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Editors

Barrier Dynamics and Response to Changing Climate

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For Nia and Davin

And for all children, young and old, who love barrier beaches as much as they do

Preface

Motivation

Many of the world's coasts feature dynamic strips of sand and/or gravel, backed by shallow coastal bays and fronting mainland shores (e.g., Stutz and Pilkey 2002) (Fig. 1). Whether they are islands (separated from each other by tidal inlets) or long spits, these barriers often protect human development on the mainland, as well as valuable back-barrier ecosystems, from storm impacts. In addition, barriers themselves host unique ecosystems and economically important development and recreational opportunities. As low-lying collections of loose sediment (often inhabited by vegetation and/or the site of structures built by humans), barriers are vulnerable to increasing rates of relative sea-level rise (the additive effects of global sea-level rise and vertical motions of the land regionally; "RSLR") and increases in the frequency of major coastal storms. In this volume, we bring together chapters authored by internationally recognized barrier researchers, whose work collectively represents our state-of-the-art understanding of barrier dynamics and the ways in which these landforms respond to changing climate.

We intend this collection to be of use for researchers who study barriers and related coastal processes, for managers and policy-makers grappling with important decisions regarding the future of barrier coastlines, and for a broader audience of educated readers with a general interest in environmental processes in a changing world. Below we provide a brief overview of barrier dynamics to assist those who are less familiar with this topic in understanding the chapters that follow. We then provide an overview of the scope of the volume by summarizing chapter content, and we conclude with some general thoughts about barrier dynamics in a changing world based on what we have come to understand thus far.

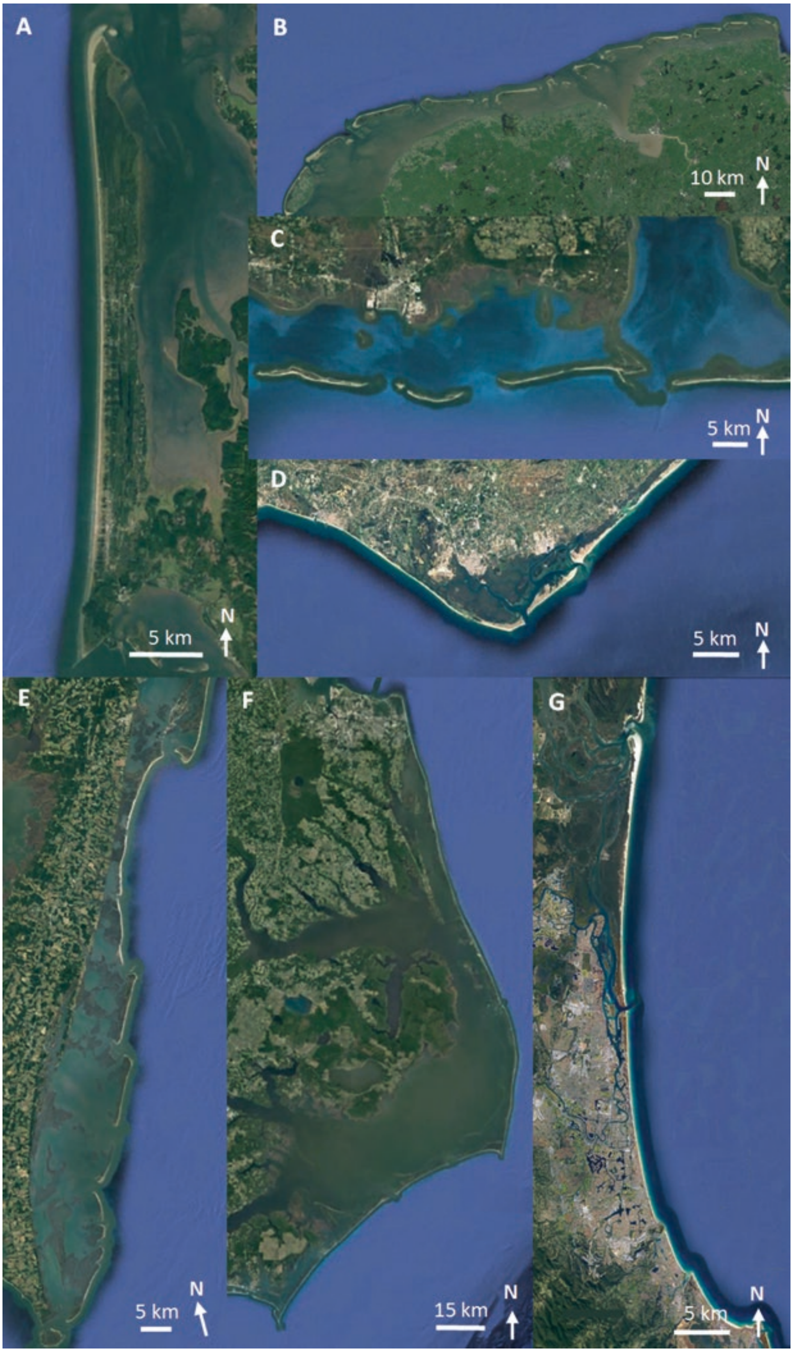

Fig. 1 Examples of barrier systems. (**a**) Long Beach Peninsula, Washington, USA; (**b**) barriers along the Wadden Sea, the Netherlands and Germany; (**c**) barriers along the Gulf of Mexico, Mississippi and Alabama, USA; (**d**) Ria Formosa National Park, Portugal; (**e**) Virginia Barrier Islands, USA; (**f**) Outer Banks, North Carolina, USA; (**g**) Gold Coast and Stradbroke Island, Australia. All images: Google 2017 TerraMetrics; Data SIO, NOAA, U.S. Navy, NGA, Gebco

An Overview of Barrier Dynamics

The visible (or subaerial) portion of a barrier—the land above the normal high-tide level—continues to exist because of major storms: storm waves and elevated water levels ("storm surge") wash sediment landward from the beach and shallow seabed, depositing it on the barrier (or sometimes in the marshes or bays landward of the barrier; see chapters by Houser et al., Moore et al., Odezulu et al., Mallinson et al., and Rodriquez et al. for details). These "overwash" events build barriers vertically through the deposition of overwash sand (also more traditionally referred to as "washover"). Most barriers are comprised primarily of sand (although some are gravel), and on sandy barriers, wind is a primary driver of sediment transport when the beach is dry, sand is available for transport (e.g., not covered by a shell lag), and the wind is sufficiently strong to carry sand grains. Self-reinforcing interactions (i.e., feedbacks) between this wind-driven—aeolian—sand transport and vegetation growth lead to the development of coastal foredunes, the seaward-most line of dunes fronting most sandy barrier islands. Once present, dunes play an important role in determining the effect of storms on barriers. Where dunes are high relative to storm water level (which is determined by the combination of tides, storm surge, and wave action), they prevent overwash from occurring during all but the strongest of storms. Where dunes are low, even a moderate storm may be an overwash event. By controlling the delivery of overwashed sediment to the barrier interior, and beyond, the cycles of dune growth and destruction control how barriers and barrier environments evolve over time, especially at short time scales on the order of decades (see chapters by Moore et al., Houser et al., and Ruggiero et al. for details). On longer time scales (e.g., centuries and millennia), however, dunes are essentially transient features, and their effects are likely swamped by the effects of factors such as sea-level rise and changes in storminess that operate at larger spatial and longer temporal scales.

On some barriers, where the rate of sediment supply is high or where sea level is falling, accumulation of sediment leads to barrier widening, as the shoreline moves seaward (e.g., chapter by Cowell and Kinsella and Moore et al.). On most barriers throughout the world today and throughout the last several millennia, however, the shoreline moves landward in the long term, tending to result in barrier narrowing. When the width of a barrier becomes equivalent to the average extent of storm-driven overwash, further shoreline erosion leads to long-term landward migration of the barrier landform itself. Many barriers, especially barrier islands, initially formed farther seaward than their present-day location and have migrated to their current position as sea level continued to rise slowly over the last few thousand years. Evidence suggests that some barriers are already experiencing an increase in migration rate in response to recent increases in sea-level rise rates (e.g., see chapters by Rodriguez et al. and Odezulu et al.)—a response that is expected to become more widespread in the future (see chapters by Ashton and Lorenzo-Trueba, Moore and Murray, and FitzGerald et al.).

The subaerial portion of a barrier is intimately connected to a large region of the nearshore seabed, a region called the "shoreface" (see chapters by Ashton and

Lorenzo-Trueba, Cowell and Kinsela, and Murray and Moore). Waves in shallow water tend to sweep sand and gravel landward (because, in shallow water, the landward velocity of water under the crest of a wave is greater than the seaward velocity of water under the trough of a wave, leading to more sand moving landward under the crests than seaward under the troughs; Fredsoe and Deigaard 1992). Over time, this tendency for landward sweeping of sediment creates a pile of sediment and the seabed becomes sloped upward toward the land. This slope, in turn, tends to inhibit further landward motion of sediment. Given enough time, the slope of the seabed increases until the slope is steep enough to prevent further landward sediment transport (in a long-term averaged sense) and an "equilibrium slope" develops. Because wave motions at the bed (and asymmetry between landward and seaward velocities) are strongest in shallow water, equilibrium slopes are steepest near shore and become progressively gentler in the offshore direction. In other words, the equilibrium profile of the shoreface tends to be concave upward. This shoreface profile extends to do a depth below which wave-driven sediment transport becomes negligible (referred to as the shoreface depth when considered over long time scales and as the closure depth when considered on shorter time scales, especially in the coastal engineering literature). This depth depends on the typical wave characteristics as well as the time scales considered. Longer time scales are more likely to include larger storms and storm waves that affect the bed to greater depths (e.g., Ortiz and Ashton 2016). Longer time scales also and allow more time for the seabed to adjust (Cowell and Kinsella this volume). Considering the longest time scales (decades to millennia), the shoreface typically extends to depths of tens of meters, which are usually reached many kilometers from shore on barrier coastlines. (For simplicity, this description of the shoreface excludes the fascinating and complex dynamics that occur in the "surf zone"—the zone of breaking waves that is usually restricted to the upper-most portion of the shoreface; Fredsoe and Deigaard 1992.)

The visible portion of a barrier, then, represents the top of this shoreface profile. During storms, when water levels become elevated by wind and waves, the landward sweeping of sediment extends past the fair weather shoreline. The sediment deposited by storm overwash processes in the long term attains an elevation related to the water levels achieved during major storms. In other words, the pile of sediment created by wave processes extends from the base of the shoreface upward as far as the waves can reach during storms. As RSLR occurs, overwash tends to occur more frequently (as storm surge elevations tend to increase). As a result, the elevation to which sediment can be piled tends to increase. Thus, if RSLR is gradual enough, the elevation of a barrier will tend to increase at the rate of RSLR. And if the rate of RSLR is gradual enough, waves will tend to maintain an approximately equilibrium shoreface profile, relative to the moving sea-level frame of reference.

The transfer of sediment from the beach and shoreface to the top and landward portion of the visible portion of a barrier tends to cause erosion of the upper shoreface. If the shoreface slope is approximately an equilibrium slope, a reduction of the slope of the upper shoreface tends to cause onshore sediment transport on the upper shoreface. The transported sediment comes from lower portions of the shoreface, which lowers the slopes there. In this way, the erosion and lowering of the slopes propagates offshore. Therefore, in the long term, the erosion of the upper shoreface that occurs during storms that produce overwash propagates to the base of the shoreface. Similarly, when sediment is gradually removed from the surf zone and upper shoreface by gradients in alongshore sediment transport, causing erosion of the beach and shoreline, that erosion propagates to the base of the shoreface. And if a gradient in alongshore sediment transport brings more sediment into a section of shoreline than it takes out, causing accretion of the beach and seaward movement of the shoreline, accretion propagates out to the base of the shoreface in the same manner.

If RSLR happens gradually enough for the shoreface profile to remain approximately in equilibrium, erosion of the beach and upper shoreface resulting from overwash processes produces a landward translation of the shoreface profile (at the same time the shoreface also translates upward in concert with sea level). In this scenario, the visible portion of a barrier and the shoreface can migrate upward and landward in unison allowing a barrier to persist indefinitely. However, many limitations, including a RSLR that is not sufficiently gradual, can cause barriers to founder, including the potential for the upper shoreface and subaerial portion of the barrier to become detached from the lower shoreface or for barriers to drown (see chapters by Ashton and Lorenzo-Trueba, Cowell and Kinsela, Fitzgerald et al., Houser et al, Mallinson et al., Mellett and Plater, Moore et al., Odezulu et al., and Rodriquez et al.). In addition to rapid RSLR, the management and manipulation of barrier environments by humans poses a threat to the continued existence of barrier landforms; actions taken to prevent or mitigate processes that represent hazards to coastal development and inhabitants can hinder the stabilizing feedbacks that tend to allow barriers to persist as sea level rises and shorelines erode (see chapters by Moore et al., Odezulu et al., and especially McNamara and Lazarus).

Scope of the Volume: An Overview of Chapters

Observation-Focused Contributions

Barriers cease to exist as subaerial landforms when RSLR rate is too high and/or too little sediment is available. A number of factors can combine to determine what rate of RSLR is “too high,” and a number of processes can influence the rate sand (or gravel) is added to, or removed from, a barrier system—including storm impacts, the topographic setting, and gradients in alongshore sediment transport related to wave climate and coastline shape. In the first section of the book, the authors of six chapters mine observational data to explore how barriers respond to changing sea level and climate forcing and the conditions under which barriers may founder, or cease to exist.

In the opening chapter, *FitzGerald et al.* discuss observations from several different barrier settings throughout the world and synthesize them into a conceptual model called “runaway barrier island transgression,” describing the potential response of barriers, and the back-barrier environments they are tied to, to high rates of RSLR. In this model, if back-barrier marshes do not keep up with high rates of

RSLR, they are replaced by open water, which triggers a cascade of effects—increases in the volume of water that must flow in and out through tidal inlets during each tidal cycle lead to consequent expansion of tidal deltas and the associated loss of sand that would otherwise be provided to barriers, leading to island narrowing, segmentation, and more frequent overwash. If the water behind a barrier becomes deep enough as RSLR outpaces back-barrier sedimentation, barriers in this scenario can eventually transition to subaqueous shoals. The case studies presented illustrate different aspects of this conceptual model, which paints a picture of what might occur in many regions as sea-level rise rates increase.

Mellet and Platter review studies of barriers from around the world that have drowned in the recent geologic past (since the last deglaciation). Geophysical observations of the seabed on continental shelves, which are becoming more widespread, reveal evidence of barriers that did not keep up with rising sea level. When a barrier migrates along a continental shelf as a persistent subaerial landform, typically little to none of the barrier sediment is left on the continental shelf. Extensive shelf deposits with the characteristics of barrier sediments—sometimes in which even the shape of the barrier remains intact—suggest that a barrier was left behind as sea level rose above it (presumably to be replaced by a new barrier farther landward). In a meta-analysis of studies of such drowned barriers, Mellett and Plater examine the prevalence of various potential causes of barrier drowning, which can be summarized as involving either high RSLR rates, low sediment supply rates, or influences of the topographic setting.

Mallinson et al. focus on geologic evidence for major changes in island configuration that occurred along a well-studied barrier island chain, the Outer Banks of North Carolina, USA. Combining analysis of the sedimentary record with numerical modeling of hydrodynamics in the back-barrier bay, Pamlico Sound, they demonstrate that the Outer Banks has, in the past, been severely segmented—separated by inlets that were much larger and more numerous than those that currently exist—more than once during the sea-level high stand of recent millennia. *Mallinson et al.* conclude that these pronounced changes in the barrier chain, and associated changes in the back-barrier environment, occurred in response to relatively minor but rapid changes in climate and/or RSLR rates, such as those that occurred during the Medieval Climate Anomaly and the Little Ice Age.

Rodriquez et al. examine the sedimentary record of overwash occurrences on a barrier on the East Coast of the USA (Onslow Beach, North Carolina) over the last two millennia. They find that the frequency and cross-shore extent of overwash deposition appear to have increased dramatically in the last century or so. Rodriquez et al. consider possible causes for the apparently anomalous overwash activity, including an unusually stormy period (a hypothesis they found to be unsupported by meteorological or historical data) and a change in alongshore sediment transport gradients that may have increased the rates of shoreline and dune erosion (possibly related to changes in wave climate). However, as the most likely explanation, they point to the global increase in sea-level rise rates since the industrial revolution—which, if true, would make these observations and analyses especially relevant to barriers worldwide.

Presenting a synthesis of their analysis of the stratigraphy of barrier deposits on Follets Island, TX, along the Gulf Coast of the USA, *Odezulu et al.* identify an order-of-magnitude increase in the rate of landward island migration during the historical period, relative to the rate estimated for the millennial (geologic) time scale. They attribute this change to a combination of increased RSLR rate and decreased rates of sediment supply from alongshore sources, caused by anthropogenic manipulations of a nearby tidal inlet and river mouth. Their analysis of stratigraphic data indicates that the barrier is undergoing a net loss of sand, because overwash sometimes extends well past the back of the barrier. The present shoreface is underlain mostly by muddy deposits that contribute little coarse sediment when eroded. Based on the depth of the water the barrier is migrating into and the volume of sediment making up the barrier presently, Odezulu et al. estimate that the barrier will likely transition to a subaqueous shoal on the time scale of a few centuries. Given the global ubiquity of anthropogenic manipulations of sediment pathways, as well as increased rates of RSLR, this study of the geologic record of a specific barrier likely has wide-ranging implications.

Houser et al. focus on the shorter time scales of dune recovery following a storm and the dependence of dune recovery on sediment availability both on the beach and the shallow seabed. Observations from the Gulf Coast (Padre Island, Texas, and Santa Rosa Island, Florida) and East Coast of the USA (Assateague Island, Virginia) indicate that the amount of sediment available for dune recovery can depend on the "geologic framework"—the material that underlies the barrier and the shallow seabed. Based on their observations, *Houser et al.* present conceptual models to explain the dependence of dune recovery on storm frequency and sediment availability and the influence of the extent of dune recovery between storms on overwash and therefore barrier response to sea-level rise.

Modeling-Focused Contributions

Theoretical considerations, in a synergy with observations, can assist in illuminating how barrier systems evolve and the ways in which they can respond to changing climate (or land-use) forcing. Theoretical investigations utilize conceptual, analytical, and numerical modeling, most often in combination with real-world observations and/or predictions of future conditions, which provide the bases for model parameterizations, scenarios to be explored, and tests of model results. Six chapters address fundamental constraints on barrier evolution and describe different aspects of the dynamics of barrier systems including conservation of mass; geometrical considerations; couplings among physical, ecological, and human processes; and how limits on the rates of change within different parts of a barrier system can affect overall system response to changing climate and land-use forcing.

In the first of the second six chapters, *Murray and Moore* examine how the considerations of mass conservation and an assumed time-invariant barrier geometry (averaged over major storm and recovery cycles) constrain barrier evolution, under a series of thought experiments that include progressively more of the factors affecting barrier response to RSLR. They use conceptual/geometrical and analytical models, and they discuss numerical modeling used to address increasingly realistic scenarios. This chapter highlights the role of shoreface erosion (landward translation) in producing new sediment that is added to the nearshore system (possibly redistributed by alongshore sediment transport). Conceptual models often assume that barriers consist entirely of mobile sediment that moves landward across an underlying substrate such that shoreface erosion only entrains sediment that is already part of the barrier, which is then added to the top and landward side of the barrier during storms. In this picture, barrier sediment "rolls" (translates) across an unaffected substrate, with no net gain or loss. In contrast, *Murray and Moore* show that although a barrier will tend to evolve toward this state under some circumstances, more generally, the lower part of the shoreface erodes into the underlying substrate, producing new sediment as a barrier responds to RSLR.

Whereas Murray and Moore's analyses assume that the barrier profile, including the lower shoreface, retains a constant geometry over long time scales, *Cowell and Kinsella* use a numerical model to address what happens when the rate at which the lower shoreface can respond to changes in sea level and barrier position is too slow for the shape of the whole shoreface profile to remain constant. These numerical experiments, in concert with geological observations from the data-rich Tuncurry Coast, in Australia, help to define an "active" upper portion of the shoreface that retains a constant geometry. This active portion extends to shallower and shallower depths as the rate of RSLR increases. The response of the shoreface below the active portion becomes time lagged, resulting in cross-shore sediment fluxes—net additions or subtractions to the sediment stored in the upper parts of the barrier profile—not related to present rates of RSLR. In these cases, barriers will respond to a combination of present and past rates of RSLR.

In a complementary numerical modeling endeavor, *Ashton and Lorenzo-Trueba* also consider how limitations on response rates can affect how barriers evolve. They include limitations on the rates of shoreface sediment fluxes as well as limits on overwash fluxes, showing that barriers could potentially drown under either limitation if overwash rates can't keep pace with RSLR or if rates of landward sediment transport on the shoreface can't keep pace with overwash. This chapter demonstrates that instead of the continuous barrier response to sea level that has typically been assumed, punctuated landward migration, alternating with extended periods in which a barrier remains stationary, may be the most common response to RSLR.

Moore et al. provide a synthesis of model findings—tested against observations—that yield insights into the role of interactions between ecological processes (vegetation dynamics) and patterns of sediment erosion, transport, and accretion, in shaping barrier environments and their response to changing climate forcing. Specifically, the work described in this chapter numerically addresses the different, sometimes species-specific, characteristics of vegetation that influence the alongshore and cross-shore shape of coastal foredunes and multiple dune fields. The authors also summarize recent work that demonstrates the importance of a competition between factors that build dunes (e.g., vegetation recovery, sand flux) and the factors that erode dunes (e.g., storms, sea-level rise) in determining local dune, or island, elevation and thus the degree of connectivity between sandy barriers and the back-barrier marshes and bays behind them. This chapter highlights the importance of feedbacks between vegetative and sediment transport processes in shaping the barrier landscape and the importance of couplings between and among landscape units, in influencing the overall evolution of barrier-marsh-bay systems as climate conditions change.

Ruggiero et al. combine field observations from the US Pacific Northwest with laboratory, field, and numerical-modeling experiments to investigate what controls dune shape. The deeply interdisciplinary body of work they synthesize addresses how the species-specific morphological characteristics and growth patterns of dune-building vegetation, in combination with physical influences (chiefly shoreline-change rates), help to determine whether dunes are low and wide versus tall and narrow. These dune and dune-field characteristics, in turn, determine how much storm protection dunes provide for landward environments and development. The authors find that the ongoing spread of invasive dune-building grass species is accompanied by changes in dune shape—and therefore changes in coastal vulnerability to storm impacts.

In the final chapter of the volume, *McNamara and Lazarus* make the case that barrier evolution and human dynamics are thoroughly coupled on developed coastlines. Engineering and management actions to protect humans and infrastructure from storm hazards and beach erosion are reactions to physical and ecomorphodynamic coastal processes. On the other hand, human actions also affect physical and ecomorphodynamic coastal processes: shoreline stabilization (chiefly through beach nourishment in recent decades) tends to prevent barriers from moving landward, and constructed dunes or seawalls tend to prevent the moderate overwash events that would otherwise increase island elevation as sea level rises. These manipulations of barrier environments alter the evolution of barrier morphology and therefore alter the hazards humans and infrastructures are exposed to—influencing future hazard mitigation efforts. Because mitigation of coastal hazards tends to be expensive, the dynamics of human decision making are inextricably interwoven with physical and ecomorphodynamic processes in barrier environments. McNamara and Lazarus review newly emerging research addressing the dynamics of this coupled system and discuss how the resulting understanding could help to guide more intentional, holistic coastal management—especially as the pressures of increasing RSLR rate, changing storm climate, and limited reservoirs of nearshore sand make continued sustainability of the current pattern of coastal land use in developed regions challenging.

State of the Science and Future Directions

Understanding the dynamics that shape barriers, and determining their fates as RSLR rate and storms change, has become the focus of much scientific inquiry. Because this scientific focus has arisen relatively recently, our understanding is evolving quickly. Given this, it is not surprising to find that leading experts, approaching barrier dynamics from different disciplinary perspectives and through the use of different case studies, may sometimes come to conclusions that are less than completely consistent. A careful comparison of the chapters in this volume reveals some contrasting interpretations and apparent contradictions, which attest to the exciting state of this field of research and point to the areas of greatest insight and learning yet to come. However, much more prominent upon review of this collection are the areas of overlap that depict an emerging collective understanding about how and why barriers come to be and how and why they change over time as the influences of physical processes, vegetative processes, climate, and human activities, as well as the interactions among these factors, shift. The newer elements of this emerging collective understanding that appear in this volume include the following:

It is becoming increasingly clear that shoreface characteristics and shoreface processes play important roles in the dynamics of barrier migration. The shoreface represents an important source of sediment to barriers, and the importance of this role is partially determined by the composition and erodibility of the material that comprises the shoreface and the degree to which the upper and lower parts of the shoreface, and the subaerial barrier, migrate in unison as conditions change. This migration may proceed continuously in some cases but is perhaps more likely to occur as periods of migration alternating with periods of relative stability. In some cases, barriers do not keep up with changing conditions and they drown, becoming subaqueous shoals. In other cases, changes in RSLR rate or storminess can segment a barrier island chain, greatly increasing the connection between the ocean and the back-barrier environment.

On long time scales, the feedbacks between vegetation and sediment transport that determine dune shape and the vulnerability of barrier environments and infrastructure to storms are likely to be swamped by the effects of rising sea level and changes in storminess. On the decadal, and perhaps centurial, scale, however, the absence or the presence and height of coastal foredunes is important in determining what the impact of storms will be. How reliably and how thoroughly dunes re-form after a strong storm depends on factors including sediment supply from the shoreface, the characteristics of the material below the sandy surface (the geologic framework), and how often strong storms occur relative to the time scale for vertical dune growth—which depends on the vegetation present as well as climatic influences. Foredune height plays an important role in determining how well connected the sandy part of a barrier is to back-barrier marsh or bay environments. These connections are important in determining how barrier-marsh-bay systems evolve overall and how vulnerable they are to increased rates of RSLR. Where humans have built dunes that are higher than natural dunes would be for a given set of conditions, overwash events may be filtered, making it harder for barriers to keep pace with rising sea level. This is only one example of the way in which the natural coastal system and the human coastal system are tightly coupled—each affecting the other repeatedly through time.

A growing number of examples highlight how RSLR, changes in storm activity, and shifts in the geographic distribution of important dune-building grasses are affecting barrier island behavior today. Often, under these influences, barriers tend to become lower and narrower and to migrate more rapidly. We can learn about barrier dynamics by studying examples of barrier response to changing conditions in the more distant past. A new influence on barrier evolution has arisen in recent centuries, however: the role of humans. As conditions begin to change more rapidly, so too will our response to coastal processes that constitute hazards to humans and development. An emerging insight of critical importance to future generations is that the management decisions we make today may unintentionally destabilize barrier landforms by preventing them from migrating and gaining elevation to keep pace with changing RSLR rates or by interrupting sediment supply pathways—potentially hastening segmentation or the conversion of barrier landforms to shoals. Where it occurs, this would lead not only to the loss of barriers but also to the increased vulnerability of mainland shores to potentially more intense coastal storms. We are well poised with our current understanding of the eco-physical system to more fully understand the ways in which couplings with the human system will affect barrier evolution in the future. This important area of future research could provide the basis for more intentional, forward-looking, and holistic management of barriers as the important natural resource—and unique landforms—that they are.

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Part I
Observations and Conceptual Models of Barrier Response to Changing Climate

Runaway Barrier Island Transgression Concept: Global Case Studies

Duncan M. FitzGerald, Christopher J. Hein, Zoe Hughes, Mark Kulp, Ioannis Georgiou, and Michael Miner

Abstract The regime of accelerating sea-level rise forecasted by the IPCC (2013) suggests that many platform marshes and tidal flats may soon cross a threshold and deteriorate/drown as back-barrier basins transform to intertidal and subtidal areas. This chapter explores how marshes may succumb to rising sea level and how the loss of wetlands will increase the extent and the overall depth of open water in the back-barrier, causing greater tidal exchange. Here, we present a conceptual model that depicts how increasing tidal prism enlarges the size of tidal inlets and sequesters an increasingly larger volume of sand in ebb-tidal delta shoals. The conceptual model is based on empirical relationships between tidal prism and inlet parameters, as well as field and theoretical hydraulic studies of tidal inlets showing that long-term basinal deepening intensifies the flood dominance of existing inlet channels and transforms some ebb-dominated channels to flood-dominated channels. This condition leads to sand movement into the back-barrier, which builds and enlarges flood-tidal deltas, filling the newly created accommodation space. The model hypothesizes that sand contributed to the growth of the ebb and flood tidal delta shoals will be at the expense of barrier reservoirs. This will result in diminished

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sand supplies along the coast, eventually leading to fragmentation of barrier island chains and the transition from stable to transgressive coastal systems. Several historical studies of barrier island systems throughout the world demonstrate barrier response to changing tidal prism and illustrate different stages of this conceptual model.

Keywords Barrier island • Tidal inlets • Transgressive shoreline • Sea-level rise • Saltmarsh deterioration • Tidal prism • Sediment transport • Inlet hydrodynamics • Coastal sand-reservoirs • Ebb-tidal delta • Flood-tidal delta • Back-barrier feedbacks • Lagoons • Virginia barrier islands • Nauset Spit • New Inlet, MA • Assateague Island • Barataria Islands • Chandeleur Islands • Copper River • Friesian Islands

1 Introduction

The future of the world's barrier coasts is dependent upon how barriers respond to climate change, specifically global warming and the ensuing acceleration in sea-level rise (Jevrejeva et al. 2012), as well as possible increased storm magnitude (Knutson et al. 2010; Grinsted et al. 2013). Most barrier coasts contain a finite volume of sediment with little net sand contributed via cross-shore or alongshore transport. Exceptions include those with contributions from nearby rivers (e.g., South African rivers, Cooper et al. 1990; Long Beach in Washington fed by the Columbia River, Dingler and Clifton 1994; northern New England barriers nourished by rivers during spring freshets and floods; Fenster et al. 2001; FitzGerald et al. 2005; Hein et al. 2012, 2014a); the movement of sand onshore from the inner continental shelf (e.g., Fire Island, Schwab et al. 2013; Hapke et al. 2010a); the erosion of updrift bluffs (e.g., Sandy Neck, Cape Cod, MA; van Heteren and van de Plassche 1997), or erosion of the barrier shoreface into a sandy substrate (e.g., Moore et al. 2010; Cowell and Kinsela this volume; Murray and Moore this volume). The lack of new sand sources coupled with the effects of sea-level rise had led to the vast majority of the world's barrier shorelines eroding (70% as estimated by Bird 1985). For example, Hapke et al. (2010b) determined that 65% of the sandy shoreline stretching from central Maine to northern North Carolina has undergone net erosion over the long-term (1800s to ~2000), at rates ranging from 0.2 m/year in Maine to 3.7 m/year in southern Delmarva/northern North Carolina. Globally, erosion has driven the expenditure of billions of private and public dollars to fund widespread beach nourishment projects, revetment construction, and rebuilding efforts associated with increasing loss of real estate and infrastructure (Nicholls et al. 2007; Doran et al. 2013).

The sand comprising barrier systems can be compartmentalized into several reservoirs including the barrier lithosome, the ebb-tidal delta, flood-tidal delta shoals, and channel deposits. Dunes, washovers, spit platforms, and recurved spits are all considered part of the barrier lithosome, which also extends seaward to the depth of closure. The depth of closure for a characteristic time interval is the most landward depth seaward of the beach for which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore (Kraus et al. 1998). The long-term loss of sand from these systems is normally a gradual process punctuated by major storms. Erosion is attributed to a variety of processes including, but not limited to: (1) sand transported offshore to regions beyond the closure depth by downwelling currents during large-magnitude storms (Niedoroda and Swift 1981; Field and Roy 1984; Snedden et al. 1988); (2) sand moved alongshore into estuaries where it becomes trapped in intertidal and subtidal shoals (Harris 1988; Dalrymple et al. 1992), thereby reducing the volume of sand bypassed to down-drift barrier shorelines; and (3) sand deposited in channels at migrating tidal inlets below the depth of the erosional shoreface. This latter reservoir will not be exhumed during the proceeding transgression and will therefore remain buried as a channel deposit on the inner shelf (Rieu et al. 2005; FitzGerald et al. 2012).

Along with these sediment sinks, sand tends to be lost to the offshore to compensate for rising sea level as the equilibrium profile deepens (Bruun 1988). Although scientists have criticized Bruun's (1988) equilibrium equation as being impractical in actual usage due to various complicating factors (e.g., grain-size variability, alongshore sediment losses, and geologic controls; Cooper and Pilkey 2004), the concept provides a valuable tool for understanding why sand is lost to the offshore, especially for periods of rising sea level before a barrier begins to migrate landward (for further discussion see: Wolinsky and Murray 2009; Rosati et al. 2013).

In addition to long-term sediment loss, rising sea level will undoubtedly alter the hypsometry of back-barrier bays and marsh systems. This will result in changes in inlet and tidal channel hydraulics, accommodation space, and net sediment transport directions. In a regime of accelerating sea-level rise (Donnelly et al. 2004; Jevrejeva et al. 2012), these responses will be most dramatic when certain thresholds are crossed, particularly those relating to wetland loss, causing rapid bay expansion and/or deepening of bay hypsometry. Coastal marshes maintain their surface elevation relative to high tide by accumulating organic sediment (predominantly plant roots) and trapping inorganic sediment delivered by tides. Both processes are dependent on the presence of vegetation. If a marsh can no longer produce enough belowground biomass and/or import enough sediment through tidal exchange to keep pace with rising high tides, it will become inundated below mean sea level (Kirwan et al. 2010). Considering the projected rate of sea-level rise during this century (Church et al. 2013), and despite possible ameliorating effects of increased sediment influx (Morris et al. 2002) or biomass production (Langley et al. 2009), the future duration of tidal inundation at many marshes will exceed the local critical period of flooding with each tidal cycle. In this case, marsh plants will perish, transforming marshes to tidal flats or open water (Kirwan et al. 2010). This is likely to occur in combination with increased marsh-edge erosion resulting from greater wave energy associated with expanding, deeper open-water areas (Mariotti et al. 2010; Mariotti and Carr 2014). Because most platform marshes behind barrier systems have low relief (commonly less than 30 cm; Eiser and Kjerfve 1986; Cahoon and Reed 1995; Silvestri et al. 2005), deterioration of marshes, once initiated, is likely to occur rapidly. The wetlands comprising Barataria Bay (behind the

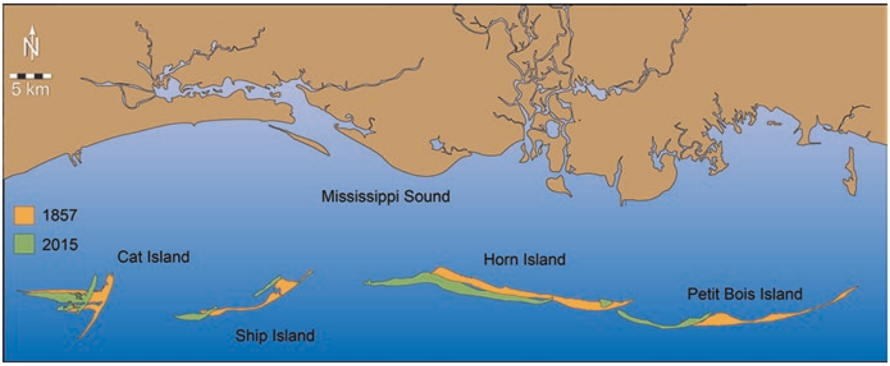

Fig. 1 Mississippi barrier footprints decreasing with time. Constructed using historical maps and aerial photographs

Grand Isle–Grand Terre barrier chain along the central Louisiana coast) provide an example of marsh collapse in just this manner. Here submergence, excavation by hurricanes, and edge erosion have led to extensive conversion of marshlands to open water at an average rate of 22 km^2/year between 1956 and 1990 (Barras et al. 1994). These changes to bay area and the consequent increase in tidal prism have produced a profound response of the barrier system, resulting from a redistribution of sediment among the coastal sand reservoirs (FitzGerald et al. 2007; and discussed below).

The long-term loss of sand from barrier chains is well illustrated along the Mississippi barrier system west of Mobile Bay, including Dauphin Island in Alabama, where a 29% decrease in the collective areas of the five islands was observed between 1840s and 2007 (Morton 2008; Byrnes et al. 2012; Fig. 1). Morton (2008) attributes much of the erosion during the past century to progressive dredging and deepening of navigation channels that decreased the volume of sand, which otherwise would have naturally bypassed the inlets and fed downdrift barriers. However, a sediment budget study of the Mississippi barriers by Byrnes et al. (2012) showed that much of the long-term loss of sand from barriers can be attributed to sand sequestered on ebb-tidal deltas and moved offshore during storms. The net loss of sand due to storm erosion is documented along many barrier islands, including the Chandeleur Islands (Sallenger et al. 2009).

In addition to the long-term loss of sand due to the combined effects of major storms, sea-level rise, and human modifications, it appears inevitable that barrier erosion will accelerate in the future as the rate of sea-level rise increases. This trend will likely be most apparent along mixed-energy barriers (sensu: Hayes 1979) as stability thresholds are crossed in back-barrier marshes due to increased inundation (FitzGerald et al. 2008). Likewise, barriers fronting bays and lagoons with tidal flats will undergo increased erosion due to flood dominance within inlet channels and the creation of bay sediment sinks (Dissanayake et al. 2012; van Goor et al. 2003). In this chapter we explore the projected loss of sand from barrier lithosomes as sand is transferred to other reservoirs within the barrier system, including ebb- and flood- tidal shoals and bays. Because this relocation of sand will be largely forced by changes to back-barrier environments, our discussion begins with a review of back-barrier marsh processes and modeling efforts. Next, we explore barrier response to changes in back-barrier hypsometry, using examples from historical records, and demonstrating how barrier sand reservoirs undergo substantial redistribution in relatively short time spans. From these illustrations, we form a conceptual evolutionary model of barrier erosion and transgression, resulting in the transformation of a barrier chain to a system of mainland-attached beaches, proximal mainland barriers, or inner shelf shoals. The processes and factors governing barrier rollover and landward migration are covered in other chapters in this book (see chapters by Ashton and Lorenzo-Trueba this volume; Cowell and Kinsela this volume; Murray and Moore this volume). Barrier systems along active deltaic shorelines are not considered in this analysis, because they consist either primarily of spit systems (e.g., Danube, Rhone, Ebro) or lack detailed historical and process data (e.g., Niger).

2 Methodology

Projecting the future response of barriers to anticipated increases in the rate of sea-level rise is difficult because most barrier chains originally evolved during periods of slow relative sea-level rise (RSLR). Even today, most barrier systems are experiencing much slower RSLR rates than those expected in the same regions by the end of this century (Church et al. 2013). During the last 100 years, global sea level has been rising at 1.2 ± 0.2 mm/year (Hay et al. 2015). The future rate is projected to be as much as four times this value (Church et al. 2013). Excepting the Grand Isle–Grand Terre barrier system in Louisiana (discussed later in the chapter), where RSLR is 9.05 mm/year (NOAA 2015a, b), there are few natural laboratories in which to study the effects of rapid RSLR on barrier systems. Compounding the difficulties of studying the impacts of accelerating RSLR is the short length of historical databases, which rarely extend back in time prior to the mid-1800s; the earliest provide only a qualitative assessment of barrier morphology and adjacent bathymetry. Despite these limitations, we have assembled historical documents from several sites that provide insights into how barriers, tidal inlets, tidal deltas, and bays have responded to changes in inlet channel dimensions, tidal prism, and bay hypsometry brought about by storms, changes in sediment supply, human alterations, and tectonic events (physical settings summarized in Table 1). At many of these sites, the cumulative effect of various forcings is the formation of a new tidal inlet (and its attendant tidal prism) or a change in tidal prism volume. These historic changes in tidal prism mimic the changes expected to occur when wetlands and/or tidal flats can no longer keep pace with RSLR and convert to open water. The morphologic responses of the barrier chains described herein, therefore, provide insight into future outcomes. We note that in some of these analyses the scenario occurs in reverse, demonstrating how the barrier system responded as tidal prism decreased.

Table 1 Study sites

	Nauset Spit and New Inlet, Cape Cod, MA	Ocean City Inlet and Assateague Island, MD	Virginia Eastern Shore Barriers	Chandeleur Islands (CI) and Isle Derniers (ID), LA	Grand Isle (GI)-East Grand Terre (EGT), LA	Copper River Delta Barriers, AK	Friesian Islands, Germany
Coastal setting							
Tectonic coastal setting (Inman and Nordstrom 1971)	Amero-trailing edge	Amero-training edge	Amero-training edge	Marginal sea	Marginal sea	Collision coast	Amero-training edge
Barrier type (Davis and Hayes 1984)	Mixed energy	Wave-dominated	Mixed energy	Wave dominated	Wave dominated	Mixed energy	Mixed energy
Sediment source	Erosion of proximal updrift sandy glacial deposit	Erosion of proximal headlands composed of Pleistocene coastal deposits	Reworking of lowstand shelf deposits; limited alongshore input from erosion of updrift headlands	Reworking of former Mississippi River delta lobes CI: St. Bernard Delta 4.6–1.8 ka; ID: Lafourche Delta 3.5–0.4 ka deposits	Reworking of former Mississippi River delta lobe Lafourche Delta; 3.5–0.4 ka deposits	Glacially liberated sediments from proximal Copper River	Reworked glacio-fluvial deposits on shelf
Spring tidal range (m)	2.3	1.2	1.7	0.5	0.5	3.5–6.5	2.7–2.9
Deep-water significant wave height (m)	2	1.6	1.2	1.6	1	3.1	1.0
Dominant waves	Northeast (winter storms)	Northeast (winter storms)	Northeast (winter storms)	CI: East-southeast; ID: Southeast	GI, EGT: South-southeast	Southeast	Northwest
Dominant alongshore transport direction	South	South	South	CI: North-South; ID: West-East	Northeast	West	East

Anthropogenic alterations	None	Jetties, nourishment	Stabilization and nourishment at Wallops Island	CI: Nourishment, north end; ID: nourishment, breakwaters	GI: Nourished, breakwaters, Terminal Jetties EGT: Nourished	None	Poldering of back-barrier, Jetties
Barrier system							
Individual barrier length (km)	2–13	40–60	3–13	2–22	4–12	14–30	25–50
Individual barrier width (km)	0.1–0.5	0.1–0.3	0.1–1.0	0.1–0.4	0.2–0.8	0.6–2.5	500–800 0.8–1.5
Barrier thickness (m)	4–6	3–8	2–8	2–8	1–12	2–8	5–24

3 Background

3.1 Marsh Deterioration Processes and Existing Modeling Results

The timeframe and rate at which future changes will occur along barrier islands, in response to accelerating RSLR, will correspond with the stability and persistence of marshes in the back-barrier. Ultimately, barrier change will be related to the rate at which marshes are converted to intertidal flats and open water areas, thereby producing a larger tidal prism, increasing back-barrier accommodation space, and changing tidal hydrodynamics throughout the system. How quickly the marsh erodes, submerges, or becomes segmented once critical thresholds of marsh inundation have been crossed (Morris et al. 2002) will depend on a number of factors that we explore in this section. Adding to the complexity of predicting marsh evolution, many of these factors will, themselves, be impacted by climate change (Kirwan et al. 2009; Kirwan and Megonigal 2013) or respond to changes in marsh area (Mariotti and Fagherazzi 2013), creating feedbacks that enhance or buffer their effects.

The areal extent of saltmarsh platform is the result of a balance between vertical and horizontal processes (Fig. 2). The vertical elevation of a marsh platform (ζ), with respect to sea level (η), is a balance between mineral and organic deposition, shallow compaction processes, and deeper subsidence processes.

$$\Delta\zeta = D_{\mathrm{i}} + D_{\mathrm{o}} - a - s - \Delta\eta \tag{1}$$

where D_{i} represents the deposition of inorganic sediment, D_{o} is organic accumulation, a represents shallow autocompaction, s is deeper subsidence, and $\Delta\eta$ is the eustatic change in sea level. On the horizontal plane, coastal wetlands are subject to both lateral erosion and deposition depending on the hydrodynamic forcing and sediment availability, including the translation of wetland boundaries and the elaboration of channel networks. All of these processes may occur simultaneously within the same system, some areas being exposed and others sheltered, with the net difference dictating whether marsh area is lost or gained (e.g., van Proosdij et al. 2005; and see Fig. 3).

Inorganic deposition varies geographically based on suspended sediment availability, but, locally, it is well correlated with marsh platform elevation (deep areas accrete faster than shallow areas; Richards 1934; Stoddart et al. 1989; French and Spencer 1993; Cahoon and Reed 1995; Temmerman et al. 2003) and proximity to a creek or water body (French and Spencer 1993; Temmerman et al. 2003). The latter is due to a rapid reduction in carrying capacity as tidal flows or waves are slowed by the marsh grass canopy (Leonard and Croft 2006; Christiansen et al. 2000; Temmerman et al. 2003), and to the direct trapping of sediment on leaf surfaces (Stumpf 1983; French and Spencer 1993). Inorganic sediment accumulation is thus dependent on type, height, and density of vegetation (Gleason et al. 1979; Mudd et al. 2004, 2010; Palmer et al. 2004; Ortiz et al. 2017), which varies based on platform elevation and flooding frequency (high marshes are dominated by plants such