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Geomorphologic Evolution of Barrier Islands along the Northern U.S. Gulf of Mexico and Implications for Engineering Design in Barrier Restoration

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ABSTRACT

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Aspects of northern Gulf of Mexico (NGOM) (Louisiana, Mississippi, Alabama, and Florida panhandle) processes and barrier islands that are pertinent to their geomorphologic response are contrasted with the broader knowledge base summarized by Schwartz (1973) and Leatherman (1979, 1985). Salient findings from studies documenting the short-term (storm-induced; timescales of hours, days, and weeks) and long-term (timescales of years, decades, and centuries) response of barrier island systems in the NGOM are synthesized into a conceptual model. The conceptual model illustrates the hypothetical evolution of three barrier island morphologies as they evolve through a typical Category 1–2 hurricane, including poststorm recovery (days to weeks) and long-term evolution (years to decades). Primary factors in barrier island geomorphologic response to storms, regardless of location, are the elevation of the island relative to storm (surge plus setup) elevation, and duration of the storm. Unique aspects of the NGOM barrier islands, compared with knowledge summarized for other barrier types, include (1) storm paths, wind speed, and large bays that create the potential for both Gulf and bayshore erosion and (2) in Louisiana and Mississippi, the potential for loading of the underlying substrate by the barrier island, which, through time, increases consolidation, relative sea level rise, overwash, morphologic change, and migration. We recommend that design of large-scale beach restoration projects incorporate the potential for (1) time-dependent consolidation of the underlying sediment due to project loading and future migration, (2) Gulf and bayshore erosion and overwash, and (3) eolian transport toward the Gulf from north winds.

ADDITIONAL INDEX WORDS: *Morphology, coastal processes, restoration, beach nourishment.*

INTRODUCTION AND GEOLOGICIAL SETTING

Barrier islands located in Louisiana, Mississippi, Alabama, and the panhandle of Florida differ in terms of their sediment source, the availability of littoral and inner shelf sediment, and the underlying substrate. Three general regions are defined and presented in Figure 1. The following discussion compares and contrasts each of these regions.

It has been well established in the literature that along the Western Region, barrier islands in Louisiana are intricately linked to abandoned deltaic lobes of the Mississippi River and subsequent reworking by littoral and inner shelf processes (for comprehensive reviews see Coleman, Roberts, and Stone, 1998; Penland and Boyd, 1981). Penland and Boyd (1981) defined three stages for deltaic barrier island formation. After a mature active delta (e.g., the modern Bird's Foot delta) was abandoned by the river, Stage 1 began with an erosional headland that fed flanking barrier islands (*e.g.,* Caminada-Moreau headland with flanking barriers, Timbalier Islands to the west, and Grand Isle to the east). Over time (millennia), subsidence and wave-induced erosion depleted the source of sediment. Stage 2 consists of a transgressive (retreating) barrier island arc (*e.g.,* Chandeleur Islands). Finally, Stage 3 occurs when erosion and subsidence reduce the barrier island to a subaqueous inner shelf shoal (*e.g.,* Ship Shoal). Until human intervention in the early 1900s (levee construction and river diversion), this cycle repeated as the river occupied new locations or former deltas and provided a new source of sediment.

Because of this cycle of delta formation and abandonment, the Louisiana barrier islands, which are composed of a relatively thin layer of fine sand that was reworked from the abandoned delta, initially overlay a thick deltaic sequence of clay and silt that was deposited during the mid- to late Holocene by the river and eventually transgress over back-barrier estuarine deposits (Coleman, Roberts, and Stone, 1998). During high-wave energy events, surface sand is typically eroded from these islands, exposing a partially consol-

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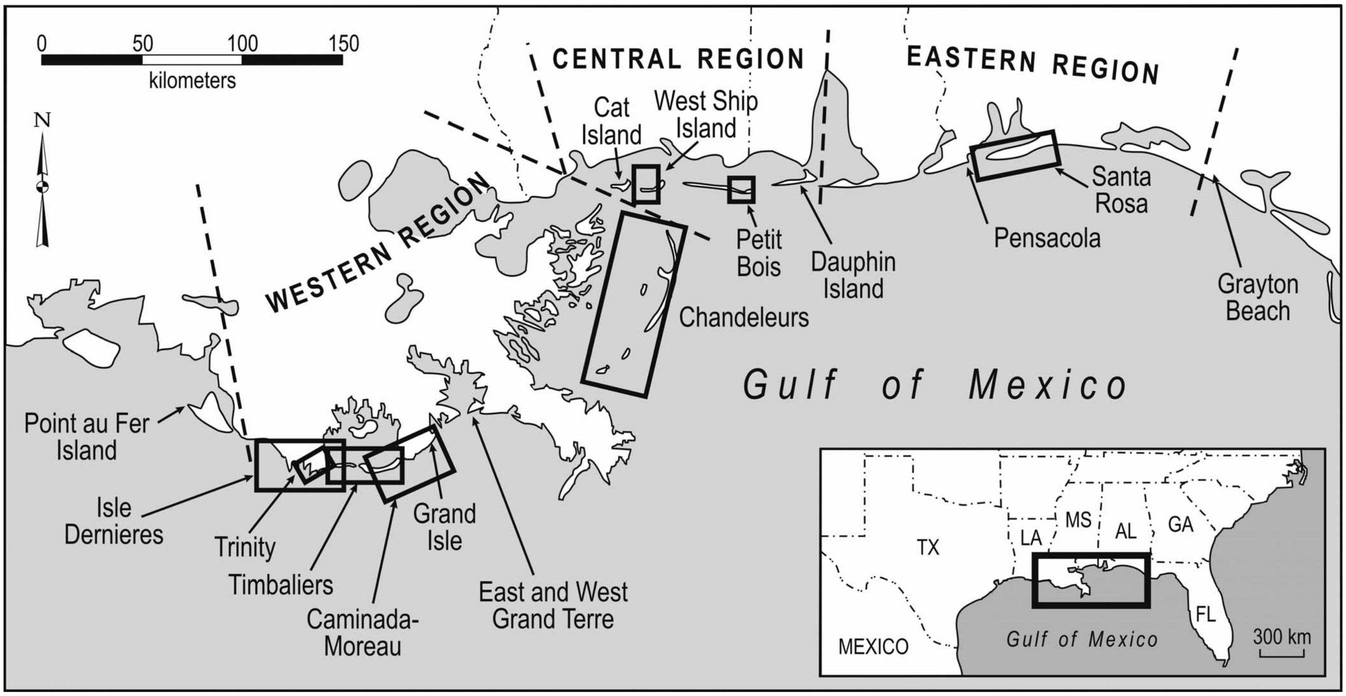

Figure 1. Location map and study sites in the NGOM (boxes) reviewed.

idated "core" comprising clay, silt, and organic material (Stone, Xu, and Zhang, 1995). Barrier islands along Louisiana's coast were created from abandoned deltaic lobes of the river, and the original primary riverine source of sediment to the littoral system is no longer available. The present day source of littoral sand is obtained from either erosion of adjacent islands or cannibalism of each island itself (Penland and Boyd, 1981). The islands are low in elevation with vegetation, including dune grasses on the primary and secondary dunes where they exist, and wetlands on the bayside/central portion of the islands. Some of the barrier islands are thinning in place (Penland *et al.,* 2005) because of a combination of rapid relative sea level rise, a lack of littoral sediment, and erosion on both the Gulf and bay shores. Relative sea level rise (RSLR) for Grand Isle, (south-central Louisiana; see Figure 1) approximated 9.85 ± 0.35 mm/y from 1947 to 1999 (NOAA, 2006a; Georgiou, Fitzgerald, and Stone, 2005).

In the Central Gulf Region, the Mississippi barrier islands along the west extending to Dauphin Island, Alabama, to the east have migrated rapidly from east to west (McBride, Byrnes, and Hiland, 1995). The exception is the westernmost island, Cat Island, which is primarily protected from offshore waves from the incident wave sheltering of the Chandeleur and Ship Islands. Migration rates of the western termini of Dauphin, Horn, and Petit Bois Islands were approximately 55.3, 31.3, and 34.5 m/y, respectively, from 1848 to 1986 (McBride, Byrnes, and Hiland, 1995). Sediment is reworked from east to west (Cipriani and Stone, 2001). Eastern Dauphin Island, with a Pleistocene core in the eastern section, is more stable than the other barrier islands, although the eastern beaches have been eroding in response to the dominant westerly directed transport. On the basis of grain size analysis, Cipriani and Stone (2001) determined that offshore sources might also provide sediment to central Petit Bois Island (located just west of Dauphin Island); similarly, Otvos (1979) concluded that the primary source of sediment for these barrier islands is the shelf. These islands range from very well vegetated, with maritime forests on east Dauphin Island, to low-elevation barriers that are overwashed and breached during hurricanes. From 1848 to 1986, long-term island area change rates were −2.5, −1.6, −1.7, and −2.0 ha/y for Cat, Ship, Horn, and Petit Bois Islands, respectively (Byrnes *et al.,* 1991). Long-term RSLR for Dauphin Island, Alabama, was 2.93 ± 0.59 mm/y (NOAA, 2006b) from 1966 to 1997.

The Eastern Region extends from Morgan Peninsula, Alabama, along the west to Grayton Beach, Florida, to the east (Figure 1). Grayton Beach is a Pleistocene headland that supplies sediment to the Florida beaches to the west, with the source tapering in the vicinity of Santa Rosa Island. Research suggests that beaches west of Santa Rosa Island have derived a significant quantity of sand from offshore during the mid- to late Holocene. The mechanism for onshore sand transport is a direct function of a distinct decrease in the inner shelf slope and an increase in modal wave energy (Stone and Stapor, 1996; Stone *et al.,* 1992). Barrier islands in this region have the most plentiful source of littoral sediment for the northern Gulf of Mexico (NGOM) barriers examined in this study. Sea level data examined over the period 1923 through

1999 indicate that this area underwent a rise in relative sea level approximating 2.14 ± 0.15 mm/y (NOAA, 2006c). On the basis of radiocarbon dates (millennial timescales) of organic material extracted from the upper shoreface, STONE and MORGAN (1993) also found that Santa Rosa Island, Florida, was relatively stable and experienced a RSLR rate that approximated the eustatic (global) sea level rise of 2.4 mm/y, as derived through the work of DOUGLAS (1992) and PELTIER (1998).

Comparing the RSLR rate for these three regions, it is evident that the Western Region experiences local subsidence, tectonic movement, or both that increase the RSLR rate approximately 7.5 mm/y in addition to the eustatic rate. This phenomenon is greatly reduced for the Central Region, where the RSLR rate is approximately 0.5 mm/y greater than the eustatic rate. The Eastern Region appears stable, with the RSLR rate approximately equal to the eustatic rate. The increase in RSLR over the eustatic rate reflects the degree to which the substrate is an active factor in long-term barrier island response. For these three regions, it is evident that the "substrate effect" is high along the Western Region and low or virtually absent along the Central and Eastern Regions.

On the basis of the discussion in this section, these three regions appear to be different. However, they share commonality through similarity in forcing processes that occur in the NGOM and how the barrier island morphology responds over short- to mid-term timescales (days to weeks to years). Through an understanding of how these islands respond to short- and mid-term forcing, we can anticipate and characterize long-term response by including knowledge of RSLR, geologic setting, and sediment availability for the region. Over longer timescales (decades to centuries), the morphologic response will be modified by regional constraints such as the underlying substrate and availability of littoral sediment.

REVIEW OF LITERATURE

Overview

To provide a contextual setting, we review three earlier compilations of barrier island literature pertinent to understanding general concepts of morphologic change regardless of coastal setting. Next, we update these previous compilations with a synthesis of NGOM literature and compare how the NGOM processes and barrier island responses differ from other coastal settings.

Early Complications

Three summaries of barrier island literature have been compiled, with a focus on reviewing modes of barrier island formation and processes causing long-term morphologic change. The first summary was by SCHWARTZ (1973), who compiled and published editorial commentary on 40 papers pertaining to barrier island evolution and morphologic change, literature that spanned a time period from 1845 to 1972. The primary focus of articles in Schwartz's compendium was the mechanism(s) for barrier island formation, whether through bar emergence (DE BEAUMONT, 1845; JOHNSON, 1919; OTVOS, 1970, 1979, 1981, 1985), spit formation and breaching (FISHER, 1968; GILBERT, 1885), or ridge engulfment (HOYT, 1967; MCGEE, 1890). In an introduction, as well as in a separate paper (SCHWARTZ, 1971), Schwartz advocated "Multiple Causality" as opposed to a singular mode of formation for barriers, depending on sediment supply, coastal and geologic setting, and trends in relative sea level change.

LEATHERMAN (1979) edited a collection of 10 papers, the majority of which had been presented at a Coastal Research Symposium on barrier island research in March 1978. In the introduction, Leatherman emphasized substantial progress in the 1970s and he contended that three processes control landward barrier island migration: inlet dynamics, overwash, and dune migration (eolian processes). This collection included a landmark paper by HAYES (1979, see also follow-on paper by DAVIS and HAYES, 1984), in which Hayes differentiated large-scale barrier island shape on the basis of tidal range and wave conditions as tide or wave dominated.

The dominating theme for LEATHERMAN's (1979) review was the importance of inlets in determining morphologic response. ARMON (1979) quantified the relative importance of inlets, overwash, and eolian transport in transgression of the Malpeque barrier system in the Gulf of St. Lawrence, Canada. Over a 33-year period (1935–1968), 90% of the landward sediment movement in the barrier system occurred at existing or former inlets. Similar studies of landward transport along barrier island systems at Cape Hatteras, North Carolina (PIERCE, 1969), and Assateague Island, Maryland (BARTBERGER, 1976), also concluded that the dominant contributions to migration were via existing tidal inlets (72% and 82%, respectively), followed by overwash (14% and 12%, respectively) and eolian transport (13% and 6%, respectively). Considering a 36-year period for Rhode Island barrier beaches, FISHER and SIMPSON (1979) concluded that tidal inlet deltas contributed approximately 57% of the total sedimentation, with washover sedimentation providing 43%. MOSLOW and HERON (1979) investigated long-term migration of the Core Banks in North Carolina, which migrated landward approximately 6.7 km over a 7000-year period. From 7000 to 4000 BP, overwash was identified as the dominant process of barrier migration, with rates ranging from 45 to 98 m/century. From 4000 to 755 BP, the rate of migration slowed as the rate of RSLR decreased, and inlet formation and migration were the dominant processes forcing barrier relocation onshore.

In the most recent summary of the literature, LEATHERMAN (1985) presented a comprehensive annotated bibliography of the barrier island migration literature through 1980. Of the 71 studies reviewed, two primary theories of barrier island migration were documented: continuous migration and in-place drowning. The majority of the studies supported the concept of continuous migration or shoreface retreat forcing landward migration of the island by rising relative sea level. In this model of retreat, the barrier island moves landward in response to rising sea level through "rolling over" itself. As with his 1979 compilation of studies, Leatherman concluded that the significant processes in shoreface retreat were, in the order of importance, inlets, overwash, and eolian processes. Eolian processes were found to be more significant for wide barrier beaches with arid and windy conditions (*e.g.,* southern Texas).

A subset of the studies supported morphologic evolution through in-place drowning of the barrier island, in which the island responds to rising sea level by aggradation (through overwash or eolian deposition on the subaerial barrier) until it is drowned and later overstepped (*e.g.,* possibly re-established at a landward position). This concept of superconstruction, in which the barrier increases elevation through overwash or eolian processes, was discussed in reference to both theories.

An additional process of potential importance pertaining to migration was discussed in reference to Virginia barrier islands and focused on autocompaction, in which the barrier island decreases in elevation because of loading on the underlying sediments. For the autocompaction process to be of importance, the underlying sediment sequences must be thick and compressible. Several papers in Leatherman's review support the concept of neocatastrophism, in which low-frequency, high-magnitude events are shown to be more important in long-term barrier island morphologic change when compared with high-frequency, low-magnitude events.

Table 1 summarizes what we consider the more salient points that emerge from these earlier compilations. The majority of these studies indicate that inlets dominate the processes responsible for barrier island migration. Inlets cause movement of the barrier island through cross-shore transfer of sediment, such as (1) flood shoal/tidal delta formation, (2) net longshore flux and subsequent inlet migration in the direction parallel to the barrier axis, and (3) welding of the ebb tidal delta onto the adjacent beach (Fitzgerald, 1988). Inlets influence migration processes even when closed, in that recently closed inlets are lower in elevation, which increases the likelihood for overwash and possible superconstruction (vertical accretion). Newly deposited, unvegetated washover fans provide a source for eolian transport which, if deposited within the subaerial barrier mass, can also increase barrier elevation.

Table 1. *Summary of concepts in previous reviews.*

Modes of barrier island formation	
Bar emergence	de Beaumont (1845); Johnson (1919); Otvos (1970, 1979, 1981, 1985)
Spit formation and subsequent breaching	Fisher (1968); Gilbert (1885)
Ridge engulfment	Hoyt (1967); McGee (1890)
Combination of modes	Schwartz (1971, 1973)
Dominant processes for landward migration	
1. Inlets (from 50% to 80% of total volume) 2. Overwash (from 10% to 40% of total volume) - Occurs more frequently at former inlet sites 3. Eolian (from 5% to 15% of total volume) - Overwash deposits provide conduits and source for eolian transport - Eolian transport has potential to increase elevation of barrier ("superconstruction") - Eolian more dominant for wide, arid barriers (e.g., Texas)	Armon (1979); Bartberger (1976); Fisher and Simpson (1979); Leatherman (1985); Pierce (1969); Rosen (1979)
Modes of migration	
1. Shoreface retreat - Via inlets, overwash, and eolian transport - Superconstruction (via overwash and eolian) - Autocompaction (compaction of underlying sediment from loading by the island, discussed for islands in Virginia)	Leatherman (1985)
2. In-place drowning - Via overwash and eolian processes - Superconstruction (via overwash and eolian) - Autocompaction (discussed for islands in Virginia)	
3. Aggradation and shoal growth	Otvos (1970, 1979, 1981, 1985)
4. Longshore processes - Spit growth and attachment - Inlet migration alongshore	Moslow and Heron (1979); Otvos (1970, 1979, 1981, 1985)
Barrier characteristics and processes	
Wave-dominated barriers - Waves 0.6–1.5 m, tides <2 m amplitude - Long, linear shape; frequent overwash	Davis and Hayes (1984); Hayes (1979)
Mixed energy barriers - Waves 0.6–1.5 m, tides 2–4 m amplitude - Short, "drumstick" shape	
Overwash is inversely proportional to barrier width	Fisher and Simpson (1979)
Rate of beach erosion directly proportional to overwash	
Significant sediment source reduces rate of migration	Oertel (1979)
Neocatastrophism - Storms are required for significant geomorphologic change	Leatherman (1985)

NGOM Literature

In this section, studies pertinent to migration and morphologic change of barriers along the NGOM are reviewed, and knowledge that we consider important to furthering our understanding of modeling past and future barrier island evolution is highlighted. The discussion is organized by region, from west to east, with study sites delineated in Figure 1.

Western Region

Regional Sediment Processes

In one of the earliest papers discussing evolution and potential for preservation of NGOM barrier islands, Peyronnin (1962) documented morphological response from 1890 to 1960 for Louisiana's barrier islands. He estimated that 1.9 million m^3/y of sediment was removed or sequestered from the barrier island system, including the nearshore above the 3.6-m contour, by wave erosion and subsidence. The influence of autocompaction as discussed for Virginia barrier islands

(Leatherman, 1985) was also observed, with the weight of sandy beach ridges (1.8–2.4 m thick) compacting the underlying marsh and reducing marsh thickness by 1–1.2 m. Kuecher (1994) also concluded that the distribution and thickness of peaty marsh soils was a first-order cause of coastal land loss in Louisiana. Kuecher discussed the consolidation associated with loading by barrier islands and hypothesized that Pelto Bay and Big Pelto Bay north of the Isle Dernieres were initiated because of loading of the prodelta muds by the barrier island chain. After the settlement began, deposition of bay muds continued loading the underlying sediment.

List *et al.* (1997) examined the applicability of the Bruun Rule to predict shoreline response from RSLR for 150 km of Louisiana coastline west of the Mississippi River. The Bruun Rule translates a beach profile upward and landward as a result of RSLR, under the assumption that the profile shape remains constant (Bruun, 1962). The authors eliminated approximately half of the profiles that did not maintain an equilibrium form over the 50- to 100-year period considered. For the remaining profiles tested, the authors assumed between 31% sand (for deltaic shorelines) and 100% sand (for sand spits) to calculate volumetric losses of fine sediment as the beach retreated. The Bruun Rule could not accurately predict shoreline response in a hindcast evaluation for the Louisiana coast. Long-term massive redistribution of sediment in the nearshore and on the shoreface was used as evidence of changes to the long-term regional sediment budget that decreased applicability of the Bruun Rule. Also, RSLR has increased the size of the bays behind barrier islands, thus increasing the tidal prism of adjacent inlets and their associated ebb and flood tidal shoals. As the barrier retreats, the redistribution of sand into the deeper bay, in addition to shoals, suggested that the barrier islands cannot maintain their subaerial form.

These two studies, and other literature discussed in the following sections, highlight the complexity of this region because of the rapid rate of RSLR, redistribution of sediment in the barrier island and nearshore system, and consolidation of the underlying substrate that has the potential to sequester sediment and effectively remove it from the active littoral system.

Morphology

Several researchers have characterized morphology and morphologic response for the Western Region. Ritchie and Penland (1988) monitored 13 cross-shore transects over a 10-year period along the barrier headland coast extending from Belle Pass to Caminada Pass (Figure 1). The coastal landforms and morphologic response were characterized as one of four types. (1) The *Washover Flat* consisted of a low-elevation washover sheet with embryonic dunes that could reach 1 m in elevation during non–storm conditions. However, the dunes did not survive more than a year, and vegetation could not grow because of the frequency of overwash, which exceeded 15 events per year. The entire flat was inundated by unrestricted sheet flow. (2) The *Washover Terrace* was slightly higher in elevation and smooth and vegetated or broken up with hummocky topography. Vegetation spread and recovered rapidly because of overwash, thereby promoting capture of eolian sediment. (3) The *Dune Terrace* had a surface 0.5–1.5 m higher than the washover terrace and exhibited more varied relief. Topographically low points along the frontal dune along the barrier could be overwashed, resulting in washover deposits on the back-barrier. (4) The *Continuous Dune* was characterized by two or more parallel dune ridges that were vegetated, with abundant backshore sand. During storms, the seaward-facing dunes were scarped and the foredunes could be completely removed. Washover fans were sparse because of the height and the morphological integrity of the vegetated dunes.

Data indicated that the overwash threshold for this coast was 1.42 m above mean sea level (MSL); consequently, approximately 75% of the Caminada-Moreau barrier headland would experience overwash. Unvegetated sand surfaces, created through the overwash process, were then prone to eolian transport of sediment into the dune system. After analysis of weather statistics, the authors found that there were two dominant wind vectors in this location, from the north and northwest. Thus, eolian transport from washover flats toward the Gulf could result in deposition at the base of the dune system, assuming the dune had sufficient relief for capture. In a recent study of sand fences placed as part of beach nourishment projects for the Isle Dernieres, Khalil and Lee (personal communucation) also noted the capacity of northern winds to build dunes if an unvegetated source of sand was available for eolian transport. For both of these studies, sediment composing washover flats rarely was transported further landward (north) by eolian processes.

In the 10 years of monitoring the coast, a substantial amount of morphological change occurred in response to storms; for example, a dune terrace was reduced to a washover sheet after two minor washover events followed by a series of cold fronts (Ritchie and Penland, 1988, profile D, p. 113). Eolian transport was observed to contribute significantly to dune building, with one profile increasing in elevation by approximately 1 m over a time period extending from April to December (1980) (Ritchie and Penland, 1988, profile H, p. 116). Stability of morphologic features was noted for locations that were vegetated or rapidly revegetated after storms. Revegetation was directly linked to a minimum number of overwash events, above which vegetation could not be re-established. On the basis of 10 years of monitoring, the authors suggested that the dunes followed a 10-year cycle, increasing volume of supra-tidal sand storage for up to 10 years that was then rapidly removed during a major storm.

Campbell (2005) identified eight unique aspects of the Louisiana coast that should be considered in coastal engineering analysis and design. (1) For six coastal segments evaluated, the profile shape exhibited a distinct break in slope (at approximately the 2–3-m isobath, no datum given), above which it had the form of an equilibrium-type profile. Below this depth, the profile was much flatter and was assumed to be a "passive depositional zone" with silts and clays. (2) Marsh sediments (assumed to be core sediments as discussed by Stone, Xu, and Zhang, 1995) were observed to be more resistant to erosion compared with sandy beaches. The

Louisiana barrier islands had (3) low dunes and a high frequency of overwash and (4) rapid subsidence and a high rate of RSLR. (5) When actively exposed to wave attack, exposed marsh areas permanently lost fine sediment. (6) Longshore sand transport in the region was less than observed or measured for exposed U.S. Atlantic and Pacific coasts, estimated to be 50,000 to 100,000 m^3/y for East and West Grand Terre. (7) Because of long-term RSLR and losses to the barrier-marsh systems, back-barrier bays were observed to increase in area, thus increasing the tidal prisms at inlets. Over time, the increasing tidal prism increased littoral system losses to larger ebb and flood tidal shoals. (8) High retreat rates on the Gulf shorelines were believed to be due to many interrelated factors and "cannot be predicted by any one process independent of the others" (Campbell, 2005, p. 238).

On the basis of this understanding, CAMPBELL (2005) developed a four-stage conceptual dynamic morphosedimentary model for barrier island retreat in Louisiana. Stage 1 of the model showed an initial barrier with a thin sand layer with median grain size of 0.1–0.14 mm over mixed deltaic sediment (sand, silt, and clay), backed by a wide marsh system. During storms, the sand was eroded and marsh vegetation and deltaic sediment were exposed to wave attack (Stage 2). In Stage 3, sand and potentially marsh sediment were eroded from the barrier as the beach retreated. Fine sediments were assumed to be lost to the passive depositional zone offshore of the observed break in profile slope, and sand was moved offshore or transported alongshore to inlets. Campbell observed that the barrier islands tended to retreat during the poststorm period, and this phenomenon was attributed to continuous wave action eroding the exposed marsh sediment. Sand eroded in Stage 3 partially returned to the barrier in the form of a sand cap on top of the deltaic sediments, which provided protection to the residual marsh (Stage 4). Overall, these processes narrow the barrier islands through time while increasing elevation (via overwash) and migrating them upslope and landward.

On the basis of shoreline position data spanning at least an 80-year period, MCBRIDE, BYRNES, and HILAND (1995) characterized eight geomorphic response types for barrier island systems in Louisiana, Mississippi, and Georgia/northern Florida. The authors found that barrier islands in Louisiana were best characterized by landward rollover, retreat, and breakup. Barrier island systems with a high rate of RSLR, such as Louisiana, were dominated by landward-directed, cross-shore processes, with longshore transport having secondary importance.

These studies are valuable in attempts to characterize NGOM subaerial beach morphology and responses as a function of relative storm-to-beach elevation. Of the four types of beach morphologies characterized by RITCHIE and PENLAND (1988), the first and fourth (washover flat and continuous dune) can be generally described as two dimensional, whereas the intermediate types (washover terrace and dune terrace) have three-dimensional variation. This distinction has potentially significant implications from a numerical modeling perspective.

Storm Response

Five studies are discussed to review the response of barrier islands in the Western Region to hurricane and cold front passage. KAHN and ROBERTS (1982) discussed the morphologic response of the Chandeleur barrier islands to Hurricane Frederic, a powerful storm that made landfall east of the islands near Pascagoula, Mississippi, on September 12, 1979. The barrier island system had two main morphologic zones: a more stable northern section with dunes 2–4 m (MSL) and a 19-km southern section with few or no dunes and elevations not exceeding 1.5 m (MSL). The southern section experienced Hurricane Frederic's waves for 24 hours before landfall, whereas the northern segment was more protected from initial storm waves.

Along the northern section, the beach width was eroded to less than 30 m, and the dunes survived the storm, although a 1–1.5-m scarp formed at the base. The southern section was most likely entirely inundated during Hurricane Frederic. Sheet flow over the barrier removed the entire subaerial beach and left washover fans extending up to several hundred meters into Chandeleur Sound. The authors attributed the differences in response observed during and after the storm to exposure of the barrier island to the storm (*i.e.,* the southern portion received waves in advance of the storm, and the northern section benefited from northerly transport of sand before landfall of the Hurricane) and the prestorm morphology of the dunes. Breaching of the northern portion of the Chandeleurs in lower portions of the dune system initially caused sand to be washed into Chandeleur Sound as the storm passed; however, this sand washed back into the Gulf with return flow after the storm. These lobate sand features were then a potential source of sand for longshore transport to facilitating infill of breaches during the post-storm recovery period.

Two studies compared how morphologic change differed for cold front passage and hurricanes along the Isle Dernieres. DINGLER and REISS (1990) documented morphologic change of a 400-m section of the Isle Dernieres from August 1986 to September 1987. During this period, tropical cyclones did not affect the area; thus, all morphologic change was due to cold fronts that frequent the area between October and May along the northern Gulf (PEPPER and STONE, 2004; ROBERTS *et al.,* 2003; STONE *et al.,* 2004). The profile was erosional in the "inshore-foreshore" portion of the barrier (defined as the area gulfward of the September 1987 berm crest), with losses ranging from 37 to 56 m^3/m. The "backshore" (remaining portion of barrier landward of the September 1987 berm crest) was accretional, with gains ranging from 7 to 29 m^3/m. In total, 19,200 m^3 was eroded from the inshore-foreshore, and 5600 m^3 was deposited on the backshore. On the basis of the thickness of sand and marsh, 13,600 m^3 of marsh deposits was considered eroded. The authors concluded that sand volume was conserved or accounted for during the study period and that the eroded marsh deposits were replaced by sand. However, the authors did not develop a barrier island sediment budget that could be used to evaluate whether a longshore transport gradient could also have contributed to erosion of the inshore-foreshore. Furthermore, erosional processes on the bayshore that occur after the passage of cold fronts were not considered a possible mechanism of reduced accretion on the bayshore (see ARMBRUSTER, STONE, and XU, 1995; STONE *et al.,* 2004).

In a follow-on study, DINGLER and REISS (1995) studied this same 400-m section of the Isle Dernieres after Hurricane Andrew, a Category 3 Hurricane that made landfall near Point Au Fer Island, Louisiana, on August 25, 1992 (see STONE and FINKL, 1995). Hurricane Andrew eroded the subaerial beach, resulting in a volumetric loss of 92 m^3/m, of which 85 m^3/m (92%) was sand. The authors noted that cold fronts have the propensity to maintain a constant beach-face slope, whereas hurricanes reduce the slope. Both types of storms removed the coarser (sand) portion of the beach, thus exposing the muddy core. Where vegetation was not present, mud rapidly eroded. Rebuilding of the coast along the study area had not occurred 1 year after Hurricane Andrew, with the mud beach remaining submerged and exposed to waves and currents.

PENLAND *et al.* (2003a, 2003b) documented the Gulf and bayside erosion and area change caused by Hurricane Andrew for the Timbalier and Isles Dernieres barrier island arcs, and compared these changes to long-term (1887/1906–1988) and short-term (1978–1988) erosion rates previously documented by MCBRIDE *et al.* (1992). In general, the maximum erosion rates caused by Hurricane Andrew were found to have occurred along the margins of existing inlets and newly formed hurricane breaches. Bayside erosion occurred as a result of gulf-directed overwash scour and waves in the bay. During a 3-month period after the storm, erosion continued on the margins of all inlets and breaches that did not recover. Accretion was associated with breach closure and development of flood tidal deltas on the bay side. The average Gulf-side erosion rate attributable to Hurricane Andrew was three times greater than the long-term erosion rate for Timbalier and East Timbalier Islands. The average bayside erosion rate by Hurricane Andrew was 1.1 times greater than the average long-term rate. For Isles Dernieres, Hurricane Andrew resulted in more than 5 and 21 times the long-term Gulf-side and bayside erosion rates, respectively.

Cold front and tropical cyclone passage have significantly different morphologic signatures on these islands. Cold front passage was observed to erode the Gulf-side sand and deposit it on the bayside marsh. In contrast, hurricanes tended to strip sand entirely from the islands and deposit it in the bay, which then could be transported back into the Gulf via return flow through breaches as the storm surge decreased. Once exposed, mud was rapidly eroded if not vegetated. Similar to LEATHERMAN'S (1979, 1985) findings, the greatest morphologic changes were observed at breaches and inlets.

Central Region

Regional Sediment Processes

BYRNES *et al.* (1991) and MCBRIDE, BYRNES, and HILAND (1995) analyzed historical shoreline position and island area change from 1847/49 to 1986 along the Mississippi Sound barrier islands. For all except Cat Island, BYRNES *et al.* found that lateral migration was typically an order of magnitude greater than cross-shore movement. Because the primary source of sand lies along the eastern portion of the region, migration rates decreased from Dauphin Island in the east to West Ship Island. Cat Island has responded differently over this time period because of the protection provided by the St. Bernard delta complex, which has been reworked into the present-day Chandeleur Islands. MCBRIDE, BYRNES, and HILAND classified Cat Island as "retreating," and Ship Island was undergoing counterclockwise "rotational instability." Horn, Petit Bois, and Dauphin Islands were characterized as "lateral movement." The eastern termini of each island were moving more rapidly, causing the inlets to widen between the barriers.

CIPRIANI and STONE (2001) quantified net annual estimates of potential net longshore sand transport rates for the Gulf side of East and West Ship, Petit Bois, and Horn Islands, Mississippi, and Dauphin Island, Alabama, on the basis of a wave transformation modeling and granulometric study. The potential net longshore transport rates had maxima directed to the west approaching 65,000 m^3/y at West Ship Island and at Western Dauphin Island. On the basis of the sediment grain size analysis, the authors inferred that offshore sources might provide sediment to central Petit Bois Island.

BYRNES, ROSATI, and GRIFFEE (personal communication) developed historical (1917/20–1960/71) sediment budgets and calculated (based on wave transformation modeling) regional sediment budgets for the Central Region with the use of shoreline position, bathymetric change, and maintenance dredging volumes for navigation channels in the study area. Pertinent findings from the study were that (1) net longshore sand transport is from east to west, and the barrier islands and adjacent passes are migrating laterally. The exception is Dauphin Island, which is anchored on the eastern end by its Pleistocene core. However, the western end continues to migrate west, elongating the island. (2) The source of sand for the region is the Mobile Pass ebb tidal shoal and the sandy shelf and shoreline to the east of Mobile Pass. (3) Cat Island is not a part of the regional littoral system and does not receive sand from the adjacent barrier islands.

These studies emphasize the interconnectivity of sediment transport between the Eastern and Central Regions, the importance of the shelf as a potential source of littoral sediment, and the dominant direction of net longshore transport from east to west.

Morphology

In their study of geomorphic response, MCBRIDE, BYRNES, and HILAND (1995) found that the Mississippi barrier islands were primarily evolving through lateral migration. The authors correlated the geomorphic response type with the rate of RSLR. The Mississippi barrier islands have a moderate rate of RSLR, and longshore transport processes dominate. In comparison, a lower rate of RSLR in addition to a sufficient sediment supply result in a progradational barrier island system, such as near the Florida/Georgia border.

Storm Response

NUMMEDAL *et al.* (1980) evaluated morphologic response of Dauphin Island, Alabama, and Chandeleur Islands, Louisiana, 9 days and 9 months after Hurricane Frederic. Two general conclusions postulated by the authors are pertinent for modeling NGOM barrier island morphologic response: (1) Hurricanes are a "major, perhaps the dominant agents in the development of barrier island morphology along the northern and western shores of the Gulf of Mexico" (NUMMEDAL *et al.*, 1980, p. 183) and (2) "the surge height is the single most important factor" in determining the geological response to a hurricane because the surge elevation determines the extent of flooding and, to a great degree, the energy of breaking waves (NUMMEDAL *et al.*, 1980, p. 184). Wave-induced turbulence is required in addition to sufficient water level to mobilize and rework sediment (*e.g.,* PEPPER and STONE, 2004).

Eastern Region

Regional Sediment Processes, Morphology, and Storm Response

STONE *et al.* (2004) measured beach change at 11 locations on Santa Rosa Island, Florida, over a 6.5-year period from February 1996 to July 2002. They documented barrier island change due to six tropical cyclones and more than 200 cold front passages. The island conserved sediment during Hurricane Opal, a Category 3 storm that made landfall on October 4, 1995, through 40 m of erosion of the Gulf shoreline and 40 m of accretion of the bayshore. However, during the subsequent 2-year period, the bayshore eroded 20 m because of bayside waves generated during the passage of cold fronts. These losses on the bayshore are believed to be net losses to the subaerial barrier as sediment is transported onto the bayside platform. The Gulf beaches did not begin to recover from Hurricane Opal until 6 years after landfall.

ARMBRUSTER, STONE, and XU (1995) monitored the north (bay) shore of a 12-km stretch of Santa Rosa Island, Florida, during the winter of 1995, documenting bayside erosion because of high-frequency (2.5–3.3 seconds) steep waves generated by northerly winds during a series of cold front passages. Long-term erosion of the bayshore was evident from peat outcrops, exposed tree roots, and beach scarps. During the 3-week study, four cold fronts affected the study area, resulting in high-frequency waves and elevated water level on the bayshore. Currents measured during a 14-hour period during one of the cold fronts were shown to be weaker than required for transport of sand offshore but sufficient for longshore transport. For the four storms that occurred during the study period, the overall result was a net loss of -1.92 m^3/m, which was measured between $+0.5$ m and -0.5 m (or deeper; -0.5 m was the extent of data) relative to the National Geodetic Vertical Datum (NGVD). Because the profile surveys only extended offshore to -0.5 m NGVD, the erosion magnitude might have been greater. This order of magnitude for bayshore erosion caused by cold front passage can be useful for developing storm response models for sandy NGOM barrier islands.

Barrier islands in the Eastern Region have the capacity to conserve sediment volume through hurricanes, although sand might be eroded from the bayshore of the islands during cold fronts if sufficient fetch is available for waves to develop in the bays. The low-gradient inner shelf might be a long-term source of sand for these islands.

Synthesis of Literature

On the basis of the 16 studies reviewed herein, several constraints and processes dominating the morphologic change of NGOM barrier islands can be summarized (Table 2). Forcing processes for morphologic change are organized in terms of timescale: short-term, representing tropical and extra tropical storms (hours to days); midterm, for poststorm recovery processes extending to time periods of constructive processes (days to decades); and long-term, for processes in and constraints of the regional system (decades to centuries).

These studies have identified several commonalities that span all barrier islands regardless of location. Over the short term, the relative elevation of the barrier island to storm elevation at the coast (surge plus wave setup) determines, to a large degree, geomorphologic response to the storm. In the poststorm recovery phase, longshore sediment transport can weld ebb-tidal deltas onshore and mend breaches. Finally, the availability of littoral sediment ultimately determines the long-term characteristics of barrier island morphology.

Unique aspects of the NGOM barrier islands compared with knowledge summarized for other barrier types include (1) storm paths, wind speeds, and large bays that create the potential for both Gulf and bayshore erosion and (2) in the West and Central Regions, the potential for loading of the underlying substrate by the barrier island, which, through time, increases consolidation, RSLR, overwash, morphologic change, and migration.

In the Western Region, several other characteristics differentiate barrier island evolution. (1) During storm passage, the thin veneer of sand overlying core sediment can be removed, thus exposing fine sediments that can be rapidly eroded during the storm and poststorm phases. These fine sediments are not returned to the barrier island system, thus reducing the overall long-term barrier volume. (2) The natural low elevation of these islands relative to mean sea level causes beach sand to be less likely for eolian transport because of a potentially damp or saturated condition and adhesion to cohesive core sediment. Thus, dunes are less likely to form naturally compared with wider and higher systems and sandy barrier island systems. (3) Finally, the rapid rate of RSLR for the Western Region has created a coastal system that has historically drowned barrier islands (*e.g.,* Ship Shoal, PENLAND and BOYD, 1981). Increasing bay areas result in larger tidal passes, which subsequently sequester more sand in tidal shoals. The result is a reduction in subaerial littoral sediment available to the regional barrier island system, which cannot keep pace with the rapid changes in RSL.

CONCEPTUAL MODEL FOR NGOM BARRIER ISLAND MORPHOLOGIC EVOLUTION

From a synthesis of the literature discussed above, we present here a conceptual model of barrier island evolution. Our

Table 2. *Processes for morphologic change in the NGOM.*

Short-Term Timescale: Hours to Days	
Minimum elevation of barrier island relative to storm surge elevation (including wave setup) and duration of the storm surge	Lower elevations are most vulnerable to overwash and breaching
Foredune elevation relative to elevation of breaking wave height	Foredune lower than breaking wave height results in more overwash and breaching
Composition of barrier (core sediment *vs.* sand)	Core sediment is more resistant to erosion if vegetated and consolidated but could be finer than barrier sand, more readily transported offshore or into the bay, and not return to the littoral system Core sediment can erode during the poststorm phase if eroded barrier sand has not yet returned to the barrier
Locations of previous breaches and washover fans	Lower elevations and sparse vegetation more susceptible to new breaching and overwash
Frequent overwash inhibits vegetation	
Vegetative cover	Increased density of vegetation reduces erosion, decreases eolian transport from the site, and increases trapping of sediment transported to the site
Bayshore erosion	Relatively large bays and long fetches facilitate formation of high-frequency steep waves that erode the bayshore
Storm surge ebb	Superelevated water in bay will result in flushing water and sediment from the bay into the Gulf, through inlets and breaches; could deepen channels and create/enlarge "ebb shoals" in Gulf
Mid-Term Timescale: Days to Decades	
Poststorm recovery	Cross-shore movement of sediments onshore* Mending of breaches via longshore transport* Welding of ebb-tidal deltas onshore* Eolian transport toward Gulf via washover corridors*
Eolian transport	Sand fencing is effective at capturing sand; however, a dry beach, minimal vegetation, and sufficient sediment source are required
Longshore transport	If sufficient source is available, could create spits and close breaches
Onshore transport	Cited as long-term source for some barrier islands with low-gradient shelf (central Petit Bois Island and inner shelf between Pensacola, Florida, and Morgan Point, Alabama)
Long-Term Timescale: Decades to Centuries	
Regional geologic setting	Littoral sediment supply Consolidation of underlying sediments from loading* Tectonic and faulting*
Relative sea level trends	Rapid *vs.* gradual increase or decrease
Bay area and inlet characteristics	Increasing bay area and depth increases inlet tidal prism, thus increasing the potential sediment sink in ebb and flood tidal shoals
Interrelationship between barrier islands, bays, regional geology, sediment supply, and redistribution of sediment to nearshore/inlet reservoirs/bays	

* These processes occur to varying degrees in the NGOM.

Table 3. *Barrier and storm conditions for conceptual model.*

Barrier Type	Description
Continuous dune	Continuous single or multiple dunes of approximately +2 m MSL; crests of dunes are vegetated; back-barrier is vegetated wetland for the majority of the barrier system; spits exist on the flanks; system is sand-rich, overlying core sediments (Figure 2)
Dune-washover terrace	Sparse dune system with maximum elevation of +1.5 m MSL; blowouts (breaks) have eroded sediment between dunes; blowouts consist of washover flats that become hummocky and vegetated during nonstorm conditions; back-barrier is a vegetated wetland or washover fan; spits can exist on flanks (Figure 2)
Washover flat	Sand-deficient system with maximum elevation of +1 m MSL that becomes frequently inundated and overwashed; vegetation exists only when enough time has elapsed between storms; vegetated core sediments might be exposed as slightly more erosion-resistant "islands" in the midst of the sandy barrier; back-barrier is a vegetated wetland; spits can exist on flanks (Figure 2)

ultimate objective is to provide a general framework with which to develop and test numerical models for the NGOM. In addition to identifying and elucidating the geological complexity of this coast, the immediate implications associated with this work pertain to engineering and design of coastal restoration projects along this region.

Three barrier types have been conceptualized on the basis of the coastal morphologies discussed by Ritchie and Penland (1988), with Ritchie and Penland's intermediate landforms (dune terrace and washover terrace) combined into one barrier type (termed "dune-washover terrace"; Table 3; Figure 2). The three barrier types conceptualized herein are Continuous Dune, Dune-Washover Terrace, and Washover Flat. Response of each barrier island type to a tropical storm or weak hurricane (TS/WH; *e.g.,* Category 1 or 2 on the Saffir-Simpson scale) is presented to illustrate how the initial morphology and existing vegetation modify the processes and determine ultimate, although possibly temporary, morphology. As shown in Table 2, the relative elevation of the barrier island to storm surge (including wave setup) and the duration of the surge are primary factors in determining response. Many other types of storms occur in the NGOM, ranging from cold fronts, occurring 20–40 times each year, to severe and catastrophic hurricanes (Category 3 or higher), occurring on average every 10–30 years (see Keim, Muller, and Stone, 2004; Muller and Stone, 2001; Stone and Orford, 2004; Stone *et al.,* 1997). The response to these different-intensity storms will bracket the TS/WH storm, with the storm surge and wave setup elevations, duration of the storm, and storm path modifying response. As presented in Table 4, we compare these various types of storms so that the discussion for a TS/WH storm herein can be set in the appropriate contextual framework regarding other storms. The TS/WH storm is represented as both forcing from the Gulf as the storm approaches land and from the bay as the storm surge and waves are generated in the bay. Wave conditions and surge in the

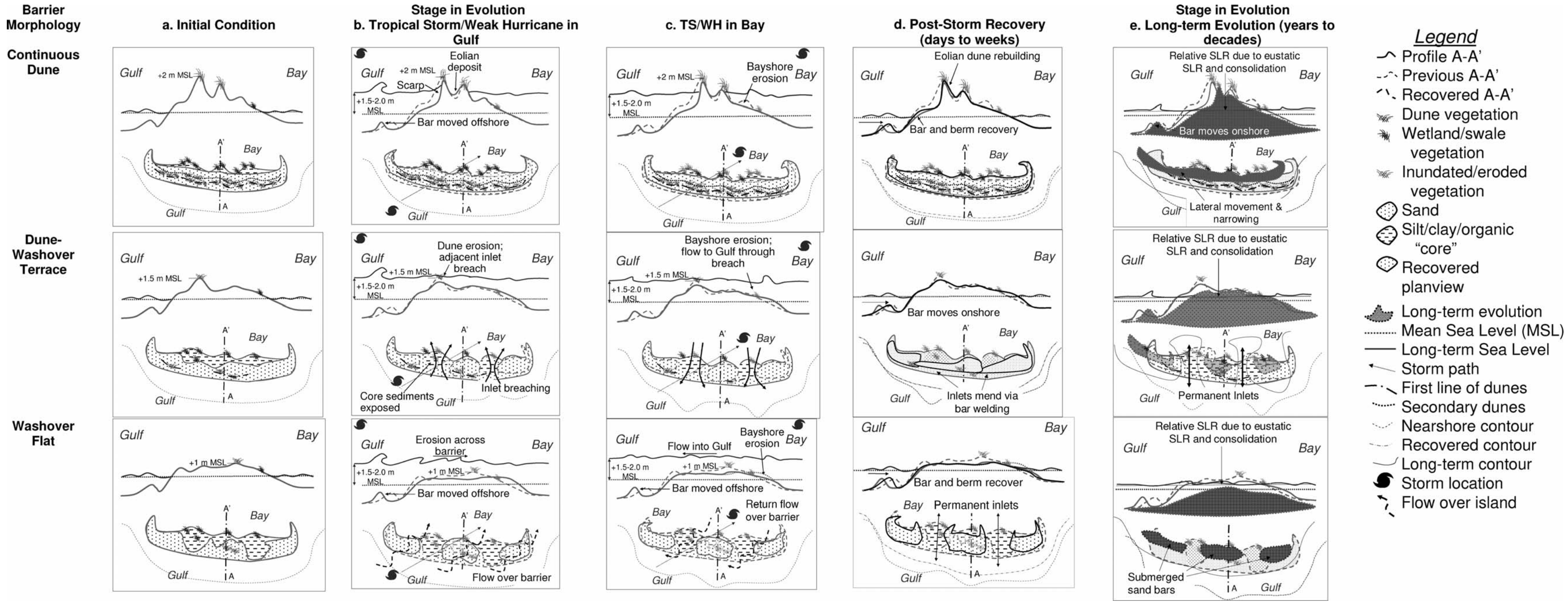

Figure 2. Conceptual model for barrier island evolution.

Table 4. *Representative processes along the NGOM.*

Storm	Frequency (events/y)	Description
Typical nonstorm conditions	Majority of year	Microtidal climate with diurnal range = 0.15 (equatorial) to 1 m (tropic)[1]; 0.36 m (mean)[2] Mean annual significant wave height = 0.8–1 m[1] Associated wave period = 4.5–5.9 s[1] Winds most frequently from southeast, but typically not of magnitude for eolian transport[2]
Cold front	20–40[1,2]	Fronts typically migrate northwest to southeast[1] Prefrontal conditions: significant deep-water wave height 3–4 m; wind from south 13[3] to 36[1] km/h Frontal: surge = 0.3–0.4 m[1]; winds from north 55 km/h[3] Postfrontal: winds from north 65–85 km/h; peak significant wave height = 2.7 m (for 5 h) and 1.5 m (for 24 h)[1] Duration: 12–24 h[1]
Tropical storm (TS) or Weak Hurricane (Category 1 or 2)	TS: 0.625 (once every 1.6 y)[6] Weak (Category 1 or 2) hurricane 0.24 (once every 4.1 y)[6]	Peak occurrence August–September (TS); September (hurricane)[1] Surge: 0.6 m (TS Isidore, September 2002); 2.2 m (Cat 2 Georges, September 1998)[1] Wind: 160 km/h (Georges)[1] Significant wave height: 2.3 m (Isidore), 2.8 m (Cat 1 Lili, October 2002)[1] 10 m (Georges)[5] Wave period: 12–14 s (Georges)[5]
Moderate to severe hurricane (Category 3+)	0.10–0.03 (once every 10–30 y)[6]	Peak in September[1] Surge: 6.7 m (Cat 5 Camille, August 1969)[1]; 1.2 m (Cat 4 Frederic, August 1979)[7]; 2–4 m (Cat 3 Andrew, August 1992)[8]; 8.5 m (Cat 3 Katrina, August 2005)[9]; 1.3 m (Cat 3 Rita, September 2005)[10] Wind: 322 km/h (Camille)[1]; 200 km/h (Frederic)[7]; 210 km/h (Andrew)[8]; 260 km/h (Katrina)[9]; 160–220 km/h (Rita)[11] Offshore waves: 14 m (Andrew)[8]; 17 m (Katrina)[9]; 12 m (Rita)[11]

[1] Georgiou, Fitzgerald, and Stone (2005).
[2] Dingler and Reiss (1990).
[3] Pepper and Stone (2004).
[4] Dingler and Reiss (1995).
[5] Stone *et al*. (2004).
[6] Ritchie and Penland (1988).
[7] Kahn and Roberts (1982).
[8] Penland *et al*. (2003a, 2003b).
[9] Interagency Performance Evaluation Team (2006).
[10] URS (2006).
[11] http://www.ndbc.noaa.gov/hurricanes/2005/rita/.

bay can cause bayshore erosion. Long-term morphologic evolution of each barrier type is also hypothesized.

Characteristics of the barrier island that determine storm response include: (1) the minimum barrier elevations relative to the maximum storm elevation (storm surge plus wave runup) and the duration of this maximum storm elevation, (2) the amount of sand and core sediment in the system, and (3) the amount and type of vegetation coverage of the barrier. Lower elevations along the barrier island represent the weaker parts of the system and determine the barrier's propensity toward overwash and breaching. The quantity of additional littoral material in barrier dunes and adjacent islands determines whether the island can rebuild and close breaches. Denser vegetation reduces the magnitude of erosion.

Storm and nearshore/bay characteristics also modify response. Storm wave height and period, nearshore slope, maximum surge, duration of the storm, and storm path determine the severity of the storm event. Similarly, bay depth and area, as well as duration of wind-generated waves, are controlling factors in the magnitude of bay surge and waves in the bay. For simplicity, these storm and nearshore factors are not varied in the conceptual model. In Figure 2, we present the hypothetical morphologic response.

A representative cross section and plan view layout is presented for the initial condition of the barrier island before the TS/WH. In the following section, response of each type of barrier is compared for each step of the storm and recovery sequence.

Figure 2b shows each type of barrier island as the storm approaches from the Gulf. The Continuous Dune is scarped near the mean water level and higher, and the dune can avalanche as the base is removed. Some eolian transport might remove sand from the dune because of winds blowing from the Gulf and deposit it in the center of the island. The offshore bar is moved further into the Gulf. Similarly, dunes on the Dune-Washover Terrace are scarped and potentially entirely removed, in that lower parts of the island adjacent to the low dunes can result in the formation of breaches. Washover sand is deposited into the bay, core sediment is exposed, and some vegetation is removed. The Washover Flat is completely inundated during the storm, with sheet flow transporting barrier sediment from the Gulf into the bay. Core sediment is exposed in areas and all vegetation is removed; permanent inlets could form.

In Figure 2c, storm surge and winds from the bay side generate waves in the bay, and bayshore erosion occurs for all barrier types. Larger and deeper bays have the potential to generate higher waves. Later in the storm cycle, resident storm surge in the bay can return to the Gulf via existing inlets at the barrier termini, overwash of the island, and return flow through new breaches (Figure 2c). Differences in response occur for the Dune-Washover Terrace and Washover Flat, which could transport barrier sand back into the Gulf through breaches or over the island proper. For the Dune-Washover Terrace, return flow through breaches could deepen them such that they subsequently capture the tidal prism and remain permanently open.

In the recovery process, offshore bars could return to their prestorm position (Figure 2d), and sand that was transported offshore through breaches during the surge return flow in the Dune-Washover Terrace could weld back to the barrier through cross-shore and longshore processes. However, core sediment that was eroded during the storm is finer than barrier sand and most likely is lost from the littoral system. Breaches that deepened during the storm could remain open, especially for the Washover Flat with its limited sand supply. The Continuous Dune and Dune-Washover Terrace might increase in elevation because of vegetation growth and vegetative trapping of eolian sediment. The Washover Flat might revegetate if the frequency of storms allows growth between events.

Over time, the cycles of storms and poststorm readjustment repeat with a net removal of sediment from the subaerial barrier island system by three phenomenon: (1) offshore losses during storms (sand and core sediment, if present and exposed); (2) losses to the bay through overwash, breaches, inlets, and erosion of the bayshore; and, potentially, (3) long-term RSLR because of consolidation of the underlying sediment, geologic faulting, anthropogenic factors, and eustatic sea level rise. Figure 2e represents the long-term loss of subaerial barrier island volume as a result of consolidation and eustatic sea level rise. A plentiful source of sand in the littoral system has the potential to fully mitigate these losses, although in the NGOM, naturally supplied sources are minimal and many barrier islands are cannibalizing themselves as a result (PENLAND and BOYD, 1981). Without an adequate source of sediment to replenish the islands, a Continuous Dune barrier will evolve into a Dune-Washover Terrace, which will then develop into a Washover Flat and will finally be reduced to a submerged sand shoal, as discussed by PENLAND and BOYD (1981). It seems likely that the morphologic change process from one barrier type to the next will accelerate through time because of the increasing number of processes that are able to act on the island as it changes form. For example, the Continuous Dune will respond to wave, wind, and inlet processes (at barrier termini); however, the Dune-Washover Terrace will have these processes as well as transport because of overwash and barrier breaching.

IMPLICATIONS FOR COASTAL RESTORATION AND ENGINEERING DESIGN

On the basis of our review, we conclude that design of restoration for the NGOM barrier islands should consider the forcing processes as listed in Table 2. For those locations with compressible substrates, such as the Western and Central Regions (Figure 1), the increased loading of the additional sediment must be integrated into the design. Vegetation should be planted in the primary dune complex and on the bayshore to provide stabilization of these regions. Sand fences should be placed such that eolian transport toward the Gulf and bay will be captured within the subaerial barrier island. To provide more ecological habitat, it might be desirable to have areas of the island that overwash occasionally. It should be accepted, however, that such a design could result in more rapid island disintegration through breakup. Alternatively, spits on the barrier termini could potentially allow overwash and unvegetated washover deposits. Figure 3 shows a conceptual design that incorporates some of these considerations.

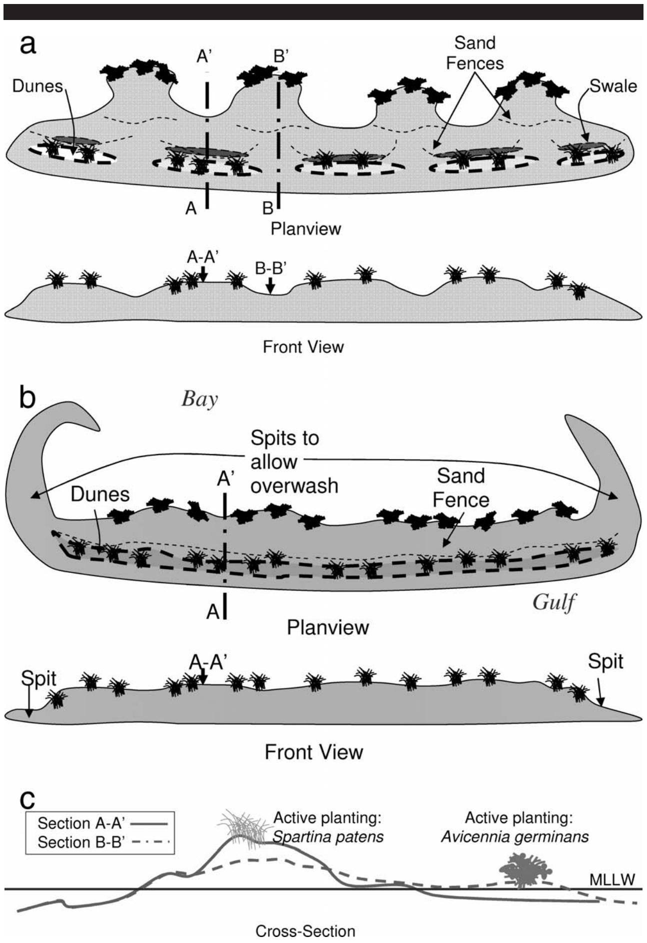

Figure 3. Conceptual design of barrier island restoration: (a) Design for overwash in middle of barrier island. (b) Design for overwash on termini of barrier island. (c) Cross section design.

In Figure 3a, the barrier island is wider opposite low areas in the dune to decrease the likelihood for breaching while permitting overwash during storms. A minimum or critical barrier width is one that will capture overwashed sediments over the project life, considering other forcing processes and response (ROSATI and STONE, 2007). If a breach occurs during a storm, littoral material in the barrier system is sufficient for closure of the breach by longshore transport. In Figure 3b, a design is presented that minimizes overwash within the central part of the island, instead using low-elevation spits on the barrier termini to provide washover deposits. For both designs, active planting of *Spartina patens* and *Avicennia germinans* or vegetation common to the local area is recommended to stabilize the dune and bayshore. Sand fencing near the base of the dune, on the bay side, is recommended to capture eolian transport from the dunes and overwash fans.

For islands that are migrating onshore and alongshore rapidly, islands of dredged material constructed in the migration path could provide future sources of sediment. These islands

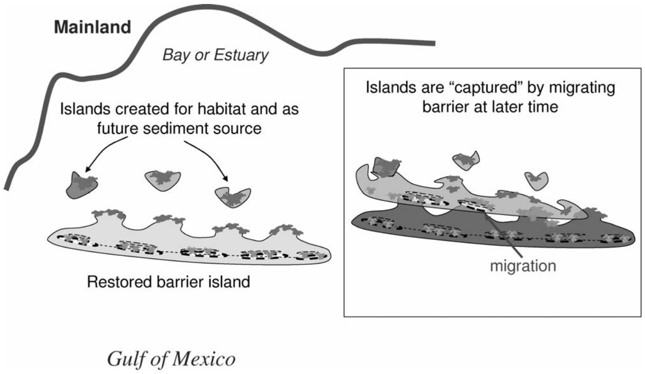

Figure 4. Regional design providing future sources of sediment for migrating barrier island.

would provide additional ecological habitat as well as a source of sediment for the barrier islands to capture as they migrated landward or alongshore (Figure 4). The islands might also partially consolidate the underlying sediments before occupation of the site by the barrier island. For barrier systems that are not migrating rapidly but are eroding on the bay side, the islands could provide partial protection from waves generated in the bay. For barrier systems that readily receive sediment from subaqueous sources (*e.g.,* Dauphin Island from the Mobile Bay ebb tidal shoal and subaerial islands; Petit Bois Island from an offshore source), a nearshore berm or submerged feeder shoals could also provide a future source as well as wave protection.

SUMMARY

In previous compilations of the literature (Leatherman, 1979, 1985; Schwartz, 1973), the dominant processes for barrier island migration were determined to be (1) inlets, (2) overwash, and (3) eolian transport. Neocatastrophic events such as storms, although relatively short in duration, were suggested as the primary cause with respect to long-term geomorphic change. Processes such as superconstruction (aggradation) of the barrier through eolian-induced deposition, shoal growth, longshore transport and spit formation, and local consolidation through self-loading of underlying substrate could be significant factors in morphologic evolution, depending on the local setting and processes.

For the NGOM, the relative significance of each process varies with location. Along the Eastern Region, a relatively abundant supply of littoral sediment both from a Pleistocene headland and the inner shelf, plus a stable substrate, creates a system that is much like those reviewed in the previous literature summaries. In this area, long-term morphologic change is similarly controlled by inlet processes, overwash, eolian transport, longshore transport, and vegetative cover. In the Central Region, a less plentiful supply of littoral sediment, a slightly consolidating substrate, and a dominant westward-directed longshore transport creates a system of five barrier islands that have, over historic timescales, migrated rapidly to the west while reducing their subaerial footprint and volume. In this region, longshore transport is the dominant process of migration, followed by overwash, breaching, and existing inlets. Finally, along the Western Region, a low regional source of littoral sediment, a consolidating substrate, and increasing bay and inlet areas have created a system that is rapidly disintegrating. Low barrier elevations in this region result in overwash and breach formation having a greater contribution to morphologic evolution. Eolian transport does not occur as readily because low barrier elevations are wet during periods when wind speed has exceeded the critical threshold for eolian transport. Sand that has overwashed the barrier might load a substrate that has not been previously loaded, thereby reducing the net subaerial beach because of consolidation. Common to all the regions is erosion of the bayshore during return flows from the bays to the Gulf after landfall of tropical cyclones, and, if bay fetch is sufficient to generate waves, the postfrontal phases of winter storms when strong northerly winds occur.

CONCLUSIONS AND FUTURE WORK

Long-term modeling of barrier island morphologic response is required to evaluate the regional restoration concepts discussed herein (*cf.* Figures 3 and 4). For the NGOM, these models should include pertinent processes, including the propensity for both Gulf and bayshore erosion and overwash, the potential for consolidation of the underlying sediment as a function of loading and time, erosion and eolian transport characteristics of vegetated and unvegetated core and sandy sediments, and the availability of littoral sediment to rebuild the island in the poststorm phase. The next step of this study is to develop the capability to model these processes and validate the model with observations of long-term morphologic response in the NGOM. Once validated, the model could then be applied to evaluate alternatives for restoration of these barrier island systems within the context of future rise in eustatic sea level and potential increase in storm frequency and severity.

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