of the late-Holocene base simulations. Both portions of the island experience a decline in cumulative sand % during the first ~2300 yrs as the shoreface progresses into a more sand deficient unit (early-Holocene lagoonal deposit). However, this decline is less rapid on northern Metompkin Island due to the higher vertical position of sand rich units (late-Pleistocene fluvial deposit) (Figure 5). During the second 2300yrs of the modeled time period, backbarrier deposits begin to compose the bulk of the shoreface allowing differences in backbarrier sand composition (North- 15%; South-50%) to further perpetuate a decline in northern substrate sand content and a slight increase in the southern substrate sand content. This difference in backbarrier sand content leads to the greatest behavioral disparity when simulating barrier island migration significantly landward of current island position (i.e., RSLRR sensitivity analysis with constant model duration and simulations of future barrier island response).

Metompkin Island, as a whole, is highly sensitive to changes in sand-supply rates, which is understandable given the sediment deficient nature of the northern group of islands within the VCR. Direct changes to the sand-supply rate, and adjustments that indirectly affect cumulative substrate sand percent during migration (i.e., sand composition of individual units and shoreface depth) have a significant impact on island migration rates and final volume during late-Holocene simulations. Most often, differences in the behavior of northern and southern Metompkin Island associated with sand availability result from inconsistencies in the underlying stratigraphy (e.g., the vertical position, sand content, and orientation of individual units). While the northern marsh deposit provides an elevated platform for the barrier island unit, the submerged lagoonal deposit of southern Metompkin Island increases the dependence on island volume in maintaining a sub-aerial island position. Therefore, when sand availability is limited (i.e., high sand-loss rate, low substrate sand content) and island volumes decrease proportionally, the migration rate of southern Metompkin Island may be expected increase more rapidly to maintain island position—possibly explaining the development of the modern shoreline offset.

While the modern substrate composition is reasonably well described, when simulating island migration over long timescales the factors that influence sediment availability (e.g., stratigraphic composition, alongshore sand-supply rates) are highly variable and usually site-specific, limiting the applicability of findings based long-term island response to sand availability alone. Similar to other GEOMBEST applications (Stolper et al., 2005; Moore et al., 2010), I also used relationships between substrate topography (i.e., substrate slope) and shoreface geometry (i.e., barrier island slope and island trajectory) to characterize long term island migration processes.

4.4 Substrate Slope Effects

Prior to performing any designed experiments, I evaluated barrier island and substrate slope geometries, in both initial and final condition, of the late-Holocene base simulations to assess how slope interactions may help to explain general island behaviors occurring in all late-Holocene simulations (Figures 14 & 15). During base simulations barrier island slope transitions from being steeper than the underlying substrate slope (4600 years BP) at the beginning to being comparable with the underlying substrate slope by the final timestep (the modern condition). Consistent with findings of Moore et al., (2010) barrier island volume increases (178% in north and 85% in south during base simulations) as average barrier island slope decreases and approaches equilibrium with the slope of the substrate. Given this slope relationship, I expect barrier island volume to increase during all late-Holocene simulations of the late-Holocene migration, unless severely limited by sand availability.

One of the main differences between northern and southern Metompkin Island (that is influential in both past and future simulations) is the slope of the underlying substrate (e.g., Figures 14 & 15). Through a comparison of the backbarrier and barrier island configuration resulting from various RSLR scenarios (i.e. constant duration and future simulations) I use the substrate slope to evaluate how antecedent topography—both large-scale average slope and short-term perturbations in the slope "experienced" by the barrier island during migration—can influence island migration.

Consistent with previous studies (Moore et. al, 2010; Stolper et. al, 2005), I find that average barrier island slope shifts from being steeper than to approximately equal with substrate slope through time. Once the barrier island slope is near equilibrium, at long time scales island migration trajectories tend to reflect average substrate slope (Wolinsky & Murray, 2009). (Note: Because the alongshore sand-budget used in my simulations is nearly balanced (-0.5 m^3/m/yr) and I do not include average barrier island slopes from simulations with varied sand-loss rates, in this substrate slope effects analysis, I used average barrier island slope in place of effective barrier island slope for simplicity). However, when looking at smaller scale variations in substrate slope, migration trajectory remains fairly constant (Figure 13) even when the island is traversing substrates of varying slope. For island migration trajectory to mirror larger-scale substrate slope constantly, migrations rates must remain reasonably stable despite these (smaller-scale) periods of substrate variability.

It might be expected that lower slopes require more landward island movement per given unit of RSLR in order to maintain vertical position. Instead, I propose a feedback between short term substrate perturbations, backbarrier sedimentation, and barrier island morphology that prevents the translation of smaller variants in substrate slope into changes in the slope of the island migration trajectory. When a landward migrating island encounters gently sloped topography (< 1 m/km) the backbarrier region (regardless of whether it consists of marsh platform or shallow lagoon) is able to expand laterally across the shallow substrate. As noted by Stolper et al. (2005), a wider backbarrier results in a thicker, more voluminous backbarrier deposit. With continued landward migration, this thicker backbarrier deposit not only reduces the backbarrier accommodation space, but also provides an elevated, seaward-positioned platform for migration, therefore allowing a stable vertical position relative to sea level to be achieved with less landward migration. Consequently, island volume declines as slower migration rates limit the liberation of sand from underlying stratigraphy, and the presence of an elevated backbarrier unit allows the equilibrium morphology to be maintained by a smaller island volume (Figure 18). If sufficiently low landward slopes persist over time, this relationship may result in the development of a positive feedback where the decrease in migration rate coupled with a low mainland slope promotes further backbarrier widening and thicker backbarrier deposits. If sufficiently gentle landward substrate slopes persist over an extended period of time a runaway backbarrier deposition scenario may develop, similar to simulated southern Metompkin Island response to SLRRs $\geq$ 2.25 mm/yr in the constant duration RSLRR sensitivity experiments (Figure 13b). However, given the undulating mainland slope characteristic of the study site (Figure 14), a more likely scenario is that the low sloping substrate transitions into a section of steeply sloped substrate which inhibits the feedback from continuing indefinitely.

Conversely, as an island encounters a substrate slope appreciably greater than the barrier island slope (> 2 m/km), migration along a continuous trajectory confines the backbarrier resulting in constant or decreased backbarrier width (as observed for northern Metompkin Island during constant duration RSLRR sensitivity experiments and future simulations). While steeper substrates may typically be associated with less landward movement per unit of RSLR, I find that restricted backbarrier expansion, both horizontal and vertical, requires island migration rates to remain fairly constant, or accelerate slightly, when migrating over steep sections of the substrate (Figure 18). As backbarrier deposits become less extensive, island volume increases to provide the vertical relief necessary for the island to remain subaerial. If substrate slope is sufficiently steep to induce backbarrier constriction, this process may lead to a narrow backbarrier, increasingly landward island positions, and may ultimately set up an opposing positive feedback where backbarrier narrowing promotes further narrowing of the backbarrier. Again, slopes this steep rarely persist (within the study site) and highly inclined substrate sections commonly progress into more gentle slopes along the undulating landward substrate surface, thereby limiting the potential for a runaway feedback in this direction as well.

Further influencing the potential for runaway feedback scenarios to develop, the sand content along the shoreface will vary with changes in backbarrier thickness, and these fluctuations in overall sand availability will likely influence island migration rates. Therefore, as the percentage of the shoreface consisting of backbarrier deposit changes, the relationship between the sand content of the backbarrier unit and the next lowest stratigraphic unit (the sand-limited early-Holocene lagoonal deposit on Metompkin Island) will be important in determining the degree to which changes in backbarrier thickness influence island response. In the case of backbarrier expansion and thickening caused by low substrate slopes, if the backbarrier deposit contains less sand than the underlying unit (i.e., northern Metompkin Island), a negative feedback between sand availability and backbarrier width could develop, where sand availability will decline as the backbarrier thickens, resulting in accelerated island migration rates and less backbarrier expansion, acting to diminish the potential for runaway backbarrier expansion. Here, accelerated island migration will likely limit backbarrier expansion so that a portion of the shoreface always remains within the underlying unit to insure sufficient sand supply during migration.

Alternatively, if the backbarrier deposit contains more sand than the underlying unit (i.e., southern Metompkin Island), a positive feedback could develop during backbarrier expansion where overall sand availability increases, migration slows, and the backbarrier expands. With continued migration, if the shoreface is entirely made up of sand-rich backbarrier material, this reinforcing feedback would essentially decouple backbarrier width and substrate slope interactions, so that backbarrier width would continue to increase, regardless of substrate slope, due to overly abundant sand availability (Figure 13b). If the backbarrier is instead progressively constricted in response to steep substrate slopes, as the proportion of the shoreface composed of backbarrier deposits decreases and sand availability changes, a similar, but opposite set of potential feedbacks exist to either promote (i.e., less sand in the underlying unit) or prevent (i.e., more sand in underlying unit) a backbarrier narrowing runaway feedback situation.

Provided that backbarrier deposition is able to persist at rates similar to RSLRR, the interaction between substrate slope and backbarrier sedimentation offers a mechanism by which an island migration trajectory can reflect large-scale average topographic slope with minimal adjustments to island migration rate due to smaller scale variations in substrate slope. Controlled primarily by substrate slope and island migration rate, the backbarrier deposit plays a passive, but potentially critical role in island migration by quickly adapting its size. If the slope of the substrate is relatively constant, this size remains invariable with little effect on island behavior (assuming all other variables are held constant). But when traversing a hummocky landward substrate surface, changes in the extent of the backbarrier unit (horizontally, and therefore vertically) allow for a more constant island migration trajectory, in effect modulating the impact of small-scale changes in substrate slope. Only when very high or very low substrate slopes persist over a significant expanse will either runaway feedback scenario have the potential to become established and persist for long periods of time. However, continuous extreme slope values would also affect the larger-scale average substrate slope, perhaps resulting in a different island migration trajectory altogether.

In addition to the rising and falling nature of the substrate topography landward of Metompkin Island, a lag effect likely delays the response to substrate slope, further discouraging rapid development of the positive feedback scenario. While the exact length of substrate and amount of time necessary for substrate slope to adequately affect backbarrier thickness and extent are unknown, the backbarrier unit must first adjust (either by thickening through a wider backbarrier or thinning when high substrate slopes limit backbarrier width) before slope effects are transferred to the island. Because of this lag period, migration trajectories are likely never entirely constant, however the responsive nature of backbarrier units makes island trajectory less variable than if the backbarrier unit did not exist. Furthermore, to maintain a consistent island trajectory without an adjustable backbarrier unit, island volume and migration rate would have to fluctuate rapidly. Such rapid island volume change may not be possible given the overall sediment deficient nature of this region, possibly threatening barrier island existence (in a form similar to the modern configuration) over longer timescales.

4.5 Implications of Future Simulations

During simulations of island behavior between 2000 and 2100 AD, increased rates of island-wide migration (North: 10-13.4m/yr; South: 5.6-9.6m/yr) are likely a function of high RSLRR and low sand availability. While my intent is not to recreate or to predict actual future island behavior in any detail, relative conformity between observed shoreline change rates (North: 7m/yr; South: 2m/yr) and island migration rates during the first 20 years of the future simulations (North: 7-8.75m/yr; South: 4.25-6m/yr, dependent upon cumulative RSLR) suggests that GEOMBEST is able to simulate island behavior at decadal timescales reasonably well. Similar to findings from late-Holocene simulations, northern and southern Metompkin respond differently to identical RSLR scenarios because of substrate composition and slope variability between the two halves of the island. Differences in the cumulative substrate sand content contributor greatly to differential island response, such that higher substrate sand content promotes slower landward migration rates along southern Metompkin Island relative to the northern half of the island. Additionally, while the migration trajectory of each island half reflects long-term average substrate slope, similar to findings from late-Holocene simulations, regional differences in landward substrate slope angle (Figure 14) result in backbarrier constriction (i.e., high substrate slope) in the northern portion of the island and constant backbarrier width (i.e., gentle substrate slope) in the south. As the northern backbarrier region is unable to maintain width through time, the thickness of the resulting backbarrier deposit decreases, adding to the disparity in migration rate between the two halves of the island.

In comparing changes in island migration rate with changes in substrate slope for the late-Holocene and future simulations, it appears that timestep length may influence both the length of the lag period and the intensity of the substrate slope and backbarrier response. As expected, changes in barrier island response (i.e., changes in thickness and extent of backbarrier deposits) occur much more rapidly during simulations having 5 year timesteps rather than simulations having 50 year timesteps (i.e., late-Holocene simulations). Without a more accurate evaluation of the length of substrate and period of time needed for substrate slope effects to trigger backbarrier response, it is difficult to assess what time step length is most appropriate for simulating this relationship. However, with SLRRs of <10 mm/yr and the considerable amount of time need for backbarrier deposits to change in thickness, we hypothesize that substrate slope interactions are far more likely to operate on centurial time scales.

During future simulations of island response having limited backbarrier deposition rates, the width of the backbarrier region decreased when migrating over substrate slopes that did not cause backbarrier narrowing when sedimentation rate was equal to RSLRR. If backbarrier sedimentation rates are not able to keep pace with future SLRRs, backbarrier regions would narrow in response to more moderate (i.e., less steep) substrate slope values, likely resulting in backbarrier that are less expansive than in the modern setting. Additionally decreased backbarriers deposition rates would reduce the ability of backbarrier units to mitigate the effects of small-scale substrate slope variability, thus requiring more extreme island behaviors (i.e., rapid changes in volume or migration rate) to maintain a constant long-term migration trajectory. If backbarrier sedimentation rates are unable to accelerate during future RSLR due to biological processes (i.e., vertical accretion of salt marsh grasses) differential island behaviors may develop based upon spatial variability in backbarrier composition.

5. CONCLUSIONS

Results from sensitivity analyses suggest barrier island behavior is most sensitive to changes in factors that appreciably alter sand availability (i.e., sand-supply rates, substrate sand content) and landward substrate slope, while island behavior is less sensitive to changes in substrate erodibility, depth dependent response rate, and shoreface depth. Reduced sand availability most commonly results in increases in island migration rates (as much as ~110% increase relative to base simulation) and decreases in island volume (up to 92% reduction) for both halves of the island. However, the migration rate of southern Metompkin Island increases more rapidly than the migration rate of its northern counterpart when sand availability is limited. This is likely due to the lower elevation of the backbarrier (lagoonal) surface behind southern Metompkin which requires vertical island position (relative to sea level) to be maintained by the barrier island alone rather than being aided by migration onto an elevated backbarrier platform, as in the north. This differential response to limited sand availability may partially explain recently observed differences in island behavior between the northern and southern halves of the island.

Sensitivity experiments which allow the island to migrate increasingly farther landward along substrates of varying slope, reveal that interactions between substrate slope and both the horizontal extent and vertical thickness of the backbarrier, appear to influence island response. As the island traverses gentle substrate slopes (~ <1 m/km), the backbarrier deposit expands horizontally resulting in thickening of the backbarrier unit through time and a more seaward island position, while the incidences of relatively steep substrate slopes (~ >2 m/km) appear to limit backbarrier expansion, or even reduce backbarrier width, resulting thinner backbarrier deposits and more landward island positions (Figure 18). If sufficiently gentle or steep slopes persist over long time periods, either self-reinforcing scenario could begin to take off in a potentially "runaway" feedback, however undulating substrate slopes within the study appear to regulate backbarrier width thereby preventing this from occurring. Additionally, as the thickness of backbarrier deposits continually adjusts to substrate slope, differences in sand content between the backbarrier unit and uppermost underlying unit alter sand availability and can either promote or prevent the establishment of runaway feedback scenarios.

Results from simulations of future island response to reported potential RSLR scenarios for 2000- 2100 (ranging from 0.6 – 1.6 m RSLR) indicate that sand availability and substrate slope interactions will likely continue to drive barrier island response. For a given amount of total RSLR by the year 2100, barrier island response is less sensitive to the exact nature (e.g., rates that increase linearly vs. polynomially) of RLSR and primarily dependent on amount of total RSLR. If Metompkin Island is able to freely migrate landward into the future, island disintegration or submergence is highly unlikely, even for RSLRR considerably faster than reported, due to sufficient substrate sand content and landward elevation change. As increased RSLRR cause the island to migrate over increasingly larger portions of the landward substrate, similar to RSLRR sensitivity experiments, variations in substrate slope influence the width and thickness of backbarrier deposits. Given the steeper substrate landward of northern Metompkin Island, the northern backbarrier constricts during future simulations requiring faster landward migration, whereas more moderate substrate slopes in the south maintain backbarrier width into the future. Disparate changes in backbarrier width, and comparatively lower substrate sand content in the north, result in more rapid future migration rates for northern Metompkin Island and continued straightening of the current shoreline offset. However, simulations in which backbarrier deposition rates do not keep pace with RSLRR (i.e., are limited to 10 mm/yr), suggest that the ability of the backbarrier region to sufficiently respond to changes in substrate slope may be reduced if backbarrier deposition rates cannot adequately accelerate into the future.

Theoretically, lower substrate slopes (compared to a steep substrate slope) would require more rapid landward migration in order to achieve the same vertical position, but given the relationship between substrate slope, changes in backbarrier extent and thickness, and island position, backbarrier response to slope variability appears to be a mechanism by which barrier islands are able to migrate along relatively constant migration trajectories (as dictated by average long-term substrate slope) over long time periods despite short-term substrate slope variation. In this case, the potential failure of backbarrier deposition rates (either in salt marsh or open lagoon) to keep pace with future RSLR, may limit the degree to which changes in backbarrier extent and thickness can mitigate small-scale slope variations, thus potentially requiring more drastic changes in island migration rate and volume in the future. Altogether, these findings highlight the potentially critical role of backbarrier environments, substrate slope and underlying stratigraphy in determining how Metompkin Island, as well as other islands within the VCR, and similar barrier islands worldwide, respond to rising sea level.

FIGURES AND TABLES

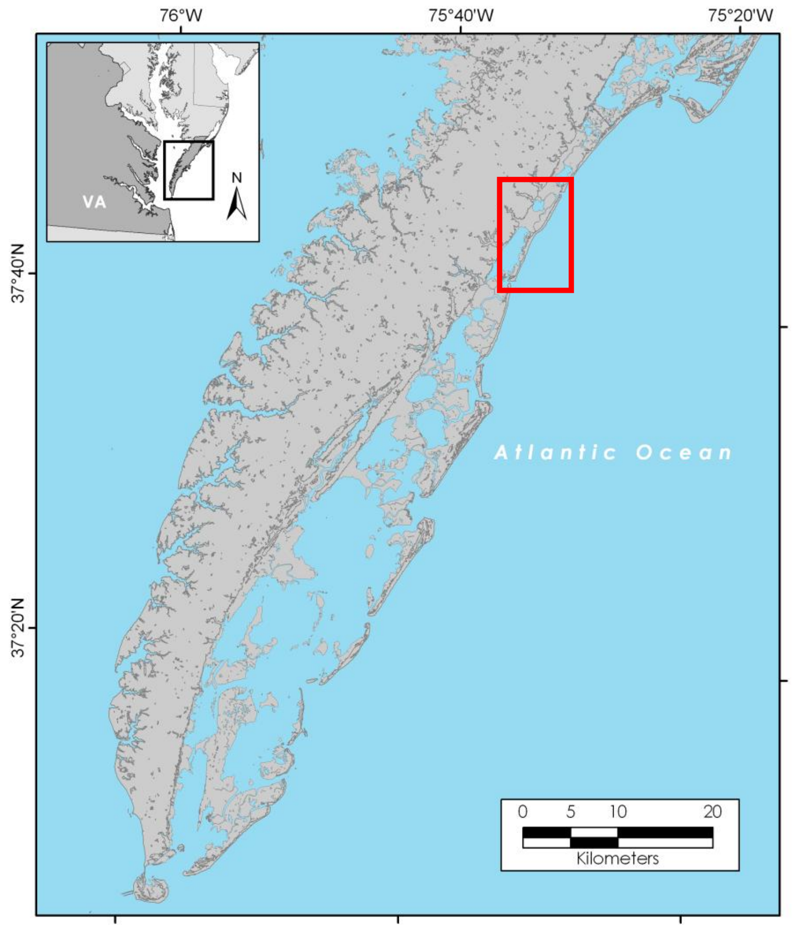


Figure 1. Location of the Delmarva Penninsual along U.S. mid-Atlantic coastline (inset). The large map of the southern Delmarva Peninsula shows landcover of mainland, marsh, and barrier islands, and the red box denotes the study site, Metompkin Island. (figure courtesy of L.W. Cole).

Figure 2. Image of Metompkin Island, VA (2007) showing the 200 m mid-island shoreline offset co-located with the mid-island shift in backbarrier environment. Northern Metompkin is backed by mostly continous platform marsh, while southern Metompkin Island is backed by shallow open lagoon with a narrow, backbarrier fringing marsh (Google Images, 2007).

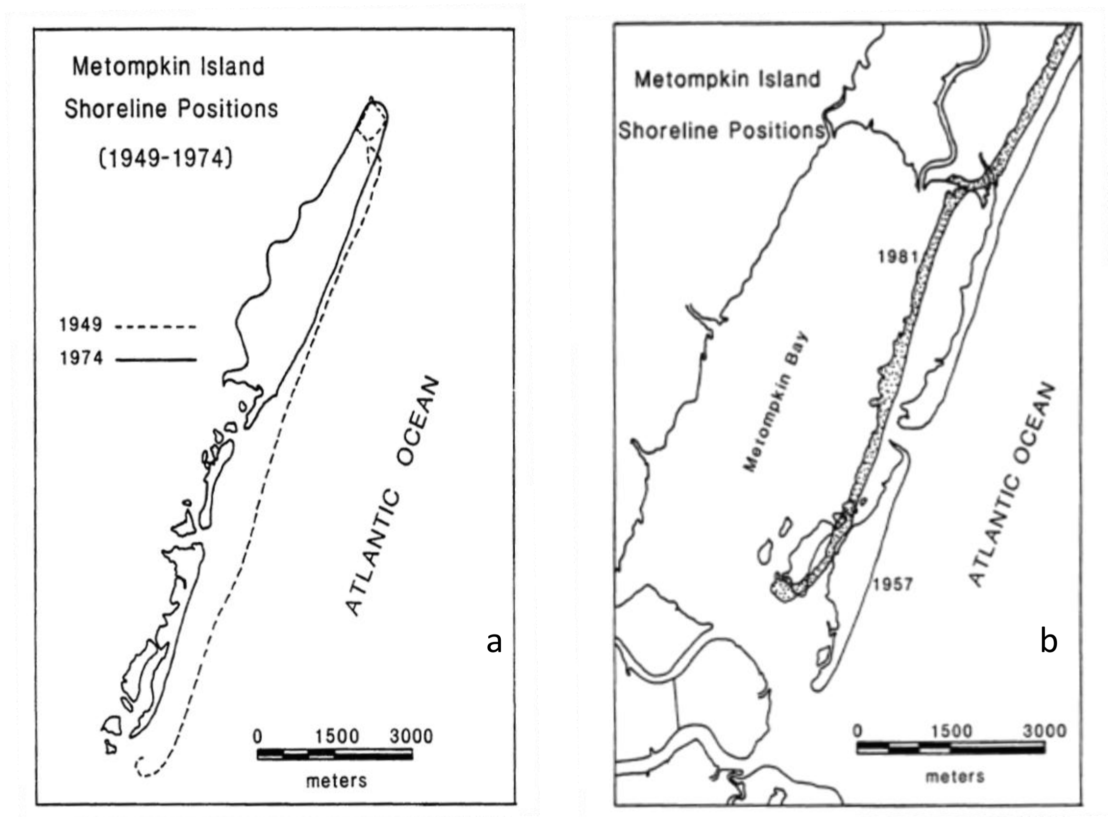


Figure 3. On the left approximate Metompkin Island shoreline position before and after breaching of ephemeral inlet in 1957 (a). Rapid island migration, additional island breeching and shoreface erosion during 1962 storm, results in a prominent mid-island offset by 1981 in right panel (b) (From Byrnes, 1988).

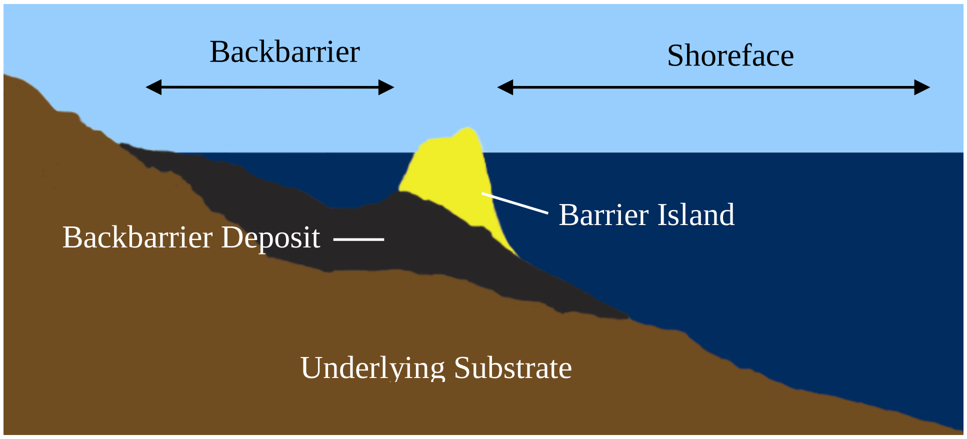


Figure 4. GEOMBEST combines the evolution of three functional realms (backbarrier, barrier, shoreface) to simulate barrier island trangression. The three primary stratigraphic units important in trangression include the barrier island, backbarrier deposits, and underlying strata (From Stolper et al., 2005; Moore et al., 2010).

Parameter		Calibration Value		Source(s)	Sensitivity Variation
		North	*South*		
Stratigraphy				Finkelstein & Ferland, 1987; Byrnes, 1988	N/A
Initial Island Position		4km offshore		Finkelstein & Ferland, 1987; Byrnes, 1988	N/A
RSLRR		1.44mm/yr		Newman & Munsart, 1965; Finkelstein & Ferland, 1987; Byrnes, 1988	0.5 – 4mm/yr
Shoreface Depth		6.5m		Everts, 1978	4 – 9m
Sand Comp. (% of total)	B.I.	95	95	Mixon, 1985; Finkelstein & Ferland, 1987; Byrnes, 1988;	10-90% for all units
	Est.	15	60		
	Strat1	20	20		
	Strat2	75	75		
Sand-supply Rate		-0.5 m^3/m/yr		US ACE, 1973; Byrne et. al, 1974; Byrnes, 1988	-2 – 2 m^3/m/yr
Backbarrier Sedimentation Rate		1.44mm/yr		Nichols, 1989; Van de Plassche, 1990	0 – 2.5mm/yr
Erodibility		1	1	Moore et al., 2010	.001-1
DDRR		1		Moore et al., 2010	.001 – 1
Max. Backbarrier Elevation		0.35m	-0.4m	modern morphology	n/a

Table 1. Model input values from base simulations representing average values during late-Holocene, and range of values tested within sensitivity analyses.

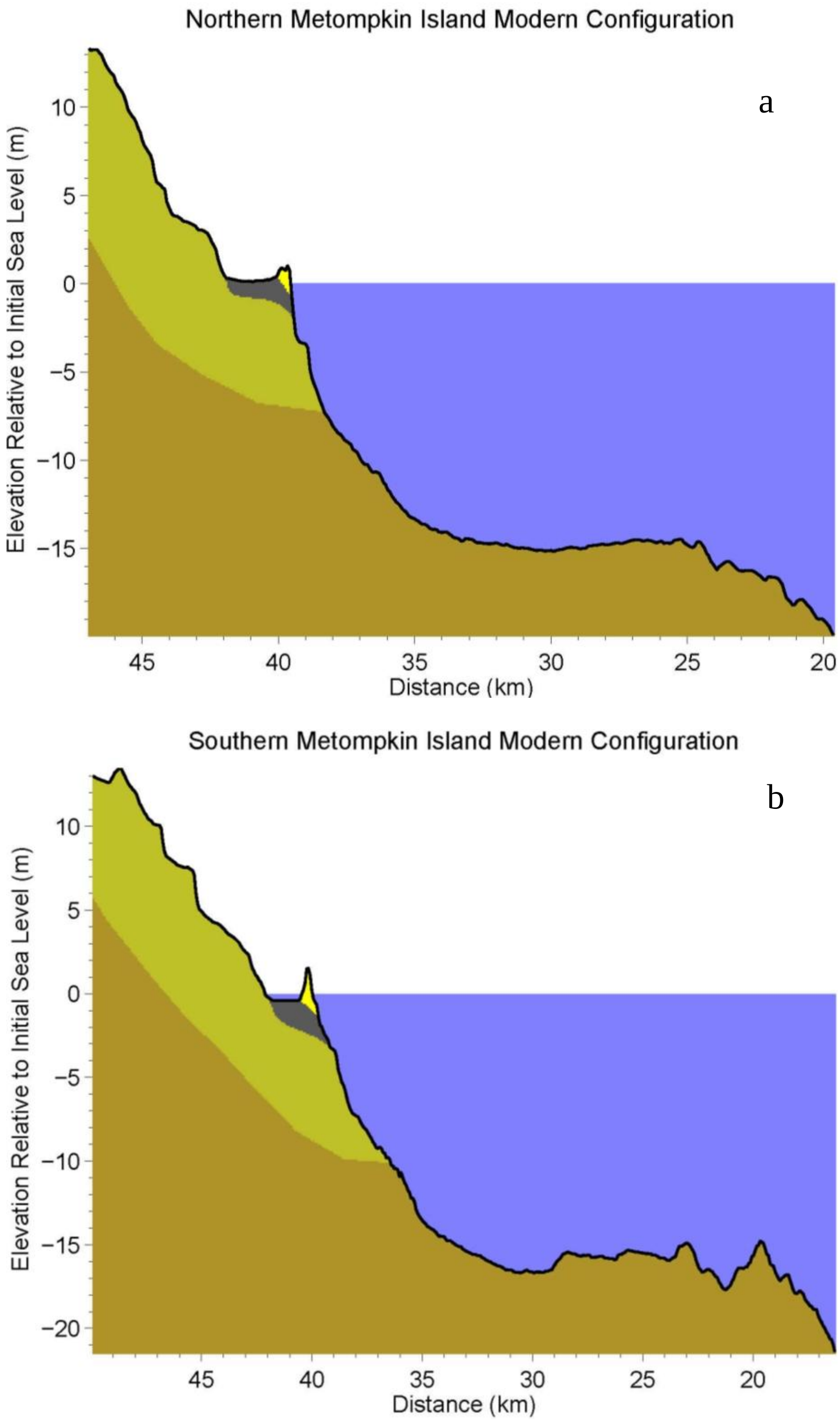


Figure 5. Representation of modern morphology and stratigraphy of northern (a) and southern (b) Metompkin Island recreated using bathymetric data and published core findings. (Yellow unit represents barrier island sand, grey material represents marsh (a) or lagoonal (b) deposits, and tan units represent underlying stratigraphic layers.)

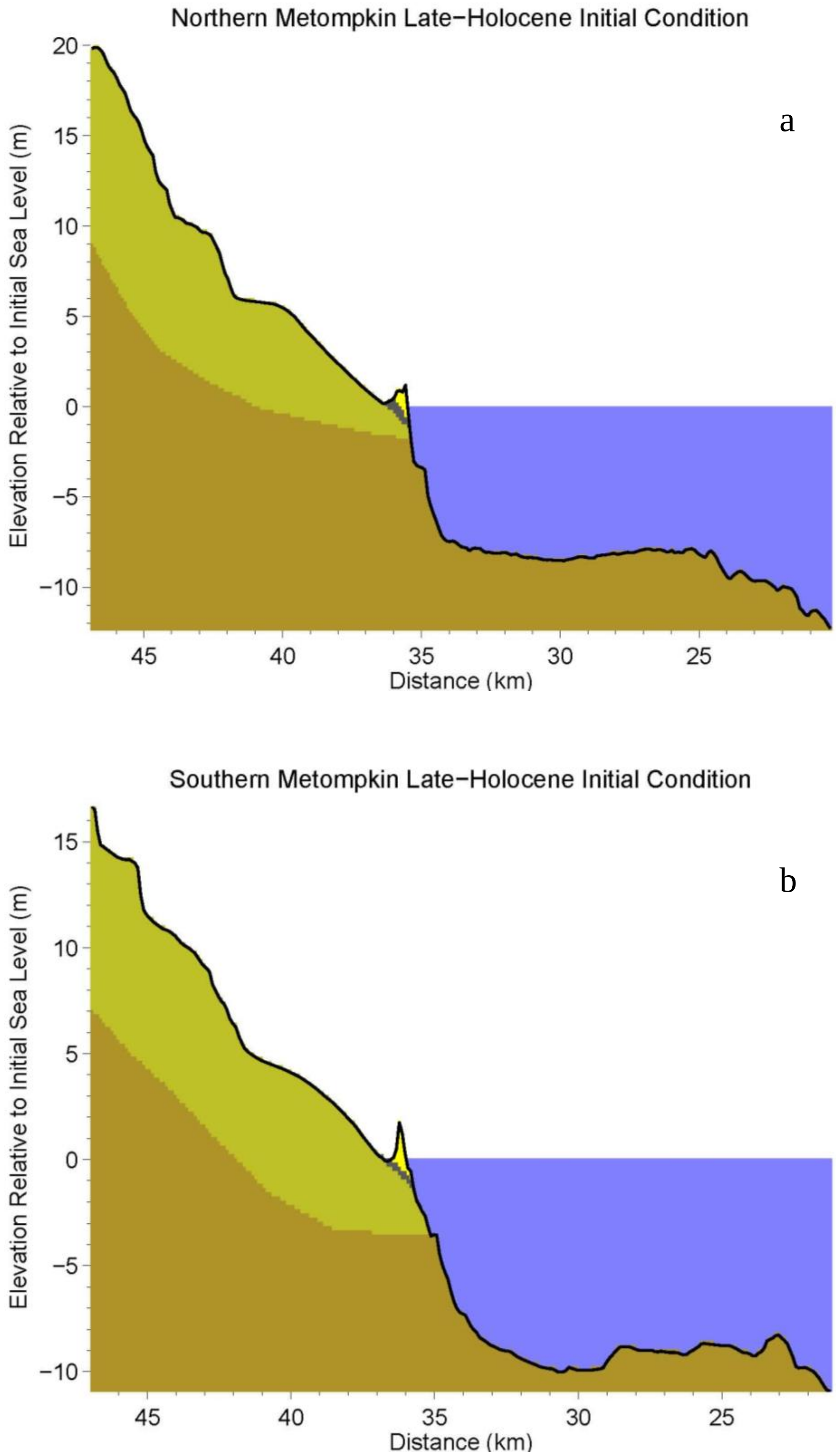
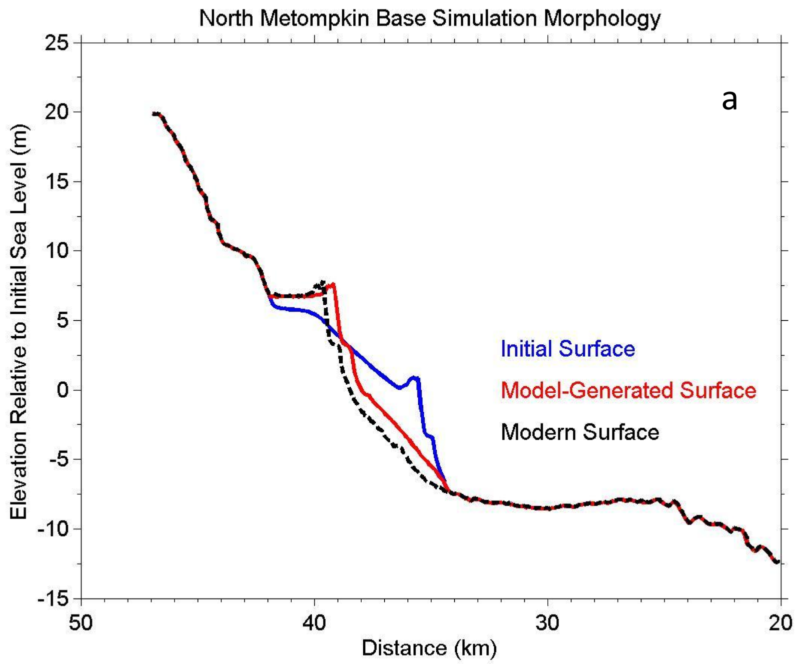


Figure 6. Based on available geological and geophysical data, plausible initial conditions for late-Holocene simulations are developed for northern (a) and southern (b) Metompkin Island. These configurations represent plausible coastal morphology and stratigraphy 4600yrs BP.



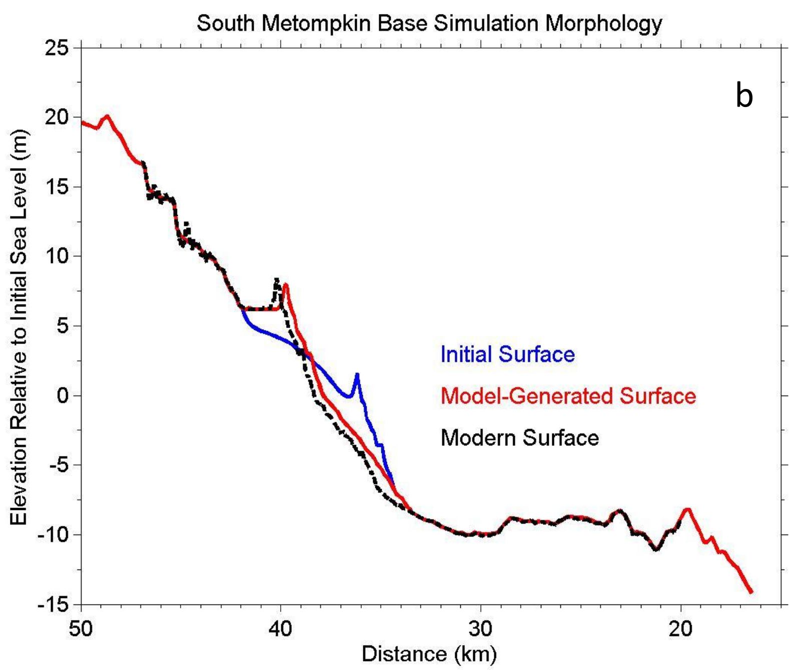


Figure 7. Initial (blue) and final (red) Morphologic surfaces resulting from calibration of northern (a) and southern (b) Metompkin Island base simulations. Black line indicates actual modern surface. Offshore position of model surface meant to represent approximate island position in 1950, prior to island breach and development of mid-island offset.

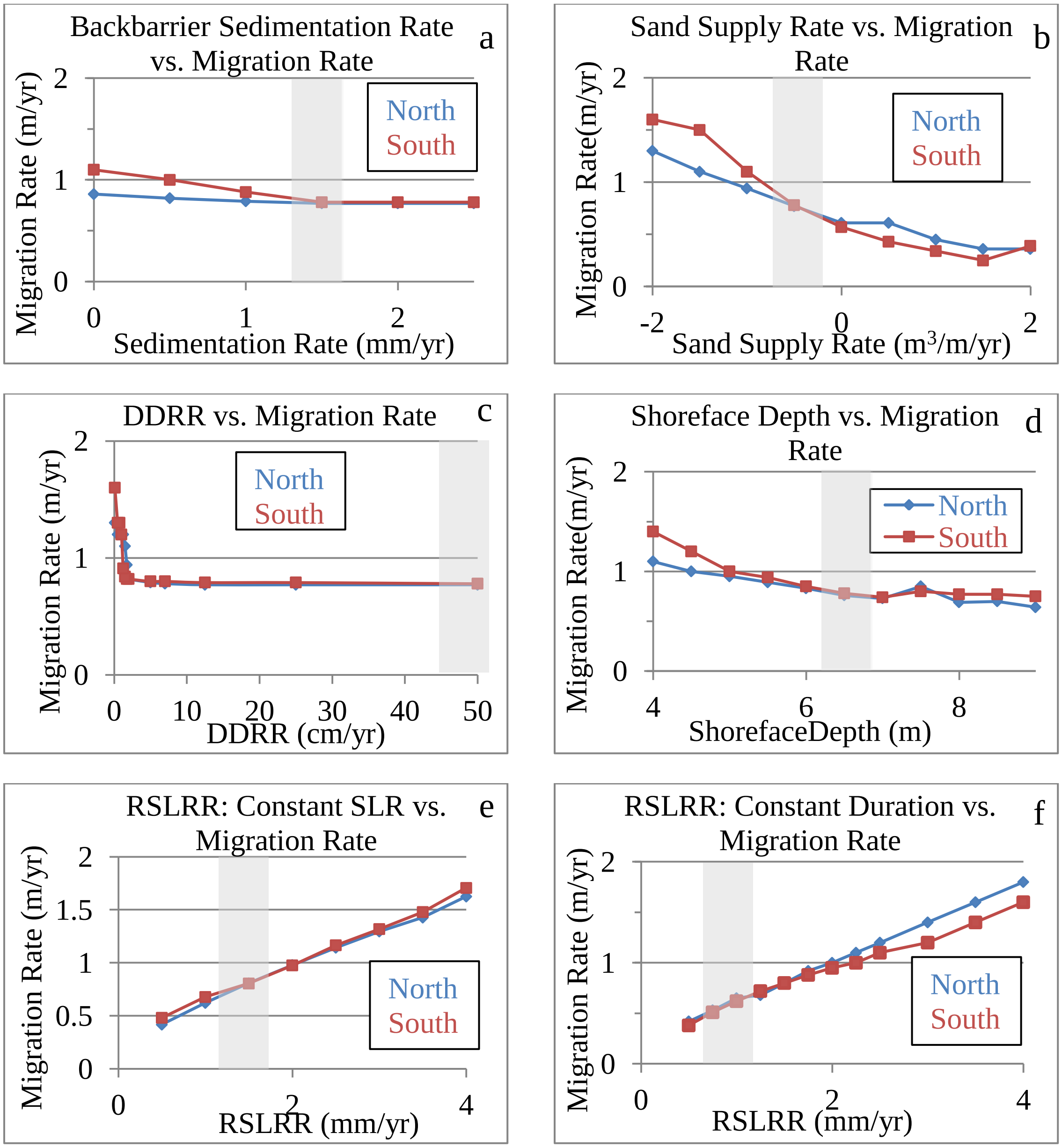


Figure 8. Sensitivty of island migartion rate to changes in back-barrier sedimentation rate, sand-supply rate, RSLRR, and shoreface depth for northern and southern Metompkin Island. Shaded region denotes parameter value from base simulation.

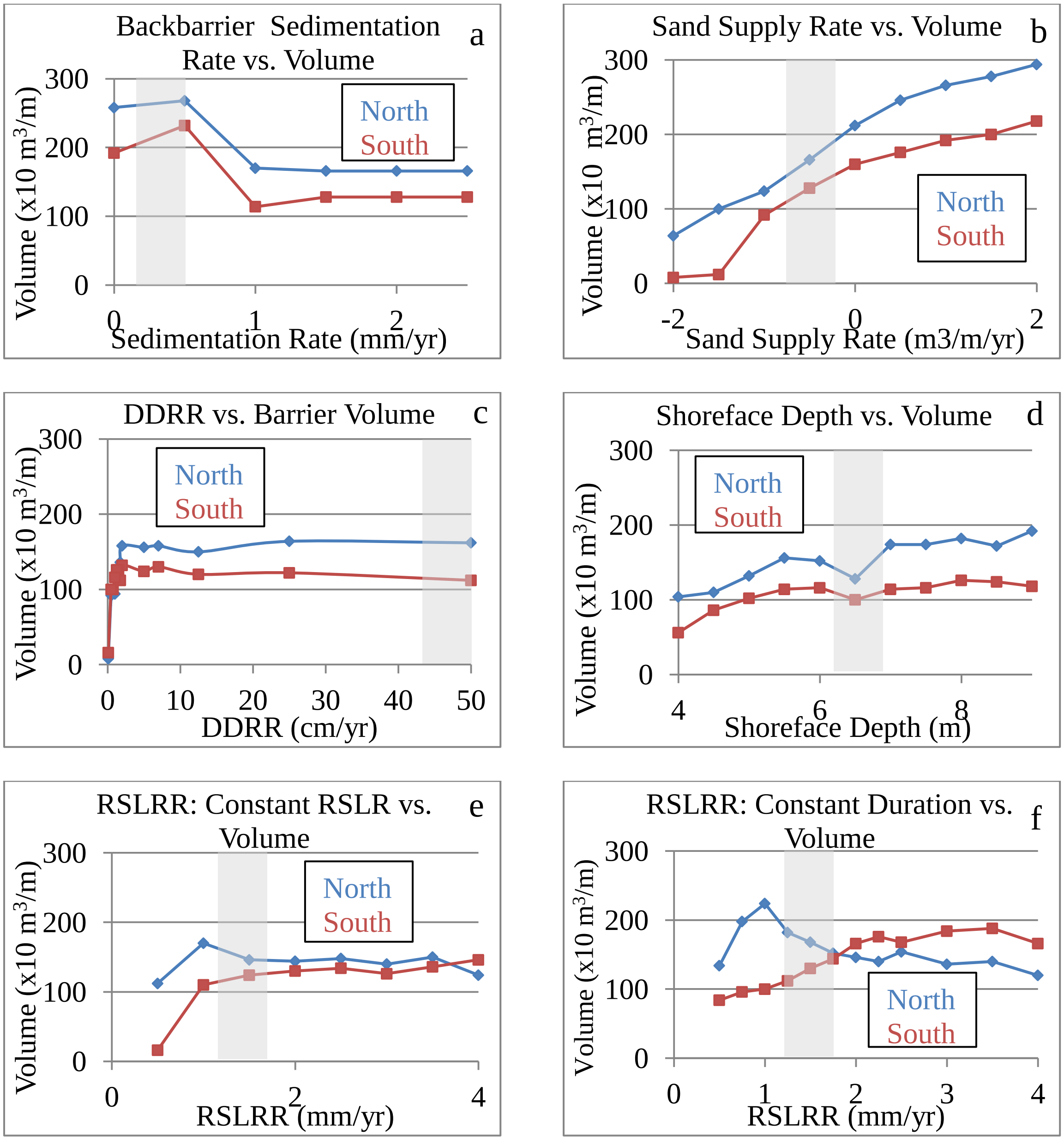
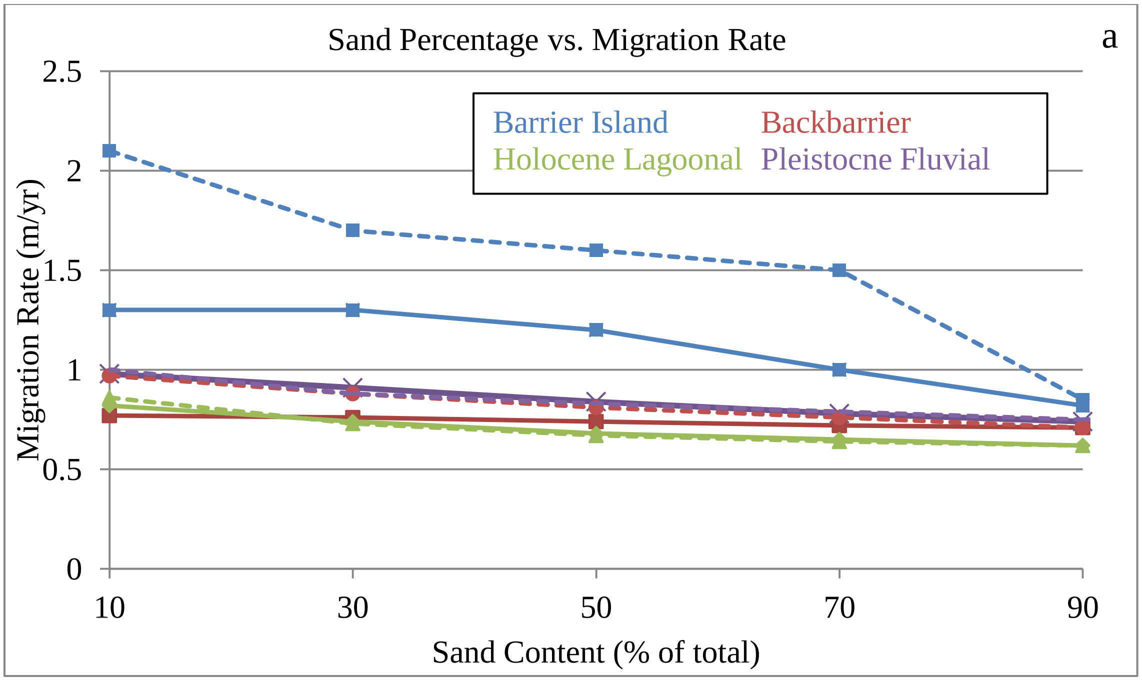


Figure 9. Changes in island volume for northern and southern Metompkin Island resulting from senstivity experiments. Shaded region denotes base simulation value.



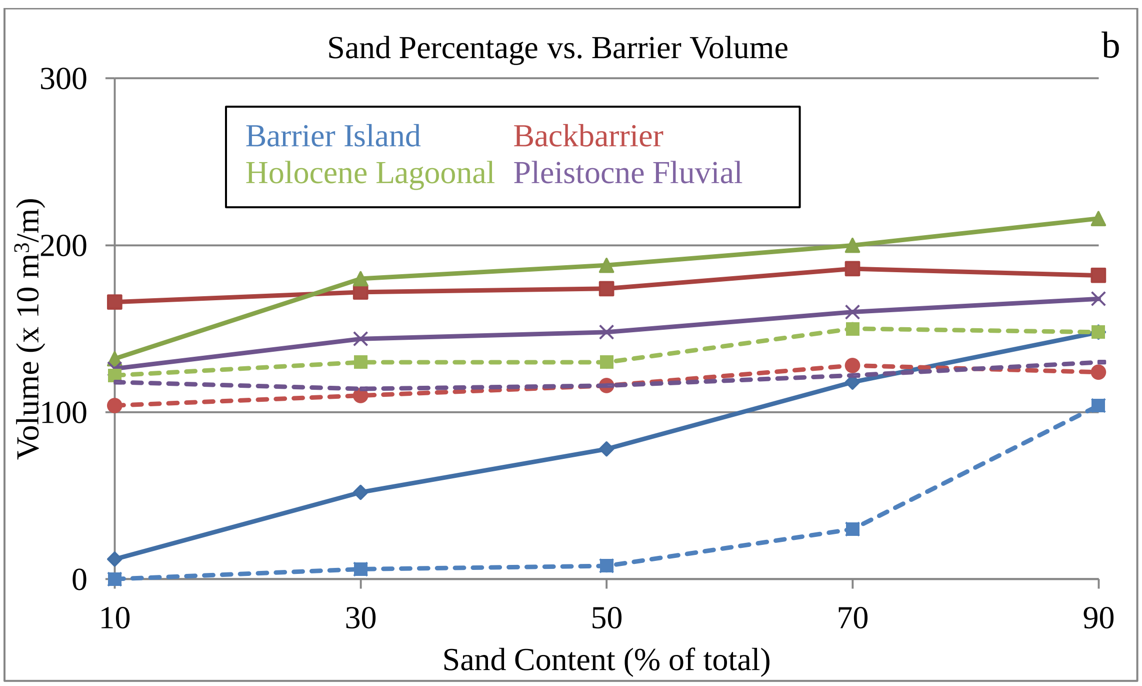
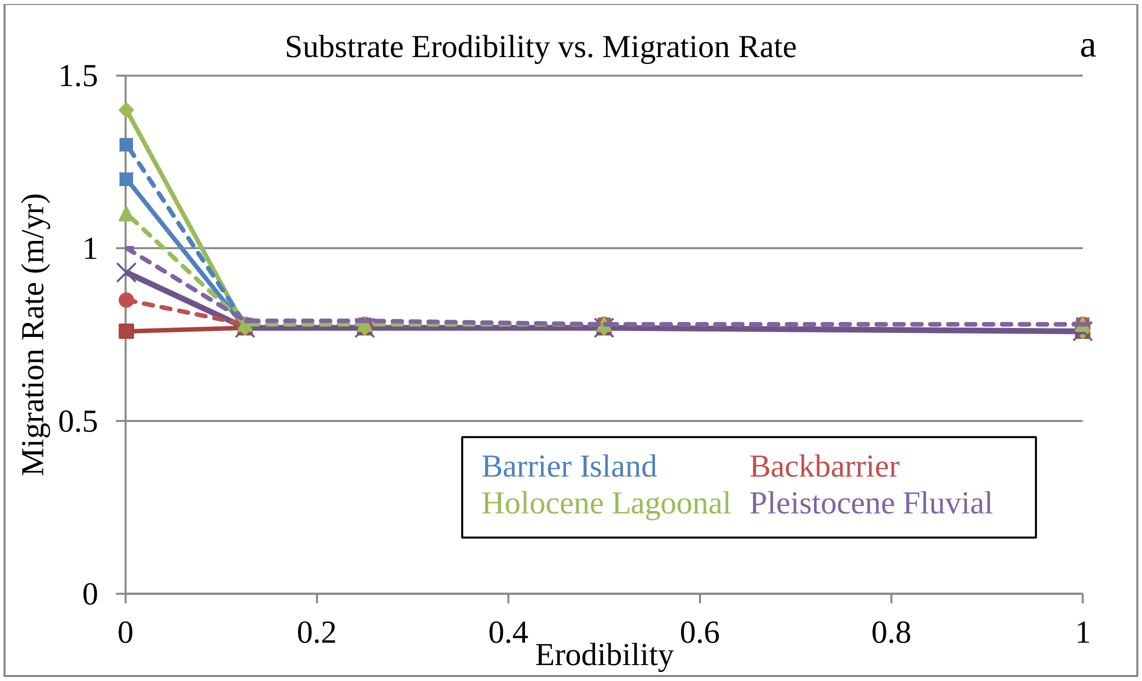


Figure 10. Sensitivity of island migration rate (a) and volume (b) to fluctuations in percent sand content of each stratigraphic unit for northern (solid lines) and southern (dashed lines) Metompkin Island.



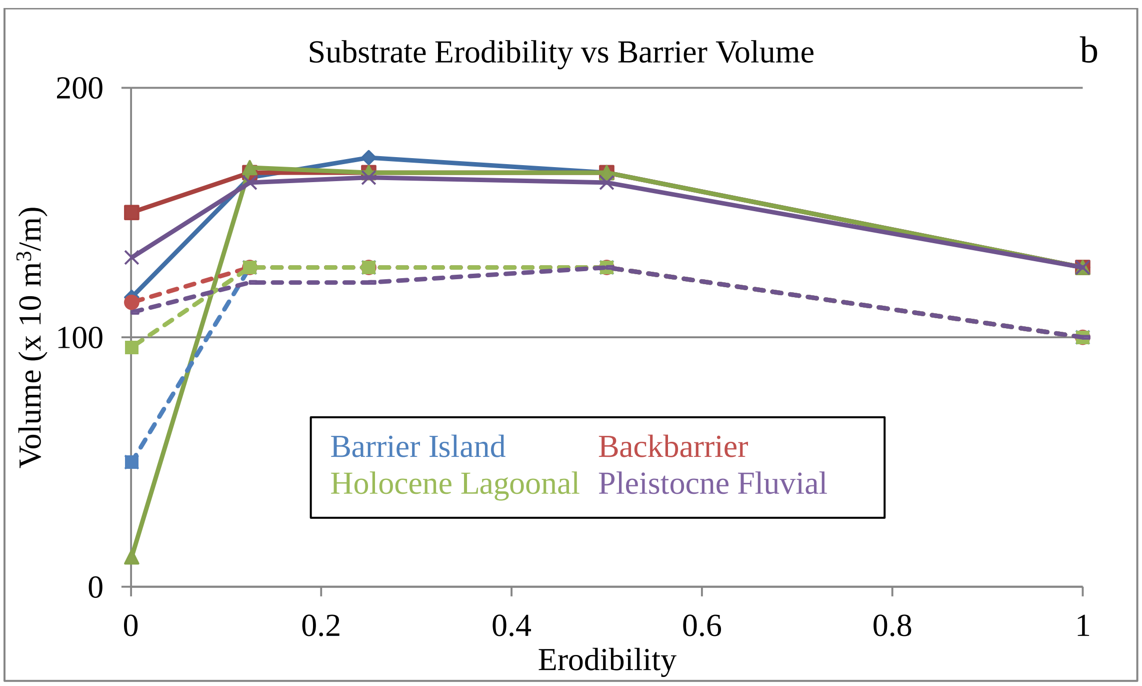
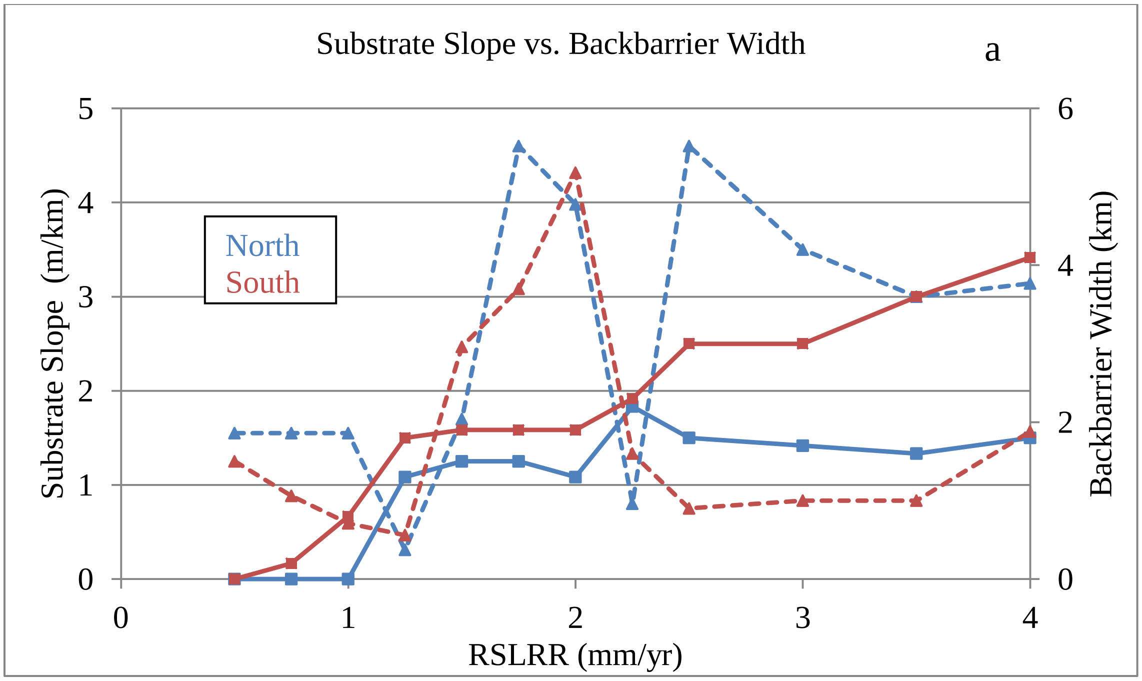


Figure 11. Sensitivity of island migration rate (a) and volume (b) to fluctuations in erodibility of each stratigraphic unit for northern (solid lines) and southern (dashed lines) Metompkin Island. See text (section 3.1.4) for description of erodibility quantification scale.



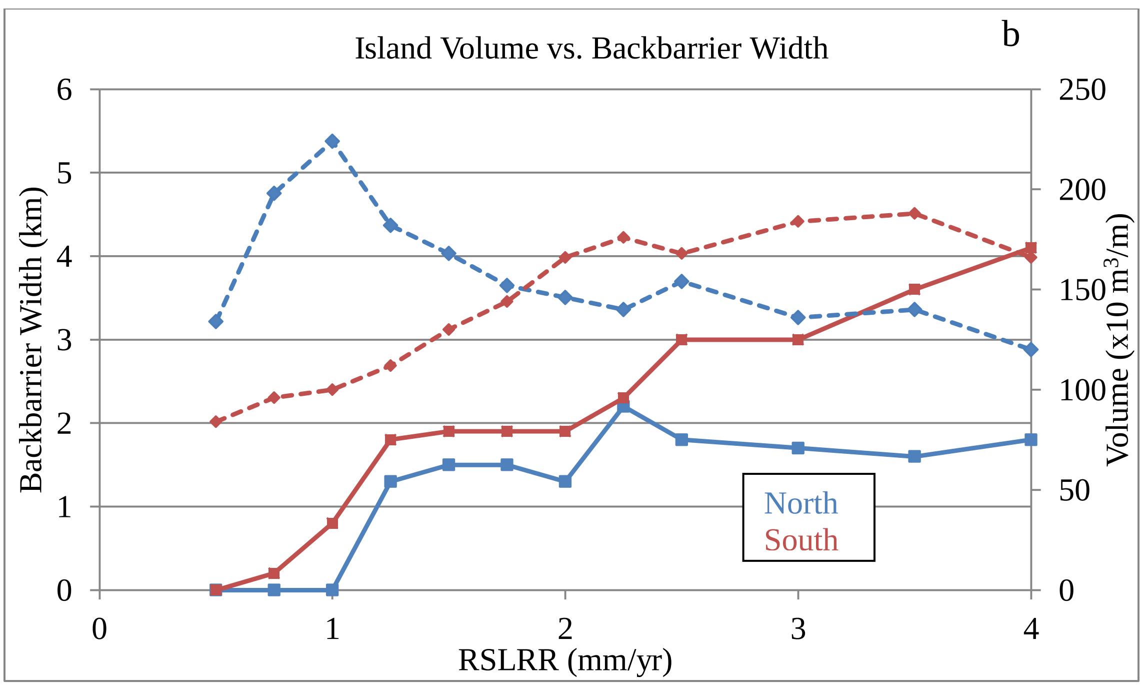
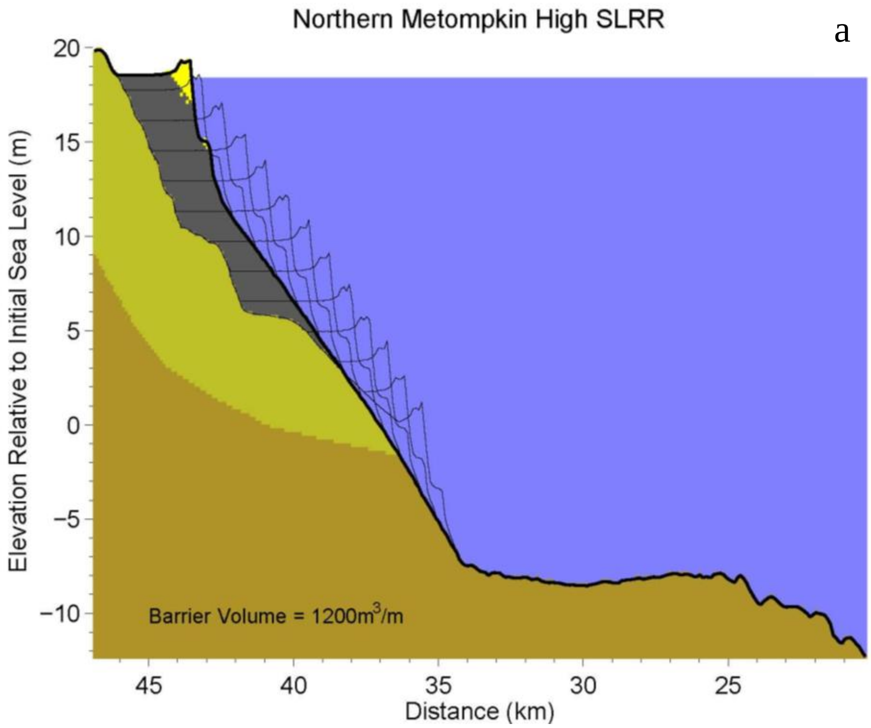


Figure 12. Changes in backbarrier width (solid lines) with landward substrate slope variability (dashed lines) during late-Holocene RSLLR sensitivity simulations shown above (a). Changes final island volume (dashed lines) compared to backbarrier width (solid lines) during late-Holocene RSLLR sensitivity simulations below (b).



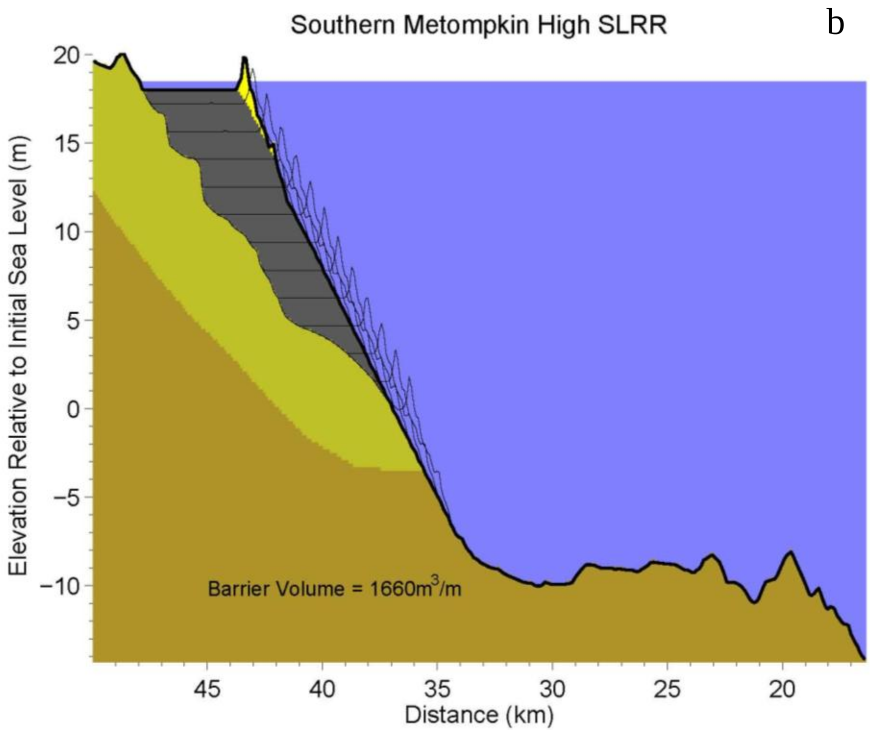


Figure 13. Final stratigraphy and morphology of northern (a) and southern (b) Metompkin Island with a 4mm/yr RSLRR during the late-Holocene time period. Gray ghost traces depict island position through time.

	1m RSLR		1.6m RSLR	
	Migration Rate (m/yr)	Volume Increase (m^3/m)	Migration Rate (m/yr)	Volume Increase (m^3/m)
North	1.02	726	1.31	851
South	0.55	309	0.88	549

Table 2. Average migration rate (m/yr) and volume change (initial subtracted from final in m^3/m) of all RSLRR scenarios when total RSLR is 1m and 1.6m RSLR for northern and southern Metompkin Island.

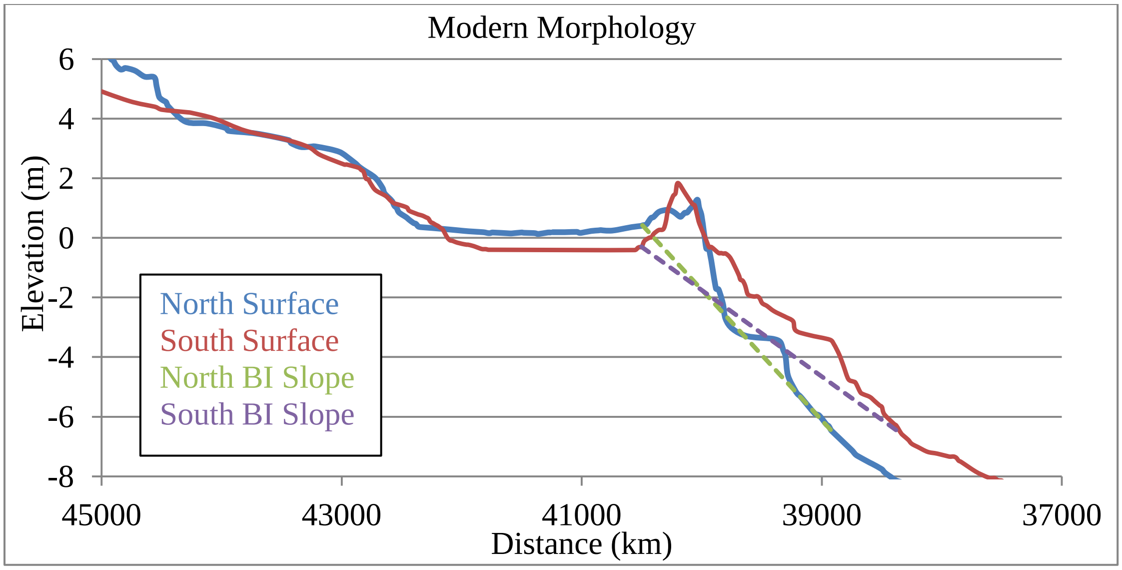


Figure 14. Modern surface morphology of northern and southern Metompkin Island used in creating initial morphology (Figure 5) and as the initial configuration for future simulations. Notice substrate slope disparities landward of modern backbarrier and differences in modern barrier island slopes.

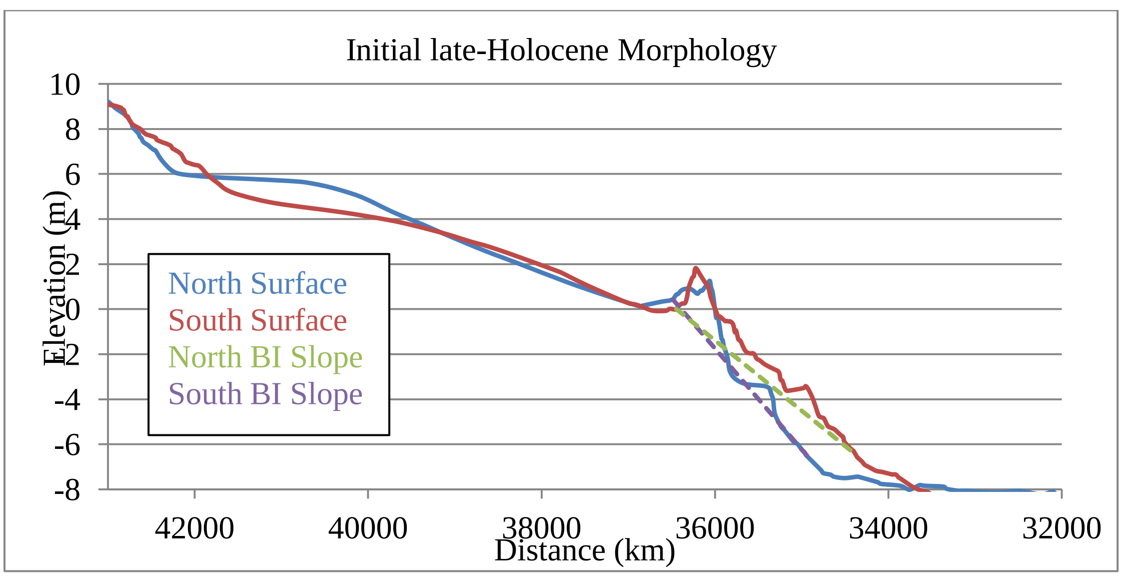


Figure 15. Initial surface morphology for late-Holocene simulations. Notice difference substrate units near modern island position (40,000-42,000 km on x-axis) between island halves.

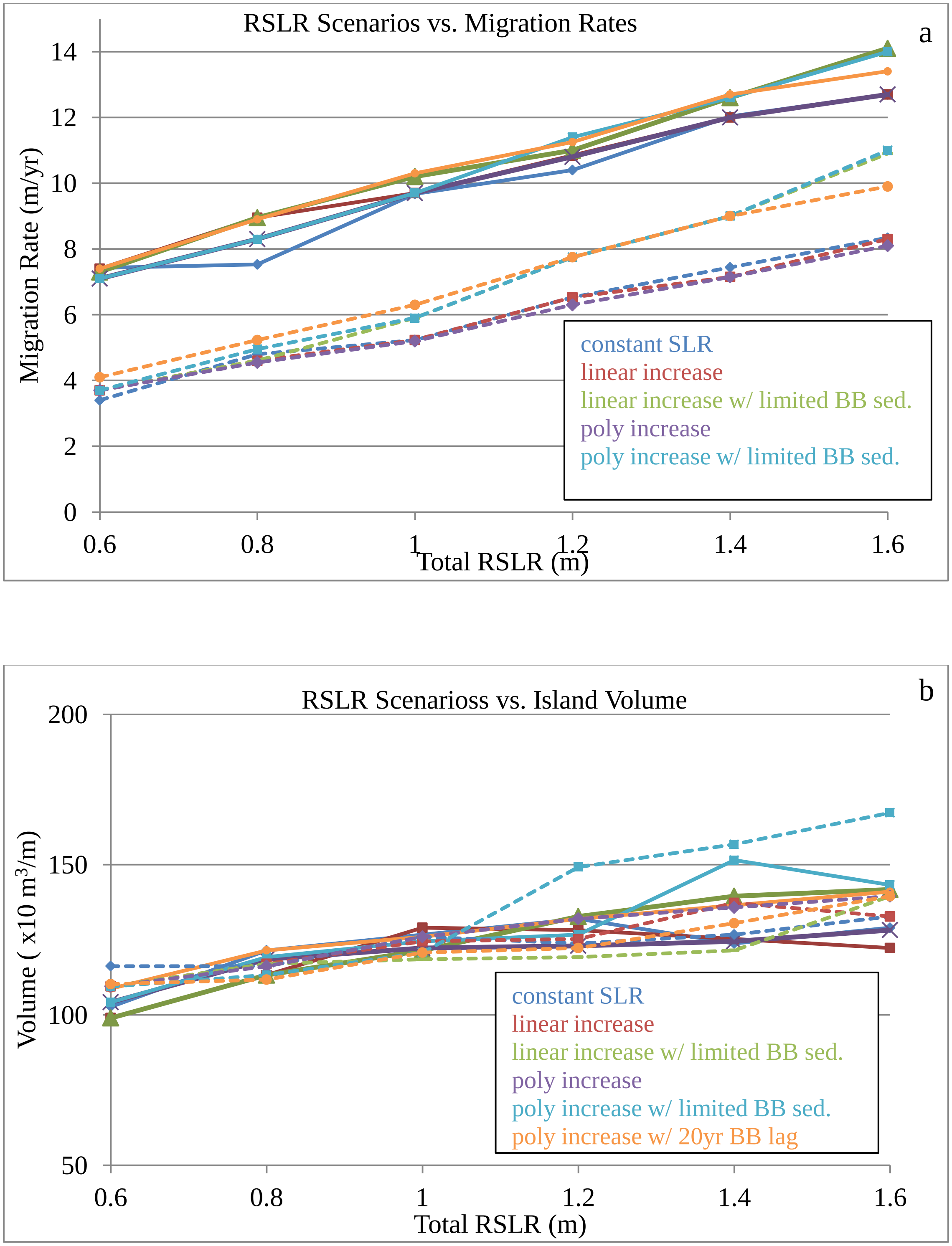


Figure 16. Migration rates (a) and final island volume (b) of northern (solid lines) and southern (dashed lines) Metompkin Island during future simulations with various RSLR scenarios, including constant RSLRR, rates that increase linearly and polynomially, backbarrier sedimentation rate limited to 10 mm/yr, and backbarrier sedimentation rates that lag behind RSLRR by 20 yrs.

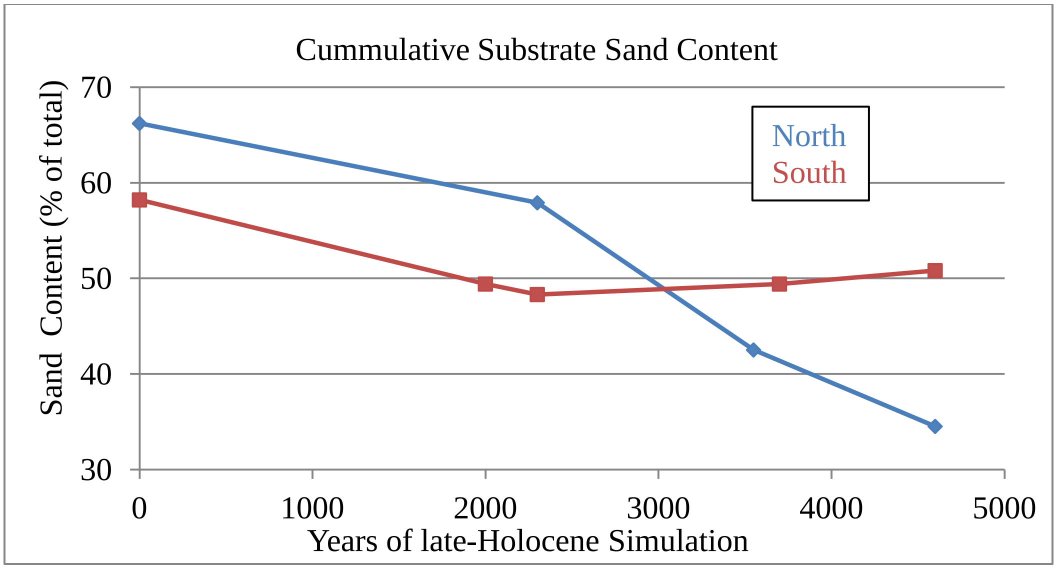


Figure 17. Cumulative sand content (% of total volume) of stratigraphic units exposed along the active shoreface over the duration of the late-Holocene base simulations.

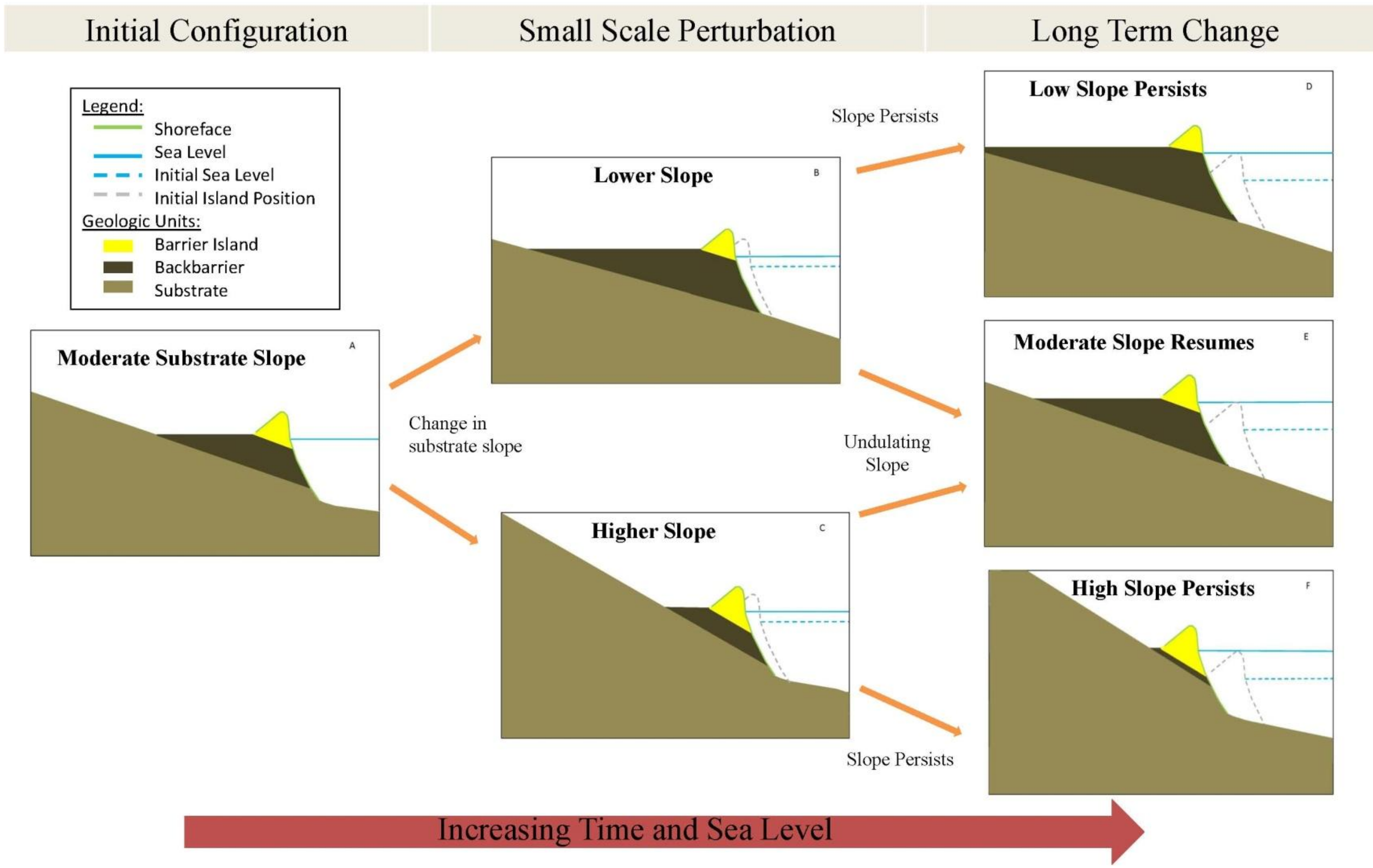


Figure 18. Starting at an initial condition with a moderate substrate slope (left panel), with temporary perturbations in substrate slopes (center panel) backbarrier width adjusts to slope allowing island migration to remain more constant through time. However over longer timescales (right panel), with continued slope variation and backbarrier response, initial configuration can be maintained (with return to modern substrate slope), or feedbacks can become established (with persistent extreme substrate slope values).

REFERENCES

Bruun, P. Sea-level rise as cause of coastal erosion. *Journal of the Waterways and Harbor Division, ASCE 88*, 117-130.

Byrne, R. J., Dealteris, J. T., & Bullock, P. A. (1974). Channel stability in tidal inlets: A case study. *Proceedings from the 14th Coastal Engineering Conference, ASCE,* , 1585-1604.

Byrnes, M. R. (1988). Holocene geology and migration of a low-profile barrier island system, Metompkin Island, Virginia. (PhD, Old Dominion University).

Church, J. A., & White, N. J. (2006). A 20th century acceleration in global sea-level rise. *Geophysical Research Letters, 33*, L01602.

Cowell, P. J., Roy, P. S., & Jones, R. A. (1995). Simulation of large-scale coastal change using a morphological behavior model. *Marine Geology*, *126*, 45-61.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., & Machmuller, M. (2009) Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Front. Ecol. Environ, 7, 73–78.

Curray, J. R. (Ed.). (1964). *Transgressions and regressions*. New York: Macmillan.

Demarest, J. M., & Leatherman, S. P. (1985). Mainland influence on coastal transgression: Delmarva peninsula. *Marine Geology, 63,* 19-33.

Dolan, R., Hayden, B. P., & Jones, C. (1979). Barrier island configuration. *Science, 204*(4391), 401-403.

Dolan, R., Lins, H. F., & Hayden, B. P. (1988). Mid-Atlantic coastal storms. *Journal of Coastal Research, 4*(3), 417-433.

Emmanuel, K. (2008). The hurricane-climate connection. *Bulletin of the American Meteorological Society, ES10-ES19*

Engelhart, S. E., Horton, B. P., Douglas, B. C., Peltier, W. R., & Tornqvist, T. E. (2009). Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. *Geology, 37*(12), 1115-1118.

Erwin, M. R., Cahoon, D. R., Prosser, D. J., & Sanders, G. M. :. H., P. (2006). Surface elevation dynamics in vegetated *Spartina* marshes versus unvegetated tidal ponds along the mid-Atlantic coast, USA, with implications to waterbirds. *Estuaries and Coasts*, *29*(1), 96-106.

Everts, C. H. (1978). Geometry of profiles across inner continental shelves of the Atlantic and gulf coasts of the United States. Fort Belvoir, Va.: U.S. Army Corps of Engineers; Coastal Research Center.

Fagherazzi, S., & Wiberg, P. L. (2009). Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins. *Journal of Geophysical Research, 114*, F03022.

Finkelstein, K. H. (1986). Backbarrier contributions to a littoral sand budget, Virginia eastern shore, USA. *Journal of Coastal Research, 2*(1), 33-42.

Finkelstein, K. H., & Ferland, M. A. (Eds.). (1987). *Back-barrier response to sea-level rise, eastern shore of Virginia* (41st ed.). Special Publications: The Society of Economic Paleontologists and Mineralogists.

FitzGerald, D. M., Fenster, M. S., Argow, B. A., & Buynevich, I. V. (2008). Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences, 36*, 601-647.

Foyle, A. M., & Oertel, G. F. (1997). Transgressive systems tract development and incised-valley fills within a quaternary estuary-shelf system; Virginia inner shelf, USA. *Marine Geology, 137*(3-4), 227.

Gutierrez, B. T., Williams, S. J., & Thieler, E. R. (2007). Potential for shoreline changes due to sea-level rise along the U.S. mid-Atlantic region. *United States Geological Survey Report Series,* (1278).

Hayden, B. P., Dolan, R., & Ross, P. (1980). Barrier island migration; thresholds in geomorphology. In D. R. Coates, & J. D. Vitek (Eds.), *Thresholds in geomorphology* (). London: George Allen & Unwin.

Hicks, S. D., DeBaugh, H. A., & Hickman, L. E. (1983). Sea level variations for the United States: 1855-1980. *National Ocean Service, U.S. Department of Commerce.*

Jevrejeva, S., Moore, J.C., Grinstad, A. (2010) How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophyscial Research Letters*, 37, L07703.

Inman, D. L., & Dolan, R. (1989). The outer banks of North Carolina: Budget of sediment and inlet dynamics along a migrating barrier system. *Journal of Coastal Research, 5*(2), 193-237.

International Panel on Climate Change (IPCC). (2007). *Climate change 2007: The physical science basis*. Cambridge and New York: Cambridge University Press.

Knutson, T.R., Mcbride, J., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., Sugi, M. (2010) Tropical cyclones and climate change. *Nature*, doi: 10.1038/ngeo779.

Larson, M. (1991). Equilibrium profile of a beach with varying grain size. *Coastal Sediments*. ASCE-1991, 905-919.

Lawson, S. E., Wiberg, P. L., McGlathery, K. J., & Fugate, D. C. (2007). Wind-driven sediment suspension controls light availability in a shallow coastal lagoon. *Estuaries and Coasts, 30*(1), 102-112.

Leatherman, S. P. (1979). Beach and dune interactions during storm conditions. *Quarterly Journal of Engineering Geology and Hydrogeology, 12*(4), 281-290.

McBride, R. A., & Moslow, T. F. (1991). Origin, evolution, and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A. *Marine Geology, 97*, 57-85.

McGlathery, K., Porter, J. H., & Wiberg, P. L. (2006). Long-term drivers, sate change and disturbance on the Virginia Coast Reserve: LTER V. *Proposal to National Science Foundation,*

Mixon, R. B. (1985). Stratigraphic and geomorphic framework of uppermost Cenozoic deposits in the southern Delmarva Peninsula, Virginia and Maryland. U.S. *U.S. Geological Survey Professional Paper 1067-G,*

Moore, L. J., List, J. H., Williams, S. J., & Stolper, D. (2010). Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina outer banks. *Journal of Geophysical Research, 115,* 27.

Moore, L. J., List, J. H., Williams, S. J., Patsch, K. (2011). Barriers on the brink: the complex intertwined roles of geologic framework, sediment availability, and sea-level rise in island evolution. To appear in Coastal Sediments '11.

Newman, W. S., & Rusnak, G. A. (1965). Holocene submergence of the eastern shore of Virginia. *Science, 148*(3678), 1464-1466.

Nichols, M. M. (1989). Sediment accumulation rates and relative sea-level rise in lagoons. *Marine Geology, 88,* 201-219.

Oertel, G. F., Allen, T. R., & Foyle, A. M. (2008). The influence of drainage hierarchy on pathways of barrier retreat; an example from Chincoteague Bight, Virginia, U.S.A. *Southeastern Geology, 45*(3), 179.

Oertel, G. F., & Woo, H. J. (1994). Landscape classification and terminology for marsh in deficit coastal lagoons. *Journal of Coastal Research, 10*(4), 919-932.

Pilkey, O. H., Young, R. S., & Bush, D. M. (2000). Comment on sea level rise shown to drive coastal erosion. *EOS Transactions, 81*(38), 437-441.

Rice, T. E., & Leatherman, S. P. (1983). Barrier island dynamics; the eastern shore of Virginia. *Southeastern Geology, 24*(3), 125-137.

Rice, T. E., Niedoroda, A. W., & Pratt, A. P. (1976). The coastal processes and geology, Virginia barrier islands. *The Virginia Coast Reserve Study*, 108-332.

Sallenger, A. H. (2000). Storm impacts scale for barrier islands. *Journal of Coastal Research, 16*(3), 890-895.

Shideler, G. L., Ludwick, J. C., Oertel, G. F., & Finkelstein, K. H. (1984). Quaternary stratigraphic evolution of the southern Delmarva Peninsula coastal zone, Cape Charles, Virginia. *Bulletin of the Geological Society of America, 95*(4), 489-502.

Stolper, D., List, J. H., & Thieler, E. R. (2005). Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behavior model (GEOMBEST). *Marine Geology, 218*, 17-36.

Van de Plassche, O. (1990). Mid-Holocene sea-level change on the eastern shore of Virginia. *Marine Geology, 91*(1-2), 149-154.

Vermeer, M. & Rahmstorf, S. (2009) Global sea level linked to global temperature. *Proceedings from National Academy of Sciences.* 106:21527–21532.

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science, 309,* 1844-1847.

Wolner, C.W.V. (2011). Ecomorphodynamic feedbacks and barrier island evolution, Virginia Coast Reserve, USA. *Master's Thesis*, University of Virginia, Charlottesville, VA, USA.