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Response of a vulnerable barrier island to multi-year storm impacts: LiDAR-data-inferred morphodynamic changes on Ship Island, Mississippi, USA

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Abstract

Barrier systems around the world are experiencing accelerated sea-level rise, reduced sediment supply, and frequent hurricane impacts. However, detailed quantitative field-based studies concerning the response to these external forcing mechanisms are scarce, particularly on the scale of entire islands. The Mississippi – Alabama barrier island chain, located along the U.S. Gulf of Mexico coastline has lost land on the order of hectares per year since records began in the 1840s, putting mainland coastal communities and important ecosystems at risk. Here we present an analysis of Light Detection and Ranging (LiDAR) digital elevation models, revealing erosional/depositional patterns and geomorphologic changes around the most vulnerable of these islands, Ship Island. Four LiDAR datasets (2004, 2007, 2010, and 2012), capturing the complete topography of the island and some bathymetry in the inlet and surrounding shallows to depths of up to 8 m, are used to investigate subaerial and subaqueous sediment volume changes between these years. The impact of Hurricane Katrina, which produced the highest storm surge ever recorded in the United States, is captured in the 2004–2007 dataset. During this time, sediment comparable to 1.5 times the 2004 subaerial island volume was lost from the area included in the topographic/bathymetric dataset. Only 1/5 of this volume was recovered to this area between 2007 and 2010. The island returned to a state of sediment loss between 2010 and 2012, albeit within the error bounds, while the areal extent of the islands continued to increase. This study examines the impact severe storm events can have on vulnerable barrier islands. It highlights the importance of utilizing 3D datasets that include both topographic and bathymetric data for morphodynamic analyses of barrier island systems.

Keywords

LiDAR; Mississippi barrier islands; Hurricane coastal erosion; Gulf of Mexico

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1. Introduction

Barrier islands are critically important landscapes representing ~10% of the global coastline (Stutz and Pilkey, 2011) where they provide important habitats and protect landward areas from the most devastating effects of storm surge. The three major influencing factors on barrier island sustainability are sea-level rise (SLR), storm impacts, and sediment supply. Their evolution is governed by a complex balance between these three elements (McBride and Byrnes, 1997; Byrnes et al., 2013; Otvos and Carter, 2013; Twichell et al., 2013). SLR alone is causing many of the world's sandy coastlines, including barrier islands, to erode dramatically (Van Straaten, 1965; Bird, 1985, 1996; FitzGerald et al., 2008). Continuing accelerated SLR (Sallenger et al., 2012; IPCC, 2014), coupled with potential increases in the frequency and intensity of major hurricanes (Emanuel, 2013), has placed many barrier island systems at risk globally (McNamara and Keeler, 2013; Woodruff et al., 2013).

Many studies have sought to quantify shoreline erosion, barrier island migration, and dune erosion using a variety of techniques (Moore, 2000) with different uncertainties (Ruggiero et al., 2003). The focus is typically on either subaqueous volumetric changes using bathymetric data, island area change above mean high water (MHW), or shoreline change (Morton, 2008; Byrnes et al., 2012; Walstra et al., 2012; Hapke et al., 2013). The sediment budget study of the Columbia River littoral cell by Buijsman et al. (2003) is one of the few examples in which subaerial and subaqueous volumetric changes are combined. Approaches often rely on mostly topographic cross-shore profiles (Smith and Zarillo, 1990). Topographic/bathymetric (topo/bathy) light detection and ranging (LiDAR) data capture both terrestrial features and subaqueous features at up to 40 m water depth (Parson et al., 1997). These datasets do not often cover entire barrier islands, however, and studies utilizing them typically only compare two datasets (Zhang et al., 2005; Houser et al., 2008). The lack of comprehensive data has led to a limited understanding of barrier island response to external evolutionary drivers (FitzGerald et al., 2008; Stutz and Pilkey, 2011; Cazenave and Le Cozannet, 2013). Quantitative analyses producing accurate sediment volume changes across barrier island systems over time can further add to our understanding and constrain numerical models aimed at examining morphological feedbacks (Murray, 2003; Moore et al., 2014; Lorenzo-Trueba and Mariotti, 2017).

In the northern Gulf of Mexico study region, documentation exists for unprecedented erosion of barrier systems associated with accelerated SLR and punctuated by storm impacts relative to geologic timescales (Anderson et al., 2010, 2014; Wallace and Anderson, 2013; Odezulu et al., 2018). The Mississippi/Alabama (MS-AL) barrier chain, located along the northern Gulf of Mexico margin, is currently one of the most vulnerable sections of coastline in the United States (Pendleton et al., 2010). Even before the devastating Hurricane Katrina impact, long-term shoreline change analysis demonstrated that N75% of the MS-AL shoreline was eroding (Morton et al., 2005). Over shorter timescales, natural sediment redistribution along the MS-AL barrier chain is controlled primarily by fair-weather, longshore processes and sediment removal from the system occurs largely due to storms (Otvos and Carter, 2008; Byrnes et al., 2013; Twichell et al., 2013). Anthropogenically, dredging activities and the presence of navigation channels also alter sediment transport and distribution pathways (Morton, 2008; Otvos and Carter, 2008; Byrnes et al., 2012).

Large-scale external processes such as the current rates of relative SLR, storms, and sediment budgets are fairly well constrained for this section of the Gulf of Mexico, thereby making it an ideal natural laboratory to examine barrier island response (Byrnes et al., 2013; Otvos and Carter, 2013). Importantly, this location was directly impacted by Hurricane Katrina with the highest storm surge ever recorded in the United States (Fritz et al., 2007), and thus allows for the unique opportunity to infer the response of an already vulnerable barrier island to an extreme, rare storm event. Few field-based studies attempt to quantitatively examine spatial and temporal trends of barrier island evolution in this region, however, and none have been able to infer these changes simultaneously across an entire island and the surrounding subaqueous areas (Houser et al., 2008; Otvos and Carter, 2008, 2013; Byrnes et al., 2012; Walstra et al., 2012). Here we aim to quantify both subaerial and nearshore subaqueous sediment volume changes, using four topo/bathy LiDAR datasets (2004, 2007, 2010, and 2012), in order to understand geomorphic evolution associated with barrier island change forcing mechanisms as well as those factors that increase vulnerability.

1.1. Geologic setting

Located along the Mississippi coast, Ship Island is a part of the MS-AL barrier island chain, which includes Cat, Ship, Horn, Petit Bois, and Dauphin Islands from West to East (Fig. 1). To the south, the islands face the open Gulf of Mexico, and to the north, the partially enclosed Mississippi Sound (MS Sound). East Ship Island is completely undeveloped, and there is limited development on West Ship Island, with the exception of the historic Fort Massachusetts built in the 1860's. Studies of heavy mineral sources (Otvos, 1978) reveal the predominance of distal eastern (Appalachian) as opposed to western (Mississippi Delta) sediment sources for the MS-AL chain. This demonstrates the importance of east to west longshore transport for barrier-shoal construction (Otvos, 2005). Relict ridges preserved on Cat, Ship, and Horn Islands reflect east to west island growth and movement (Otvos and Giardino, 2004). Based on optically-stimulated luminescence ages, the western Mississippi barrier islands first formed between ca. 4.6 and 3.7 ka (Otvos and Giardino, 2004), and the adjacent 42 km-long New Orleans (Pine Island) barrier-shoal complex (Saucier, 1963, 1994) conforms with these ages (Otvos, 1978; Stapor Jr. and Stone, 2004). The barriers stabilized at a relative SLR rate <2 mm/yr (Otvos, 2004; Törnqvist et al., 2004, 2006; González and Törnqvist, 2009), similar to other barrier systems (Timmons et al., 2010; Hein et al., 2014; Anderson et al., 2014, 2016; Fruergaard et al., 2015). The modern relative SLR rate in the vicinity of Ship Island is 4.137 ± 0.9 mm/yr (NOAA, 2018), averaged between 1978 and 2015, approximately double the apparent stabilization rate. The Ship Island barrier sands extend up to ~600 m beyond the back-barrier shoreline into the MS Sound and ~1000 m from the shoreline seaward into the Gulf of Mexico (Twichell et al., 2013). This deposit, along with the underlying fine transgressive sands, overlie early Holocene muds that lie ~8 m below the surface and extend out ~3 km seaward beyond the shoreline (Twichell et al., 2013). Barrier sands are overlaid partially by St. Bernard prodelta muds at their most shoreward edge, and shoreface sands are currently topped by a modern erosional unconformity. Along the back-barrier, late Holocene muds also overlie barrier sands (Twichell et al., 2013).

Significant wave height influencing the barrier chain is low with an average of 0.7 m in the winter and 0.4 m in the summer (NDBC, 2016; Buoy 42007). The calculated depth of closure for the area is ~7 m using USACE Wave Information Studies data over the past 33 years (Brutsché et al., 2014; Fig. 1). This depth of closure is verified geologically by the presence of modern muds onlapping the barrier sands (i.e., shoreface toe) beginning at a depth of ~8–10 m on the shoreface (Twichell et al., 2013). The islands are microtidal with a mean tidal range of 0.45 m and a diurnal range of 0.49 m (NOAA, 2013). The MS-AL back-barrier is an open lagoon (MS Sound) reaching depths of N5 m directly behind the barrier platforms which are separated by inlets ~10 km wide. As a result, the lagoon accommodates a large tidal prism, and both the shoreface and back-barrier can be exposed to high-energy waves (Walstra et al., 2012).

The region is frequently impacted by hurricanes and other storms, with the eyes of 13 tropical storms passing within 100 km of Ship Island since 1960 (NOAA, 2016). Direct hurricane impacts occur here approximately every 10–12 years (Byrnes et al., 2012). The two most intense recorded events, hurricanes Camille and Katrina, impacted the island directly in 1969 and 2005, respectively. Hurricane Camille made landfall as a category-5 hurricane 45 km to the west of Ship Island in August of 1969, forming the inlet that remains today as Camille Cut. Camille brought maximum winds of ~250 km/h to the MS coast and a surge of 4.3 m to Ship Island (USACE, 1970). Katrina impacted approximately 65 km to the west of Ship Island as a strong category-3 hurricane with maximum winds of ~200 km/h along the MS coast and a surge of 8 m on Ship Island (Waple, 2005; Fritz et al., 2007). The geomorphology of Ship Island is heavily influenced by events like Camille and Katrina in addition to more frequent, smaller-scale events. The multi-year LiDAR datasets available for Ship Island provide an opportunity to examine changes over multiple storm events in detail (Table 1).

1.2. Controls on barrier island geomorphology

1.2.1. Sea-level rise—By the end of this century, the rate of eustatic SLR is expected to increase by two to three times (Thomas et al., 2004; Church and White, 2006; Overpeck et al., 2006; Pfeffer et al., 2008; Church et al., 2013). SLR is the controlling factor in barrier island transgression over geologic timescales (Bird, 1985, 1996; FitzGerald et al., 2006, 2008). A rate of SLR faster than barriers can keep pace with by means of back-barrier deposition and island rollover can result in runaway transgression and eventual drowning (FitzGerald et al., 2008; Anderson et al., 2010, 2014). Barrier island systems can also respond to SLR in a way that conserves their mass as they migrate landward (Van Straaten, 1965; FitzGerald et al., 2008). A sufficient sediment supply and/or a relatively small back-barrier accommodation space can allow an island to maintain its subaerial volume as it transgresses in response to SLR (Brenner et al., 2015). Back-barrier deposits, including marshes, reduce accommodation space as well as tidal prism moving through inlets while providing a foundation for the barriers to transgress upon (FitzGerald et al., 2008; Sallenger Jr et al., 2009; Moore et al., 2010, 2014; Walters et al., 2014).

Ship Island's back-barrier sand deposition is limited in volume and extent compared with Florida barriers in the Apalachicola area (Twichell et al., 2013). This is primarily due to the

large accommodation space of MS Sound directly behind the island that washover deposition only slowly fills. Back-barrier deposition that does occur is unable to keep pace with SLR, providing no opportunity for marsh formation. This set of circumstances contributes to higher retreat rates (Brenner et al., 2015). Tidal deltas sequester much of the sandy sediment, typical of a system experiencing runaway transgression (FitzGerald et al., 2008).

1.2.2. Storm impacts—Storms can remove sediment to the back-barrier area via overwash and breaching, or move beachface sediments offshore when breaching does not occur (Houser et al., 2008). Repeated storm-induced breaching can cause a barrier island to become increasingly segmented and eventually submerge (Sallenger Jr., 2000; FitzGerald et al., 2008). While extratropical storms and El Niño events can also cause considerable sediment redistribution along the west (Ruggiero et al., 1997, 2001) and east coasts (Sallenger Jr., 2000) of the United States, hurricanes historically cause the most dramatic geomorphologic changes along Gulf of Mexico barrier island systems on daily to annual timescales (Sallenger Jr., 2000; Otvos and Carter, 2008).

Ship Island has been periodically breached along its vulnerable, lowlying central section (i.e. the barrier neck), with the first recorded occurrence in 1852 (Morton, 2008; Otvos and Carter, 2008). East and West Ship Island were re-unified by natural spit growth between storm impacts (Otvos and Carter, 2008; Byrnes et al., 2012). Since the impact of Hurricane Camille in 1969, the inlet (Camille Cut) has remained open. Hurricanes Camille (1969) and Katrina (2005) caused the most extreme and lasting geomorphic changes on Ship Island in the last century (Otvos and Carter, 2008). Katrina significantly expanded Camille Cut, almost completely eroding away the low elevation portion of East Ship Island, halting the island growth progress, and causing severe shoreline erosion in other parts of the island (Fritz et al., 2007; Morton, 2008). To date, the volume of sediment transported, lost, and/or recovered in the years following Katrina has remained unknown.

Wave height data obtained from three National Data Buoy Center stations (42012, 42067 and 42007) quantifies the wave climate near Ship Island (Fig. 2). A 24-h running mean of wave energy shows severe events that occurred on short (daily) timescales (Fig. 2A). The largest spike in wave energy occurred in 2005, reflecting the Katrina impact (400 kJ/m²). Other observable spikes from the buoys include Hurricane Ivan in 2004 (200 kJ/m²), Hurricane Gustav in 2008 (170 kJ/m²), and Tropical Storms Ida (110 kJ/m²) and Lee (100 kJ/m²) in late 2009 and 2011, respectively. Monthly averages (Fig. 2B) show that these shortlived events dominate the wave climate. They contribute ~15% of the total energy but only account for <1% of the time during the study period. The ultimate response of the island to these waves depends on many factors in addition to their energy, including wave direction, tidal level, and possible storm surge (Anthony, 2013; Johnson et al., 2015), as well as sediment supply and geomorphology.

1.2.3. Sediment supply—A healthy barrier island will be in a dynamic equilibrium between erosion and deposition. Decreases in sediment supply can leave an island in a state of net sediment loss, resulting in decreasing size and possible drowning (Byrnes et al.,

2013). Prevailing easterly winds drive longshore transport in the northern Gulf of Mexico region reflected by east to west migration of the islands (Byrnes et al., 2012).

Despite the seemingly large subaqueous volume of sand supplied alongshore to the chain each year (305,000 m³), there is still a net loss of sediment (Byrnes et al., 2013). In fact, Ship Island has the largest sediment deficit in the chain at -174,000 m³ per year averaged from 1917 to 2005 (Byrnes et al., 2013). This makes it difficult for the barrier to grow or recover after erosive storm events, and explains Ship Island's relatively small volume above sea level for its length compared with other northern Gulf of Mexico barriers in Florida (Twichell et al., 2013).

All MS-AL barriers are in a transgressive/erosional state with occasional progradational/depositional landforms such as spits. This transgression is primarily fueled by movement of sediment to the back-barrier via storm overwash, or sediment removal to the deep Gulf of Mexico by storm waves (Otvos and Carter, 2013). Natural island healing after these events is driven by fair-weather sediment supply. In these conditions, shore-parallel bars form in the near shore on the shallow platforms (Otvos and Carter, 2008).

Permanent sediment loss from the system can be partially attributed to ship channel dredging (Morton, 2008; Otvos and Carter, 2008). Dredging currently removes a net volume of about 50,000 m³/yr of sediment, averaged from 1917 to 2009, from the Horn Island Pass littoral zone, located updrift of Ship Island between Horn and Petit Bois Islands (Byrnes et al., 2012). This represents a considerable volume when compared with Ship Island's average yearly sediment deficit of 174,000 m³, calculated between 1917 and 18 and 2005–10 (Byrnes et al., 2012). Dredging decreases the natural longshore transport supply and deepens inlet channels from natural depths of around 5 m to up to 20 m in the Gulfport Ship Channel, located directly west of Ship Island (Morton, 2008). Sediments in the channels are far below fair weather wave base, functionally isolating one barrier from the next. This is evidenced by the lack of sand transport between Ship and Cat Islands (Byrnes et al., 2013). Significant area loss is documented for all islands in the MS-AL chain, but Ship Island is the most vulnerable, being one of the farthest from the sand source, and showing more degradation than any other barrier in the chain (Byrnes et al., 2013).

1.3. Study goals

Island area trends suggest that Ship Island, along with the rest of the MS-AL barrier chain has been shrinking at unprecedented rates throughout historic time (Byrnes et al., 2013). Ship Island has experienced a 66% area loss between 1849 and 2005 (Otvos and Carter, 2008). However, a modern detailed volumetric analysis has yet to be conducted for the combined topographic/bathymetric (topo/bathy) system, particularly on a shorter timescale. The goals of this study are to quantify these changes by observing the short-term barrier morphodynamics associated with storms and provide the most high-resolution geomorphological analysis of the Ship Island system to date. This is accomplished by examining coupled topo/bathy LiDAR datasets over three time slices, a novel technique that can be applied to other barrier islands for conducting high-resolution sediment volume change calculations. Our analysis aims to add to the collective understanding of natural barrier island evolution in the current regime of accelerated SLR, frequent intense storm

impacts, and limited sediment supply. Quantitative barrier evolution datasets, particularly for entire islands, are scarce globally. However, this information is critical towards furthering our understanding of barrier island response to external evolutionary drivers (FitzGerald et al., 2008; Stutz and Pilkey, 2011; Cazenave and Le Cozannet, 2013) and constraining numerical models (Murray, 2003; Moore et al., 2014; Lorenzo-Trueba and Mariotti, 2017).

2. Methods

2.1. LiDAR data

Topo/bathy LiDAR surveys of Ship Island were collected in 2004, 2007, 2010, and 2012 (Table 1). Files were provided in .xyz or .las format and included only the bare earth surface (i.e., vegetation and all other returns were removed). Point clouds were clipped to the desired latitude and longitude range, and converted to [x, y, z] ASCII files using the LAsTools© (Isenburg, 2015).

Once in ASCII format, the data were further processed in MATLAB®. Originally referenced to NAVD88, the elevations were converted to mean high water (MHW). Correction values from the NW, NE, SW and SE corners of the study area were obtained from NOAA's VDatum Transformation software. Values were averaged to determine a MHW value on Ship Island of 0.36 ± 0.01 m below NAVD88. Thus, all z values were converted from NAVD88 to MHW by subtracting 0.36 m. This provided a geomorphologically accurate shoreline for comparison of subaerial and subaqueous features.

2.2. Digital elevation models

Point clouds were gridded to 5×5 m² cells using a linear interpolation algorithm to create digital elevation models (DEM). This resulted in the creation of unrealistic DEM surfaces outside the LiDAR data coverage. DEM surfaces beyond a range of ~50 m from the boundary of these data were excluded from the DEM. The geographical extent of the bathymetric data differs from year to year primarily because of water clarity, but also due to instrument limitations and flight line patterns. The geographically smallest datasets used in this study are 2004 and 2010 (Table 1). 2007 and 2012, however, have complete coverage of the shallow platforms around the islands, and reach depths up to ~8 m in the 2012 dataset (Fig. 3).

Analysis of the DEMs included sediment volume and sediment volume change calculations, and the creation of difference grids using surface-subtraction and transect extraction methodologies similar to Buijsman et al. (2003). Sediment volume above MHW, calculated using Eq. (1), indicates the sediment volume of the subaerial island:

$$V_{topo} = \iint Z_{topo} dx dy \quad (1)$$

where V_{topo} is volume (m³), Z_{topo} is elevation above MHW for each grid square (m; always positive), and $dx dy$ is grid square area (5×5 m²). Sediment volume below MHW was examined indirectly using the volume of water using a similar calculation:

$$V_{bathy} = \iint Z_{bathy} dx dy \quad (2)$$

where V_{bathy} is water volume (m^3) and Z_{bathy} is elevation for each grid square below MHW (m; always negative). In order to compare years with varying bathymetric data extents, the grids are trimmed to the largest area common to all four datasets before volume is calculated. Topographic and bathymetric sediment volume changes are calculated using Eqs. (3) and (4), respectively (Fig. 4). Topographic volume change is calculated by subtracting V_{topo} at time 1 (V_{t1}) from V_{topo} at time 2 (V_{t2}) (Eq. (3)). Bathymetric volume change is the negative difference between V_{bathy} at time 2 (V_{b2}) and time 1 (V_{b1}) (Eq. (4)).

$$\Delta V_{topo} = V_{t2} - V_{t1} \quad (3)$$

$$\Delta V_{bathy} = -(V_{b2} - V_{b1}) \quad (4)$$

Total topo/bathy sediment volume change is the sum of these two values, where $V_{sediment}$ is the overall volume change in the data coverage area from one year to another (Eq. (5)).

$$\Delta V_{sediment} = \Delta V_{topo} + \Delta V_{bathy} \quad (5)$$

Difference grids were created from dataset A to dataset B, for example, by subtracting Z values of each grid square in dataset B from the corresponding grid square in dataset A. Difference grids are limited to the area where the two datasets, A and B, overlap. This is independent from the largest common area used in volume calculations, and only relies on the two grids being differenced, as the difference grids are solely for visualization and not for quantitative comparison from one time slice to another.

Despite reaching depths of up to 8 m, the topo/bathy datasets do not all capture the entire active sediment transport zone. Volume changes in our study area may still occur due to alongshore transport and cross-shore sediment transport across the boundaries of the DEMs. Irrespective of limitations in area coverage, we are still able to quantify subaerial and nearshore subaqueous sediment volume changes within the coverage area (i.e. observed system) (Fig. 3).

Volumetric change calculations from year to year are conducted within a common area shared between all years (method 1). Area-averaged subaqueous sediment volume changes were also calculated within the common area shared between 2007, 2010, and 2012, excluding the most spatially limited 2004 dataset, for comparison (method 2). For method 2, changes from 2007 to 2010, 2010–2012, and 2007–2012 were $0.34 \text{ m}^3/\text{m}^2$, $-0.15 \text{ m}^3/\text{m}^2$, and $0.19 \text{ m}^3/\text{m}^2$, respectively. These overall trends were the same as those calculated with method 1: $0.24 \text{ m}^3/\text{m}^2$, $-0.11 \text{ m}^3/\text{m}^2$, and $0.13 \text{ m}^3/\text{m}^2$, respectively. This test verifies that

excluding portions of the data for the sake of constancy between years does not change the conclusions reported here.

Cross-sectional profiles of East and West Ship Island are created directly from the point clouds using a linear interpolation algorithm. Transects are chosen to bisect the islands perpendicular to their Gulf of Mexico shorelines at several representative locations on East and West Ship Island, as well as across Camille Cut to show changes in the inlet size and depth over the study period.

2.3. Errors

Vertical and horizontal LiDAR point errors are reported in the metadata for each dataset. Since the 2004 dataset, these errors have been reduced due to improvements in collection and processing. The vertical and horizontal point errors of the 2004 LiDAR dataset are ± 0.15 m and ± 1 m, respectively, for both topographic and bathymetric points. These LiDAR data, with a data density of at least 1 sample/m², are linearly interpolated to 5×5 m² grid cells. The effect of these errors on the elevation error per grid cell has not been computed. The elevation error over the entire DEM, relevant to the integral volume calculations, is at least an order of magnitude smaller than ± 0.15 m because the total error is proportional to the grid cell error normalized by the square-root of the number of grid cells. Hence, we ignore this error for our volume calculations.

Another error that may be more relevant in this study is an observed vertical offset between two surveys. A vertical offset of ~ 0.12 m was detected between the 2004 and 2010 datasets over portions of Fort Massachusetts on West Ship Island. This brick fortress is assumed to be relatively stable. Vertical biases can be corrected for when they are known over the entire survey area. Unfortunately, the extent of this bias and how it varies in space is unknown. Hence, we conservatively assume that our volume change calculations for all three periods may be affected by this vertical error (± 0.12 m).

3. Results

3.1. Digital elevation models

DEMs were created for 2004, 2007, 2010, and 2012 showing the topo/bathy distribution around Ship Island and the aerial extent for each dataset (Fig. 3). Difference grids show elevation changes from 2004 to 2007, 2007 to 2010, and 2010 to 2012 (Fig. 5). Geomorphological changes can be quantified for the three time slices in the difference plots to provide local and overall rates of erosion and deposition.

In 2004, Ship Island has the largest surface area and Camille Cut is at its smallest, by both width and cross-sectional area, relative to the other years. The narrow, low-lying, spit-like feature extending from East Ship Island towards West Ship Island, referred to here as the barrier neck, constricts Camille Cut to only ~ 1 km wide (Otvos and Carter, 2008; Fig. 3, 2004). Most of the neck exists at < 1 m elevation. The 2004 dataset displays the smallest bathymetric data coverage, so limited information exists concerning the shallow platform around the island at this time. The shoreface of both East and West Ship drops off quickly to depths of ~ 5 m on the Gulf side (McBride et al., 2013).

The first time slice, 2004 to 2007, shows the most erosion of all three difference grids, where the 2004 island area is reduced to what remains in the 2007 DEM (Fig. 3, 2007). The strongest erosional signatures occur where the low-lying neck existed and along the southern shorelines, where erosion was N1 m/yr (Fig. 5, 2004–2007). The north shore of West Ship also experienced significant erosion of ~0.5 m/yr. Deposition of up to ~0.8 m/yr occurred south and west of where the low-lying neck existed before its total erosion.

Island area decreased by ~43% and volume decreased by ~40% between 2004 and 2007 (Fig. 3, 2007). Camille Cut was widened from <300 m to nearly 5 km. The eastern tips of both islands narrowed by ~100 m, and a pond formed in the central portion of East Ship Island. 2007 data provides complete coverage of the shallow bathymetry around the islands, showing the wide shallow shelves < 2 m deep to the north of both islands, and deeper water directly abutting the southern shores (Fig. 3, 2007). Shoals < 2 m deep also extend off the eastern tip of East Ship Island several kilometers into Dog Keys Pass. These eastern shoals appear in the 2010 and 2012 datasets as well and do not generally change shape.

From 2007 to 2010, the difference grid shows an increase in overall deposition, though up to ~0.6 m/yr of erosion still exists along the southern shorefaces, and the Camille Cut shoals (Fig. 5). Deposition of 1 m/yr or more occurred in a small patch along the northwest tip of West Ship Island, where the old Gulfport Harbor Navigation Channel (no longer in use) runs (USACE, 2010). Areas on the order of 0.1 km² on the eastern back-barriers of both East and West Ship Islands show ~0.6 m/yr of deposition. Other depositional hot spots of the same magnitude occur along the edges of the shallow platform and along the western Camille Cut channel. The majority of the shallow platform around the island is experiencing negligible change or slight deposition (+0.1 to +0.2 m/yr).

Between 2007 and 2010, the island increased its area by ~15% and its volume by ~33%. The net deposition on the island reduced the size of the pond on East Ship by ~50%. The previously narrowed eastern island tips are in-filled to elevations <1 m above MHW, and part of the low-lying neck reappears. The two channels in Camille Cut have also evolved, with the eastern channel becoming deeper and more linear, and the western channel narrowing.

The 2012 bathymetric data coverage is the largest of all four datasets, and shows all the shallow (<3 m) water around the islands as well as deeper portions in MS Sound to the north and the Gulf of Mexico to the south. The western channel of Camille Cut is narrower and curves along the shoreface of West Ship Island. The eastern channel is relatively stable from 2010 to 2012. The 2012 state of the islands shows a slight increase in aerial extent, ~9%, but a slight decrease in island volume, within the error bounds, since 2010.

3.2. Island transects

Two transects (A, B) are constructed perpendicular to the Gulf of Mexico shoreline of West Ship Island, three (C, D, E) lie across East Ship Island, and one across Camille Cut (F) (Fig. 1). 2004, 2007, 2010, and 2012 profiles were created along each of these transects, and include both subaerial and subaqueous sections. The vertical error for all profiles is ±0.12 m. One transect was chosen on both East and West Ship to reflect the most stable, high

elevation, portions of these islands (Fig. 6A & D). These transects cross areas with the highest elevations and the most vegetation. The other transects cross portions of the island with low dune systems that are frequently overwashed. Transects A and D do not show significant elevation change from year to year in the central portion of the islands, but retreat is still visible on the south-facing shorelines.

The narrowing of the eastern tip of West Ship Island is reflected in the profiles along transect B (Fig. 6B). By 2007, the shoreline has stepped back ~100 m, and the foredune ridge has been reduced to approximately half of its 2004 elevation. Between 2010 and 2012, the shoreline retreats ~40 m, and the foredune elevation remains approximately the same (Fig. 7, Table 2). An offshore bar at ~1 m depth is also visible in these final two profiles.

Transects C and E cross the western and eastern tips of East Ship Island respectively (Fig. 6C & E). Transect C crosses a portion of the low-lying neck. In 2004 the profile shows a low-elevation (0.5 m) ridge that becomes a fully submerged shoal at ~2 m depth. The shoal approaches MHW in 2010, and emerges by 2012. An offshore bar is also visible at ~0.75 m. Transect E, on the eastern portion of the island, shows shoreline retreat from 2004 to 2012 similar to that along transect B (Table 2, Fig. 6B). The elevation of the foredune ridge along transect E remains approximately the same through these years. The barrier here is narrowed from ~200 m to ~100 m from 2004 to 2007, followed by widening in 2010 and 2012 to ~260 m and finally ~280 m.

The Camille Cut transect shows the disappearance of the low-lying neck between 2004 and 2007 (Fig. 6F). Growth along the western tip of East Ship Island appears in the 2010 and 2012 profiles where the eastern part of Camille Cut emerges above MHW. The western channel of Camille Cut is present in all four profiles, but shallows from 2007 to 2010/2012 by ~2 m. The eastern channel reaches its greatest depth, ~4 m, by 2012.

3.3. Topo/bathy volumes and areas

The combined island area in 2004 was $\sim 3.90 \times 10^6 \text{ m}^2$, which was reduced to $\sim 2.24 \times 10^6 \text{ m}^2$ by 2007, post-Katrina (Table 3). From 2007 to 2010 the island grew to $\sim 2.44 \times 10^6 \text{ m}^2$ and again from 2010 to 2012 to $\sim 2.80 \times 10^6 \text{ m}^2$. An increase at an approximately linear rate of $\sim 0.11 \times 10^6 \text{ m}^2/\text{yr}$ island area is calculated from the LiDAR datasets for 2007–2012, but overall from 2004 to 2012, the island lost a total of $\sim 1.10 \times 10^6 \text{ m}^2$.

Subaerial island volumes and bathymetric volumes were calculated, and each showed distinct trends (Table 3). Island volume decreases drastically, similar to island area, from 2004 to 2007. It is reduced by $\sim 1.2 \times 10^6 \text{ m}^3$ over this time slice (from $\sim 3.0 \times 10^6 \text{ m}^3$), primarily due to the removal of the low-lying neck and nearshore material. From 2007 to 2010, the island increases its volume by $\sim 0.6 \times 10^6 \text{ m}^3$ (Table 4). The largest addition of volume in this time slice is backbarrier spit growth and in the old shipping channel (Fig. 5). In the final time slice from 2010 to 2012, the island returns to negative volume change within the error of the analysis. The volume increase from 2007 to 2012 is not linear like the observed increase in area (Fig. 8).

Subaqueous sediment volume changes are calculated within the largest data area covered by all four datasets (Fig. 3). Between 2004 and 2007, $4.1 \times 10^6 \text{ m}^3$ of sediment is removed from the bathymetric coverage area, indicating a net deepening (Table 4). From 2007 to 2010, the subaqueous sediment volume increased by $\sim 1.4 \times 10^6 \text{ m}^3$, indicating an overall shallowing. In the last time slice, 2010 to 2012, $0.7 \times 10^6 \text{ m}^3$ of sediment is removed from the observed bathymetry. This trend of erosion and deepening below the MHW line, followed by deposition and shallowing, mostly observed in the back-barrier shallows and in Camille Cut by 2010, parallels the observed subaerial area changes (Fig. 8).

Overall totals reveal a net loss of sediment in the subaerial and subaqueous portions of the island within the data coverage area. The total sediment loss from 2004 to 2007 is $\sim 5.3 \times 10^6 \text{ m}^3$ (Table 4). Sediment volume increase from 2007 to 2010 is $\sim 2.0 \times 10^6 \text{ m}^3$, and from 2010 to 2012, a slight negative change within the error bounds is observed. The total sediment volume lost since 2004 is a minimum value due to the lack of data coverage for 2004 as compared to the 2007, 2010, and 2012 datasets.

4. Discussion

4.1. Stormy period (2004–2007)

Erosion and land-loss dominate the stormy period, 2004 to 2007, which captures Ivan in 2004 and the severe Katrina impact of 2005. Katrina's eye passed 65 km to the west of Ship Island, exposing it to the strong front-right quadrant of the cyclone (i.e. higher winds and water level set-up). Wave energy during Katrina was approximately double that observed during Ivan's passing (Fig. 2A), and Ivan caused only minimal erosion compared with Katrina on Ship Island (Morton, 2007). Surge observed on Ship Island during Ivan was only 1.57 m (National Weather Service, 2016), compared with the 8 m Katrina surge, the highest ever recorded in the United States (Fritz et al., 2007).

With increasing storm surge, wave energy is focused farther up the beach, allowing for erosion of the foredune and other inland features (Sallenger Jr., 2000). This can lead to island overtopping, as in the case of Katrina on parts of Ship Island (Otvos and Carter, 2008). Ship Island's most mature dune ridges were overtopped by Katrina's storm surge, whereas Ivan's surge and waves likely did not overtop foredunes along most of the island. Katrina's storm surge and waves effectively flattened the East Ship neck into a wide, subaqueous platform (Otvos and Carter, 2008). This explains the erosive signature of the neck surrounded by a depositional feature in the shallow nearshore, back-barrier, and former channel (Fig. 5, 2004–2007). A new primary channel emerged ~ 3 km east of the original where East Ship Island's wide back-barrier platform ends (Fig. 3, 2007). Inlets across the MS-AL chain, including Camille Cut, widened in response to Katrina (Fritz et al., 2007).

The shorefaces and beaches of both East and West Ship Island also suffered severe erosion between 2004 and 2007. Shoreline retreat occurred along the stable central portions of both islands; ~ 30 m on West Ship, and ~ 70 m on East Ship (Table 2). Inundation of these stable portions during Katrina is responsible for the erosion as well as the death of all remaining pine trees and the formation of a pond on East Ship Island (Otvos and Carter, 2008). On the eastern tip of West Ship Island, some sediment removed from the shoreface was overwashed

and redeposited in the partially subaerial back-barrier spit within the coverage area (Fig. 5). This also may have occurred on East Ship, but the back-barrier shallows are not within the 2004 data coverage. Similar back-barrier spits do appear on East Ship in later years.

Not all of the sediment removed from the subaerial island (washover), shallow platform, shorefaces, or the low-lying neck was redeposited in the shallow back-barrier or in Camille Cut. Between 2004 and 2007, the island lost nearly half of its subaerial volume. The total topo/bathy system observed in this study lost a minimum of $\sim 5.3 \times 10^6 \text{ m}^3$ over this period, ~ 1.5 times the 2004 subaerial island volume (Table 4). Storm erosional processes, including overwash and beachface/foreshore erosion removed a significant amount of sediment from the observed system during this period. The geomorphological consequences of Ship Island's sediment removal are visible in the 2007 DEM (Fig. 3). The lack of a back-barrier marsh has likely contributed to land loss, as a marshy back-barrier can trap washover sediments in the shallow back-barrier (i.e., within our coverage area) rather than allow them to spread out into a large lagoon (Sallenger Jr et al., 2009; Moore et al., 2010, 2014). A back-barrier marsh can also provide a surface to transgress upon in the short term, allowing the island to keep pace with SLR (Brenner et al., 2015). The extreme erosion and lack of natural recovery observed in the Ship Island system over this period is similar to patterns observed on the runaway transgressive Chandeleur Islands in Louisiana (Sallenger Jr et al., 2009; Twichell et al., 2013; Moore et al., 2014).

4.2. 2007–2010 and 2010–2012

Overwash processes in combination with the lack of new sediment delivery from the east (Byrnes et al., 2012), can explain why only $\sim 37\%$ of the sediment volume lost from the observed system between 2004 and 2007 was restored between 2007 and 2012. Sediments contributing to this limited natural recovery likely came from within fair weather wave base in the shallow platform surrounding the island (Otvos and Carter, 2008). Storm impacts between 2007 and 2010, though less intense than Katrina, were also likely influential (Fig. 2). Gustav's impact in 2008 did not cause extreme erosion like that observed during Katrina (Morton, 2010). In fact, the 2007–2010 period is more depositional even than the final time slice, 2010–2012, which experienced the lowest overall wave energy, and no major events (Fig. 2).

This illustrates the potential for lower-intensity hurricanes, like Gustav, to redistribute sediment within the active system and contribute to island transgression without volume loss (Priestas and Fagherazzi, 2010). During this period, the West Ship nearshore zone experienced $\sim 3.2 \times 10^5 \text{ m}^3$ of sediment loss per year and spit growth in the back-barrier accounted for the deposition of $\sim 2.7 \times 10^5 \text{ m}^3$ per year. East Ship experienced less nearshore erosion, $\sim 1.6 \times 10^5 \text{ m}^3$ per year, and spit development on the back-barrier sequestered $\sim 2.4 \times 10^5 \text{ m}^3$ of sediment per year, indicating additional sediment sources, possibly including erosion of the flood tidal delta to the east (Fig. 5, 2007 to 2010). Reworking of the material delivered to the back-barrier accounts for the widespread but slow (on the order of 10 cm/yr or less) accretion across the back-barrier shallow platforms. Storm impacts causing little to no net erosion by depositing in the back-barrier like this are observed in other systems, such

as the Florida barriers during the impacts of Dennis and Ivan (Wang et al., 2006; Priestas and Fagherazzi, 2010).

Overwash and back-barrier deposition on Ship Island, likely due to Gustav, is focused at the narrowest and lowest-lying eastern tips (Fig. 5). This is similar to breaching patterns observed in the northwest Florida barriers (Houser et al., 2008). A high fair-weather incident wave angle can focus shoreline erosion to a certain end of a barrier island (Ashton and Murray, 2006). This causes increased erosion on the eastern tips of most islands in the MS-AL chain, exacerbated by the sediment deficit from the east, making them vulnerable to storm overwash (Morton, 2008). Sediment removal from the shoreface to back-barrier via storm breaching, and consequently retreat rates, is increased along these low-lying sections of Ship Island during all time slices (Fig. 7B & E).

Wider sections of the islands experienced more sediment loss to the shoreface, and beach erosion was limited. This sediment contributes to offshore bars that appear in 2010 and 2012 along transects A, B, and C (Fig. 6). Areas where sediment is moved farther down the shoreface rather than overwashed are observed to recover more quickly along another northern Gulf of Mexico barrier system (Santa Rosa Island, FL) and in Texas (Morton et al., 1995; Houser et al., 2008) over subdecadal timescales. Nearshore berm movement and accretion will likely move much of this sediment back on to the shoreface eventually. Some of the material eroded from the East and West Ship Island shorefaces will also move west into Camille Cut and into the old section of the Gulfport Harbor Navigation Channel respectively.

The East Ship neck growth into Camille Cut during this period likely sources some of its sediment from loss to the shoreface on East Ship Island as well as the erosion of shoals in Eastern Camille Cut. The post-2007 morphology of Camille Cut reduces the velocity at which tidal currents pass through the inlet by increasing its cross-sectional area while experiencing no tidal prism change. The subaqueous platform should naturally extend into the inlet from east-to-west from longshore sediment delivery, slowly reducing the size of Camille Cut and eventually fusing the two islands. The newly dominant eastern channel may hinder East Ship Island's ability to naturally extend past this point and heal Camille Cut, however.

Accretion above MHW, including dune growth, relies on windblown sediment delivery from the beach during fair-weather conditions in most barrier systems (Nickling and Davidson-Arnott, 1991). 2010 profiles along transects A, B, D and E show an aggraded foredune ridge relative to 2007, suggesting that aeolian processes are rebuilding the foredune ridges in some locations along the islands (Fig. 6). This likely represents the first phase of post-storm recovery observed in other barriers studied in the Gulf of Mexico (Morton, 1988; Morton et al., 1994, 1995). The island does increase in volume and area between 2007 and 2010, but only recovers ~1/5 of the volume lost between 2004 and 2007 (Table 4). All of the recovered volume, and most of the recovered area, appears between 2007 and 2010 (Fig. 9).

The final time slice, 2010 to 2012, shows a system primarily affected by a sediment supply limitation. The island experiences no hurricanes during this period, but does not show dune,

foreshore, or back-barrier deposition. Ship Island has been in an overall sediment deficit since records began in 1917 (Byrnes et al., 2013), and the system's return to an approximately neutral sediment flux within error bounds before it was able to fully recover from the storm impacts could be related to this long-term trend. Back-barrier spit growth and platform accretion have essentially halted. Nearshore erosion continues as before, fueling some continued spit growth along the East Ship neck. The foredune ridge, and other subaerial portions of the island begin to erode at rates up to ~0.3 m/yr. As sediment sources around the island deplete, aeolian supply dwindles despite a relatively constant rate of aeolian removal.

In response to storms, the shoreface can begin adjusting quickly, moving sediments back towards the shore in days and weeks (Ruggiero et al., 2005), but in some cases, barrier island adjustment and recovery can take many years (Morton, 1988; Morton et al., 1994, 1995; Stone et al., 2004). Other Gulf of Mexico barrier systems show slow post-storm recovery and continued beach erosion, like that of Ship Island, even during relatively fair-weather periods (Morton, 1988; Morton et al., 1994, 1995; Stone et al., 2004). Evidence suggests that only beaches with relatively low long-term erosion rates completely recover to pre-storm conditions (Morton, 1988; Morton et al., 1994, 1995), and thus the amount of beach recovery can be linked with the underlying long-term trend (Zhang et al., 2002). Given Ship Island was eroding rapidly even before Katrina (Morton et al., 2005), our data support this notion.

4.3. Overall trends

Our analysis, based on the four 2–3 year snapshots of the system, does not capture short-term, event-scale dynamics but important observations still emerge. A typical pre-storm profile is characterized by a steep upper shoreface which adjusts to stormy periods by shallowing its slope in response to higher wave energy. The sediment removed from the upper shoreface is often deposited in the lower shoreface. These trends are documented on centennial and millennial timescales (Wallace et al., 2010), but are observed here over a span of 8 years. The upper shoreface is the steepest in 2004, where data are available. From this point on, the profiles consistently move towards an idealized post-storm profile, indicating continued adjustment to the storm impacts, and an insufficient sediment supply to rebuild a pre-storm shoreface profile (Fig. 6).

The aerial extent of Ship Island has been measured many times since the 1800s, by aerial imagery and later by satellite (Fig. 10). The overall trend is one of land loss from a total area of ~6 km² in the mid 1800s, when it was still unified, to a total area of only ~2 km² by 2005 (Waller and Malbrough, 1976; Byrnes et al., 2013; Otvos and Carter, 2013). This overall, long-term trend can be explained by insufficient sediment delivery and accelerating SLR. With more frequent data collection, shorter-term changes can be observed before and after storm impacts (Otvos and Carter, 2013). Katrina's areal impact and the subsequent recovery are inferred from island areas calculated in this study, and the findings are supported by previously published data (Fig. 10).

Volume change studies conducted on larger temporal and spatial scales can be compared to values presented here. Byrnes et al. (2013) compute bathymetric volume changes from

1917/18 to 2005/10 for the entire barrier chain. Ship Island's average subaqueous sediment change over this time period is a net loss of 174,000 m³/yr (Byrnes et al., 2013). The subaqueous sediment volume change calculated in this study, averaged from 2004 to 2012 within the data coverage area, is a net loss of about 430,000 m³/yr. When the subaerial sediment volume change from this study is included, the net sediment loss increases to about 500,000 m³/yr from 2004 to 2012. Although the data coverage in this study is smaller than that considered by Byrnes et al. (2013), areas not covered here primarily experienced erosion or no change over the past 100 years, making it unlikely that we are over-estimating net erosion. Considering this, the average rate of sediment loss appears to be more than double over the past 10 years compared with the past 100 years.

5. Conclusions

- A. Ship Island experienced a stormy period from 2004 to 2007, dominated by the Katrina impact. This is followed by a period of recovery with only minor storm events, including Gustav, from 2007 to 2010. The final period is characterized by slight overall erosion, within error bounds, from 2010 to 2012. During the erosional stormy period, a minimum net sediment loss of $\sim 5.3 \times 10^6$ m³ occurred. By 2012, only $\sim 1/5$ of the sediment volume lost during the stormy period was recovered. An average volume change of about $-500,000$ m³/yr occurred across all three periods.
- B. Given the long-term erosion of Ship Island (Waller and Malbrough, 1976; Byrnes et al., 2013; Otvos and Carter, 2013), our volumetric data support the notion that storm-impacted beaches with relatively high long-term erosion rates are less likely to recover to pre-storm conditions (Morton, 1988; Morton et al., 1994, 1995), and thus the amount of beach recovery is related to the long-term trend (Zhang et al., 2002).
- C. The foreshore and shoreface provided the primary sediment source for areas of growth during fair-weather periods, with overwash focused on the low-lying, narrow sections. This follows the typical transgressive barrier island processes, also seen in systems like the Chandeleur Islands in Louisiana (Sallenger Jr et al., 2009; Twichell et al., 2013; Moore et al., 2014).
- D. Natural island volume recovery halted after 2010, though island area continued to increase. This highlights the importance of volumetric versus areal assessments to characterize barrier island geomorphology.
- E. Shorefaces along Ship Island do not appear to have recovered from the stormy period, including Katrina's impact. Considering the ongoing SLR of 4.1 mm/yr, the limited sediment supply, and the removal of sediment due to dredging, net sediment loss will likely continue on the islands unless a mediation, such as beach and foreshore nourishments, occurs.

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Fig. 1.

Study area map. The Mississippi-Alabama barrier island chain is located in the northern Gulf of Mexico. East and West Ship Islands (white inset box) are shown here in relation to surrounding inlets and the two adjacent barrier islands. The general topo/bathy (DeWitt et al., 2012; collected in 2008 and 2009 overlain by 2007 island area) and the 7 m depth of closure (white dashed line) are shown. Elevation transect locations are indicated by black lines and labeled with letters A–F (white inset box).

Fig. 2.

Buoy wave energy data plotted as (A) 24-h running mean and (B) monthly-averaged wave energy. Spikes associated with storm events in plot A are labeled with their category (C) or tropical storm (TS) status. LiDAR dataset collections used in this study are indicated by arrows. Buoys 42007 and 42067 are both <40 km from Ship Island, while buoy 42012 is located ~135 km to the east (inset map). Buoy 42012 experienced overall higher wave energy than the other two, and wave height data was scaled by a factor of 0.15 to match wave energy observed at buoy 42007. Hurricane and tropical storm tracks are labeled on the inset map (modified from Google Earth; storm tracks from NOAA). Ivan II is the weakened second passing of Hurricane Ivan after looping inland.

Fig. 3.

The gridded topo/bathy data DEMs derived from available LiDAR for 2004, 2007, 2010, and 2012. The extent of each DEM is limited by LiDAR data coverage. All analyses were conducted within the greatest common data area (dashed outline, 2004). Geomorphological features labeled include ES-East Ship Island, WS-West Ship Island, CC - Camille Cut, LLN - Low-lying Neck, SP - Shallow Platform, P-Pond, and the Old Gulfport Ship Channel. Black dashed lines indicate the new and old Camille Cut channels.

Fig. 4. Conceptual model of the difference calculation. (A) Example profiles 1 and 2 and their associated topographic (V_t) and bathymetric (V_b) volumes illustrated in cross section. (B) ΔV_{topo} and ΔV_{bathy} shown between profiles 1 and 2.

Fig. 5. Difference grids, created by subtracting one DEM year from another, are plotted here with the first year's island outline in white. The scale indicates erosion (negative values) and deposition (positive values). Insignificant changes/data gaps are shown in black.

Fig. 6.

Transect profiles for the four datasets (see Fig. 1 for location). Distance along transects A–E is from north to south (Mississippi Sound to Gulf of Mexico). Mean high water level is indicated by the dashed horizontal line. A and B cross West Ship Island, and C, D and E East Ship Island. Transect F spans Camille Cut from west to east.

Fig. 7. Retreat rates (meters per year) are plotted for each transect (A–E). Data are shown in Table 2. Total values reflect the average rate of retreat from 2004 to 2012.

Fig. 8. Plots of total island area (A_{topo}), subaerial island volume (V_{topo}) and subaqueous island volume (V_{bathy}) show values for the four datasets: 2004, 2007, 2010 and 2012. The Katrina event occurred in 2005 and is indicated by the vertical gray bar.

Fig. 9. Total bathymetric and topographic sediment volume changes in the three time slices. Error bars indicate the $\pm 0.12 \text{ m}$ error multiplied by the area of the island or bathymetric zone of interest.

Fig. 10.

Previously published area values (Diamond: Waller and Malbrough, 1976; Triangle: Otvos and Carter, 2008; Square: Byrnes et al., 2013) for Ship Island are compared with those calculated from the DEMs used in this study (Circle).

Table 1

LiDAR dataset sources, dates of collection, and point cloud coverage examples showing central East Ship Island and the surrounding bathymetry. These datasets are publicly available from NOAA's online Data Access Viewer.

Date Collected	East Ship Island Point Cloud Coverage	Source
April 2004		USACE NCMP JALBTCX <i>SHOALS</i> system
June 2007		NASA Wallops, USGS Coastal and Marine Geology Program, National Park Service <i>EAARL</i> system
April 2010		USACE NCMP JALBTCX <i>CHARTS</i> system
May 2012		USACE NCMP JALBTCX <i>CZMIL</i> system

Table 2

Shoreline retreat distances and rates calculated for transects A–E. Transect locations are shown in Fig. 1.

	A	B	C	D	E
2004–2007	30 ^a	110	N/A	70	140
2007–2010	10	60	N/A	30	40
2010–2012	0	40	N/A	20	0
Total (m)	40	210	130	120	180
Rate (m/yr)	5.0	26.3	16.3	15	22.5

^a Indicates an estimated value where data do not reach MHW.

Table 3

Topographic and bathymetric coverage areas, volumes, and associated errors for each LiDAR digital elevation model.

Year	Topo area (m ²)	Topo volume (m ³)	Topo volume error (m ³)	Bathy area (m ²)	Bathy volume (m ³)	Bathy volume error (m ³)
2004	3.90×10^6	3.0×10^6	4.7×10^5	3.81×10^6	6.1×10^6	4.6×10^5
2007	2.24×10^6	1.8×10^6	2.7×10^5	5.58×10^6	10.2×10^6	7.0×10^5
2010	2.44×10^6	2.4×10^6	3.1×10^5	5.45×10^6	8.8×10^6	6.5×10^5
2012	2.80×10^6	2.3×10^6	3.4×10^5	5.30×10^6	9.5×10^6	6.4×10^5

Table 4

Topo/Bathy sediment volume and area changes over each time slice. Net volume and area changes as well as time-averaged rates of volume and area change are calculated. The uncertainty applied (± 0.12 m) is based on the observed bias.

	Sediment volume change $\times 10^6 \text{ m}^3$	Island area change $\times 10^6 \text{ m}^2$
2004–2007		
Bathy	–4.1	
Topo	–1.2	–1.7
Total	–5.3	
2007–2010		
Bathy	1.4	
Topo	0.6	0.2
Total	2.0	
2010–2012		
Bathy	–0.7 ^a	
Topo	–0.1 ^a	0.4
Total	–0.8 ^a	
NET CHANGE	–4.1	–1.1
AVE RATE	–500,000 m^3/yr	–140,000 m^2/yr

^a Indicates values that are close to the magnitude of the uncertainty resulting from the bias and represent small or insignificant change that may be positive or negative.