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Historical Changes in the Mississippi-Alabama Barrier-Island Chain and the Roles of Extreme Storms, Sea Level, and Human Activities

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ABSTRACT

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Barrier-island chains worldwide are undergoing substantial changes, and their futures remain uncertain. An historical analysis of a barrier-island chain in the north-central Gulf of Mexico shows that the Mississippi barriers are undergoing rapid systematic land loss and translocation associated with: (1) unequal lateral transfer of sand related to greater updrift erosion compared to downdrift deposition; (2) barrier narrowing resulting from simultaneous erosion of shores along the Gulf and Mississippi Sound; and (3) barrier segmentation related to storm breaching. Dauphin Island, Alabama, is also losing land for some of the same reasons as it gradually migrates landward. The principal causes of land loss are frequent intense storms, a relative rise in sea level, and a sediment-budget deficit. Considering the predicted trends for storms and sea level related to global warming, it is certain that the Mississippi-Alabama (MS-AL) barrier islands will continue to lose land area at a rapid rate unless the trend of at least one causal factor reverses. Historical land-loss trends and engineering records show that progressive increases in land-loss rate correlate with nearly simultaneous deepening of channels dredged across the outer bars of the three tidal inlets maintained for deep-draft shipping. This correlation indicates that channel-maintenance activities along the MS-AL barriers have impacted the sediment budget by disrupting the alongshore sediment transport system and progressively reducing sand supply. Direct management of this causal factor can be accomplished by strategically placing dredged sediment where adjacent barrier-island shores will receive it for island nourishment and rebuilding.

ADDITIONAL INDEX WORDS: *Sediment budget, barrier restoration, channel dredging, human modifications.*

INTRODUCTION

Barrier-island chains worldwide are being recognized as finite natural resources with high social value for recreation and storm protection, but with uncertain futures (Pilkey, 2003). The uncertainty comes from the fact that some barrier-island chains are disintegrating rapidly as a result of combined physical processes involving sediment availability, sediment transport, and rising sea level. Accelerated rates of land loss and decreases in area should be expected for these ephemeral features, because present physical conditions are different from those that existed when many of the barrier islands first formed (Bird, 2003). In many coastal areas during the past few thousand years, sediment supply has diminished, rates of relative sea-level rise have increased, and hurricanes and winter storms have been frequent events that generate extremely energetic waves capable of permanently removing sediment from the island chains.

Recent attention has focused on the accelerated land loss and morphological changes of barrier-island chains in the north-central Gulf of Mexico that resulted from impacts of Hurricane Katrina (Sallenger *et al.,* 2006). Barrier islands at greatest risk of further degradation, the Chandeleur-Breton Island, Grand Terre Island, Timbalier Island, and Isle Dernieres chains in Louisiana, are associated with the Mississippi River delta (McBride and Byrnes, 1997). These chains of transgressive barrier islands have progressively diminished in size as they migrated landward and/or disintegrated in place (McBride *et al.,* 1992; McBride and Byrnes, 1997). In contrast, the MS-AL barrier islands (Figure 1) are not migrating landward as they decrease in size. Instead, the centroids of most of the islands are migrating westward in the direction of predominant littoral drift through processes of updrift erosion and downdrift deposition (Byrnes *et al.,* 1991; Otvos, 1970; Richmond, 1962). Although the sand spits and shoals of the MS-AL barriers are being transferred westward, the vegetated interior cores of the islands remain fixed in space.

The objectives of this investigation were to document the historical changes in position and land area of the MS-AL barrier islands, examine the physical factors that are most

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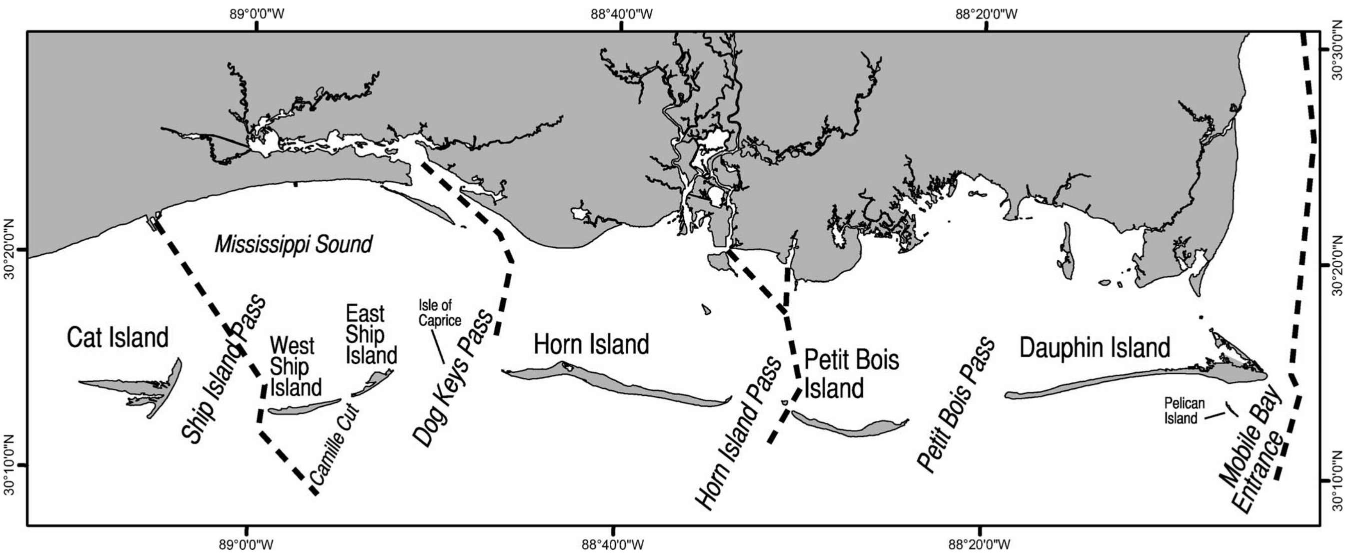

Figure 1. Locations of the Mississippi-Alabama barrier islands and associated tidal inlets. Deep-draft shipping channels (heavy dashed lines) leading to the mainland are maintained by periodic dredging.

likely driving those changes, and develop a basis for predicting the trends of future changes given the present physical setting and expected future oceanographic and meteorological conditions. These objectives were accomplished by sequentially comparing barrier-island geometries and locations, investigating the regional historical trends of sea level and sediment supply, and evaluating the morphological impacts of extreme storms since the late 1800s.

PHYSICAL SETTING

Because tidal range in the north-central Gulf of Mexico is low, <0.5 m (Rosati *et al.,* 2007), wind-driven waves and associated currents are the primary mechanisms for entraining and transporting nearshore sediments. Average significant wave heights in the winter are 0.6 m, whereas in the summer they are 0.4 m (Rosati *et al.,* 2007). Average wave periods for the same seasons are 4 and 3.5 seconds, respectively. Maximum deep-water wave height in the northern Gulf of Mexico of 27.7 m was recorded during Hurricane Ivan in 2004 (Wang *et al.,* 2005). During most of the year, predominant winds from the southeast drive alongshore currents to the west (Cipriani and Stone, 2001). The westerly flow of nearshore currents is enhanced by the counterclockwise circulation of wind associated with tropical cyclones as they approach the MS-AL coast on northwesterly or northerly tracks. The strong nearshore currents result in high-volume net-westward sediment transport that likely surpasses the normal westward alongshore sediment transport generated by the predominant southeasterly winds (Morton, 1988).

Wide tidal inlets separate the MS-AL barrier islands (Figure 1). The islands are the subaerial expression of a nearly continuous sand platform that is substantially shallower (<−4 m) than the surrounding waters of the Gulf of Mexico or Mississippi Sound (Curray and Moore, 1963). Sand that formerly maintained the islands was derived from the continental shelf; erosion of barrier-island segments to the east, including the ebb-delta shoals at the entrance to Mobile Bay; or from the sandy platform underlying the barriers (Otvos, 1979). Although the barriers generally are low (<4 m) and the intervening tidal inlets are wide, the islands and underlying shoal platform absorb some of the storm-generated wave energy in the gulf before it reaches the mainland shores. Exceptions are the large, extremely intense hurricanes, such as Camille (1969) and Katrina (2005), that completely overtop the barrier islands and generate high storm surge and waves in Mississippi Sound that directly impact the mainland shores.

HISTORICAL CHANGES IN THE MISSISSIPPI-ALABAMA BARRIER ISLANDS

Prior Morphological Studies

The MS-AL barrier islands are so dynamic and the magnitudes of their movement so great that changes in their positions and land areas have been topics of scientific investigation for decades. Several regional studies dealt with changes in shoreline position of the offshore islands. For example, Waller and Malbrough (1976) reported rates of shoreline change at transects around the islands and the sequential magnitudes and rates of updrift island erosion and downdrift island accretion. Shabica *et al.* (1983) reported rates of gulf shoreline change between 1957 and 1980 and overwash-penetration distances for the barrier islands. Rucker and Snowden (1989) measured the orientations of relict forested beach ridges on the Mississippi barriers and concluded that the ridges and swales were formed by recurved spit deposition at the western ends of the islands. Knowles and Rosati (1989) documented morphological and bathymetric changes around

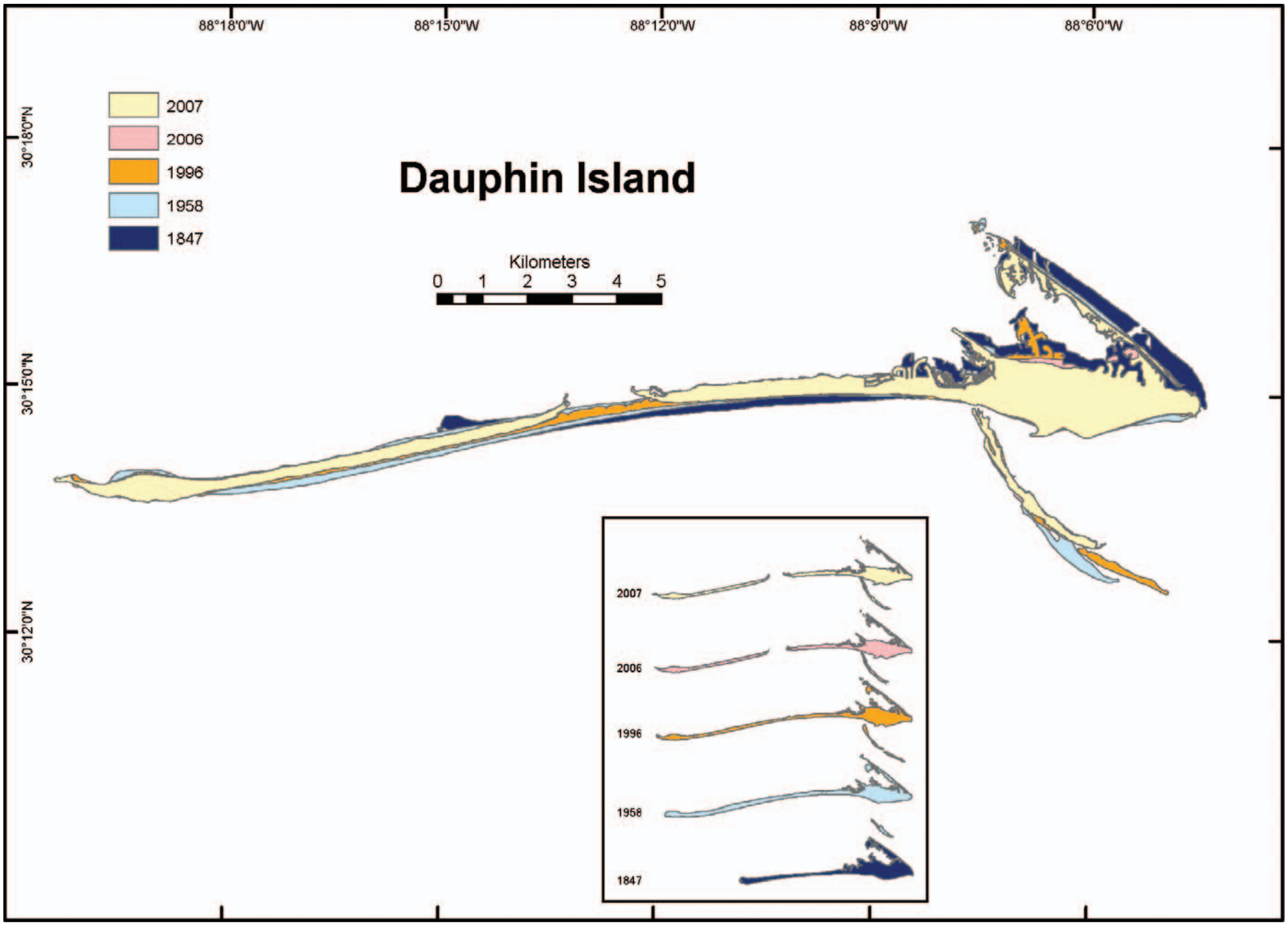

Figure 2. Morphological and spatial changes in Dauphin Island between 1847 and 2007.

Ship Island between 1848 and 1986. Their bathymetric comparisons for successive periods revealed the alterations in Mississippi Sound related to dredging of the Gulfport Ship Channel. Byrnes *et al.* (1991) compared the island shapes and calculated subaerial change rates. McBride, Byrnes, and Hiland (1995) developed a morphological classification of long-term shoreline responses that recognized eight types of barrier-island change including *in situ* narrowing, lateral movement, and breakup. Otvos and Carter (2008) provided a detailed account of storm-related morphological changes along the MS-AL barrier-island chain. The present study extends the land-change analyses of Byrnes *et al.* (1991) and Otvos and Carter (2008) by illustrating the barrier-island transformations between the mid-1800s and 2007, assessing the physical factors that were likely responsible for the substantial losses in land area, and qualitatively predicting the most likely future changes along the barrier-island chain.

Materials and Methods

Several different approaches were used to document long-term historical changes in barrier-island shape, size, and position. Most of the island perimeters (shorelines) used to investigate long-term subaerial changes in the Mississippi barrier islands were acquired from the Mississippi Office of Geology (2004). Electronic datasets included (1) high-water lines digitized from historical topographic sheets and aerial photographs and (2) high-water lines surveyed between 1998 and 2002 using global positioning system (GPS) equipment. Comparable historical topographic and aerial photographic high-water lines also were compiled and digitized for Dauphin Island. The 2006 high-water line for Dauphin Island was derived from high-resolution aerial photographs provided by the Geological Survey of Alabama. All of the high-water shorelines are horizontally controlled but vertically uncontrolled. In contrast, both horizontally and vertically controlled shorelines were derived from U.S. Geological Survey (USGS)/National Aeronautics and Space Administration (NASA) lidar surveys. The lidar vertical elevations are referenced to the North American Vertical Datum of 1988. Lidar surveys were conducted for the Mississippi islands in September 2005, 2 weeks after Hurricane Katrina, and for the Mississippi islands and Dauphin Island in June 2007. Mor-

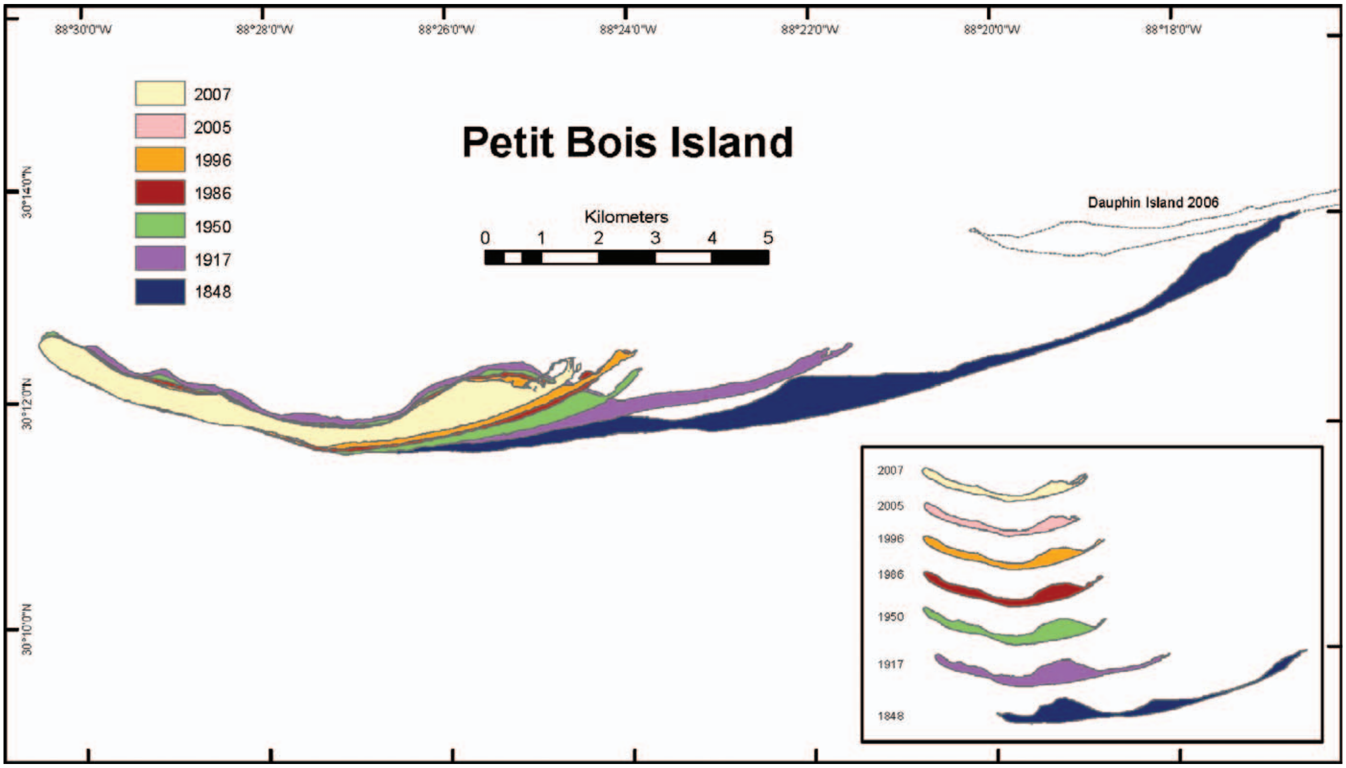

Figure 3. Morphological and spatial changes in Petit Bois Island between 1848 and 2007.

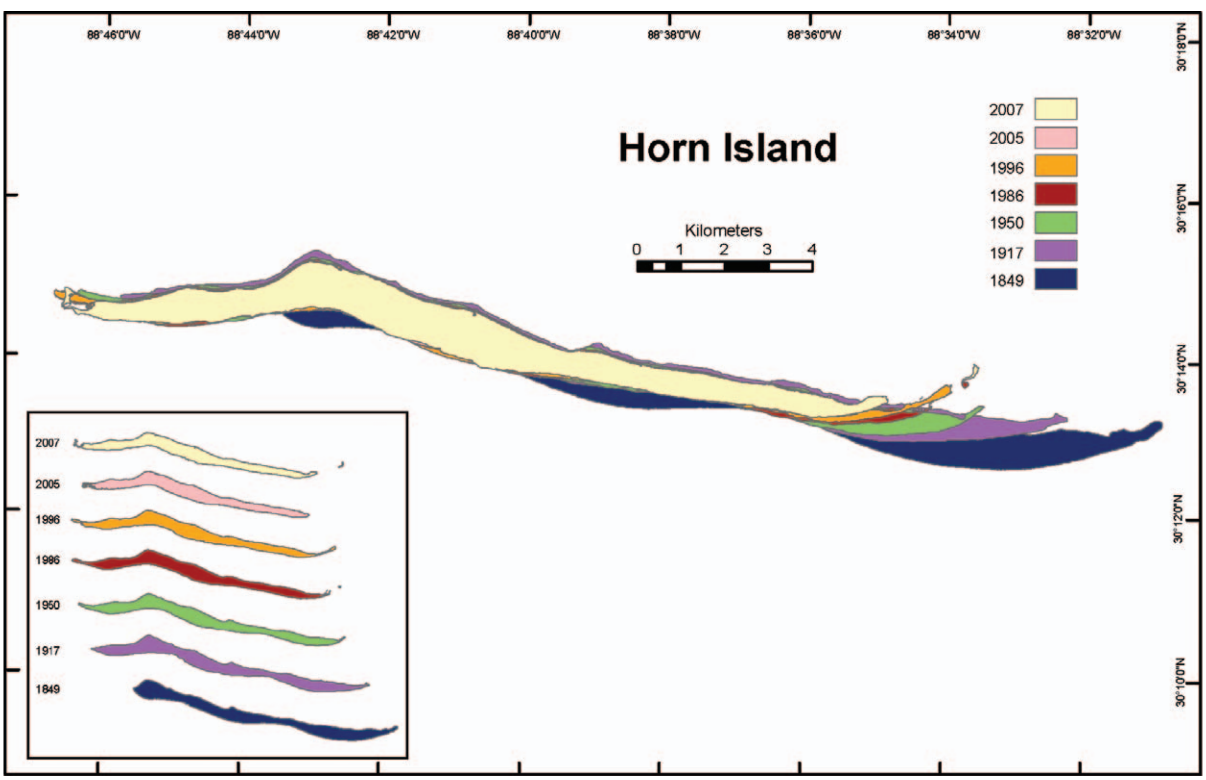

Figure 4. Morphological and spatial changes in Horn Island between 1849 and 2007.

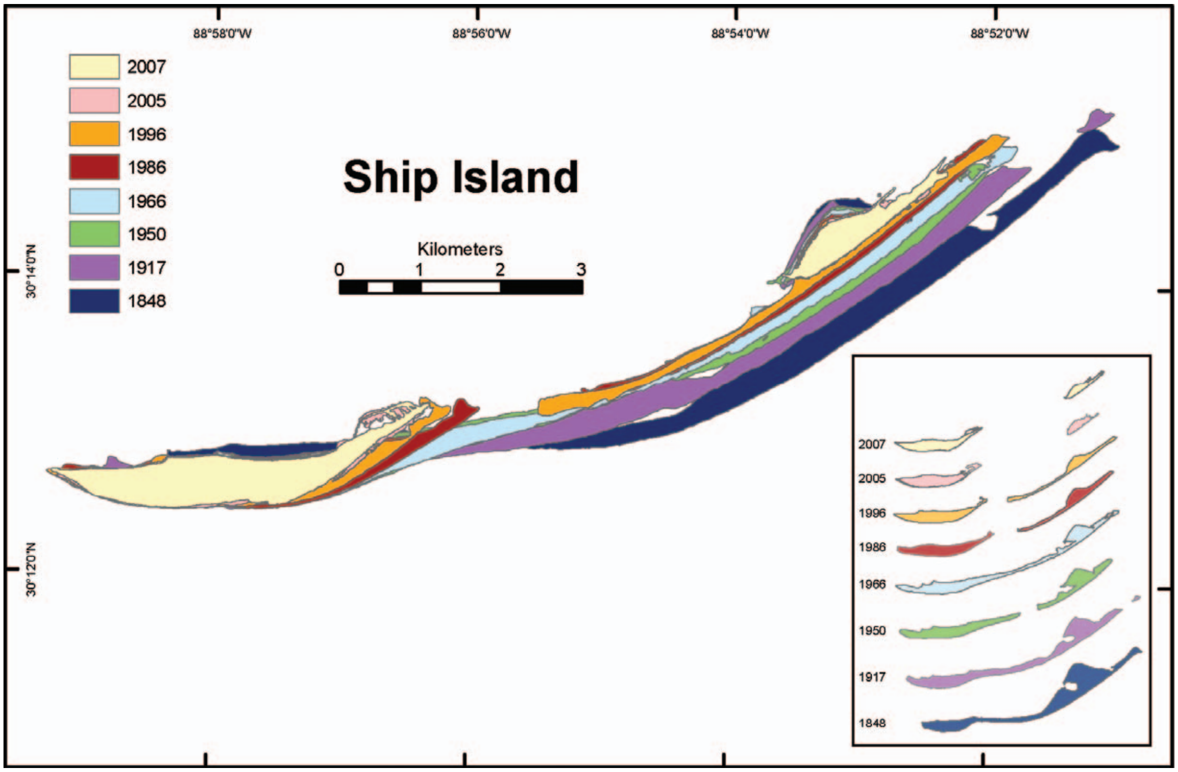

Figure 5. Morphological and spatial changes in Ship Island between 1848 and 2007.

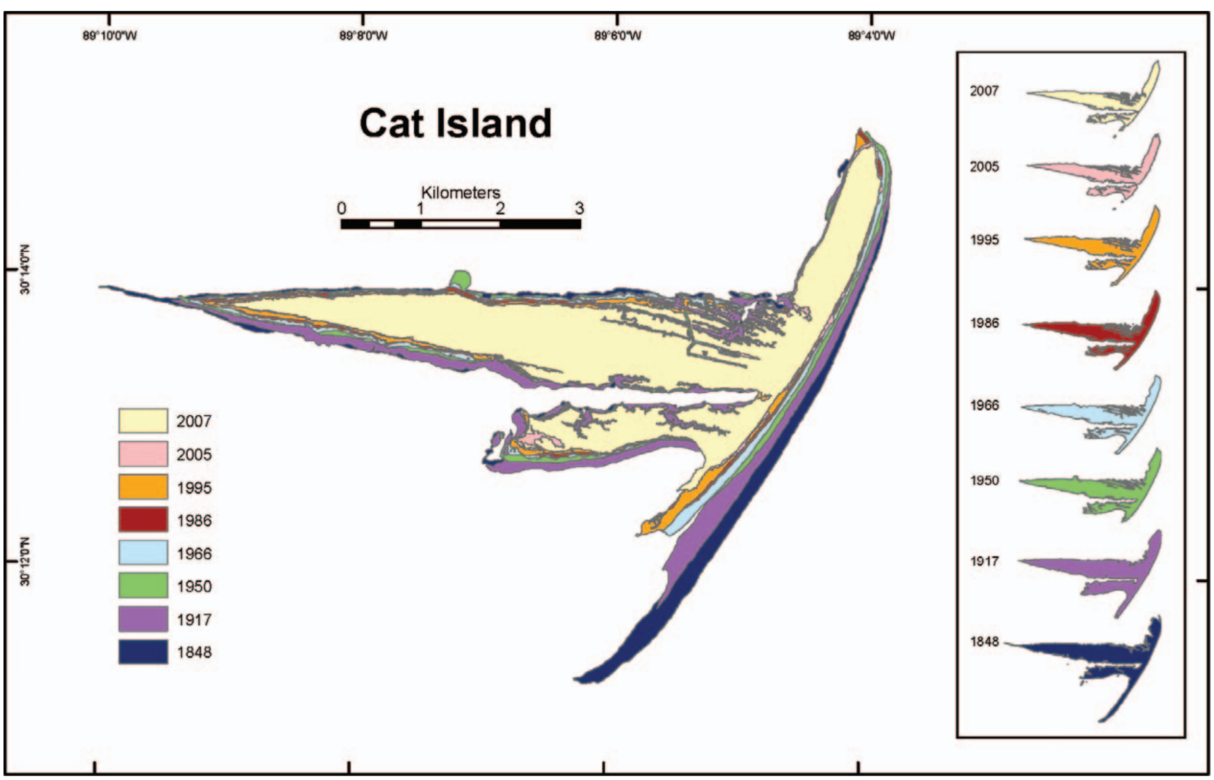

Figure 6. Morphological and spatial changes in Cat Island between 1848 and 2007.

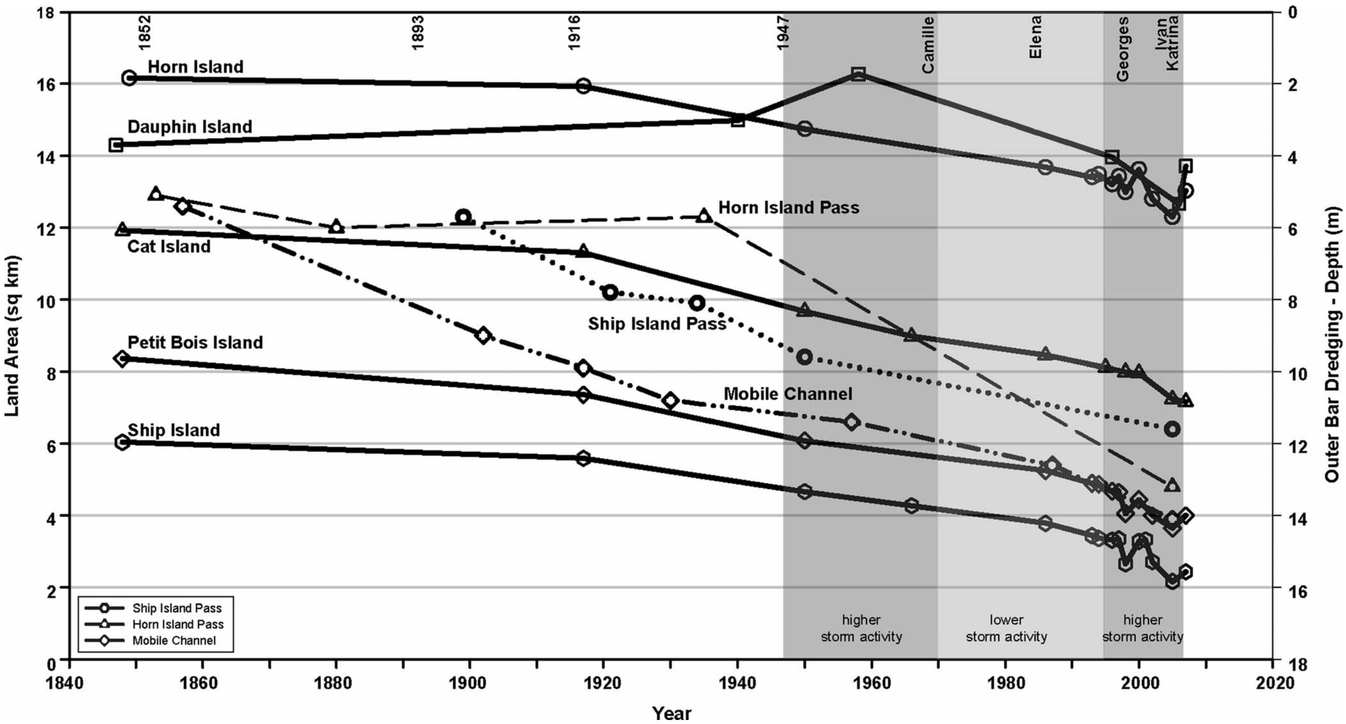

Figure 7. Historical land-loss trends for the Mississippi-Alabama barrier islands relative to the timing of major hurricanes that impacted the islands, cycles of variable storm intensities, and depths of shipping channels dredged through the outer bars at three tidal inlets within the barrier-island chain.

ton, Miller, and Moore (2004) discussed definition and establishment of the operational mean high-water line used to extract shorelines from lidar data.

Each of the shoreline positions has some uncertainty associated with the original data sources. In general, the older shoreline perimeters have the greatest positioning errors and the most recent shoreline perimeters have the least error. According to Shalowitz (1964), horizontal-positioning errors for the late 1840s shorelines were within 10 m. Metadata indicated that the GPS-surveyed shorelines were within 5 m, and error analyses for the lidar surveys indicate that they were within about 1 m of their true horizontal position (Stockdon *et al.,* 2002). Additional analytical uncertainty is introduced by digitizing the pre-GPS and lidar shorelines. Prior assessments of digitizing errors using similar data sources and techniques have been found to be minimal (Anders and Byrnes, 1991; Crowell, Leatherman, and Buckley, 1991).

Morton, Miller, and Moore (2004) discussed in detail the errors associated with extraction, digitization, and rectification of shoreline proxies. They also quantified, at selected coastal sites in the United States, the horizontal and vertical offsets introduced by combining shoreline proxies that are uncontrolled with respect to elevation (high-water line) and lidar-derived shorelines that are controlled with respect to elevation (operational mean high-water line). For the microtidal, low-wave-energy Gulf of Mexico, the measured horizontal offsets were well within the range of horizontal errors previously reported for the vertically uncontrolled high-water lines.

Table 1. *Average rates of land-area change for Dauphin Island for selected periods. Rates are in ha/y. Positive numbers indicate land gain, and negative numbers indicate land loss.*

1847–1917	1847–1940	1940–1958	1958–1996	1996–2007	1847–2007
*	+0.73	+7.17	−6.1	−2.2	−0.4

* 1917 posthurricane survey shows much of the island was submerged.

Island Histories and Morphological Changes

Each of the MS-AL barrier islands had a unique evolution between the mid-1800s and 2007 that altered its shape, position, and future vulnerability to storm impacts. The most significant changes are evident from sequential comparison of the island geometries (Figures 2–6) and areal change rates (Figure 7 and Tables 1 and 2). The 2005 and 2007 island shorelines and land areas provide a basis for documenting the nearly instantaneous impacts of Hurricane Katrina on the barrier islands and their partial recovery 2 years after that extreme storm.

Dauphin Island

Before Petit Bois Island separated from Dauphin Island and migrated westward in the 18th century, Dauphin Island was the largest island in the MS-AL island chain. Those events significantly reduced the size of Dauphin Island and

Table 2. *Average rates of land-area change for the Mississippi barrier islands for selected periods. Rates are in ha/y. Negative numbers indicate land loss.*

Period	Petit Bois Island	Horn Island	Ship Island	Cat Island
1840s–1917	−1.5	−0.3	−0.6	−0.9
1917–1950	−3.9	−3.6	−2.8	−4.9
1950–1986	−2.3	−3.0	−2.4*	−3.4
1986–2007	−5.9	−3.1	−6.4	−6.1
2000–2007	−6.3	−8.6	−12.1	−11.3
1840s–2007	−2.7	−2.0	−2.3	−3.0

* Includes increased land area from artificial island fill.

Table 3. *Percent changes in land area of the Mississippi-Alabama barrier islands between the late 1840s and 2007. Areas are in hectares.*

Island	1840s Area	2007 Area	% Net Loss
Dauphin	1429	1372	4
Horn	1616	1303	19
Cat	1192	717	40
Petit Bois	836	400	52
Ship	604	243	60

provided space for its subsequent regrowth. In contrast to its relatively stable eastern end, the narrow western three-fourths of Dauphin Island has changed dramatically as a result of two independent processes. The island has grown westward at its western terminus through lateral spit accretion and inlet migration (Figure 2). In fact, the downdrift end of the island has grown so far westward that it overlaps the former position of the eastern end of Petit Bois Island in the mid-1800s (Figure 3). Also, the narrow island segment has migrated landward primarily as a result of gulf beach erosion and storm-overwash deposition, supplemented by formation and filling of breaches.

The 1853–54 topographic map shows that Dauphin Island was breached in two places by wide inlets opened as a result of hurricanes in the northern gulf in 1851 and 1852 (U.S. Army Corps of Engineers, 1965). The breaches were not open at the time of the 1847 topographic survey.

Areal changes for Dauphin Island during the early 1900s are not well defined because inclusion of the 1917 shoreline perimeter would have greatly biased the land-change trend as a result of the submerged conditions mapped immediately after the 1916 hurricane. Unlike the Mississippi barriers, the area of Dauphin Island increased (Figure 7) between 1847 and 1940 and between 1940 and 1958 at average rates of 0.73 and 7.17 ha/y, respectively, as a result of spit accretion on the western end of the island (Figure 2, Table 1). After 1958, the island entered a net erosional phase that has persisted. Land loss rates, which averaged −6.1 ha/y between 1958 and 1996, decreased to −2.2 ha/y between 1996 and 2007. The most recent short-term decrease in land-loss rate is somewhat biased because Hurricane Katrina redistributed sand along the tidal-delta spit (Pelican Island), gulf beaches, and western end of Dauphin Island as the barrier partly recovered from the losses caused by Katrina.

Petit Bois Island

Petit Bois Island underwent the most rapid and radical historical changes. The wide triangular segment of the island located on its extreme western end in 1848 (Figure 3) was located in the center of the island by 1917. The triangular segment formed the eastern end of the island by 1950 as a result of continued erosion of the eastern spit and extension of the western spit. Since then, Petit Bois has continued to narrow, and the eastern shore has rotated counterclockwise because of wave refraction and associated differential erosion and overwash along the eastern gulf beach.

Between 1848 and 2007, Petit Bois Island lost 52% of its land area (Table 3). During the first period of record (1848 and 1917), land loss rates were the highest for any of the MS barriers, but they were relatively low at about 1.5 ha/y (Table 2). Since then, land loss rates have progressively increased from −3.9 ha/y between 1917 and 1950 to −5.9 ha/y between 1986 and 2007. Land-loss rates decreased slightly to −2.3 ha/y between 1950 and 1986. Most recently (2000–2007), the average rates of land loss were the highest at −6.3 ha/y, which includes the losses attributable to Hurricane Katrina.

Horn Island

Long-term morphological changes to Horn Island (Figure 4) were similar to those for Petit Bois Island. The eastern part of Horn Island eroded substantially and some of that sediment was transferred to the western tip of the island that grew by lateral spit accretion. The island orientation changed where the spit attached to the former western end of the island. Beach erosion around the island perimeter also caused it to narrow in general, but some accretion along the gulf shore caused the island to widen and retain its quasi-sinusoidal alongshore pattern. Like Petit Bois, Horn Island lost substantially more land area on the eastern end than it gained on the western end, and the eastern end rotated counterclockwise as a result of wave refraction and associated differential erosion.

Of all the Mississippi barrier islands, Horn Island experienced the least cumulative land loss (19%) since 1849 (Table 3) and the lowest land loss rate for the initial period of record (1849–1917), when areal losses averaged −0.3 ha/y (Table 2). Average land loss rates increased to −3.6 ha/y for the next period (1917–1950), then decreased slightly to −3.0 ha/y between 1950 and 1986 and −3.1 ha/y between 1986 and 2007. For Horn Island, the average short-term land loss rates were highest (−8.6 ha/y) between 2000 and 2007.

Ship Island

Ship Island also experienced robust change during the past century and a half. The most significant changes were rapid retreat of the eastern spit and erosion of the adjacent stable triangular segment (Figure 5). The central narrow segment also retreated landward as the eastern and western stable segments narrowed due to erosion around the perimeter. Ship Island also has been prone to breaching during storms that resulted in barrier segmentation. Historical documents indicate that the narrow segments of Ship Island were breached by hurricanes in 1853, 1947, and 1969 (Camille). The 1950 USGS topographic map and the 1958 U.S. Department of Agriculture air photos (Waller and Malbrough, 1976) indicate that Ship Island was separated into east and west segments either continuously or for long periods before Hurricane Camille. However, the pre-Camille breaches eventually shoaled, and the narrow barrier segments were rebuilt by constructive non–storm waves that reworked sand from the surrounding platform, enabling the narrow barrier segments to become subaerial once again. Since 1969, Ship Island has been separated into east and west segments.

Between 1848 and 2007, Ship Island lost about 60% of its initial land area (Table 3), and the land loss rates generally increased. Average losses of −0.6 ha/y between 1848 and 1917 increased to −2.8 ha/y between 1917 and 1950 (Table 2). A slight decrease to −2.4 ha/y occurred between 1950 and 1986, when approximately 20 ha of land were artificially added to the island near Fort Massachusetts. Land loss rates subsequently increased to 6.4 ha/y between 1986 and 2007. Within that period, land losses averaged −12.1 ha/y between 2000 and 2007, because Hurricane Katrina severely eroded Ship Island and recovery was relatively minor.

Cat Island

The island that changed the least morphologically was Cat Island, which has remained a relatively stable landform throughout its recent history. This is because interior elevations and the orientation of Cat Island prevent breaching and overwash by storm waves except along spits of the eastern shore. Although the core of the island has not moved, the island perimeters have shifted as a result of substantial unequal erosion along the east-facing shore (Figure 6). Greater erosion along the southern spit compared to the northern spit caused a clockwise rotation of shoreline position, spit shortening, and retreat of the western spit. Erosion around the rest of the island has caused island narrowing.

By 2007, Cat Island had lost 40% of the land area it encompassed in 1848 (Table 3), and land loss rates generally increased during that period. For the initial period of record between 1848 and 1917, land loss rates averaged −0.9 ha/y (Table 2). The average rate of land loss increased to −4.9 ha/y between 1917 and 1950, but decreased slightly to −3.4 ha/y between 1950 and 1986. Between 1986 and 2007, the land loss rate on Cat Island averaged −6.1 ha/y, with the rate between 2000 and 2007 averaging −11.3 ha/y. Land-loss rates for these latter periods include both the effects of Hurricane Katrina and the poststorm recovery period.

Patterns and Processes of Land Loss

Sequential comparisons of barrier-island shapes and positions (Figures 2–6) reveal similar patterns of change both for individual islands and for multiple islands within the barrier-island chain. The systematic patterns of land loss common to all of the islands are barrier narrowing and unequal lateral migration. Dauphin Island and Ship Island are also prone to barrier breaching and island segmentation, which is another repeated pattern of land loss.

Barrier narrowing results from long-term beach erosion around the perimeter of an island that is driven by the impact of high-energy waves and currents in both the Gulf of Mexico and in Mississippi Sound. The energetic waves and currents are generated by intense wind systems circulating around centers of low barometric pressure in the summer (tropical cyclones) and winter (cold fronts). Beach erosion along the sound-side shores of the Mississippi barriers has been substantial and is reflected in the narrowing of Petit Bois and Horn Islands (Figures 3 and 4). Sound-side erosion also contributed to the narrowing of Ship Island and the need to protect Fort Massachusetts with beach fill. However, gulf shoreline erosion has been a more significant factor in narrowing the MS-AL barrier islands than sound-side erosion.

Land loss associated with unequal lateral migration results when the volume of sand eroded from the updrift end of the barrier island is substantially greater than the concomitant volume of sand transferred to the downdrift end of the island and deposited in a terminal spit. The updrift erosion also involves landward shoreline rotation at the updrift end of the island.

Island segmentation caused by storm-channel breaching can also contribute to land loss by direct erosion of the barrier and by exposing more shore to erosive processes. Only the narrow segments of Dauphin Island and Ship Island have been breached repeatedly by storm channels (Figures 2 and 5), and only recently have those channels been so large and sand-transport rates so low that the channels persisted after the poststorm recovery period. Channels opened through Ship Island by hurricanes in 1852, 1916, and 1947 eventually filled, as did channels on Dauphin Island after hurricanes in 1852, 1916, 1947, and 1979 (Frederic). Breaching of Cat Island and Horn Island has been prevented partly by their slightly higher elevations and broader widths. In addition, the size of nearby tidal inlets large enough to accommodate the storm-surge buildup prevented the hydraulic-head differential between the Gulf of Mexico and Mississippi Sound that is a prerequisite for island breaching.

HISTORY OF HUMAN MODIFICATIONS

The eastern half of Dauphin Island has been partly stabilized by groins and riprap around Fort Gaines and the construction of bulkheads along the sound-side shores. Except for these surficial modifications, the MS-AL barrier islands are mostly undeveloped and have remained generally in a natural state despite the use of some of the islands for national defense purposes. Some of the tidal inlets are unaltered, whereas three have been modified and linked to mainland ports by navigation channels (Figure 1) that are maintained by periodic dredging. Unlike major shipping channels through tidal inlets elsewhere, the MS-AL inlets and dredged entrance channels have not been stabilized by hard structures, such as jetties anchored at the ends of the islands.

Mobile Ship Channel

Interest in dredging a navigation channel between Mobile, Alabama, and the Gulf of Mexico began in 1826 (Bisbort, 1957; U.S. Army Corps of Engineers, 1953). By 1857, the Mobile Ship Channel was dredged to a depth of 3 m across Mobile Bay to intersect with the tidal inlet that separates Dauphin Island and Fort Morgan Peninsula. In 1857, the original controlling depth of the outer bar at the Mobile Bay Entrance was 5.4 m. Dredging enlarged the outer-bar channel to 9 m deep and 90 m wide in 1902, 9.9 m deep and 135 m wide by 1917, 10.8 m deep and 135 m wide by 1930, 11.4 m deep and 180 m wide by 1957, and 12.6 m deep and 180 m wide by 1987 (Ryan, 1969). From the time of initial entrance-channel dredging, the controlling depth of the outer bar was exceeded, and by 1930 the natural thalweg depth of the outer bar had been exceeded. At its maintained depth of 14.3 m, the entrance channel exceeds the original outer-bar controlling depth by 8.9 m. As dimensions of the Mobile Ship Channel steadily increased, so did the average annual maintenance dredging requirements (Bisbort, 1957).

Horn Island Pass (Pascagoula Channel)

In 1853, the natural controlling depth across the outer bar at Horn Island Pass was 4.5 m, and average depths of the inlet thalweg were about 5.1 m. Deepening of Horn Island Pass and modifications that would later become part of the ship channel to Pascagoula began as early as 1880 (U.S. Army Corps of Engineers, 1935). At that time, a channel across the outer bar was dredged to a width of 60 m and a depth of 6 m, but the channel subsequently shoaled to a depth of 5.4 m (U.S. Army Corps of Engineers, 1904). By 1935, the dredged channel across the outer bar was 5.7 m deep and 90 m wide (U.S. Army Corps of Engineers, 1935). In 2005, maintained dimensions of the outer-bar channel were 13.2 m deep and 135 m wide, and maintained dimensions of the Horn Island Pass Channel were 12.6 m deep and 180 m wide. The dredged bar-channel depth in 2005 was 7.8 m below the original controlling depth of the outer bar. Perhaps of greatest importance, with regard to sediment-transport alterations, is the channel adjacent to the western end of Petit Bois Island. There a segment was dredged to 16.8 m with the intent of trapping sediment (Bunch *et al.,* 2003) that likely would have bypassed around the ebb-delta shoals under natural conditions (Fitzgerald, Kraus, and Hands, 2001).

Ship Island Pass (Gulfport Harbor)

In 1899, the federal government began work on a channel through the Ship Island Pass outer bar, which had a natural controlling depth of about 5.7 m (U.S. Army Corps of Engineers, 1935). Between 1901 and 1903, private investors interested in the economic development of Gulfport, Mississippi, dredged the Gulfport Ship Channel across Mississippi Sound to connect with the Ship Island Pass channel, which borders the western end of Ship Island. The initial dredged dimensions of the ship channel across the sound were 90 m wide and 5.7 m deep (U.S. Army Corps of Engineers, 1935). By 1921, the shipping channel had been deepened to 7.8 m (Knowles and Rosati, 1989). In 1934, the channel across the outer bar was about 90 m wide and 8.1 m deep (U.S. Army Corps of Engineers, 1935). By 1950, the channel through Ship Island Pass and the outer bar was 90 m wide and 9.6 m deep (Knowles and Rosati, 1989). These channel dimensions remained unchanged until at least 1988 (Grandison, 1988). In 2005 the channel through Ship Island Pass and the outer bar was 122 m wide and it had been deepened to 11.6 m, or double the natural controlling depth of the outer bar.

Ship Island Restoration

After Fort Massachusetts was constructed on Ship Island in the 1860s, beach erosion near the western end of the island eventually exposed the fort to periodic flooding, and waves from Mississippi Sound threatened to undermine the structural integrity of the fort (Henry, 1976). To protect the fort from frequent inundation and destruction, approximately 382,000 m^3 of sand dredged for maintenance of Ship Island Pass (Gulfport Ship Channel) was used to rebuild approximately 1.5 km of the northwestern side of the island in 1974 (Henry, 1976). When sound-side beach erosion continued, more than 280,000 m^3 of sand was added through periodic dredge and fill events in 1980 (76,460 m^3), 1984 (160,566 m^3), and 1991 (44,346 m^3). The repeated fill projects advanced the shore into Mississippi Sound as much as 125 m and to a depth of 2–2.5 m (Chaney and Stone, 1996). Ineffective erosion-mitigation structures placed along the sound-side shore near the fort included two sunken barges to act as a breakwater and a rock seawall, which was undermined and failed (Chaney and Stone, 1996).

Impacts on Sediment Transport

Four prior studies evaluated the impacts of dredged navigation channels on sediment transport and sediment budget of the MS-AL barrier islands. Knowles and Rosati (1989) estimated sediment-transport rates in the vicinity of Ship Island between 1848 and 1986. They reported that sediment transported westward was deposited in the Ship Island Pass navigation channel, which increased periodic maintenance dredging and prevented sediment accumulation on the western tip of Ship Island at rates ranging from 31,000 to 121,000 m^3/y.

Douglass (1994) calculated sediment-transport rates along Dauphin Island and compiled dredging records for the ebb-delta segment of the Mobile Ship Channel between 1974 and 1989. The total volume of sediment dredged from the ebb-delta segment during the 15-year period was nearly 12 million m^3, and the sediment volume removed for maintenance averaged more than 450,000 m^3/y. On the basis of these large sediment volumes and their position with respect to the former outer bar, Douglass (1994) concluded that the Mobile Channel served as a sediment trap that disrupted the littoral transport system.

Cipriani and Stone (2001) examined textural trends of the gulf shore beaches and calculated net alongshore sediment-transport rates for the region. The results of their study indicated zero sediment exchange across most of the tidal inlets. They also concluded that the dredged channel at Horn Island Pass acted as a sediment sink.

Rosati *et al.* (2007) showed that sediment volumes dredged from Horn Island Pass and Ship Island Pass increased exponentially since the early 1900s when systematic channel modifications began. The rates of sediment removed from the navigation channels separating the barrier islands accelerated between 1950 and 1960 such that average annual dredging from Horn Island Pass increased from about 26,000 m^3/y to about 394,000 m^3/y; average annual sediment volumes removed from Ship Island Pass increased from 33,000 m^3/y to about 443,000 m^3/y. The order of magnitude increases in dredging rates partly reflect increased channel dimensions, but they also indicate enhanced ability of the enlarged channels to impound sand in transport. Rosati *et al.* (2007) concluded that the dredged channels at Horn Island Pass and Ship Island Pass were probably total traps for sediment transported in the littoral drift zone.

These studies provide strong direct evidence that the overdeepened channels through the former outer bars prevent sediment bypassing around the ebb-tidal deltas that would have supplied the shores of downdrift barrier islands.

Management of Dredged Sediment

Sediment dredged from the MS-AL shipping channels typically has been placed in designated disposal sites along the margins of the channels or in unconfined open-water disposal sites offshore from the barrier islands (Knowles and Rosati, 1989). These practices conducted around the tidal inlets between the barrier islands permanently removed large volumes of beach-quality sand from the sediment-transport system that otherwise would have nourished the adjacent barrier islands and mitigated land losses. Although most of the disposal practices contributed to a reduction in the sediment budget of the barrier islands, several have been beneficial. These include direct placement of dredged material on Ship Island to protect Fort Massachusetts (Henry, 1976), enlargement of a shoal using a disposal area between Petit Bois Island and Horn Island, and construction of submerged berms on the ebb-tidal delta at the entrance to Mobile Bay (Hands and Allison, 1991).

ASSESSMENT OF FACTORS CONTROLLING BARRIER-ISLAND LAND LOSS

The remarkable temporal similarity of generally accelerated rates of land loss for each of the MS-AL barrier islands (Figure 7) indicates that one or more of the primary regional factors causing land loss has changed substantially since the mid-1800s. The three most likely causes of land loss in the Gulf Coast region are frequent intense storms, a relative rise in sea level, and a reduction in sediment supply (Morton, 2003).

Storm Cycles

Most of the intense hurricanes that make landfall in the Gulf of Mexico originate in the North Atlantic Basin, although a few originate in the Caribbean Sea. Tropical cyclone activity in the North Atlantic occurs in multidecadal cycles that are controlled by fluxes in global atmospheric patterns (El Niño-Southern Oscillation), sea-surface temperatures, and other climatic factors (Emanuel, 1987; Goldenberg *et al.,* 2001; Gray, 1990). Records for statistical analyses of North Atlantic storms are incomplete before the early 1900s (Landsea *et al.,* 1999); therefore, any results of statistical analyses using storm counts or metrics from the mid-to-late 1800s period could be misleading. It is generally recognized that periods of high storm activity in the North Atlantic extended from the late 1940s through the late 1960s and since 1995, but the 1970s through the early 1990s was a period of low storm activity (Goldenberg *et al.,* 2001; Gray, 1990). The trends of historical land losses for the Mississippi barrier islands collectively illustrate a progressive increase with time, which correlates partly with the periods of high storm activity (Figure 7). However during the period of low storm activity, land-loss rates continued to increase, calling into question a predominant causal relation between storm activity and a progressive increase in land-loss rates. The post-1995 acceleration in rates of barrier-island land loss may be partly a result of the increased storm activity since 1995.

Winter storms affecting the MS-AL barrier islands are substantially more frequent than tropical cyclones. North winds and the cumulative wave energy that they generate and dissipate on the islands are largely responsible for erosion of the Mississippi Sound shores of the islands (Chaney and Stone, 1996). The systematic erosion of the sound-side shores also contributes to island narrowing and the associated land loss.

Sea Level

The longest sea-level record in the northern Gulf of Mexico is for Galveston, Texas, where average annual measurements are available since 1910 (National Oceanic and Atmospheric Administration,, 2008). The sea-level record for Pensacola, Florida, extends back to 1923. Both of these records, which cover the periods of increased rates of barrier-island land loss, are highly correlated and show the same trends in the relative rise in sea level and the same details of the short-term secular variations. Neither of these tide-gauge records, which together characterize the region of the MS-AL barrier islands, shows a historical accelerated rise in sea level that would explain the rapid increase in barrier-island land loss rates. Taking into account the differences in vertical land movement at Galveston (subsiding) and Pensacola (relatively stable), the tide-gauge records show a relatively uniform rate of relative sea-level rise for the periods of record. The historical tide-gauge record at Dauphin Island (1966–1997) showed a rate of relative sea-level rise (2.9 mm/y) that is comparable to the rate recorded at Pensacola (2.1 mm/y). Both of these rates of relative sea-level rise are only slightly greater than the eustatic rise in sea level of about 1.8 mm/y (Douglas, 2001).

Sand Supply

Historically, large volumes of sand have been released to the alongshore sediment-transport system as a result of erosion of the MS-AL barrier islands, but much of that sand has not benefited downdrift island segments or adjacent barriers. The volume of sand supplied to the MS-AL barrier islands by alongshore currents has been reduced progressively since the late 1800s as the outer bars at the entrance to Mobile Bay, Horn Island Pass, and Ship Island Pass were dredged to increasingly greater depths (Figure 7; Byrnes *et al.,* 1991; Douglass, 1994; Rosati *et al.,* 2007; Waller and Malbrough, 1976). In the mid-1800s, the natural controlling depths of tidal inlets connecting Mississippi Sound with the Gulf of Mexico were from 4.5 to 5.7 m. Since then, the outer-bar channels have been repeatedly dredged to depths well below their natural depths and that of the surrounding seafloor. The initial shallow dredging would have had minimal effect on sediment transport, but the cumulative effects of nearly simultaneous deepening of the navigation channels through the outer bars would eventually prevent the sediment-transport system from transferring sand to the downdrift barriers. This temporal progression is consistent with observations at Ship Island Pass that shoaling was substantially greater than maintenance dredging by the 1950s (Knowles and Rosati, 1989), and at Horn Island Pass and Ship Island Pass that trapped sediment volumes increased exponentially as channel dimensions increased (Rosati *et al.,* 2007).

The channel modifications eventually disrupted the littoral system and rendered it incapable of transferring sand across the ebb-tidal deltas. Most of the sand in transport along the Gulf shores of the MS-AL barriers became trapped in the navigation channels (Cipriani and Stone, 2001). The impounded sand was then removed by dredging and placed mostly in disposal sites (Knowles and Rosati, 1989) where it was unavailable for barrier-island nourishment. The temporal increase in sand volume removed from the littoral system as a result of channel dredging (Bisbort, 1957; Rosati *et al.,* 2007) generally matches the historical trend of progressive increases in barrier-island land loss (Figure 7).

Each of the MS-AL barrier islands is affected by one of the navigation channels that compartmentalize the alongshore sediment-transport system and reduce sand supply. The navigation channels act as sediment sinks, removing sand that otherwise would have been available for beaches immediately downdrift of the channel if the ebb-tidal delta had not been modified (east Dauphin Island, east Horn Island, Cat Island spits). Sand also goes into the channel instead of constructing a platform and spit for island extension at the downdrift ends of some barriers (Petit Bois Island and Ship Island). Dauphin Island is probably least affected by the induced reduction in sand supply, because the large volume of sand stored in the ebb-tidal delta is still available for remobilization and barrier nourishment.

Sea-level rise is the primary driver of coastal land loss over geological time scales (centuries, millennia), whereas storms are the agents of sediment redistribution and land loss for short time scales (years, decades). However, land-loss potential associated with these processes can be offset or at least minimized if sediment supply is abundant. But when sediment supply is reduced, then land loss is exacerbated because the sediment redistributed by storms is not replenished by the sediment-transport system.

FUTURE BARRIER-ISLAND TRENDS

Accurately predicting the future sizes, configurations, and positions of the MS-AL barrier islands depends on an accurate record of geological and historical changes to the islands and knowledge of future conditions. The future conditions would include sand supply rates, sediment transport rates, relative sea-level rise rates, regional storm frequency and intensity, and the likely responses of the barrier islands to future storms compared to those of the past. Without this extensive knowledge base, even limited qualitative predictions would require assumptions of future conditions. Such assumptions include: (1) no additional modifications to the littoral system that would alter wave energy and sand supply; (2) rates of sea-level rise will be at least as high if not higher than those of the past century; and (3) storms will have similar tracks and be at least as frequent and intense as they were during the 20th century.

The uncertainty of the ages and origins of the MS-AL barrier islands also inhibits accurate predictions of their fate. Clearly the extant oceanographic and geological conditions are substantially different from those when the barrier islands first formed and accumulated sand. Although it is a well-known fact that short-term rates of change of natural systems commonly exceed long-term, time-averaged rates of change, the historical rates of land loss of the MS-AL barriers greatly exceed the geological rates of land loss. Considering the size (land area) of each barrier island in the mid-1800s and the comparable land loss rates during the past century and a half (Figure 7), each island has been reduced in area to the mid-1800 size of the next smallest island. Only Dauphin Island experienced a period of net land gain that delayed its reduction in land area to that of the next smallest island.

Under low to moderate rates of relative sea-level rise, barrier islands typically do not lose their entire land mass, because eventually they become so low and narrow that surficial processes are dominated by storm overwash. For these conditions, sand eroded from the open-ocean shore is transported entirely across the barrier island and deposited in the adjacent marsh or lagoon. In this transgressive state, the barrier is able to maintain a minimum volume as it migrates landward across the marsh surface or shallow water. Although the western three-fourths of Dauphin Island is presently a transgressive landform (Figure 2), it is not clear that Petit Bois, Horn, or Ship Islands will eventually enter a transgressive phase, wherein the predominant sand-transport direction is onshore rather than alongshore. The predominance of westward alongshore sand transport both at geological and historical time scales indicates that this motion will likely prevail in the future, being driven by the prevailing winds, storm waves, and associated currents. Even the low, narrow, updrift spits of the Mississippi barrier islands that were predisposed to overwash and landward migration were constrained by the adjacent beach-ridge interior cores to the extent that the spits became shorter as they progressively moved landward, but the cores remained stationary (Figures 3–5). Wave energy in Mississippi Sound has kept the sound-side of the barrier chain relatively deep. A substantial volume of overwash sand would be necessary to extend the platform into deeper water while maintaining a subaerial barrier island instead of a subaqeous shoal. Thus, water depths in the sound also inhibit onshore barrier migration.

The future of the Mississippi barrier islands depends largely on the future of their cores and whether sufficient sand is available for platform construction as sea level continues to rise and storms modify the island geometries. Petit Bois and Ship Islands are prevented from migrating westward because the dredged channels maintained near their downdrift ends intercept sand that would have either forced westward inlet migration or filled the channel margin, constructing an inlet-margin platform and promoting lateral island extension. The presence and ages of large shoals preserved on the inner continental shelf off the Texas and Louisiana coasts are reminders that conditions favorable for drowning some barrier islands occurred previously in the northern Gulf of Mexico as a result of rapid sea-level rise during the late Holocene. Also, the demise of the Isle of Caprice and Dog Keys shoals provides historical evidence of total island destruction (Rucker and Snowden, 1988).

Prediction of future morphological and land-area changes perhaps is easiest for Dauphin Island, because it is still anchored to the Pleistocene core that provides stability to its eastern end. Armoring of the eastern end with bulkheads on the sound side and a riprap revetment along the inlet margin provides additional protection from erosion, thus minimizing additional land loss and mobility. The primary sand source of the island, the ebb-tidal delta at the Mobile Bay Entrance, is still attached and periodically supplies additional sediment to the gulf shores of the island. This sand eventually becomes the beach and dune sand that supplies downdrift spit growth and island extension. It would also supply storm-washover deposition, which enables the barrier to maintain mass as the western three-fourths of the island migrates landward. The future of the Ivan/Katrina breach through Dauphin Island is an uncertainty that will significantly influence future land-loss trends and island position. The island has been breached repeatedly west of the island core near the shallow subsurface contact between Holocene and Pleistocene sediments (Otvos and Giardino, 2004) and at other locations about 10–20 km from its eastern end. Historical documents show that wide storm breaches through Dauphin Island eventually shoaled and the beach and alongshore transport systems were restored naturally over time scales of decades. Unfortunately, the depths of previously incised channels are not well documented, so it is not possible to compare the present channel volume with those of the previous breaches as a way of forecasting if the present breach will eventually close.

Of the MS-AL barrier islands, Cat Island is the most stable in terms of position and the least modified by extreme-storm processes. This is because the northern and southern spits absorb energy from destructive, westward-propagating waves, whereas the St. Bernard Delta platform and associated Chandeleur Island chain shield the island core from northward-propagating waves. Because Cat Island is partly protected, its east-west oriented beach-ridge complexes will continue to lose area around their margins by persistent erosion, and its northeast-southwest transgressive segment will continue to retreat northwestward. Continued erosion of the island perimeter could eventually cause Cat Island to be reduced to a shoal.

The historical changes to Ship Island may be the best predictors of future morphological changes for Petit Bois and Horn Islands, the other two lateral-accretion barriers. Ship Island was reduced in size as a result of island narrowing, unequal lateral transfer, and island segmentation. The maintenance of deep dredged channels near the western ends of Petit Bois Island and Ship Island prevent lateral inlet migration and construction of shoal platforms onto which the barrier islands could be extended. Ship Island will continue to narrow and lose land area as a result of updrift erosion; however, further breaching is not likely, because the island segments are short compared to widths of the adjacent and intervening tidal inlets. Petit Bois Island will continue to narrow and lose land area as a result of updrift erosion. It will likely be segmented by breaching at one of the two sites where complete overwash occurs frequently along the narrowest, concave-landward, central part of the island (Figure 3). Horn Island also will continue to lose land as a result of unequal lateral transfer and barrier narrowing, but it has a low risk of segmentation by breaching because most of the island consists of beach-ridge topography that is oriented obliquely to the gulf shoreline. If a storm breaches Horn Island, the breach likely would occur in the narrow central part of the island (Figure 4).

DISCUSSION AND CONCLUSIONS

Relative rates of lateral inlet and island migration are recorded in the morphologies and widths of individual segments of the MS-AL barrier islands. Wide island segments, consisting of beach ridges and swales recurved landward, represent relatively slow migration and lateral filling of tidal inlets, which is driven by alongshore sediment transport and wave refraction around the inlet margins. In contrast, narrow straight segments record relatively rapid rates of island construction across a pre-existing platform that minimized tidal currents and wave refraction at the western end of the islands.

Storm processes, in conjunction with the regional bathymetry, may preferentially focus extreme waves and storm surge onto Ship Island, because the island is located between the generally east-west trend of the MS-AL barriers and the generally north-south trend of the Chandeleur Islands. Wave focusing caused by the boundary conditions may partly explain why storm-surge elevations from Hurricanes Katrina and Camille were substantially higher on Ship and Cat Islands than on the other MS-AL barriers (Fritz *et al.,* 2007). Wave focusing also may explain the greater vulnerability of Ship Island to storm impacts compared to the other MS-AL barrier islands.

The beach-ridge remnants that form the cores of the Mississippi barriers are evidence of an abundant sand supply in the geological past. Conditions of surplus sand no longer prevail, and the deficit in the sediment budget is causing the barrier islands to erode and lose surface area and volume. Average rates of barrier-island land loss for the past 150 years (Tables 1 and 2) are substantially greater than those experienced for the previous several thousand years, otherwise the barrier islands already would be much smaller or reduced to shoals. This trend indicates that historical rates of land loss are accelerated compared to those of the recent geologic past. Long-term historical rates of barrier island

land loss are remarkably similar considering the individual locations, orientations, and histories of the islands. Because the rates of land loss have been temporally consistent for each of the islands, an inverse relation exists between island size and percent reduction in land area (Table 3). Consequently, Horn Island has lost the smallest percentage of land area (19%), and Ship Island has lost the greatest percentage of land area (60%). The low percentage of land area reduction for Dauphin Island (4%) is an anomaly related to the initial period of land gain. In 2007, Dauphin Island was 16% smaller than in 1958, when it achieved its greatest historical land area since it was separated from Petit Bois Island. The long-term historical trends (Figure 7) also show that no particular period uniquely defines the island areas and configurations. Consequently, barrier-island restoration to a template for a particular time, such as pre-Hurricane Camille conditions, is arbitrary.

The predominant mechanism of land loss for Petit Bois, Horn, and Ship Islands has been unequal updrift erosion and downdrift deposition. The second most important mechanism was island narrowing. Recently, island segmentation has contributed to land loss on Ship and Dauphin Islands. Both of these islands were breached previously, but their beaches and barrier flats were subsequently restored naturally. The historical record for Ship Island indicates that its vulnerability to breaching progressively increased with time. Because of its diminished state, the Camille Cut inlet will not shoal naturally, and the East and West Ship Island segments will not become reattached as they have in the past. Whether the western end of Dauphin Island will receive enough sand in the next few years to fill the breach and restore the beach and barrier flat is uncertain.

Out of the three primary causes of land loss, sediment-budget deficiencies have been responsible for the greatest historical changes in the MS-AL barrier-island chain. Historical trends of increasing land loss, for each of the five islands, show a remarkable temporal correlation to dredging activities within the region. This correlation indicates that sediment-budget deficits stem from long-term reductions in sand supply caused by progressively deeper dredging of navigation channels across the outer bars of three tidal inlets. The channels have compartmentalized and interrupted the alongshore sediment-transport system, acting as sediment sinks and trapping sand that normally would have bypassed around the ebb-tidal delta and fed the barrier islands downdrift. The other two primary factors also contribute to barrier-island land loss, but their temporal trends are either constant (sea-level rise) or cyclical (storm activity) and cannot easily explain the observed accelerated rates of land loss. Not all of the historical land loss can be attributed to sand trapped in the navigation channels, and it is certain that the barrier islands would be losing land even if the outer bars had never been modified by dredging. For example, some of the sand removed from the islands during storms is deposited in Mississippi Sound and is dispersed over shoals or in deeper water as accommodation space is created by the eustatic rise in sea level.

The natural future trends for the MS-AL barrier islands will be continued rapid land loss as a result of rising sea level, frequent intense storms, and reduced sand supply. Both theory and modeling predict that storm intensity (Emanuel, 2005) and the rate of sea-level rise (Meehl *et al.,* 2005) will likely increase in the future as a result of global warming. If these predictions hold true, then the rates of barrier-island land loss would also increase; however, the magnitudes of the increases are uncertain. Despite uncertainties regarding the likely magnitudes of the effects of global warming, the potential for increased storm activity and rates of sea-level rise should be taken into consideration when management and restoration plans for the islands are formulated. Sand supply is the only factor contributing to barrier-island land loss that can be managed directly, and further increases in land-loss rate can be mitigated by the strategic placement of dredged material so that adjacent barrier-island shores receive it for island nourishment and rebuilding.

Most human activities on barrier islands have direct impacts on island morphologies and surficial processes (Stutz and Pilkey, 2005). However, disruption of the sand-transport system in the central Gulf of Mexico as a result of dredging had an indirect effect on the historical changes of the MS-AL barrier-island chain. Indirect anthropic impacts on barrier islands are sometimes more significant than direct impacts because they can remain undetected for long periods of time.

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