Evolution of the barrier islands in Mississippi during and following Hurricane Katrina

IMPACTS OF HURRICANE KATRINA ON THE GEOMORPHOLOGY
OF THE MISSISSIPPI BARRIER ISLANDS

A research report submitted to:
National Park Service

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**Figure 45.** Characteristic (a) pre-storm and (b) post-storm cross-shore profiles for Ship Island.
SUMMARY OF RESULTS

On all three islands, the morphological impact of Hurricane Katrina depended on the pre-storm average elevation as predicted by the Sallenger (2000) model of hurricane impacts. Specifically, the shoreline change, overwash penetration (see Morton, 2007) and volume change were inversely related to the pre-storm average elevation (Figures 1 and 2). The sediment eroded from the areas of higher average elevation (during swash and dune impact) was deposited on the shoreface as a nearshore bar. In these areas, the backbarrier island morphology remained intact, fronted by a short overwash terrace. In areas where the average pre-storm elevation was at a local minimum, the island experienced overwash early in the storm (ie. limited swash and dune impact), leading to sediment losses to the backbarrier, with some sediment deposited in the sound. These areas had limited bar development.

Some of the greatest change in island morphology occurred at the eastern ends of Horn and Petit Bois Islands and at both ends of Ship Island. The eastern end of each islands were eroded and there was a reorientation of the island to the dominant wave direction (from the SE). One of the most dramatic changes (outside the loss of land on Ship Island) was the migration of the spit terraces on the eastern end of Petit Bois Island. Based on 2001 NOAA bathymetry data, it appears that the spit terrace decreased in elevation by ~1.5 m and migrated to the north by ~315 m (Figure 3). As the nearshore bar on this terrace continues to migrate landward (to the north), it is anticipated that a small spit will emerge on the terrace as was present in the 2001 bathymetry. In contrast, the western end of Petit Bois and Horn Islands accreted (in volume and shoreline position) through alongshore sediment delivery from the east.

Based on the results of this study, there was little change in the sediment volume for Petit Bois and Horn Islands. Most of the sediment eroded from the beachface and dune systems was deposited on the shoreface as bars and recovery will depend on the onshore migration of these features. The length of time for bar migration and beachface recovery along the Gulf Coast remains poorly understood. Sediment volume on Petit Bois and Horn Islands was only lost from the islands were the overwash terraces extended to backbarrier shoreline. This sediment is most likely lost from the system through cold front erosion, although it is possible that the sediment is distributed alongshore. In contrast, significant changes in volume were observed on Ship Island due to the lower elevation of the island were it was eroded during Hurricane Camille and only partly recovered and due to the higher storm surge and wave height on the island. The sediment was deposited along the backbarrier shoreline and into Mississippi Sound, which will limit the potential for post-storm recovery.
Figure 1. Relationship between average pre-storm elevation and (a) post-storm elevation and (b) elevation change (post-pre elevation) for Petit Bois, Ship and Horn Islands. Also shown is the relationship for Santa Rosa Island for Hurricane Ivan.
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Figure 3. Pre- and post-storm bathymetry for the eastern end of Petit Bois Island showing the landward (northern) migration of the nearshore terrace and lose in elevation.
STUDY OVERVIEW

Hurricanes and tropical storms produce elevated water levels and large waves, capable of eroding the beachface and causing overwash and barrier breaching. In general, the morphological response of a barrier island can include:

1. shoreface erosion and bar formation and migration (also known as the Bruun Rule)
2. erosion alongshore by longshore transport
3. migration onshore via roll-over or over stepping (net sediment transfer landward)

The Bruun rule is a simple two-dimensional model of shoreline response to sea level change (including surge), in which the equilibrium profile remains unchanged as the shoreline moves in response to rising sea level (Cooper and Pilkey, 2004). Sand that moves from the upper portion of the beach profile accumulates at the lower portion of the profile, thus maintaining shoreline geometry. However, this type of response assumes that 1) geology does not play a role in shoreline shape, 2) sediment is only moved by waves, and 3) there is no significant movement beyond the depth of closure, the seaward limit of sediment transport. (USACE, 2002). When water levels exceed the height of the foredune or the beach ridge, the island experiences overwash. Sallenger (2000) describes this translation from offshore erosion during swash and impact regimes to overwash as a balance between the elevation of the storm surge relative to the vertical geometry of the coast, (Figure 4) which in turn depends on the extent and height of foredune or beach ridge development (Thieler and Young, 1991; Sallenger, 2000).

Figure 4. Hurricane Impact levels of Sallenger (2000).
The swash regime occurs during periods of low wave energy. Impacts in the swash regime are restricted to the swash zone, the zone between to the foreshore of the beach seaward of the foredune. As a consequence, the foreshore is eroded and sand transported offshore, and is returned (slowly) to the beach during periods of low wind and wave energy (Sallenger, 2000). When the storm tide (astronomical tide plus storm surge) increases, it will eventually collide with the base of the foredune (D\text{low}), and sediment is eroded offshore. During particularly strong storms, sand can be moved offshore beyond the point where it will be transported under non-storm conditions (Sallenger, 2000).

The overwash regime occurs when the run-up height exceeds the dune crest (R\text{high} > D\text{height}), and water and sediment flow landward across the barrier. Although there is some loss of sediment offshore as the dune is first impacted, most of the sediment eroded from the dune is deposited landward as overwash (Sallenger 2000). This sediment can be only returned to the recovering foredune through aeolian transport from landward offshore winds originating on land and blowing offshore (Leatherman, 1979). If sediment is not returned to the beachface from the overwash or new sediment is made available from alongshore or the shelf, the island will experience a net landward migration or roll-over. The inundation regime occurs when surge levels greatly exceed the height of the foredune, such that the island is completely submerged. This can lead to island overstepping.

A good example of the importance of vertical geometry on the morphological response during an extreme storm is the impact of Hurricane Camille on Dauphin Island (Morton and Sallenger 2003). Prior to the storm, island elevation varied from 2 to 3 m with the largest dunes on the eastern end of the island. The maximum surge during Hurricane Camille reached 2.8 m; such that the eastern end of the island was in a “collision regime.” Morphologic changes due to overwash gradually changed westward along the island where overwash and surge impacts progressively increased. The western end of the island not only had smaller dunes but also a steeper bathymetric gradient. In these areas, beach erosion via direct wave impact was magnified because storm waves energy was not dissipated offshore with the presence of shallow water or a nearshore bar (Thornton et al. 2006). The smaller dunes provided less protection and more sediment was transported landward as overwash (Morton and Sallenger 2003).

While the Sallenger model focuses on the foredune height, the alongshore extent and presence of secondary dunes can also be important. Topographic relief such as dunes and swales confine the surge into channels or low interdune areas and accelerate flow (Morton 2002; Leatherman 1977). Sediment transport within these areas can be further amplified by the shallow flows and high wind stress (Morton and Sallenger 2003). As found by Houser et al. (in press), overwash penetration and offshore erosion was increased in areas with discontinuous foredunes through lateral erosion, and decreased in areas where secondary dunes were present. Overwash penetration on Santa Rosa Island, Florida, following

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Hurricane Ivan (2004) varied with the cross-island geometry and specifically with the presence of secondary dunes.

The shoreline of the Gulf Islands National Seashore along the Mississippi coast suffered significant beach erosion and widespread overwash and breaching. The impact of Hurricane Katrina on the barrier island chain depended on the vertical geometry of the coast, which in turn depends on the extent and height of foredune development (Sallenger, 2000). The erosion sustained by the islands during past extreme storms such as Hurricane Camille (1969) and more recently Hurricanes Ivan and Dennis has precluded growth of the islands. The anticipated increase in the frequency of extreme storms with the warming of Atlantic sea-surface temperatures (Keim et al., 2004) will reduce the time available for the barrier island to recover. The erosion sustained by the barrier islands along the Mississippi coast during Hurricane Katrina will condition the response of the islands to future extreme storms and will therefore affect their longer-term evolution.

The ability of a barrier island to redevelop and the time required for that rebuilding depends on the availability of sediment. Recent evidence suggests that the barrier islands along the northern Gulf of Mexico can conserve mass during catastrophic hurricanes through the generation of overwash fans (Stone et al., 2004). These overwash fans are, however, eroded during the passage of cold-fronts (Stone and Morgan, 1993; Armbuster et al., 1995; Chaney and Stone, 1996; Armbuster, 1997; Stone et al., 2004; McBride and Byrnes, 1997) that generate strong northerly winds and steep high-frequency waves (Kraus et al., 1991). Despite recent studies documenting the immediate impact of extreme storms and the post-storm erosion of overwash deposits on the barrier islands of the Gulf of Mexico, the mechanisms responsible for post-storm changes in the island volume and the sediment transport pathways along the backbarrier have not been examined.

Island recovery can also occur through sediment delivery from alongshore and the onshore migration and eventual welding of nearshore bars created during the storm event. The model of Wright and Short (1984) is the most commonly cited morphometric model. It describes three basic forms and process signatures within a continuum of beach states from dissipative to reflective. In this model, beach states are differentiated with respect to the dimensionless fall velocity ($\Omega$): 

$$\Omega = \frac{H_b}{w,T}$$

Wright and Short proposed that the beach would be dissipative when $\Omega > 6$, intermediate when $1 < \Omega < 6$, and reflective when $\Omega < 1$. To develop their model, Wright and Short (1984) used a morphological database spanning more than 6 years, consisting of pre- and post-storm surveys from a number of
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environmentally different beaches in Australia. It was found that over the longer term, a given beach will tend to exhibit a *modal* (or most frequently recurrent) state, which depends on the modal wave conditions, around which a spread of higher or lower waves may prevail (Wright and Short, 1984). Recovery from the nearshore bar occurs via bar migration onshore when waves are shoaling and breaking landward of the bar crest (Plant et al., 2001; Houser and Greenwood, 2005). Transport of sediment onshore is associated with the oscillatory skewness and skewed accelerations that develop as the wave breaks (Houser and Greenwood, 2005). Unlike offshore migration during storms, beachface recovery requires an extended period of low-wave activity to enable bar migration onshore and ultimately bar attachment to the beachface.

**Mississippi Barrier Islands**

The Mississippi barrier islands are arranged east to west as follows: Petit Bois, Horn, East Ship, West Ship, and Cat Islands (Figure 5). Presently, these islands are part of the Gulf Islands National Seashore and are managed by the National Park Service. The National Park Service is currently updating its 1979 historical management plan to a plan that will adequately address issues facing the islands for the next 15-20 years (National Park Service, 2006).

The islands originated during the Pleistocene period in response to water level changes (Otvos, 1979). The framework of the islands (from northwest Florida to the Mississippi delta) consists of numerous low-profile, well-preserved sand beach ridges and swales (Waller and Malbrough, 1976). The arrangement of these ridges and swales relates to the origins of sediment supply for the islands, suggesting that the beach ridge topography was formed during a period of abundant sediment supply. The present sand supplies are the result of spit growth supplied by sediments derived from the east by sediment discharged by the Apalachicola River, and locally by the Mobile River and Mississippi River (Schmid, 2003; Waller and Malbrough, 1976). Since formation, the islands have experienced significant lateral migration to the west while remaining approximately the same distance offshore. In systems with multiple subparallel barriers, longshore currents can transport sand from adjacent islands, which serve as a new source of sediment for recovery (Leatherman, 1979). However, the physical disconnect between islands and the dredging of the passes may have reduced or even completely removed the longshore source of sediment.

Island formation in Mississippi has been attributed to two mechanisms. The first suggests that sediment was transported from Mobile Bay area to an offshore continental shelf source (Shepard 1960). This offshore sediment source provided sediment supply to the islands via onshore bar progression (Shepard 1960). The second mechanism involves broad shoals composed of soft and unconsolidated sands between Mobile Bay and Pensacola which supplied sands to the west across the Mobile tidal inlet (Kwon,
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Figure 5. Map of the Mississippi barrier islands.

1975) as prevailing easterly winds enhanced longshore currents (Waller and Malbrough, 1976). Through time, silt and muddy sand layers originating from the Mobile Point Peninsula and Dauphin Island consolidated to form emerging islands formed between eastern Dauphin Island and New Orleans (Otvos, 1979). Otvos (1979) collect core-hole data and used comparisons of microfauna to demonstrate that the mainland shore of the islands remained unbarred in the Mid-Late Holocene period. This suggests that the Mississippi barrier islands emerged from shoals in their present locations and shifted west with longshore sediment transport over time (Otvos, 1979). In contrast to the Mississippi mainland coast, an acoustic survey of the Horn and Petit Bois shore found that present passes within the Mississippi Sound were not inherited from Late Pleistocene stream entrenchment (Otvos, 1979). Prevailing winds are out of the east and enhance longshore currents that move sediment westward (Waller and Malbrough, 1976). Soil samples from the islands reveal a progressive decrease in median grain size to the west (Waller and Malbrough, 1976). The combination of a decreasing sediment size and the westward lateral drift trend of the islands further enforces the idea of that sediment is transported alongshore from the Mobile Bay.

Six hurricanes (category 3 or greater on the Saffir-Simpson Scale) have made landfall in the Mississippi
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area since 1969. These hurricanes include; Camile (1969), Frederic (1979), Elena (1985), Andrew (1992), and Ivan (2004) (NOAA, 2006). Most recently, Hurricane Katrina made landfall as a category 3 with sustained winds of 59.2 ms\(^{-1}\) near Buras, Louisiana, on August 29, 2005 (Knabb et al., 2005). The storm had an eye wall radius of 13-48 km and hurricane force winds extending out 135 km to the east and west. Peak winds of 77.2 ms\(^{-1}\) were recorded on August 28 about 306 km southeast of the mouth of the Mississippi River (Knabb et al., 2005). The storm created a storm surge that extended from Western Louisiana and into the Florida Panhandle (Knabb et al., 2005); surge levels were between 3-5 m along the eastern Mississippi coast from Gulfport to Pascagoula (Knabb et al., 2005). The extreme surge levels are attributed to the storm’s large horizontal size, with the surge being further increased by the large waves (and set-up) created the previous day when the storm reached a category 5 level (Knabb et al., 2005). Measurements taken by the National Data Buoy Center (NDBC, 2005) suggested a significant wave height (defined as the average of the one-third highest waves) of 9 m with a wave period of 17 s as early in the storm measured at buoy 42040, (approximately 115 km south of Dauphin Island, Alabama; Knabb et al., 2005). The alongshore variation in predicted wave and surge heights are presented for each island in Figure 6.

![Wave Height and Surge Height](image)
Figure 6. Alongshore variation in wave height and surge height at (a) Petit Bois Island, (b) Horn Island and (c) Ship Island.
METHODOLOGY

Changes to the barrier islands of the Gulf Islands National Seashore in Mississippi (Petit Bois, Horn, East Ship and West Ship) will be characterized by documenting conditions relative to the pre-storm morphology and the role of past extreme storms in shaping the morphology. This analysis will be completed through LiDAR elevation maps (pre- and post-storm) provided by the National Oceanographic and Atmospheric Administration (NOAA). In the past, research involving morphologic change to barrier islands was limited to data collected by surveying techniques and aerial photo interpretation. These methods produced coarse resolutions and were highly time-consuming (White and Wang, 2003). The Laser Imaging Detection and Ranging System (LiDAR) is an active remote sensing application (Zhang et al., 2005), that uses a high-frequency laser directed at the earth’s surface through an opening in the bottom of an overhead aircraft. The laser system records the time difference between emissions of the laser beam and the reception of the reflected laser signal in the aircraft (Meredith et al., 1999). A rotating oscillatory mirror mounted to the front of the laser allows it to swath back and forth, providing a large coverage swath area below the plane (Zhang et al., 2005). The system uses the combination of a high-speed scanning system and a high-repeating laser-pulse frequency to determine x, y, and z values across the terrain below, thus producing a data set of high spatial resolution in little time (White and Wang, 2003). The aircraft position is monitored by a GPS receiver mounted to the aircraft and a second GPS station mounted to the ground is used for differential corrections (Zhang et al., 2005).

LiDAR elevation points were interpolated into digital elevation models (DEM), using the inverse distance weighted method (IDW) with a power of ten and using the six nearest neighbours. The IDW interpolation assumes that the interpolating surface should be influenced most by nearby points and should be less influenced by distant points. Specifically, the interpolated surface is a weighted average of the points, and the weight of each point decreases with distance. Because both elevation and depth are spatially autocorrelated, using a weighted distance interpolation method explicitly accounts for interrelationships between points. The interpolation yielded a root mean-square error of 0.16 for the pre-storm data set and a root mean square error (the difference between the interpolated value and the actual value) of 0.10 for the post-storm data set. Subaerial profiles were created from transects exported from DEMs. Elevation profiles were constructed through the use of the LiDAR Data Handler tool within ArcMap, which exports elevation data from the DEM. Points were exported from the DEM at 2 m intervals along transects. Transects were spaced at 40 m intervals along the island and provided a cross-shore elevation reference from the Gulf shoreline inland to the limit of the LiDAR data or tree line. Pre-storm LiDAR data for the island extended to transect 24 at the eastern tip of the island. Post-storm LiDAR data were limited in capturing the eastern end of the island and data was unavailable beyond transect 20.

Subaqueous changes to the island were examined through bathymetric profiles on both the Gulf and sound sides of the islands as well as the inlets between each island. Pre-storm bathymetric profiles were
constructed using bathymetric data from 1975 obtained from NOAA Hydrographic surveys; however, gulf-side data for the middle portion of the island were unavailable. The NOAA survey was collected using single beam sonar across the entire portion of the Mississippi Sound and for portions of the Gulf side of the Mississippi barrier islands. Bathymetry points were interpolated using the inverse distance weighted method, with a power of two, using the eight nearest neighbors. The interpolation yielded a root mean-square error of 0.59. Pre-storm bathymetric profiles were extracted at 7.5 m cross-shore intervals from the model using the NOAA LiDAR Data Handler tool within ArcMap. Post-storm bathymetric data were collected with the use of a Lowrance depth finder unit (model LMS-339) following the storm. Data were collected on June 1 and 2. Post-storm transects were collected at 400 m (ten times the distance of the land transects) intervals along the shoreline and extended from the shoreline to a distance of 1 km offshore on the Gulf side and to a distance of 500 m on the sound side. Transect intervals of 400 m provided a scale that indicated alongshore bathymetric variability, while offshore data collection distances of 1 km and 500 m indicated closure of pre- and post-storm bathymetric profiles. A similar bathymetric model was created using the post-storm sonar data. Tide variations during the collection of bathymetric data were subtracted from the data based on tide data collected at the NOAA Pascagoula tide station based on NAVD 1983.

Data Analysis

The analysis of pre-storm and post-storm data obtained from both the subaerial and subaqueous portions of the islands was examined through the use of empirical orthogonal functions (EOF) analysis. EOF analysis identified patterns in how the island responded to the storm and related changes to pre-storm morphology both subaerial and subaqueous. EOF analysis is similar to principal component analysis (PCA), except that the variable is examined through space rather than through time (Aubrey, 1979). The eigenvalues correspond to a statistically optimal description of the data with respect to how the variance is concentrated in the modes (Larson et al., 2003). EOF analysis allows a user to reduce the number of variables and to detect structures in the interactions between variables. This allows variables to be classified and can identify redundancies and associations in the data (Houser et al., in press). EOF analysis has previously been used in coastal geomorphology to describe nearshore bar behavior (Larson et al., 2003; Houser and Greenwood 2005) and morphological controls on hurricane impacts (Houser et al. in press).

The relationships between pre- and post-storm topographies (bathymetric and aerial) were examined through canonical correlation analysis (CCA). This analysis identifies patterns that occur simultaneously in two different data sets and describes the nature of those patterns (Houser et al., submitted).
IMPACTS TO PETIT BOIS ISLAND

Oblique aerial photographs of the post-storm morphology are presented in Figure 8, and the pre- and post-LiDAR images for Petit Bois Island are provided in Figures 9 and 10. The pre- and post-storm average elevation of the island across each of the survey transects are provided in Figure 12. While areas with large elevations were reduced in height, there were several areas of the island where the post-storm average elevation increased, suggesting accretion during or immediately following the storm. A review of the detailed analysis is provided in the following sections.

Volume Change

Over 460,000 m$^3$ of sediment was lost from the aerial portion of the island with an average volume loss of -28 m$^3$ m$^{-1}$ length of shoreline (Figure 7). However, the volume change varied from an accretion of 63 m$^3$ m$^{-1}$ length of shoreline to a loss of -100 m$^3$ m$^{-1}$ at the eastern end of the island. In comparison, the net change in sediment volume along Santa Rosa Island ranged from an erosion of 238 to 43 m$^3$ per unit width of beach during Hurricane Ivan. Assuming that the nearshore profile maintained its shape, an additional 243,000 m$^3$ of sediment was lost from the sub-aqueous portion of the island. Assuming that the sediment losses from the island and the shoreface were equally distributed within the offshore survey area (15 million m$^2$), the sediment would only represent a change of 0.05 m which is within the sampling error of the depth sounder ($\pm 0.10$ m).

Shoreline Change

On average the shoreline retreated by ~35 m but varied considerably from a gain (accretion) of 118 m to a loss (erosion) of 254 m. As shown in Figure 7, the change in shoreline position is related to the volume change. Areas of shoreline erosion are associated with the largest losses of sediment, while areas of shoreline accretion are associated with the smallest loss of sediment and sometimes a volume gain. Shoreline accretion was observed along the western end of the island despite the general loss of island volume, while both shoreline and volume loss were observed at the eastern end of the island. In the centre of the island there is an increase in island volume and little change (<5 m) in shoreline position. Consistent with Morton (2007), Petit Bois narrowed and the eastern shore rotated counterclockwise as a result of wave refraction and associated differential erosion and overwash along the eastern Gulf beach. This rotation is associated with a change towards a swash-alignment caused by a loss of updrift sediment.
Figure 7. (A) Alongshore variation (by transect) in volume change for Petit Bois Island from West to East. The alongshore variation has been smoothed using a 3-point moving average. Positive change represents accretion and negative change represents erosion. (B) Alongshore variation (by transect) in shoreline position for Petit Bois Island from West to East. The alongshore variation has been smoothed using a 3-point moving average. Positive change represents accretion and negative change represents erosion.
Figure 8. Oblique aerial photographs of morphological change to Petit Bois Island following Hurricane Katrina. Photographs were taken November 30, 2005 and all photographs from the aerial survey are provided on the accompanying compact disc.
Figure 9. Pre-storm LiDAR data for Petit Bois Island.
Evolution of the barrier islands in Mississippi during and following Hurricane Katrina

Figure 10. Post-storm LiDAR data for Petit Bois Island.
Elevation Change

The alongshore variation in average elevation based on the pre- and post-storm LiDAR data are provided in Figure 12. In contrast to the considerable change in elevation observed along Santa Rosa Island during Hurricane Ivan (>2 m), the average elevation change on Petit Bois was 0.10 m. The change in average elevation varied from a loss of 0.64 m to a gain of 0.57 m in the centre part of the island where island accretion was observed for both the shoreline and the island volume. A scatter plot of the alongshore variation in island volume change and average elevation change is also provided in Figure 12.
Figure 12. (a) Alongshore variation in pre- and post-storm elevation and (b) the relationship between volume change and the change in average elevation (post-pre-storm elevation).
Figure 13. (a) Relationship between pre-storm elevation and elevation change. Also shown (b) is the relationship between pre-storm elevation and change in profile volume.
Figure 14. (a) Relationship between pre-storm elevation and post-storm elevation. Also shown (b) is the relationship between pre-storm elevation and shoreline change.
Evolution of barrier islands in Mississippi during and following Hurricane Katrina

Morphology Change

Based on the scree plots, both the pre- and post-storm data sets found six eigenmodes to be statistically significant with the percent of total variance explain at 81% and 92%, respectively. The primary eigenmode (E1) for the pre-storm morphology explains 31% of the variance and shows a large and wide ridge ~150 m landward of the average shoreline (Figure 15a). The second eigenmode (E2) explains 28% of the variance and exhibits a small ridge ~120 m from the shoreline with a higher than average backbarrier elevation. The third eigenmode (E3) exhibits a large ridge ~90 from the shoreline, which is dominated by a large berm and swale ~40 from the average shoreline. The fourth eigenmode (E4) exhibits a large ridge ~120 from the shoreline, and a secondary ridge with greater elevation ~250 m from the average shoreline. The fifth eigenmode (E5) also exhibits a large ridge ~120 from the shoreline, and a secondary ridge with greater elevation ~320 m from the average shoreline. The sixth eigenmode (E6) is characterized by the largest ridge at ~120 m from the shoreline.

In contrast to the pre-storm morphology, the post-storm morphology (for all eigenmodes) is characterized by a single ridge at different distances from the new average shoreline. The primary eigenmode (E1) for the post-storm morphology explains 65% of the variance and shows a large and wide ridge ~188 m landward of the average post-storm shoreline (Figure 15a). The second eigenmode (E2) explains 34% of the variance and exhibits a small ridge ~190 m from the shoreline with a small ridge ~375 m landward. The third eigenmode (E3) exhibits a large ridge ~276 from the shoreline. The fourth eigenmode (E4) exhibits a large ridge ~190 from the shoreline that grades into a higher than average shoreline elevation that suggests accretion. The fifth eigenmode (E5) also exhibits a large ridge ~190 from the shoreline, and a secondary ridge with greater elevation ~330 m from the average shoreline. The sixth eigenmode (E6) is characterized by the largest ridge at ~242 m from the shoreline.

The alongshore variation in the pre- and post-storm eigenmodes is presented as factor scores in Figure 16. Consistent with the shoreline, volume and elevation data, there appears to be 3 parts to the island: western, middle and eastern. The western section of the island (transects 1-164) is characterized by pre-storm E1, E6 and E4, while the eastern section of the island (transects 289-400) is characterized by pre-storm E2, E3 and E5. The middle section of the island is characterized by pre-storm E3. Canonical correlation analysis between the factor scores for the pre- and post-storm morphology yields a correlation of 0.73 (p<0.05). Results of the analysis are presented in Table 1 below. The correlated pairs are plotted in Figure 17.
Table 1. Canonical correlation coefficients $(r)$ between the pre- and post-storm profiles for Petit Bois Island, with the largest coefficients (strongest relationships) highlighted.

<table>
<thead>
<tr>
<th>Pre-Storm Profiles</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.48</td>
<td>-0.11</td>
<td>0.11</td>
<td>0.22</td>
<td>-0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>E2</td>
<td>0.21</td>
<td>0.82</td>
<td>-0.11</td>
<td>-0.07</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>E3</td>
<td>0.42</td>
<td>-0.15</td>
<td>-0.32</td>
<td>-0.25</td>
<td>-0.30</td>
<td>0.07</td>
</tr>
<tr>
<td>E4</td>
<td>0.26</td>
<td>0.02</td>
<td>0.60</td>
<td>-0.06</td>
<td>0.03</td>
<td>-0.07</td>
</tr>
<tr>
<td>E5</td>
<td>0.17</td>
<td>0.13</td>
<td>0.17</td>
<td>-0.11</td>
<td>0.55</td>
<td>0.01</td>
</tr>
<tr>
<td>E6</td>
<td>0.35</td>
<td>0.00</td>
<td>0.02</td>
<td>0.53</td>
<td>-0.09</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

Bathymetry Changes

The characteristic post-storm bathymetry profiles are shown in Figure 18a and the alongshore variation (as factor scores) is shown in Figure 18b. In general, there is a change from a relatively steep offshore profile at the western end of the island to a more dissipative profile at the eastern end of the island. This change in profile shape is accompanied by a change in bar position from far offshore and deep (Bathy E4) to close onshore and shallow (E1). Each of the bars exhibited a steep onshore face suggesting some onshore migration during or following Hurricane Katrina.

The distance of the bar offshore and the depth to the bar crest were positively correlated, such that water depths over the bar increased as the distance between the bar and the shoreline increased. The position of the bar exhibits an alongshore variation at a spacing of ~72 transects. In general, the bar is offshore where the average pre-storm elevation is at a local minimum. At these locations the shoreline was observed to retreat and there was net loss of sediment volume. In contrast, shoreline retreat and volume loss were at a local minimum and some accretion was observed where the average pre-storm elevation was relatively large. At these locations, the post-storm bar was relatively close to shore and the depth to the bar crest was at a local minimum. These results suggest that where the average pre-storm elevation was large, sediment was deposited on the inner-shoreface as a nearshore bar. Intervening areas also suggest that sediment was deposited from these areas on the shoreface. The sediment lost in the intervening (low elevation) areas was deposited in the backbarrier as overwash fans that in some locations extended into the sound (see Figure 8). The overwash and loss of shoreline and profile volume was worst at the eastern end of the island, which was the updrift end of the island.
Figure 15. Characteristic (a) pre-storm and (b) post-storm cross-shore profiles for Petit Bois Island.
Figure 16. Alongshore factor scores for the pre-storm and post-storm characteristic profiles.
Figure 17. Comparison of cross-island profiles (factor scores) for the pre- and post-storm eigenvalues with strong correlations identified through canonical correlation analysis.
Figure 18. (a) Characteristic offshore profiles for Petit Bois Island and (b) alongshore factor scores for the characteristic profiles.
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Figure 19. Alongshore variation in the distance of the nearshore bar offshore relative to (a) the depth to the bar crest and (b) the average pre-storm elevation of the island.
Figure 20. Alongshore variation in the distance of the nearshore bar offshore relative to (a) shoreline change and (b) the change in profile volume.
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IMPACTS TO HORN ISLAND

Oblique aerial photographs of the post-storm morphology are presented in Figure 22, and the pre- and post-LiDAR images for Horn Island are provided in Figures 23 and 24. Similar to Petit Bois Island, areas with large elevations were reduced in height, but there were several areas of the island where the post-storm average elevation increased, suggesting accretion during or immediately following the storm. A review of the detailed analysis is provided in the following sections.

Volume Change

Over 2,270,000 m$^3$ of sediment was lost from the aerial portion of the island with an average volume loss of -120 m$^3$ m$^{-1}$ length of shoreline (Figure 24). However, the volume change varied from an accretion of 64 m$^3$ m$^{-1}$ length of shoreline near the eastern end of the island to a loss of -539 m$^3$ m$^{-1}$ at transect 159. Assuming that the nearshore profile maintained its shape, an additional 360,000 m$^3$ of sediment was lost from the sub-aqueous portion of the island. Assuming that the sediment losses from the island and the shoreface were equally distributed within the offshore survey area (15 million m$^2$), the sediment would only represent a change of 0.09 m which is within the sampling error ($\pm$0.10 m) of the depth sounder.

![Volume Change](image)

**Figure 21.** Alongshore variation (by transect) in volume change for Horn Island from West to East. The alongshore variation has been smoothed using a 3-point moving average. Positive change represents accretion and negative change represents erosion.
Figure 2. Oblique aerial photographs of morphological change to Horn Island following Hurricane Katrina. Photographs were taken November 30, 2005 and all photographs from the aerial survey are provided on the accompanying compact disc.
Figure 23. Pre-storm LiDAR data for Horn Island.
Figure 24. Post-storm LiDAR data for Horn Island.
Figure 25. Pre- and post-storm locations of beachface ridges.
Shoreline Change

On average the shoreline retreated by ~3 m but varied considerably from a gain (accretion) of 174 m to a loss (erosion) of 136 m (Figure 26). Unlike Petit Bois, the change in shoreline position is not related to the volume change. Areas of shoreline erosion are not consistently associated with the largest losses of sediment, while areas of shoreline accretion are not associated with the smallest loss of sediment and sometimes a volume gain. Whereas Petit Bois had an alongshore trend from erosion (in the east) to accretion (in the west), Horn Island exhibits some erosion in the east and accretion in the west, with considerable (and almost periodic) variability through the middle transects. Both shoreline change and volume change exhibit statistically significant variations at alongshore length scales of ~3000 and 1700 m. At the 3000 m length scale, volume and shoreline change are in-phase (and positively correlated), but the variables are in quadrature (out-of-phase) at the 1700 m length scale. In other words, areas of large volume change are to the east of areas with large shoreline change at the 1700 m length scale.

Figure 26. Alongshore variation (by transect) in shoreline position for Horn Island from West to East. The alongshore variation has been smoothed using a 3-point moving average. Positive change represents accretion and negative change represents erosion.
Elevation Change

The alongshore variation in average elevation based on the pre- and post-storm LiDAR data are provided in Figure 28. The change in average elevation varied from a loss of 2.3 m to a gain of 0.38 m at the eastern end of the island. The loss in average elevation tended to be greatest at the western end of the island and near the middle (transects 250-350) where large dune features had been present before the storm. A scatter plot of the alongshore variation in island volume change and average elevation change is provided in Figure 28. While there appears to be 2 separate populations, both suggest that a greater loss in average elevation is associated with larger volume losses. In this respect, change in elevation is coherent and in-phase with changes in volume change at all length scales.
Figure 28. (a) Alongshore variation in pre- and post-storm elevation and (b) the relationship between volume change and the change in average elevation (post-pre-storm elevation).
Figure 29. (a) Relationship between pre-storm elevation and elevation change. Also shown (b) is the relationship between pre-storm elevation and change in profile volume.
Figure 30. (a) Relationship between pre-storm elevation and post-storm elevation. Also shown (b) is the relationship between pre-storm elevation and shoreline change.
Morphology Change

Based on the scree plots, both the pre- and post-storm data sets found six eigenmodes to be statistically significant with the percent of total variance explain at 75% and 86%, respectively. The primary eigenmode (E1) for the pre-storm morphology explains 32% of the variance and shows a large and wide ridge ~260 m landward of the average shoreline (Figure 31a). The second eigenmode (E2) explains 28% of the variance and exhibits a small ridge ~86 m from the shoreline with a large berm and swale at ~30 m from the shoreline. The third eigenmode (E3) exhibits a large ridge 170 m from the shoreline while the fourth and sixth eigenmodes (E4 and E6) only exhibit secondary ridges ~370 and 350 m from the shoreline. The fifth eigenmode (E5) exhibits a large ridge ~125 m from the average shoreline.

In contrast to the pre-storm morphology, but similar to Petit Bois, the post-storm morphology (for all eigenmodes) is characterized by a single ridge at different distances from the new average shoreline. The primary eigenmode (E1) for the post-storm morphology explains 62% of the variance and shows a large and wide ridge ~182 m landward of the average post-storm shoreline (Figure31b). The second eigenmode (E2) explains 32% of the variance and exhibits a small ridge ~134 m from the shoreline. The third eigenmode (E3) exhibits a large ridge ~392 from the shoreline. The fourth eigenmode (E4) exhibits a large ridge ~288 while the fifth eigenmode (E5) has no ridge. The sixth eigenmode (E6) is characterized by the largest ridge at ~322 m from the shoreline.

The alongshore variation in the pre- and post-storm eigenmodes is presented as factor scores in Figures 32. Unlike Petit Bois, there does not seem to be a well-defined alongshore pattern Canonical correlation analysis between the factor scores for the pre- and post-storm morphology yields a correlation of 0.73 (ρ<0.05). Results of the analysis are presented in Table 2 below and the correlated pairs are plotted in Figure 33.

Table 2. Canonical correlation coefficients (r) between the pre- and post-storm profiles for Horn Island, with the largest coefficients (strongest relationships) highlighted.

<table>
<thead>
<tr>
<th>Pre-Storm Profiles</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.11</td>
<td>0.22</td>
<td>0.47</td>
<td>0.25</td>
<td>0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>E2</td>
<td>0.04</td>
<td>-0.11</td>
<td>0.03</td>
<td>-0.18</td>
<td>0.17</td>
<td>-0.07</td>
</tr>
<tr>
<td>E3</td>
<td>0.07</td>
<td>-0.16</td>
<td>-0.10</td>
<td>0.51</td>
<td>-0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>E4</td>
<td>0.58</td>
<td>-0.09</td>
<td>-0.15</td>
<td>0.00</td>
<td>-0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>E5</td>
<td>0.12</td>
<td>-0.04</td>
<td>0.12</td>
<td>0.06</td>
<td>-0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>E6</td>
<td>0.01</td>
<td>-0.06</td>
<td>0.03</td>
<td>0.17</td>
<td>-0.10</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Figure 31. Characteristic (a) pre-storm and (b) post-storm cross-shore profiles for Horn Island.
Figure 32. Alongshore factor scores for the pre-storm and post-storm characteristic profiles.
Evolution of the barrier islands in Mississippi during and following Hurricane Katrina

**Figure 33.** Comparison of cross-island profiles (factor scores) for the pre- and post-storm eigenvalues with strong correlations identified through canonical correlation analysis.

Bathymetry Changes

The characteristic post-storm bathymetry profiles are shown in Figure 34a and the alongshore variation (as factor scores) is shown in Figure 34b. In general, there is a change from a relatively dissipative (gentle) offshore profile at the western end of the island to a more reflective profile at the eastern end of the island with a large prominent bar. This change in profile shape is accompanied by a change in bar morphology from no bar (Bathy E1) to a pronounced bar that is distant from the shoreline (E4). Each of the bars exhibited a steep onshore face suggesting some onshore migration during or following Hurricane Katrina.

Similar to the average pre-storm elevation and shoreline and volume change, the distance and depth of the bar crest offshore exhibit an alongshore variation at a spacing of ~120 transects. Within a distance of 30 transects (from west to east), the bar increases in height by ~1.4 m at which point it moves inshore by ~130 m. When the bar is further offshore it is relatively symmetric but becomes increasingly asymmetric as it approaches the shore. Where the bar is relatively far offshore and well developed (large in height...
and asymmetric), the shoreline accreted during the storm (Figure 35a), the volume loss is at a local minimum (Figure 36b) and the average pre-storm elevation is at a local maximum (Figure 35b). Where the bar is close to shore and depth over the crest is relatively deep (a small bar), the shoreline tended to erode, the volume loss is at a local maximum and the average pre-storm elevation is at a local minimum. Similar to Petit Bois, these results suggest that where the average pre-storm elevation was large, sediment was deposited on the inner-shoreface as a nearshore bar. Like Petit Bois Island, the sediment lost in the intervening (low elevation) areas was deposited in the backbarrier as overwash fans that in some locations extended into the sound (see Figure 22). The overwash and loss of shoreline and profile volume was worst at the eastern end of the island, which was the updrift end of the island.
Figure 34. (a) Characteristic offshore profiles for Horn Island and (b) alongshore factor scores for the characteristic profiles.
Figure 35. Alongshore variation in the distance of the nearshore bar offshore relative to (a) the depth to the bar crest and (b) the average pre-storm elevation of the island.
Figure 36. Alongshore variation in the distance of the nearshore bar offshore relative to (a) shoreline change and (b) the change in profile volume.
IMPACTS TO SHIP ISLAND

Oblique aerial photographs of the post-storm morphology are presented in Figure 38, and the pre- and post-LiDAR images for Ship Island are provided in Figures 39 and 40. While areas with large elevations were reduced in height, there were several areas of the island where the post-storm average elevation increased, suggesting accretion during or immediately following the storm. A review of the detailed analysis is provided in the following sections. However, due to limited data from West Ship Island and on the post-storm location of the shoreline the following discussion will focus largely on East Ship Island.

Volume Change

Over 680,000 m$^3$ of sediment was lost from the aerial portion of East Ship Island, with an average volume loss of 245 m$^3$ m$^{-1}$ length of shoreline (Figure 37). However, the volume change varied from a minimum of 20 m$^3$ m$^{-1}$ to a maximum of 848 m$^3$ m$^{-1}$ length of shoreline near the centre of the island. In contrast, some accretion was observed on West Ship Island, although there was an average loss of 42 m$^3$ m$^{-1}$ length of shoreline.

![Figure 37](image_url)

**Figure 37.** Alongshore variation (by transect) in volume change for Ship Island from West to East. The alongshore variation has been smoothed using a 3-point moving average. Positive change represents accretion and negative change represents erosion.
Figure 38. Oblique aerial photographs of morphological change to Ship Island Island following Hurricane Katrina. Photographs were taken November 30, 2005 and all photographs from the aerial survey are provided on the accompanying compact disc.
Figure 39. Pre-storm LiDAR data for Ship Island.
Figure 40. Post-storm LiDAR data for Ship Island.
Elevation Change

The alongshore variation in average elevation based on the pre- and post-storm LiDAR data are provided in Figure 41. The change in average elevation on East Ship Island varied from a loss of 3.9 m to a loss of 0.17 m. The loss in average elevation was greatest on East Ship Island where large dune features had been present before the storm. A scatterplot of the alongshore variation in island volume change and average elevation change is provided in Figure 42.

![Figure 41](image)

**Figure 41.** (a) Alongshore variation in pre- and post-storm elevation for Ship Island.

Morphology Change

Based on the scree plots, both the pre- and post-storm datasets have six eigenmodes that are statistically significant, with the percent of total variance explained at 74% and 76% respectively. The primary eigenmode (E1) for the pre-storm data explains 43% of the variance and shows a large and side ridge in the centre of the island at ~225 m from the shoreline. All eigenmodes exhibit this same ridge, but with smaller amplitude and with other ridges landward and seaward of this central ridge.
Figure 42. Relationship between (a) profile volume change and the change in average elevation (post-pre storm average elevation), and (b) pre-storm average elevation and volume change.
Figure 43. (a) Relationship between pre-storm elevation and elevation change. Also shown (b) is the relationship between pre-storm elevation and change in profile volume.
Similar to the other islands and in sharp contrast with the pre-storm morphology, the post-storm eigenmodes are characterized by a single storm ridge at varying distances from the shoreline. The primary eigenmode (E1) is characterized by a single ridge at a distance of 125 m from the pre-storm shoreline. The second eigenmode is characterized by a ridge ~375 m from the pre-storm shoreline, while E3 is characterized by a ridge at the shoreline. The remaining eigenmodes (E4, E5 and E6) have ridges at 225, 125 and 325 m from the pre-storm shoreline respectively.

No discernable alongshore patterns were observed in either the pre-storm or the post-storm morphology for Ship Island in general or East Ship Island alone. No statistically significant relationships were observed using Canonical Correlation Analysis between the pre- and post-storm characteristic profiles.

Bathymetry Changes

Unlike Petit Bois and Horn Islands, the offshore bathymetry of Ship Island is not characterized by a nearshore system and the analysis used for the other islands could not be used for Ship Island. The offshore bathymetry transects for both West and East Ship Island are presented in Figure 45.
Figure 44. Characteristic (a) pre-storm and (b) post-storm cross-shore profiles for Ship Island.
Figure 45. Post-storm cross-shore profiles for Ship Island.
REFERENCES


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