Response and Recovery of Horn and Petit Bois Islands, Mississippi, USA to Tropical Cyclone Impacts: 2004 - 2016

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ABSTRACT

Horn and Petit Bois islands are two of five Mississippi (MS) barrier islands that provide physical protection from tropical cyclones threatening the MS Gulf Coast, in addition to critical habitat for the northern Gulf of Mexico (GOM). In September 2004, Hurricane Ivan removed a large volume of sediment from the eastern ends of Horn and Petit Bois islands with its 1 to 2 m storm surge and ~194 kph wind speeds. Then, in August 2005 Hurricane Katrina severely impacted the two islands again with its 3.5 to 5.5 m storm surge on Horn and Petit Bois islands, and estimated maximum sustained wind speeds of 204 kph at landfall in southeast Louisiana. Using topographic light detection and ranging (LIDAR) datasets from 2004 to 2016, spatial and temporal changes of the islands' area, sediment volumes, and shorelines were measured to ascertain their geomorphic responses and recovery rates following the impacts of these devastating tropical cyclones. During the 2004–05 hurricane seasons, Horn Island lost ~13.3% of its pre-hurricane Ivan land area, lost ~35.9% sediment volume, and had a total average shoreline change rate of –10 m/yr. Petit Bois Island also lost ~13.3% of its pre-Ivan land area, lost ~27% sediment volume, and had a shoreline change rate of –33 m/yr. Between 2005 (post-Katrina) and 2016, Horn Island recouped ~6.6% of its pre-Ivan land area and ~4.3% sediment volume, whereas Petit Bois Island recovered ~4% of its pre-Ivan land area and ~22.9% sediment volume. The overall averaged shoreline change rates between 2004 and 2016 were –2 m/yr for Horn Island and –3 m/yr for Petit Bois Island. These changes reflect that Horn Island is no longer stable, as its sediment supply cannot keep pace with the current rate of sediment loss, and that because Petit Bois Island's narrow central shoreline is retreating at a rate of 10 m/yr, the island is at risk of breaching during the next storm. Highlighting complex island response, the relationship between area and shoreline changes to that of volume changes was inconsistent.

1. INTRODUCTION

Barrier islands worldwide are increasingly at risk of being lost or deteriorated due to a myriad of forcing mechanisms (Fearnley et al., 2009; Lentz and Hapke, 2011; Odezulu et al., 2018). Accelerating rates of sea level rise (SLR) (Jevrejeva et al., 2014), increased tropical cyclone frequency and intensity (Walsh et al., 2016), and variations in sediment supplies (Gabriel and Kreutzwiser, 2000) have contributed to beach erosion, shoreline migrations, and/or submergence of barrier islands in many coastal zones (Morton, 2008; Salzmann et al., 2013; Rodriguez et al., 2018). Additionally, the dredging of shipping channels for navigation and the installation of artificial coastal structures around barrier islands have altered patterns of sediment delivery (Edwards, 2006; Morton, 2008; Otvos and Carter, 2008; Byrnes et al., 2013).

Temporal and spatial distributions of barrier islands using two-dimensional (2D) datasets have quantified area, width, and shoreline positions for decades (Waller and Malbrough, 1976; Morton et al., 2004; Sciaudone et al., 2016) using various field, hydrographic, and remote-sensing methods. Recently, the availability of high-resolution LIDAR data have expanded those analysis capabilities into three-dimensions (3D), allowing for the quantification of elevation and/or sediment volume on beaches and barrier islands worldwide, such as on the United States' East, West, and Gulf coasts (Buijsman et al., 2003; Preistas and Fagherazzi, 2010; Lentz and Hapke, 2011; Conery et al., 2018), the northeast Canadian coast (Xhardé et al., 2011), and United Kingdom coasts (Saye et al., 2005). While LIDAR data exist for a variety of coastal and nearshore environments, few studies have conducted high-resolution difference analyses over large areas (Buijsman et al., 2003; Zhang et al., 2005; Gares et al., 2006; Eisemann et al., 2018). By

47   quantifying centimeter to decimeter-scale vertical changes (NOAA, 2012) over large coastal

48   regions (10s of kilometers), barrier island response to sea level rise, storm impacts, and sediment

49   supply can be better understood over annual to decadal timescales. Additionally, these data can

50   be used to constrain barrier island evolutionary numerical models, such as XBEACH (Harter and

51   Figlus, 2017), BIT (Masetti et al., 2008), GEOMBEST (Moore et al., 2007), and BRIE (Nienhuis

52   and Lorenzo-Trueba, 2019).

53   In the United States, barrier island chains located along the northern GOM perimeter are

54   considered among the most vulnerable to erosion or submergence (Otvos and Carter, 2013;

55   Eisemann, 2016; Eisemann et al., 2018), due to a combination of the aforementioned

56   environmental and anthropogenic forces. Of particular concern to the northern GOM community

57   is the Mississippi-Alabama (MS-AL) barrier island chain. Previous work examining changes on

58   decadal to centennial scales concluded the MS-AL barrier islands have undergone long-term

59   shoreline erosion (Waller and Malbrough, 1976; Byrnes et al., 1991; Morton et al., 2004) and

60   significant land area reductions since the mid-1800's (Waller and Malbrough, 1976; Morton, 2008;

61   Otvos and Carter, 2013) primarily due to tropical cyclone impacts, sediment budget deficits, SLR,

62   and human activities (Waller and Malbrough, 1976; Morton, 2008; Otvos and Carter, 2008; Byrnes

63   et al., 2013). Of these forcing mechanisms, research has focused mainly on changes before and

64   after major storm events (Morton and Sallenger, 2003; Schmid, 2003; Froede, 2006; Fritz et al.,

65   2007; Morton, 2010; Jones, 2015). A shoreline change study by the United States Geological

66   Survey (USGS), using four historical shoreline positions and one LIDAR-derived modern

67   shoreline, determined the long-term (~150 yrs) shoreline change rate for Mississippi was –2.3 m/yr

68   (15 year, short-term rate of –2.1 m/yr), and for Alabama –0.4 m/yr (20 year, short-term rate +0.3

69   m/yr) (Morton et al., 2004). While this method of coastal monitoring provides quantitative

70 analyses of shoreline change in a 2D plane, it omits the spatial changes occurring on barrier

71 islands' interiors (e.g., dunes, ridges, swales, ponds and lagoons). By incorporating 3D barrier

72 island changes, highly dynamic spatial and temporal processes can be quantified. This study seeks

73 to extend the current state of knowledge of the MS barrier islands by quantifying area, volume,

74 and shoreline change on Horn and Petit Bois islands (Fig. 1).

75 **1.1** *Regional Setting*

76 The MS-AL barrier island chain (Fig. 1) is a set of six offshore islands situated from 5 to

77 20 km seaward of the mainland coast. From west to east, the five main islands in the MS-AL

78 barrier island chain are Cat Island, Ship Island, Horn Island, and Petit Bois Island in Mississippi,

79 and Dauphin Island on Alabama's southwest coast. This approximately 100 km long assemblage

80 of islands and tidal passes form the geographical demarcation between the Mississippi Sound and

81 the northern GOM (Eleuterius, 1978). The islands are composed of 50 to 100% fine to pebble-

82 sized (0.21 to 4 mm) quartz sand (Waller and Malbrough, 1976; Cipriani and Stone, 2001), 2 to

83 50% heavy minerals (0.061 to 0.495 mm) (Foxworth et al., 1962; Cipriani and Stone, 2001), and

84 <2% calcium carbonate shells (Cipriani and Stone, 2001).

85 The initiation of the MS-AL barrier chain took place between 6 ka and 4 ka years BP

86 (Otvos, 2005; Hollis, 2018) when the western side of incipient Dauphin Island, anchored by the

87 Pleistocene Gulfport Formation towards the east (Otvos, 1985), intersected with landward

88 migrating marine shoals at an ~2 mm/yr SLR rate. As SLR decelerated below 2 mm/yr, the in-

89 situ shoals received enough sediment from alongshore and offshore sources to vertically aggrade

90 and stabilize (Otvos, 1979, 1981, 2018; Hollis, 2018; Hollis et al., 2019), forming modern day

91 Dauphin Island. Horn Island formed ~5 ka years BP at an ~1 mm/yr SLR rate (Otvos, 2005; Gal,

92 2018). Sand sourced primarily from the ravinement of the Biloxi and Pascagoula river

93 paleochannels south of Horn Island contributed considerably to its evolution (Gal, 2018). Ship

94 Island and the eastern part of Cat Island formed ~4.6 ka years BP as westward littoral transport

95 facilitated the vertical aggradation of Mississippi shoals over preexisting Holocene sandy-muds

96 (Otvos, 1985, 2001). The extent of westward progradation of the barrier islands ceased when it

97 encountered the advancing St. Bernard delta lobe of the southeast Louisiana coast, ~3.8 ka to 1.8

98 ka years BP (Twichell et al., 2013). Evidence of intense hurricanes impacting the northern GOM

99 have been geologically documented between ~2.2 to 1.9 ka and ~0.9 to 0.6 ka years BP by Bregy

100 et al. (2018), and modern day Petit Bois Island was given its own designation following a

101 hurricane-induced separation from Dauphin Island, likely in the mid-eighteenth century (Otvos,

102 1979). The sixth "island", West Petit Bois Island (WPBI), originated as spoils of dredging

103 operations from the Pascagoula Shipping Channel between 1917 and 1920 (Byrnes et al., 2013).

104 In May 2018, WPBI was officially added to the National Park Service's Gulf Island National

105 Seashore (Everitt, 2018), which previously included western Cat, Ship, Horn, and Petit Bois

106 islands.

107   The MS-AL barrier chain is set in a subtropical climate on a passive margin. Surface winds

108 are predominately from the east (E) and southeast (SE) between April and August, from the south

109 (S) in July, and from the E and northeast (NE) between September and March (Waller and

110 Malbrough, 1976; Byrnes et al., 1991; Zavala-Hidalgo et al., 2014). The islands are subject to

111 averaged significant wave heights of 0.4 to 0.7 m (Byrnes et al., 2013) and diurnal tides of 0.3 to

112 0.6 m (Waller and Malbrough, 1976).

113   Meteorological systems in this region strongly influence the geomorphology of the MS-

114 AL barrier islands. Under moderate conditions, the wave climate controls a net sediment flux of

115 230,000 – 305,000 m^3/yr via littoral drift (Byrnes et al., 2013). However, during periods of severe

116   weather, increased water levels increase normal wave heights (Byrnes et al., 1991) causing dune

117   and shoreface erosion. Severe weather systems include tropical cyclones, extratropical cyclones,

118   and cold fronts. Of these three systems, tropical cyclones have been acknowledged to cause the

119   most discernible changes to the sediment budgets of the islands (Morton and Sallenger, 2003;

120   Otvos and Carter, 2008; Jones, 2015). This is because their high velocity, sustained surface winds

121   and gusts (>119 kph) (NOAA, 2012) initiate dune blowouts (Gabriel and Kreutzwiser, 2000), and

122   generate high energy waves and storm surges, leading to island fragmentation, island breaching,

123   overwash (Otvos and Carter, 2008; Morton, 2010), inundation (Sallenger, 2000; Fritz et al., 2007),

124   and/or saltwater flooding (Waller and Malbrough, 1976). The less severe, yet more frequently

125   occurring extratropical cyclones and cold fronts are accompanied with directional-shifting, mild

126   to moderate (with occasionally gusting) surface winds and lower-energy waves (Masselink and

127   van Heteren, 2014), which have been recognized as erosive (Keen, 2002), restorative (Chaney,

128   1999), or adjusting (Stone et al., 2004) forces to the barrier islands.

129   **1.2** *Study Sites*

130   Horn Island (Fig. 2) is ~19.5 km long and is centrally located in the MS-AL barrier island

131   chain. Its orientation is largely shore-parallel with a southern, concave coastline near its center.

132   Horn Island was first identified as Mississippi's "most stable barrier island" by Byrnes et al. (1991)

133   due to its resiliency to tropical cyclone impacts, relative to the other islands. They determined that

134   from 1849 to 1986 Horn Island sustained no breaches or major shoreline alterations and had the

135   least cumulative percent change (15%) in its land area during that time (Byrnes et al., 1991). On

136   a short-term time scale, 1976 to 1986, Byrnes et al. (1991) found that Horn Island's rate of areal

137   change was –6.4 hectares/yr (or –0.064 km^2/yr). These results were later corroborated in similar

138   studies by Morton (2008), showing a 19% land area change for the period of 1849 through 2007,

139 and a short-term change rate of –5.7 hectares/yr (or –0.057 km^2/yr) between 1986 and 1998

140 (Morton, 2007). In a more recent study, Gal (2018) found that the continued stabilization of the

141 island is due to sand sourced from the ravinement of two incised valley paleochannels that

142 converge and intersect Horn Island.

143   Petit Bois Island (Fig. 2), situated between Horn and Dauphin islands, is ~10.4 km long

144 with a convex southern shoreline, and has a distinct triangular shape on its eastern half. A 1732

145 map of the north-central GOM coast by French cartographers Anville and Haye (1752) depicted

146 only four barrier islands fronting the MS Sound, indicating modern-day Petit Bois Island was once

147 part of Dauphin Island. Otvos (1979) suggests an unnamed hurricane, possibly in 1740, segmented

148 the island in two. Since then, Petit Bois Island has been migrating laterally to the west via updrift

149 erosion and downdrift accretion (Byrnes et al., 1991) between episodes of tropical cyclone

150 impacts. Its short-term areal change rates were found to be –2.8 hectares/yr (or –0.028 km^2/yr)

151 between 1976 and 1986 (Byrnes et al., 1991) and –10.0 hectares/yr (or –0.1 km^2/yr) between 1986

152 and 1998 (Morton, 2007). Petit Bois Island's western flank is currently abutting the Pascagoula

153 Shipping Channel, preventing its continued westward migration due to ongoing dredging

154 operations by the U.S. Army Corps of Engineers (Byrnes et al., 2013).

155 **1.3** *Cyclone History*

156   During the study period (2004-2016), eight tropical cyclones passed within a 200 km radius

157 of Horn and Petit Bois islands (Table 1). Hurricane Cindy (2005), Hurricane Katrina (2005),

158 Tropical Storm Lee (2011), and Hurricane Isaac's (2012) storm tracks all passed to the west of the

159 islands, meaning they experienced the "right sides" of the tropical cyclones. In the northern

160 hemisphere, the right sides of tropical cyclones are where the strongest winds and storm surges are

161 produced (Landsea, 2014). In these instances, the islands would have been subjected to more

162 erosive forces than those storms passing to the islands' east (Fearnley et al., 2009), such as in the

163 cases of Hurricane Ivan (2004), Tropical Storm Arlene (2005), Hurricane Dennis (2005), and

164 Tropical Storm Ida (2009). Horn and Petit Bois islands' geomorphic responses to these tropical

165 cyclones and their post-storm periods have been digitally captured using LIDAR technology.

166 **1.4** *Study Goals*

167 Previous studies on MS-AL barrier island evolution using various methods have

168 demonstrated long-term vulnerability (Waller and Malbrough, 1976; Byrnes et al., 1991, 2013;

169 Morton et al., 2004; Morton, 2008; Otvos and Carter, 2013; Eisemann et al., 2018). The unique

170 approach taken here is the use of multi-year, 3D, high-resolution LIDAR data to analyze the

171 geomorphic responses of the islands before and after tropical cyclone impacts, including periods

172 with no activity. This technique was first employed on Ship Island (Fig. 1) by Eisemann et al.

173 (2018), as no studies had quantified sediment volume changes in high-resolution on the MS-AL

174 barrier chain. The present study expands upon Eisemann et al.'s (2018) work by applying similar

175 LIDAR-based methods to Horn and Petit Bois islands to determine land area and volume

176 differences, and rates of shoreline change between 2004 and 2016. The goal of this study is to

177 compare the changes on Horn and Petit Bois with those of Ship, allowing us to better understand

178 the complex responses of these islands to variations in sediment supply, sea level rise, and storm

179 impacts. Specifically, what immediate geomorphic changes resulted from a hyperactive hurricane

180 season versus the following years when fair-weather conditions drove changes? This approach

181 provides insight into barrier island processes, such as overwash, dune accretion/erosion, and

182 shoreface erosion, rarely quantified, which will be of broad scientific interest. Additionally,

183 specific to LIDAR-derived geomorphic changes, are shoreline and areal changes always

184   proportional to volume changes for barrier islands? Answering this question is key to providing

185   general methodological approaches that will be internationally applicable.

186   Lessons learned from this study have global implications, as there is a dearth of high-

187   resolution, yet large spatial scale volumetric analyses for numerous barrier islands in a single

188   chain. Data derived from this study could be important input parameters for generalized barrier

189   island numerical modeling around the world.

190   **2. METHODS**

191   **2.1** *LIDAR Acquisition and Digital Elevation Model Generation*

192   LIDAR datasets for Horn and Petit Bois islands were acquired from the National Oceanic

193   and Atmospheric Administration's (NOAA) Data Access Viewer for years 2004, 2005, 2007,

194   2011, and 2016 (Table 2). These 3D, high-resolution datasets provide continuous surfaces across

195   a wide geographic area, allowing for the differences in elevation, shoreline positions, sediment

196   volume, and area of the barrier island platforms to be calculated during the 12.5-year study period.

197   LIDAR data analyses were conducted for five periods: April 2004 – December 2005, December

198   2005 – June 2007, June 2007 – June 2011, June 2011 – October 2016, and the entire period from

199   April 2004 to October 2016. The first period (2004 – 2005) captured two cycles of the North

200   Atlantic hurricane seasons, which included three major (category 3 or higher) tropical cyclone

201   impacts to the northern GOM, whereas the following three periods had 0 to 2 tropical cyclones per

202   year (category 2 or lower) during the next 11 hurricane seasons. The final period, 2004 to 2016,

203   looks at the net differences from beginning to end. The data time series provided the opportunity

204   to determine the islands' geomorphic responses and recoveries to these meteorological events.

205   Topographic-bathymetric point data in XYZ (longitude, latitude, elevation) format were

206   provided referenced to the earth's bare surface (excluding vegetation or artificial structures), to the

207 NAD83 horizontal datum in decimal degrees, and to the NAVD88 vertical datum in meters (m).

208 A sample set of elevation points (Z-values) from the entire study area's four-corners were then

209 processed through NOAA's VDatum Transformation v3.6 tool to obtain an average conversion

210 offset value between the NAVD88 and local mean high water (MHW) datums. This offset (or

211 correction) value was then applied across the entire dataset, allowing for comparisons of elevation

212 and sediment volume changes to be more spatially accurate. The resulting MHW is 0.36 m ± 0.01

213 m above NAVD88, therefore, subtracting 0.36 m from each terrain elevation point effectively

214 transformed the datasets from NAVD88 to local MHW (consistent with Eisemann et al., 2018).

215   Digital elevation models (DEMs) for each year (Fig. 3) were then generated using

216 MATLAB software gridded to 5 x 5 m^2 cellular resolution (linear interpolation algorithm; from

217 Eisemann et al., 2018). Individual datasets were uniformly cropped to contain point data for each

218 barrier platform as a separate area of interest. The gridded cells were then tabulated to yield total

219 areas and volumes for each island per year. LIDAR survey coverages, however, of Horn and Petit

220 Bois islands were spatially variable in both topography and bathymetry. Only two of the five

221 datasets (2007 and 2016) contained nearshore bathymetry down to 14 m depth (relative to MHW),

222 whereas all five datasets contained topographic elevation of Horn and Petit Bois islands. Two

223 caveats with respect to the topographic elevation points are that: a.) the 2004 dataset excluded

224 ~0.95 km^2 (satellite estimated area) of coverage from the northern-most side of Horn Island (Fig.

225 3, 2004, missing coverage) and ~0.62 km^2 (satellite estimated area) of coverage from the northeast

226 side of Petit Bois Island, and b.) the 2005 dataset excluded ~0.22 km^2 (satellite estimated area) of

227 coverage from the northeast side of Petit Bois Island during the flight surveys for those years. As

228 a result of these observations, all LIDAR-derived area values were cross-referenced to satellite

229 imagery to ensure subaerial LIDAR data points were captured for both islands.

230 **2.2** *LIDAR Uncertainty*

231   Positional uncertainty is reported in the metadata accompanying each LIDAR dataset. The

232 reported maximum vertical uncertainty of all five datasets was 20 cm, and the maximum horizontal

233 uncertainty was 100 cm (Table 2). These uncertainty values are primarily associated with

234 collection errors in the onboard aircraft equipment, including the GPS, the inertial navigation unit,

235 and the unit that points the direction of the laser (Hodgson and Bresnahan, 2004; Lentz and Hapke,

236 2011). Quality control of post-processed LIDAR data can be assessed by calculating the horizontal

237 and vertical offsets between multiple datasets using a stationary structure within the confines of

238 the respective study area (Lentz and Hapke, 2011; Eisemann et al., 2018). The present study area

239 did not contain a permanent structure to apply this quality control assessment to, so using methods

240 from Eisemann et al. (2018), the five datasets were plotted over Fort Massachusetts on Ship Island,

241 and the vertical error was measured at ±0.09 m (applied to all datasets). Horizontal uncertainty

242 was not a considerable factor relative to the large-scale changes identified in the results, as

243 confirmed by cross-validation with aerial satellite imagery.

244 **2.3** *Subaerial Area Analyses*

245   To identify the total area and total areal changes in the subaerial landscape between two

246 DEMs, 2D surface contours of the islands' perimeters were generated using the 0 m MHW

247 elevations of each dataset. Once the 2D surfaces were created and gridded to 5 x 5 m^2 (25 m^2)

248 cells, the summation of the cells produced the total area of each individual dataset. Subtracting an

249 older dataset from the subsequent, more recent dataset (for example, 2016 minus 2011) resulted in

250 the total areal changes between the two years. As previously mentioned, ~0.95 km^2 is missing

251 from Horn Island and ~0.62 km^2 is missing from Petit Bois Island's 2004 LIDAR surveys. Total

252 area calculations removed these missing sections for each subsequent year. Therefore, the total

253 areal change values between two subsequent datasets reflect these limitations and represent

254 minimum change values. Calculations were performed using MATLAB software.

255 **2.4** *Volumetric Analyses*

256   DEM surfaces were directly analyzed using subtraction calculations (from Buijsman et al.,

257 2003 and Eisemann et al., 2018) to determine sediment volume gains and/or losses relative to the

258 local MHW datum. Elevation differences between overlapping datasets in coincident cell volumes

259 between time-1 (t_1) and time-2 (t_2) were calculated and output into new gridded surfaces to

260 spatially visualize where changes occurred on the islands. These differences in elevation (in

261 meters) were then multiplied by the area of each cell (25 m^2) to yield the volumetric changes in

262 cubic meters (m^3). Repeating this method on all datasets for topographic sediment volume

263 (ΔV_{topo}) (Eq. 1) and two datasets for bathymetric sediment volume (ΔV_{bathy}) (Eq. 2) allows us to

264 observe trends in sediment volume changes throughout the 12.5-year period. Where ΔV_{topo} and

265 ΔV_{bathy} returned positive values, sediment accreted, and where ΔV_{topo} and ΔV_{bathy} returned

266 negative values, sediment eroded (consistent with Eisemann et al., 2018):

267 $$\Delta V_{topo} = V_{t_2} - V_{t_1} \tag{1}$$

268 $$\Delta V_{bathy} = -(V_{t_2} - V_{t_1}) \tag{2}$$

269   Difference grids were created from one year relative to the previous year but are solely for

270 visualization purposes and are not used for volume change analyses. On account of the 2004

271 dataset having the geographically smallest area for topography, total subaerial volume calculations

272 for all individual datasets were adjusted to the greatest common areas of Horn and Petit Bois

273 islands' 2004 dataset, delineated by the pink dashed perimeter in Figure 3. Therefore, total

274 subaerial volume change values between two subsequent datasets reflect these limitations and

275 represent minimum change values. Additionally, because the 2007 dataset was the geographically

276 limiting dataset for bathymetry, the total bathymetric sediment volume and their differences

277 between 2016 and 2007 are limited to this area.

278 **2.5** *Transect Elevation Profiles*

279   Elevation profile bundles were created from transects taken on Horn and Petit Bois islands

280 by subsampling LIDAR elevation data along those transects. One east and three south trending

281 transects on each island were selected to capture the largest geomorphic variabilities in topography

282 and bathymetry. Individual dataset profiles were plotted along these transect lines from 3D point

283 data using a linear interpolation algorithm (Buijsman et al., 2003), however, bathymetry was

284 limited to the 2007 and 2016 datasets.

285 **2.6** *Shoreline Analyses*

286   The ArcGIS v10.5 software package and the USGS's Digital Shoreline Analysis System

287 (DSAS) v4.3 tool (Thieler et al., 2009) were used to quantify the 12.5-year shoreline change rates

288 on Horn and Petit Bois islands. The 2D DEMs were imported as XYZ files into ArcMap, and the

289 0 m MHW shorelines were reproduced and projected to the WGS84 UTM Zone 16 North

290 horizontal datum. The DSAS tool was then used to create bulk cross-shore transects spaced at 25

291 m intervals perpendicular to Horn and Petit Bois islands. This resulted in ~1200 transects for Horn

292 Island and ~610 transects for Petit Bois Island which were used to calculate end point rate statistics.

293 The statistical results yielded average annual rates of shoreline change, reported in meters per year

294 (m/yr). Finally, a visual inspection was conducted on questionable transects (i.e., those cutting

295 through broken/fragmented shorelines) to remove any potentially anomalous data, and cross-

296 checks were made to satellite imagery to confirm shoreline positions and geomorphic features.

297 Zero-meter shoreline contours were all adjusted to the 2004 dataset for Horn and Petit Bois islands,

298 so the total average shoreline change rates are considered minimum change values.

299 **2.7** *Wave and Wind Data Analyses*

300   To understand the dynamics of physical forces and the effects they have on the islands'

301 geomorphologies, historical wave and wind data were obtained from several offshore buoys near

302 Horn and Petit Bois islands. First, significant wave height data were extracted from two moored

303 National Data Buoy Center (NDBC) buoy datasets and one University of Southern Mississippi

304 buoy (via Bender et al., 2010) to time-average wave energy calculations. Station 42007, situated

305 ~17 km south of Horn Island, provided one data-point per hour for each 24-hour period from

306 January 2004 to December 2009 (NDBC, 2018). Station 42012-Orange Beach, ~23 km southeast

307 of Petit Bois Island, provided one data-point per hour for each 24-hour period from April 2009 to

308 December 2016 (NDBC, 2018). Station 42067-USM3M01's (~20 km south of Horn Island)

309 significant wave height data were obtained from Bender et al. (2010). Using significant wave

310 heights and Holthuijsen's (2007) random-phase/amplitude model, wave energy (*E*) was calculated

311 using

312 $$E \ = \ \rho g (\tfrac{1}{16})(H_{m_0})^2,$$ (3)

313 where ρ is the density of seawater (1029 kg/m^3), *g* is the acceleration due to gravity (9.81 m/s^2),

314 and H_{m_0} is significant wave height (m). This equation produces units of wave energy per area in

315 Joules per meter squared (J/m^2). Wave energy was then time-averaged over 24-hour periods for

316 the entire study period and used in conjunction with wind data to assess geomorphic changes.

317   Next, historical wind speeds and wind directions were extracted from two NDBC buoy

318 datasets to create wind-rose diagrams using the 'WindRose.m' v1.3.1.0 MATLAB function

319 (Pereira-Valadés, 2015). Hourly averaged wind data from January 2004 to December 2008 were

320 used from station 42007, and from January 2009 to December 2016 data were used from station

321 PTBM6, located approximately 0.25 km southwest of Petit Bois Island (NDBC, 2018). The wind-

322　rose diagrams portray graphical representations of wind speeds, directions, and directional

323　frequencies (or magnitudes) from January 2004 – December 2016.

324　　　　Wave and wind periods were selected to be slightly longer than the LIDAR dataset periods

325　in order to capture the meteorological and oceanographic trends driving the geomorphic changes

326　on the islands. For these two parameters, period 1 (P1) is from January 2004 to December 2005,

327　period 2 (P2) is from January 2006 to July 2007, period 3 (P3) is from August 2007 to June 2011,

328　period 4 (P4) is from July 2011 to December 2016, and period 5 (P5) is from January 2004 to

329　December 2016 (Table 3). These data were used to determine direction and magnitude of wind

330　waves approaching the islands, and for determining storm activity which impacted the islands.

331　**3. RESULTS**

332　**3.1** *Wave and Wind Data*

333　　　　Wave energy as a function of time is plotted in Figure 4. Each line represents a 24-hour

334　mean energy, with maximum energies all corresponding to tropical cyclone impacts. Hurricane

335　Katrina produced the highest average (26.6 kJ/ m^2) (Bender et al., 2010), followed by hurricanes

336　Gustav (15.8 kJ/m^2), Ivan (13 kJ/m^2), Isaac (11.2 kJ/m^2), Ike (10 kJ/m^2), and tropical storm Ida (8

337　kJ/m^2). Hurricane Katrina's landfall in August 2005 generated the largest (43.5 kJ/m^2) single value

338　(Bender et al., 2010) for the study period. Although hurricanes Gustav and Ike's storm tracks fell

339　outside of the designated 200 km radius (gray circle in Fig. 4), their storm surges and wave energies

340　were large enough to cause erosion to the low-elevated portions of the islands. The mean wave

341　energy for this study was 0.423 ± 0.80 kJ/m^2. Statistical summarizes of wave data are in Table 3.

342　　　　Figure 5a is a wind-rose diagram depicting the distributions of wind speeds, wind

343　directions, and their magnitudes, for 2004 to 2016. The wind-rose indicates the dominant direction

344　for the study period was from the SE, meaning that for 8.1% of the time (or 11.2 months of

345   available data) prevailing winds were from the SE. Using a modified Beaufort Wind Scale (Storm

346   Prediction Center, n.d.), this wind rose diagram also illustrates that moderate winds (4.0 to 7.9

347   m/s) were present for 50.6% of the time (70.3 months), gentle winds (0 to 3.9 m/s) were present

348   for 34.1% of the time (47.3 months), strong winds (8.0 to 11.9 m/s) were present for 13.9% of the

349   time (19.3 months), and gale to storm force winds (≥12 m/s) were present for 1.3% of the time

350   (1.9 months). The 24-hour mean wind speed for this study was 5.33 ± 2.6 m/s and the maximum

351   (10-minute mean) wind speed was 34.4 m/s from the S-SE (Howden et al., 2008) during Hurricane

352   Katrina.

353   Figure 5b is a wind-rose diagram for July 2011 to December 2016. During this time, the

354   dominant wind direction was from the ENE, inconsistent with trends analyzed from all other

355   periods. The cause of this anomalous shift in wind direction was likely due to a low number of

356   tropical cyclones and an increased number of cold fronts passing through the area, relative to other

357   periods. Following the passage of a cold front, postfrontal, northerly winds transport sand from

358   both the mainland coastline and the north sides of Horn and Petit Bois islands towards the south,

359   which results in deposition along the southern foredunes and beaches. Thomason (2016) reported

360   that 205 cold fronts passed through coastal Louisiana and Mississippi from January 2011 to March

361   2016, and Iowa State University's Environmental Mesonet recorded ~35 more passed through the

362   end of 2016.

363   **3.2** *Horn Island*

364   Figure 6 is a transect map of one east trending and three south trending transect lines cast

365   through Horn Island. LIDAR-derived elevation profiles for each year were plotted along the

366   transects to identify internal changes on the island. Cross-shore transects through Horn Island

367   were selected to approximately quadrisect the island.

368   **3.2.1** *Elevation Transect Data*

369   **3.2.1.1** *Transect H1*

370   Transect H1 (Fig. 7) is located on the western half of Horn Island. In the 2004 elevation

371   profile, the northern half of the island is generally <1 m, except for a few ~1.5 m backbarrier dunes,

372   and the southern half of the elevation profile is between 1 and 2.3 m, including one foredune and

373   two secondary dunes. The 2005 profile shows reduced surface elevations to all these dunes, with

374   the largest reduction to the southern foredune. On the 2007 profile, vertical elevation gains as

375   much as 0.5 m above the 2005 profile can be observed on the interior of the transect, whereas no

376   gains were observed on the shorelines. Bathymetry of the 2007 profile exhibits a steep upper

377   foreshore slope on the south-side down to –3 m, and a steep slope down to –2 m on the north-side.

378   The 2011 profile indicates dune scarping and vertical accretion on both north and south facing

379   dune ridges. The 2016 profile shows elevation increases of at least ~0.5 m across the entire length

380   of the transect, including shoaling in the bathymetry.

381   **3.2.1.2** *Transect H2*

382   Transect H2 (Fig. 8) is positioned through central Horn Island. The 2004 profile shows

383   the greatest variability in topographic elevations, including dune ridges between 2.5 and 3.6 m.

384   The profiles for 2005, 2007, and 2011 indicate erosional trends in relation to storms. The exception

385   is the northern and southern dunes, where elevation gains are observed from 2007 to 2016. The

386   2016 topographic profile is generally accretional, and elevations gains of 0.2 to 0.7 m over the

387   2011 profile can be observed. Bathymetric profiles from 2007 to 2016 show that erosion occurred

388   on the north side of the transect, whereas accretion occurred on the south side.

389   **3.2.1.3** *Transect H3*

390   Transect H3 (Fig. 9) is located on the eastern half of Horn Island. In 2004, the highest

391   elevation points along this transect (from north to south) were a 4.6 m backbarrier dune and a 2.8

392   m interior dune, with a shallow lagoon situated just below MHW between the two; and, two

393   additional interior ridges between 2 and 2.3 m high. By 2005, the elevation profile shows the

394   backbarrier dune eroded by 0.3 m, while the interior dune flanking the lagoon eroded by 2.5 m,

395   and the two interior ridges eroded as much as 1 m. There was, however, ~1 m of sediment

396   accretion between kilometers 0.5 and 0.6 in the cross-shore direction between 2004 and 2005. The

397   2007 profile is generally accretional along the entire transect, except for the lagoon which

398   exhibited deepening. The 2011 profile shows a taller and narrower backbarrier dune, a reduction

399   in elevation in the center of the transect, and a vertically accreted foredune ~3 m in elevation. The

400   2016 elevation profile generally trends positive over 2011 across the majority of the transect,

401   including a final backbarrier dune height of 4.4 m. The foredune, however, that was present in the

402   2011 profile had eroded down to between 1.6 and 2 m in height by 2016.

403   **3.2.1.4** *Transect H4*

404   Transect H4 (Fig. 10) is a centrally positioned, east trending transect along the island

405   indicating maximum elevations existed in 2004. Elevation profiles for 2005, 2007, and 2011 are

406   all largely erosional. Specifically, peaks in the central 2005 profile, between along-shore distances

407   of 8 and 11 km, continued to erode between the 2007 and 2011 profiles. The 2016 elevation profile

408   was almost entirely accretional over the 2011 profile. Several of the 2016 dunes between

409   kilometers 12 and 13 in the along-shore distance even reached or exceed the 2004 elevations.

410   **3.2.2** *Subaerial Area and Shoreline Changes*

411   Area and shoreline (Table 4) changes between 2004 and 2016 were quantified for Horn

412   Island using differences in the 0 m MWH elevation points. Horn Island had a subaerial area of

413   13.43 km^2 in April 2004, which decreased to 11.64 km^2 by December 2005. During this time, the

414   eastern tip lost 0.31 km^2 and the western tip lost 0.17 km^2, contributing to a total average shoreline

415   change rate of –10 m/yr. From late 2005 to June 2007, the island's area increased to 12.34 km^2.

416   This increase was primarily due to spit progradation on the tips, and the re-emergence of 0.04 km^2

417   of the 2004 far eastern tip, resulting in a total average shoreline change rate of +4.2 m/yr. From

418   mid-2007 to June 2011, Horn Island slightly reduced to 12.25 km^2 when the remnant tip

419   resubmerged, causing a total average shoreline change rate of –1.9 m/yr. Beyond 2011, Horn

420   Island's area continued to expand via spit progradation and lagoonal infilling to reach 12.52 km^2

421   by October 2016, yet had a negative total average shoreline change rate of –0.8 m/yr. The reason

422   for this apparent conflict is because the shorelines of the interior lagoons were not considered in

423   the DSAS calculations (only peripheral shorelines were), but the overall area of the island was

424   accounted for within MATLAB. The overall net changes to Horn Island between 2004 and 2016

425   indicate that the subaerial area had decreased by at least 0.91 km^2, and the total average shoreline

426   change rate was –2 m/yr.

427   **3.2.3** *Volume Changes*

428   Subaerial elevation differences between 2004 and 2016 were quantified from points above

429   MHW and are reported as changes in sediment volume. In April 2004, Horn Island contained

430   1.695 x10^7 m^3 of sediment and by December 2005 contained 1.086 x10^7 m^3. Horn lost 6.09 x10^6

431   m^3 (Table 5) of its volume due to erosion on the eastern and western tips, along with interior

432   surface erosion as much as –4 m (Fig 11a). Between late 2005 and June 2007 (Fig. 11b), minor

433   sediment gains occurred on the island's tips and southern foreshore; however, continued erosion

434   of the interior dune fields contributed to the further loss of 0.76 x10^6 m^3 of sand. From mid-2007

435   to June 2011, elevation gains between 0.5 and 2 m were observed on Horn's western tip, parts of

436   the southern foreshore, and several interior lagoons (Fig. 11c), yet the island lost another 1.05×10^6

437   m^3 sediment. From mid-2011 to October 2016, sediment volume on Horn increased by 2.54×10^6

438   m^3 to a final volume of 1.159×10^7 m^3. Sediment gains were mainly accumulated across the

439   island's southern shore-parallel dune ridges, and interior lagoons (Fig. 11d). The net volumetric

440   change (Fig. 11e) to Horn Island between 2004 and 2016 was a minimum of $–5.36 \times 10^6$ m^3. A

441   summary of Horn's subaerial area and volume quantities for the five datasets are graphically

442   represented in Figure 12.

443   Bathymetric elevation differences were quantified from points below MHW, to a

444   maximum depth of –4 m (Fig. 13) and are reported as changes in sediment volume. In 2007, the

445   nearshore water volume around Horn Island was 9.065×10^6 m^3 (Table 6), which increased to

446   9.462×10^6 m^3 in 2016. Erosion as much as 4 m took place largely on the southeastern shoreface,

447   creating accommodation for a larger volume of water in this vicinity. On the northern side of the

448   island, sediment deposition as much as 1 m occurred in the nearshore. The overall bathymetric

449   sediment volume change for Horn Island between 2007 and 2016 was $^{-}3.97 \times 10^5$ m^3, indicating

450   an overall deepening.

451   **3.3** *Petit Bois Island*

452   Figure 14 is a transect map of one east trending and three south trending transect lines cast

453   through Petit Bois Island. LIDAR-derived elevation profiles for each year were plotted along the

454   transects to identify internal changes on the island. Cross-shore transects through Petit Bois Island

455   were selected to capture a tidal channel (PB1), the narrowest width (PB2) and the widest width

456   (PB3) of the island.

457   **3.3.1** *Elevation Transect Data*

458   **3.3.1.1** *Transect PB1*

459   Transect PB1 (Fig. 15) is located on the western end of Petit Bois Island. Shoreline

460   movement at the MHW line was minimal on either side of the island between 2004 and 2016.

461   Ridge and swale topography dominated this part of the island in 2004, and the two highest peaks

462   along this transect were 2.7 and 3 m in elevation. The 2005 elevation profile shows the southern

463   berm had been reduced by 0.25 m, the northern berm reduced by 0.7 m, and incisions made to the

464   tidal channel in the cross-shore direction between kilometers 0.2 and 0.3. The 2007 profile is

465   accretional on both sides of the channel yet becomes erosional toward the south. The 2011 profile

466   is generally accretional with elevation gains in several of the dunes, yet the southern berm retreated

467   ~21 m from 2007. The 2016 profile also displayed vertical gains across the entire transect, with

468   respect to both topographic and bathymetric elevations.

469   **3.3.1.2** *Transect PB2*

470   Transect PB2 (Fig. 16) is centrally located on Petit Bois Island. Evidence of island

471   narrowing on the south-side, and sediment redistribution to the north-side is visible in this set of

472   profiles. In 2004, the width of the subaerially exposed land mass along this transect was 373.4 m,

473   the southern foredune ridge was 1.6 m high by 90 m wide, and the back half of the island was

474   almost entirely <1 m in elevation. By 2005, the foredune was reduced to 1.4 m high by 167 m

475   wide. In the subsequent profiles, the foredune began to vertically accrete and narrow, so that by

476   2016 it measured 2.5 m high by 49 m wide. The southern shoreline retreated 117 m between 2004

477   and 2016, with the largest retreat taking place between 2011 and 2016; and the northern shoreline

478   retreated 13.5 m between 2004 and 2016. Thus, the width of the subaerially exposed landmass in

479   2016 was 242.9 m. Bathymetry changes between 2007 and 2016 indicate the northern side of the

480   island vertically accreted by ~1 m, whereas the south side lost an average of 2 m.

481   **3.3.1.3** *Transect PB3*

482   Transect PB3 (Fig. 17) is located through the eastern portion of Petit Bois Island, capturing

483   it widest backbarrier. The 2004 profile is limited to the southern half of the island along this

484   transect. It shows several peaks no higher than 2.2 m. The 2005 profile, limited to the southern

485   two-thirds of the transect, is erosional and indicates ~40 m of shoreline retreat occurred on the

486   south-side. The 2007 elevation profile shows erosion to the southern foredune, then the profile

487   becomes accretional towards the north. The 2011 and 2016 profiles also indicate accretion. The

488   most notable features are the buildup of the backbarrier dune from 2007 to 2016, foredune

489   scarping, and shoreline erosion on the south side. Bathymetry profiles from 2007 to 2016 show

490   erosion occurred on the southern shoreface, while accretion occurred on the northern tidal flat of

491   the MS Sound.

492   **3.3.1.4** *Transect PB4*

493   Transect PB4 (Fig. 18) is a centrally positioned, east trending transect indicating the

494   greatest topographic variability was in 2004. Elevation profiles for 2005, 2007, and 2011 are all

495   erosional with the largest loss occurring between along-shore distances 3 and 4 km. The exception

496   being between the along-shore distances of 6 and 7 km, where accretion is observed. The 2016

497   elevation profile for Petit Bois Island was nearly entirely accretional. The most notable feature

498   along this transect is the western-most dune, which grew to 4.9 m by 2016, after losing 1.3 m

499   between 2004 and 2005.

500   **3.3.2** *Subaerial Area and Shoreline Changes*

501   Petit Bois Island's subaerial area was 4.00 km^2 in April 2004, which decreased to 3.47 km^2

502   by December 2005. During this time, the eastern tip lost ~0.07 km^2 and the shoreline retreated as

503   much as 90 m, causing the island to narrow, and yielding a total average shoreline change rate of

504   –33 m/yr (Table 7). From late 2005 to June 2007, expansion of the eastern and western tips

505 increased the island's area to 3.74 km^2, resulting in a total average shoreline change rate of +5.2

506 m/yr. Between 2007 and 2011, Petit Bois Island's southeastern shoreline retreated between 35

507 and 50 m, and the area decreased to 3.64 km^2, producing a total average shoreline change rate of

508 –2.7 m/yr. By 2016, the southeastern shoreline continued to show evidence of retreat (Figs. 16

509 and 17), whereas the southwest shoreline advanced between 25 and 40 m. As a result, the island's

510 area slightly decreased to 3.63 km^2 and the total average shoreline change rate was –1.5 m/yr from

511 2011 to 2016. Overall, the net changes to Petit Bois Island between 2004 and 2016 indicate the

512 subaerial area had decreased at least 0.37 km^2 and the total average shoreline change rate was –3.1

513 m/yr.

514 **3.3.3** *Volume Changes*

515 Petit Bois Island had 3.778 x 10^6 m^3 of sediment volume in April 2004 and 2.757 x 10^6 m^3

516 by December 2005 (Table 8). The loss of 1.021 x 10^6 m^3 between these years resulted from erosion

517 on the southern facing foredunes, eastern tip, and back barrier dunes. During this time, sediment

518 buildup on the interior dunes (Fig. 19a) occurred as a direct result of overwash from Hurricane

519 Katrina's storm surge. From late 2005 to June 2007, recovery began on the southern foreshore,

520 southeast tip, and western backbarrier tidal flats, while the central and western interior dune fields

521 underwent minor erosion, leading to a volume change of +1.34 x 10^5 m^3 (Fig. 19b). Between mid-

522 2007 and July 2011, the volume increased by only 0.68 x 10^5 m^3, mainly on the southeast foredune

523 (Fig. 19c). The largest accumulation of sediment to the island occurred between mid-2011 and

524 October 2016, when it gained 6.65 x 10^5 m^3 (Fig. 19d). Sediment accretion along the shore-parallel

525 southern dune ridges were due to the passages of cold fronts during this time. Despite these gains,

526 erosion to the south-central shoreface decreased the width of the narrowest part of the island.

527 Overall, the net subaerial volumetric change (Fig. 19e) on Petit Bois Island between 2004 and

528   2016 was a minimum of -1.54×10^5 m^3. A summary of Petit Bois Island's subaerial area and

529   volume quantities for the five datasets are graphically represented in Figure 20.

530   Table 9 shows the nearshore water volume around Petit Bois Island was 9.236×10^6 m^3 in

531   2007, then decreased to 8.072×10^6 m^3 in 2016. On the north side of the island, accretion up to a

532   maximum of +1 m (Fig. 21) was documented on the nearshore seafloor, reducing accommodation

533   for water volume in these areas. Shoreface erosion (as much as -4 m) was greatest on the southeast

534   and central parts of the island. In contrast, Petit Bois Island incurred the largest sediment gains

535   (as much as +4 m) to the shoreface in between these two erosional spots. The overall bathymetric

536   sediment volume change for Petit Bois between 2007 and 2016 was $+1.164 \times 10^6$ m^3, indicating

537   shallowing.

538   **4. DISCUSSION**

539   **4.1** *Morphological Impacts / Responses of the 2004-2005 Hurricane Seasons*

540   The 2004 and 2005 hurricane seasons produced three category 3 hurricanes which

541   impacted the northern GOM within 200 km of the study area. First, Hurricane Ivan passed 54 km

542   east of Petit Bois Island in September 2004, generating local storm surge heights of 1-2 m (Stewart,

543   2004), wave energy of 13 kJ/m^2, and maximum 2-hr sustained wind speeds of 25.2 m/s (90.7 kph).

544   In July 2005, Hurricane Dennis passed 132 km east Petit Bois Island with a storm surge height of

545   0.8 m (Bevan, 2005), wave energy of 4.9 kJ/m^2, and maximum 4-hour averaged wind speeds of

546   16.6 m/s (59.8 kph). Seven weeks later, at the end of August 2005, Hurricane Katrina made

547   landfall 100 km to the west of Horn Island with storm surge heights of 3.5 to 5.5 m (Fritz et al.,

548   2007), wave energy of 26.6 kJ/m^2 (Bender et al., 2010), and maximum 10-min averaged wind

549   speeds of 34.4 m/s (123.8 kph) (Howden et al., 2008) near Horn and Petit Bois islands.

550   The hurricanes' extreme atmospheric and oceanographic forces produced within a 12-

551   month period collectively caused numerous geomorphic changes to Horn and Petit Bois islands.

552   On Horn Island, the most obvious change was the loss of ~0.4 km^2 of the eastern tip, accounting

553   for 1.54 x 10^5 m^3 of sand between April 2004 and September 2005 (Fig. 22). The loss of this tip

554   was initiated with a breach during Hurricane Ivan from the 1 to 2 m storm surge to the low-lying

555   (0.5-1 m) sandbar. The breach was widened via erosion during Hurricane Dennis, and finally

556   completely submerged by Hurricane Katrina's storm surge. The western tip of Horn Island,

557   however, lost half as much land area (~0.2 km^2), yet ~100,000 m^3 more sand (total 2.49 x 10^5 m^3)

558   during Hurricane Katrina alone. Additional topographic changes between 2004 and 2005 included

559   dune lowering and flattening (2004 & 2005 profiles in transects H1-H3, Figs. 7-9), shoreface

560   erosion (Fig. 11a), washover deposits, and the loss of vegetation density (Carter et al., 2018) due

561   to saltwater inundation and burn. Therefore, as a result of these three storms, Horn Island had a

562   subaerial areal change rate of –1.07 km^2/yr, a subaerial volume change rate of –3.65 x 10^6 m^3/yr,

563   and a shoreline change rate of –10 m/yr between 2004 and 2005.

564   Petit Bois Island was also negatively affected during the 2004 and 2005 hurricane seasons.

565   Similar to Horn Island, both hurricanes Ivan and Dennis caused erosion to the eastern tip of Petit

566   Bois, yet Hurricane Katrina produced the greatest geomorphic changes to the whole island. Figure

567   23 shows a zoomed in view of erosion to Petit Bois' southwestern foredune, illustrating where

568   ~4,600 m^3 of sand (source sediment) was overwashed by Katrina's storm surge, and where ~2,650

569   m^3 of that sediment was deposited. The penetration distance of the overwashed sand was 217 to

570   240 m from the source. During this period, Petit Bois Island's southeastern foredunes were eroded

571   as much as 1.5 m in elevation, whereas the southwestern foredunes eroded as much as 4 m (Fig.

572   19a). Additionally, erosion along a low-lying tidal channel (Fig. 15; between kilometers 0.2 and

573   0.3 in the cross-shore distance) was initiated between 2004 and 2005 which lasted for the following

574   six years. Storm surge inundation also caused a 37% reduction in vegetation density across the

575   island (Carter et al., 2018). The geomorphic alterations between 2004 and 2005 caused Petit Bois

576   Island to incur a subaerial areal change rate of -0.32 km^2/yr, a subaerial volume change rate of $-$

577   6.13 x 10^5 m^3/yr, and an average shoreline change rate of -33 m/yr.

578   **4.2** *Morphological Responses from 2005 to 2016*

579   In the absence of intense, large-scale, tropical cyclones in the study area for the following

580   eleven hurricane seasons, the local fair-weather wave and wind climates became the dominant

581   forces driving sediment transport and morphological changes on the islands. Average significant

582   wave height from 2005 to 2016 was 0.65 m, average wave energy was 0.421 ± 0.65 kJ/m^2, and the

583   prevailing wind-wave direction was from the SE. Since, wind facilitates aeolian transport of sand

584   grains on barrier beaches and dunes through saltation and creep (Bagnold, 1941), grain sizes of

585   0.25 mm on Horn and Petit Bois islands are capable of being moved and/or transported at minimum

586   speeds of 4.1 m/s, measured 1 cm above the surface (calculated using Bagnold's, 1941 equations).

587   Winds near Horn and Petit Bois islands ≥ 4 m/s were present for 61% of the time, yielding favorable

588   conditions for aeolian sediment erosion or re-distribution. Wind speeds and directions also impact

589   wave dynamics in the area, such that wind generates surface waves and influences their direction

590   of travel (Thomason, 2016). The prevailing SE, moderate winds for the majority of the 12.5-year

591   study period (consistent with Zavala-Hidalgo et al., 2014) created a westward direction of sediment

592   transport (Byrnes et al., 2013). Strong to gale force winds, however, blew from the north ~17%

593   of the time which caused sediment from the back side of the islands to redistribute to the interior,

594   or transported sediment of the southern foredunes offshore.

595   **4.2.1** *2005 (Post-Katrina) to 2007*

596 Between 2005 and 2007, Horn and Petit Bois islands entered a post-storm phase. During

597 this period, the islands experienced deposition in the form of spit growth on the eastern and western

598 tips (Figs. 11b and 19b), sediment accretion on their southern foreshores and beaches, a resurfaced

599 segment of the far-eastern 2004 tip of Horn Island (Fig. 11b), and the formation of a new lagoonal

600 perimeter on Petit Bois Island's northeastern side (Fig. 19b). Deposition on the islands' southern

601 shorelines were carried from the east, and though this period had the lowest average wave energy

602 (0.342 ± 0.48 kJ/m^2), the islands experienced their greatest shoreline expansions. Erosion of the

603 islands' interior dune ridges resulted from the lack of substantial vegetation necessary to retain

604 sediment in place (Carter et al., 2018). As a result, wind erosion of 2 to 3 m in elevation on Horn

605 and 0.5 to 1 m in elevation on Petit Bois occurred on the central part of the islands, as winds blew

606 dominantly from the E-SE. This resulted in deposition in several lagoons and ponds thereby

607 reducing their open water area. The depositional and erosional processes between 2005 and 2007

608 led to a subaerial areal change rate of +0.44 km^2/yr, a subaerial volume change rate of -4.8×10^5

609 m^3/yr, and a shoreline change rate of +4.2 m/yr for Horn Island; and, for Petit Bois Island a +0.17

610 km^2/yr subaerial areal change rate, a $+8.46 \times 10^4$ m^3/yr subaerial volume change rate, and a +5.2

611 m/yr shoreline change rate.

612 **4.2.2** *2007 to 2011*

613 The following period, 2007 to 2011, was climatically similar to the previous, with regards

614 to wave energy and prevailing wind direction, and the islands experienced relatively minor

615 geomorphic changes. Doran et al. (2009) reported that after Hurricane Gustav the dune elevation

616 changes on Mississippi's barrier islands were near 0 m, central Horn Island gained ~100 m of

617 shoreline, and Petit Bios Island lost ~50 m of shoreline at its center. LANDSAT imagery from

618 August to September 2008 revealed the combined effects of hurricanes Gustav and Ike did cause

619   erosion to the eastern ends of Horn and Petit Bois, but both islands showed signs of areal recovery

620   by February 2009; therefore, erosion caused by these storms was not evident in the LIDAR dataset

621   of 2011. In general, Horn Island's interior continued to erode during this period, while the tips

622   continued to add sediment and recover from the 2004-05 hurricane seasons. Petit Bois Island also

623   accumulated ~7.7 x 10^4 m^3 of sediment to its eastern tip's low-lying platform and backshore, and

624   ~6.7 x 10^4 m^3 of sediment on a small section of the southwestern berm (Fig. 19c). The southern

625   shoreline, however retreated between 20 and 40 m (Figs. 16 and 17), causing this side of the island

626   to narrow. The depositional and erosional processes from 2007 to 2011 led to a subaerial areal

627   change rate of –0.02 km^2/yr, a subaerial volume change rate of –2.68 x 10^5 m^3/yr, and a shoreline

628   change rate of –1.9 m/yr on Horn Island; and, on Petit Bois Island a subaerial areal change rate of

629   –0.03 km^2/yr, a subaerial volume change rate of +1.74 x 10^4 m^3/yr, and a shoreline change rate of

630   –2.7 m/yr.

631   **4.2.3** *2011 to 2016*

632   During the period of 2011 to 2016, Horn Island accumulated 2.54 x 10^6 m^3 of sediment and

633   Petit Bois Island accumulated 6.65 x 10^5 m^3, their largest quantities of sediment volumes (Tables

634   5 and 8) following the 2004-05 hurricane seasons. Notable areas of geomorphic change on Horn

635   and Petit Bois islands were to their southwestern foredunes and interior eastern halves (Figs 11d

636   and 19d), where Horn gained ~6.5 x 10^5 m^3 of sediment in these areas and Petit Bois gained ~2.8

637   x 10^5 m^3. Specific changes to the islands included dune building and lagoon in-filling (example in

638   Fig. 24) on both islands, erosion to the south-central shoreline of Horn Island, and an ~60 m retreat

639   (transect P2, Fig. 16) on Petit Bois Island's south-central shoreline. Changes during this period

640   may be explained by a variance in climatic conditions, likely resulting from an increased number

641   of cold fronts (Thomason, 2016) which moved into the study area from the north, relative to the

642 low number of tropical cyclones (Table 1). The wind-rose in Figure 5b shows the direction of

643 prevailing winds for this period were largely out of the ENE, an irregularity from the expected SE.

644 Winds from the northerly directions are responsible for relocating sediment from the north side of

645 the island to the central and south side, and for lowering water levels immediately south of the

646 islands as winds blow offshore. The spatial differences between 2011 and 2016 led to Horn Island

647 having a subaerial areal change rate of +0.05 km^2/yr, a volume change rate of +4.76 x 10^5 m^3/yr,

648 and a shoreline change rate of –0.8 m/yr, and Petit Bois Island having a subaerial areal change rate

649 of –0.002 km^2/yr, a volume change rate of +1.25 x 10^5 m^3/yr, and a shoreline change rate of –1.5

650 m/yr.

651 **4.3** *Morphological Changes Across Entire Study Period: 2004 – 2016*

652 The morphologies and change rates of Horn and Petit Bois islands have only varied

653 moderately during the entire study period, as both were exposed to the same mean wave energies,

654 wind speeds, and sea level rise rate of +0.004 mm/yr between 2004 and 2016 (NOAA Tide Gauge

655 8735180 at Dauphin Island, AL, 2018). Horn Island exhibited net erosional trends to its subaerial

656 area, volume, and shorelines, and to its subaqueous nearshore sediment volume. Net topographic

657 sediment loss on Horn Island, between 2004 and 2016, occurred at an average rate of –4.29 x 10^5

658 m^3/yr, most of which occurred on the island's interior dunes and tips. Horn Island's average

659 subaerial area and total average shoreline change rates were relatively small for the overall study

660 period, –0.07 km^2/yr and –2 m/yr respectively.

661 Petit Bois Island also exhibited net erosional trends between 2004 and 2016. The average

662 rate of change to Petit Bois' subaerial area was –0.03 km^2/yr, while its shoreline change rate was

663 –3.1 m/yr, and its subaerial sediment volume change rate was –1.23 x 10^4 m^3/yr. In addition to

664 these trends, Petit Bois Island somewhat reoriented during this period and experienced in-place

665 island narrowing and lengthening. The extent of this in-place narrowing on Petit Bois' south-

666 central and southeastern shorelines are shown in transects PB2 (Fig. 16) and PB3 (Fig. 17). The

667 rates at which the shoreline retreated between 2004 and 2016 on transect PB2 was ~10 m/yr, and

668 on PB3 was ~8 m/yr.

669 Mean wind speeds (P1: 5.29 ± 2.9 m/s; P2: 5.16 ± 2.7 m/s; P3: 5.45 ± 2.5 m/s; P4: 5.16 ±

670 2.5 m/s; P5: 5.33 ± 2.6 m/s) of the study periods did not vary significantly, thus they did not appear

671 to have a direct correlation with observed spatial changes on Horn and Petit Bois islands. There

672 also did not appear to be a correlation with respect to mean wind speed and accretion/erosion. It

673 was observed, however, that for periods where the dominant wind direction was out of the SE,

674 erosion occurred, and when the dominant direction was out of the ENE, accretion occurred.

675 Several clear trends were observed with regards to wave energies and their effects on the

676 islands' geomorphologies. First, the highest mean wave energy (0.485 ± 1.44 kJ/m^2) for a single

677 period was observed in period 1 (2004-05). During this period, both Horn and Petit Bois islands

678 experienced the largest amounts of erosion and land loss to their areas and volumes. Second, when

679 the islands experienced instances of wave energies >10 kJ/m^2, accompanying storm surge heights

680 of at least 1 m generated erosion to low-lying areas of Horn and Petit Bois islands.

681 **4.4** *Overall Trends*

682 Area and shoreline positions of the MS-AL barrier islands have been surveyed since the

683 1800's. Figure 25 shows the historical subaerial area sizes of Horn and Petit Bois islands since

684 1848/49, indicating negative trends. Horn Island has lost ~3 to 3.5 km^2 in the past ~170 years,

685 while Petit Bois Island has lost ~4 to 4.5 km^2 in the same amount of time (Waller and Malbrough,

686 1976; Byrnes et al, 1991; Morton, 2007, 2008; Carter et al., 2018), including data from this study.

687 Short-term areal change rates found during this study were –0.07 km^2/yr for Horn Island and –0.03

688   km^2/yr for Petit Bois Island. These values were within an order of magnitude of previous results

689   between 1986 and 1998 (Morton, 2007). Short-term changes of shoreline positions of the MS

690   barrier islands were also measured at a mean rate of –2.1 m/yr, between 1986 and 2001 (Morton

691   et al., 2004). In this study, Horn Island's shoreline change rate was –2 m/yr and Petit Bois Island's

692   rate was –3 m/yr. Since Horn and Petit Bois islands have no history of artificial restorations, island

693   growth or stability is limited by the amount of sediment supplied by natural processes. Byrnes et

694   al. (2013) measured the bathymetric sediment flux of the MS-AL barrier islands between 1917/20

695   and 2005/10 and concluded there was a net deficit of ~3.38 x 10^5 m^3 between the western ends of

696   Dauphin and Horn islands, though a direct comparison is challenging due to limited bathymetric

697   coverage in our study.

698   Lastly, the geomorphic responses of Horn and Petit Bois islands were compared with those

699   of Ship Island, MS (Fig. 26). All three islands experienced severe erosion from the tropical

700   cyclone impacts of the 2004-05 hurricane seasons. In the years following these storms, Ship Island

701   (2007 to 2012) naturally recovered 0.56 km^2 (14.4%) of its pre-hurricane Ivan subaerial area

702   (Eisemann et al., 2018); and, from 2005 to 2016 Horn Island recovered 0.88 km^2 (~6.6%) of it pre-

703   Ivan subaerial area, whereas Petit Bois Island recovered 0.16 km^2 (~4%) of its pre-Ivan subaerial

704   area. Net topographic and bathymetric sediment volume losses on Ship Island, from 2004 to 2012,

705   were 4.1 x 10^6 m^3 (average loss 500,000 m^3/yr) (Eisemann et al., 2018), whereas between 2004

706   and 2016, net topographic sediment loss on Horn Island was 5.36 x 10^6 m^3 (average loss of 429,000

707   m^3/yr) and on Petit Bois Island net topographic sediment loss was 1.54 x 10^5 m^3 (average loss of

708   12,300 m^3/yr). These trends show Horn, Petit Bois, and Ship islands are responding similarly to

709   sea-level rise, storm impacts, and sediment supply variations over short timescales.

710   **5. CONCLUSIONS**

711   This study quantified the differences in subaerial area, subaerial sediment volume,

712   bathymetric sediment volume, and shoreline change rates of Horn and Petit Bois islands to

713   understand their geomorphic responses and recoveries to tropical cyclone impacts between 2004

714   and 2016. Horn Island lost a minimum of 6.09×10^6 m^3 of subaerial sediment volume during the

715   high energy events of the 2004-05 hurricane seasons, mainly on its interior dunes, and eastern and

716   western tips. Following these tropical cyclone impacts, Horn Island slowly began rebuilding part

717   of its eastern and western tips, and southern foredunes, yet continued to lose sediment in its interior

718   for an additional six years (2005 to 2011), due to aeolian erosion. Since, Horn Island was only

719   able to recover ~4.3% of the lost subaerial sediment volume (relative to 2004) from 2005 to 2016,

720   it is concluded that the island is no longer stable, and that Holocene shoreface ravinement processes

721   are not contributing significant amounts of sand (Gal, 2018) to the island fast enough to keep pace

722   with the current rate of loss. Petit Bois Island, on the other hand, recouped ~22.9% of its 2004

723   (pre-Ivan) subaerial sediment volume between 2005 and 2016. Most of these gains were to the

724   island's low-lying interior, at the expense of its southern foreshore. Furthermore, because Petit

725   Bois Island's narrow center was only ~240 m in 2016 and narrowing at a rate of ~10 m/yr, the

726   island is vulnerable to breaching during the next storm.

727   Also, when considering the responses of the islands' area and shoreline changes to that of

728   volume changes, the relationship was inconsistent. About 60% of the time, when Horn and Petit

729   Bois islands' areas and shorelines increased or decreased, so did the volume. The other ~40% of

730   the time, the volume change trend was opposite to that of the areas and shorelines. These findings

731   indicate the assessment of an island over sub-decadal timescales cannot be based on a singular

732   parameter (such as either area or volume alone), but that their longevity ultimately depends on

733   both the amount of area an island occupies coupled with the quantity of sediment volume it retains.

734 Furthermore, given that barrier islands globally are declining from various processes,

735 understanding the complex responses of regional barrier island chains in high-resolution remains

736 of the utmost importance for generalized numerical modeling, in addition to management and

737 policy decisions (Dolan and Wallace, 2012).

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1063

1064 **FIGURE CAPTIONS**

1065 **Figure 1.** Map depicting the north-central Gulf of Mexico coast and the MS-AL barrier island
1066 chain. Modified from ESRI ArcMap v10.5.1.

1067

1068 **Figure 2**. Map depicting Horn Island (left), West Petit Bois Island (middle), and Petit Bois
1069 Island (right). West Petit Bois Island was not included in this study as it is a landform generated
1070 from dredge spoil materials of the Pascagoula Shipping Channel. Imagery from Google Earth
1071 Pro. Inset maps modified from ESRI ArcMap v10.5.1.

1072

1073 **Figure 3**. Digital elevation models of Horn and Petit Bois islands representing island elevation
1074 (topographic and bathymetric) relative to the local mean high water (MHW) datum. The 2004

1075 survey of Horn Island (on the left) is missing ~0.95 km^2, the 2004 survey of Petit Bois Island (on
1076 the right) is missing ~0.62 km^2, and the 2005 Petit Bois survey is missing ~0.22 km^2 of topographic
1077 coverage on the islands' northern sides, indicated by the "missing data" and orange shading over
1078 these land surfaces. These missing 2004 and 2005 areas were artificially filled-in with the orange
1079 shading using Google Earth Pro satellite imagery to show the extent of the missing LIDAR data.
1080 The pink dashed perimeters on the 2004 dataset of Horn and Petit Bois islands represent the
1081 greatest common coverage area available for use in subaerial volume calculations across all five
1082 datasets. Bathymetric coverage was only available for the 2007 dataset (limited to the nearshore)
1083 and the 2016 dataset (up to 14 m MHW depth). Bathymetric volume change calculations were
1084 limited to the greatest coverage area of the 2007 dataset. The color bar depicts elevation, in meters
1085 (m), above or below the local mean high water (MHW) reference datum.

1086

1087 **Figure 4**. Hurricane tracks and wave energy. (Map) Plotted here are the six tropical cyclones that
1088 contributed the largest amounts of wave energy between 2004 and 2016. The light gray circle
1089 denotes the boundary of the 200 km radius around Horn and Petit Bois islands. (Graph) Wave
1090 energy data averaged over 24-hours from Jan. 2004 to Dec. 2016. The blue line graphs are from
1091 NDBC Station 42007, the orange line graphs are from NDBC Station 42012, and the dashed green
1092 line is from NDBC Station 42067-USM3M01 (based on data from Bender et al., 2010). Energy
1093 data for station 42012 were scaled by 0.15 to match station 42007 (from Eisemann et al., 2018).
1094 Time gaps on the graph represent periods of unavailable buoy data.

1095

1096 **Figure 5**. (A) Wind climate of the study area depicted for January 2004 to December 2016 (total
1097 study period). The dominant wind direction was from the SE. (B) Wind climate depicted for July
1098 2011 to December 2016 (anomalous period). The dominant wind direction was from the ENE
1099 during these years, showing a deviation from the expected SE direction. Each wind-rose displays
1100 16 cardinal directions (0° and 360° = N) from which wind blew, percent frequency of directions
1101 (represented by petal length), and magnitudes of each speed interval (defined in the legend). Wind
1102 data from January 1, 2004 to December 31, 2008 was obtained from NDBC Station 42007, and
1103 wind data from January 1, 2009 to December 31, 2016 was obtained from NDBC Station PTBM6.

1104

1105 **Figure 6**. Map of transects through Horn Island. H1, H2, and H3 are south trending, cross-shore
1106 transects, and H4 is an east trending, along-shore transect.

1107

1108 **Figure 7**. Elevation profiles for transect H1. The 2004 (blue), 2005 (red), and 2011 (purple)
1109 profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1110 contain both topographic and bathymetric data points. The cross-shore transect distance originates
1111 in the north (H1) and terminates in the south (H1'). The mean high water (MWH) line is
1112 represented with the dashed blue line at 0 m elevation. The vertical error bar represents ±0.09 m
1113 error.

1114

1115 **Figure 8**. Elevation profiles for transect H2. The 2004 (blue), 2005 (red), and 2011 (purple)
1116 profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1117 contain both topographic and bathymetric data points. The cross-shore transect distance originates
1118 in the north (H2) and terminates in the south (H2'). The mean high water (MWH) line is
1119 represented with the dashed blue line at 0 m elevation. The vertical error bar represents ±0.09 m
1120 error.

1121

1122 **Figure 9.** Elevation profiles for transect H3. The 2004 (blue), 2005 (red), and 2011 (purple)
1123 profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1124 contain both topographic and bathymetric data points. For the interior lagoon, at 0.2 km in the
1125 cross-shore distance, all five datasets contained shallow bathymetry. The cross-shore transect
1126 distance originates in the north (H3) and terminates in the south (H3'). The mean high water
1127 (MWH) line is represented with the dashed blue line at 0 m elevation. The vertical error bar
1128 represents ±0.09 m error.

1129

1130 **Figure 10**. Topographic elevation profiles for transect H4. The 2004 (blue), 2005 (red), 2007
1131 (yellow), 2011 (purple), and 2016 (green) profiles contain topographic elevation points. The along-
1132 shore transect distance originates in the west (H4) and terminates in the east (H4'). The smoothed
1133 black line represents the 500 m running mean across all datasets. The dashed blue line at 0 m
1134 elevation represents the mean high water (MWH) line. The vertical error bar represents ±0.09 m
1135 error. Bathymetry is not captured in this set of profiles.

1136

1137 **Figure 11**. Subaerial elevation differences on Horn Island from 2004 – 2016. This set of images
1138 represents differences in elevations (above MHW) at each XYZ point between two
1139 corresponding datasets. Differences in elevations were obtained by subtracting the younger year
1140 from the older year (ex: 2005 – 2004) and are reported in meters. Positive elevation change (cool
1141 colors) represents sediment gain, negative elevation change (warm colors) represents sediment
1142 loss. The black color box corresponds to values between -0.5 and 0.5 m elevation change.
1143 Elevation gains or losses were then calculated across the total area to yield volumetric change
1144 totals in m^3 (Table 5). The white shoreline perimeter in each map represents the most recent
1145 shoreline in the set. The 2004 dataset did not have full coverage, thus figures A and E have gray
1146 "missing survey coverage" annotations.

1147

1148 **Figure 12**. Graphs depicting Horn Island's subaerial area (km^2) and subaerial volume (m^3)
1149 calculated for each of the five LIDAR datasets: 2004, 2005, 2007, 2011, and 2016. LIDAR-
1150 derived subaerial area values, represented by the gray boxes and gray line graph (left y-axis),
1151 reflect areal changes for their respective years, minus the ~0.95 km^2 missing section from the 2004
1152 dataset. LIDAR-derived subaerial volume, represented by the black boxes and black line graph
1153 (right y-axis), reflect the areal footprint of the 2004 dataset (pink-dashed perimeter in Fig. 3). The
1154 error bars on the subaerial volume data points represent ±0.09 m error, whereas the error bars on
1155 the subaerial area data points represent what the area would be given a ± 0.09 m vertical
1156 displacement.

1157

1158 **Figure 13**. Differences in elevations (below MHW) at each XYZ point between the 2007 and
1159 2016 datasets. Differences in elevations were calculated by subtracting the 2007 values from the
1160 2016 values. Units of change are in meters. Positive change (cool colors) represents sediment
1161 gain on the nearshore seafloor, negative change (warm colors) represents sediment loss from the
1162 nearshore seafloor, and the black color box corresponds to minimal or no changes. The white
1163 shoreline perimeter represents the 2016 shoreline.

1164

1165   **Figure 14**. Map of transects through Petit Bois Island. PB1, PB2, and PB3 are south trending,
1166   cross-shore transects, and PB4 is an east trending, along-shore transect.

1167

1168   **Figure 15.** Elevation profiles for transect PB1. The 2004 (blue), 2005 (red), and 2011 (purple)
1169   profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1170   contain both topographic and bathymetric data points. The cross-shore transect distance
1171   originates in the north (PB1) and terminates in the south (PB1'). The mean high water (MWH)
1172   line is represented with the dashed blue line at 0 m elevation. The vertical error bar represents
1173   ±0.09 m error.

1174

1175   **Figure 16**. Elevation profiles for transect PB2. The 2004 (blue), 2005 (red), and 2011 (purple)
1176   profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1177   contain both topographic and bathymetric data points. The 2005 and 2011 profiles on the south
1178   side of the island do not extend to the MHW line in this transect due to LIDAR survey gaps. The
1179   cross-shore transect distance originates in the north (PB2) and terminates in the south (PB2').
1180   The mean high water (MWH) line is represented with the dashed blue line at 0 m elevation. The
1181   vertical error bar represents ±0.09 m error.

1182

1183   **Figure 17**. Elevation profiles for transect PB3. The 2004 (blue), 2005 (red), and 2011 (purple)
1184   profiles only contain topographic elevation points. The 2007 (yellow) and 2016 (green) profiles
1185   contain both topographic and bathymetric data points. The 2004 and 2005 datasets have
1186   incomplete survey coverage in the north, and the 2004 and 2011 profiles do not extend to the
1187   MHW line on the south of this transect due to LIDAR survey gaps; the maximum extents
1188   available are plotted above. The cross-shore transect distance originates in the north (PB3) and
1189   terminates in the south (PB3'). The mean high water (MWH) line is represented with the dashed
1190   blue line at 0 m elevation. The vertical error bar represents ±0.09 m error.

1191

1192   **Figure 18**. Topographic elevation profiles for transect PB4. The 2004 (blue), 2005 (red), 2007
1193   (yellow), 2011 (purple), and 2016 (green) profiles contain topographic elevation points. The along-
1194   shore transect distance originates in the west (PB4) and terminates in the east (PB4'). The
1195   smoothed black line represents the 500 m running mean across all datasets. The dashed blue line
1196   at 0 m elevation represents the mean high water (MWH) line. The vertical error bar represents
1197   ±0.09 m error. Bathymetry is not captured in this set of profiles.

1198

1199   **Figure 19**. Subaerial elevation differences on Petit Bois Island from 2004 – 2016. This set of
1200   images represents differences in elevations (above MHW) at each XYZ point between two
1201   corresponding datasets. Differences in elevations were obtained by subtracting the younger year
1202   from the older year (ex: 2005 – 2004) and are reported in meters. Positive change (cool colors)
1203   represents sediment gain, negative change (warm colors) represents sediment loss. The black color
1204   box corresponds to values between -0.5 and 0.5 m elevation change. Elevations gains or losses
1205   were then calculated across the total area to yield volumetric totals in m^3 (Table 6). The white
1206   shoreline perimeter in each map represents the most recent shoreline in the set. The 2004 and 2005
1207   datasets did not have full coverage, thus figures A, B, and E have gray "missing survey coverage"
1208   annotations.

1209

1210　**Figure 20**. Petit Bois Island's subaerial area (km^2) and subaerial volume (m^3) calculated for each
1211　of the five LIDAR datasets: 2004, 2005, 2007, 2011, and 2016. LIDAR-derived subaerial area
1212　values, represented by the gray boxes and gray line graph (left y-axis), reflect areal changes for
1213　their respective years, minus the ~0.62 km^2 missing section from the 2004 dataset. LIDAR-derived
1214　subaerial volume, represented by the black boxes and black line graph (right y-axis), reflect the
1215　areal footprint of the 2004 dataset (pink-dashed perimeter in Fig. 3). The error bars on the subaerial
1216　volume data points represent ±0.09 m error, whereas the error bars on the subaerial area data points
1217　represent what the area would be given a ± 0.09 m vertical displacement.

1218

1219　**Figure 21**. Differences in elevations (below MHW) at each XYZ point between the 2007 and 2016
1220　datasets. Differences in elevations were calculated by subtracting the 2007 values from the 2016
1221　values. Units of change are in meters. Positive change (cool colors) represents sediment gain on
1222　the nearshore seafloor, negative change (warm colors) represents sediment loss from the nearshore
1223　seafloor, and the black color box corresponds to minimal or no changes. The white shoreline
1224　perimeter represents the 2016 shoreline.

1225

1226　**Figure 22**. Geomorphic changes on Horn Island's eastern tip between April 2004 and September
1227　2005. Satellite imagery provides a record of geomorphic change between LIDAR surveys, and in
1228　this case shows destabilization of the tip as early as April 2004 and not from a single event.
1229　Imagery from USGS LANDSAT 5 & 7.

1230

1231　**Figure 23**. Washover deposits on Petit Bois Island following Hurricane Katrina. (Top) LIDAR
1232　difference plot between April 2004 and December 2005, with island location inset map and
1233　zoomed-in view. The red and yellow indicates erosion, the green indicates accretion, and the black
1234　indicates 0 to ± 0.5 m change. (Bottom-left) A September 2003 snapshot of Petit Bois Island;
1235　earliest pre-Katrina imagery. (Bottom-right) A snapshot taken 2 days after Hurricane Katrina's
1236　impact in August 2005, showing washover deposits to the interior of the island (scale is same as
1237　2003 image). The red outlines illustrate the location of the foredune which provided ~4,600 m^3
1238　source sediment that was overwashed during Hurricane Katrina's storm surge. The green outlines
1239　illustrate where ~2,650 m^3 of that sediment was deposited. Imagery from Google Earth Pro.

1240

1241　**Figure 24**. Dune building and lagoon in-filling on Horn Island: 2011 – 2016. (Top) LIDAR
1242　difference plot between June 2011 and October 2016, with island inset map and red box around
1243　the zoomed-in imagery location. The green indicates accretion, the red indicates erosion, and the
1244　black indicates 0 to ± 0.5 m change. On the south-western foredune (in the upper left corner) is an
1245　example of the process of dune building. (Bottom-left) A snapshot of Horn Island taken in
1246　September 2010; closest available to 2011 imagery. The green, transparent shading over the lagoon
1247　is where the sediment will be filled in between 2011 and 2016. (Bottom-right) A snapshot taken
1248　in February 2017, showing evidence, in green shading, where sediment filled-in this part of the
1249　lagoon (scale is same as 2010 image). Imagery from Google Earth Pro.

1250

1251　**Figure 25**. Historical areas of Horn and Petit Bois islands. (Top) Area values of Horn Island from
1252　previously published literature with those of this study. (Bottom) Area values of Petit Bois Island
1253　from previously published literature with those of this study. The 2011 and 2016 (upright triangles)
1254　values represent the total (unclipped) LIDAR-derived area values of Horn and Petit Bois islands

for comparison with other studies. Black squares: Waller and Malbrough, 1976; Gray diamonds: Byrnes et al., 1991; Gray dots: Morton, 2007 & 2008; Gray inverted triangles: Carter et al., 2018; Gray upright triangles: Gremillion et al., present study.

Figure 26. Comparisons of Horn, Petit Bois, & Ship islands to tropical cyclone impacts. (Top) LIDAR-derived subaerial area sizes of Horn Island (blue line and left y-axis) with missing ~0.95 km^2, Petit Bois Island (orange line and right y-axis) with missing ~0.62 km^2, and Ship Island (black line and right y-axis) (Eisemann et al., 2018). (Middle) LIDAR-derived subaerial volumes of Horn Island (blue line and left y-axis), Petit Bois Island (orange line and right y-axis), and Ship Island (black line and right y-axis) (Eisemann et al., 2018) all clipped to the greatest geographical common areas of their respective 2004 datasets. (Bottom) Combined 2004-2016 wave energy graph and wind-rose diagrams for the 4 periods (gray shading) constraining the LIDAR dataset in this study.

TABLE CAPTIONS

Table 1. Tropical cyclones: 2004 – 2016. Listing and descriptions of tropical cyclones passing within a 200 km radius of Horn and Petit Bois islands, and the dates of pre- and post-storm LIDAR datasets used for analyses.

Table 2. LIDAR datasets with coverage for both Horn and Petit Bois islands. Uncertainty values reported by respective agencies are in root mean square error (RMSE). Dataset credit is attributed to the Joint Airborne Lidar Bathymetry Center of Expertise for 2004, 2005, 2011, and 2016, and to the U.S. Geological Survey, Florida Integrated Science Center for 2007. *Data sources: OCM Partners, 2017.

Table 3. Wave energy statistics table for each of the five sub-periods, selected to constrain the five LIDAR datasets. Mean wave energies are averaged over 24-hours (with standard deviation values to the right of the ± symbols). Maximum wave energies are based on 24-hour averages. [A] Because NDBC station 42007 failed six hours prior to Hurricane Katrina's landfall, the maximum wave energy for P1 was calculated using the maximum significant wave height value of NDBC Station 42067-USM3M01 (from Bender et al., 2010), and the 24-hr average value from Bender et al. (2010) was calculated into the mean wave energy for P1 and P5.

Table 4. Horn Island's Subaerial Area and Shoreline Changes: 2004 – 2016. Values adjusted to the area of greatest data availability of the 2004 dataset.

Table 5. Horn Island's Subaerial Volume Changes: 2004 – 2016. Values adjusted to the greatest common area defined by shoreline overlap of the 2004 dataset.

Table 6. Horn Island's Bathymetric Changes: 2007 – 2016. Values adjusted to the greatest common bathymetric area of the 2007 dataset.

Table 7. Petit Bois Island's Subaerial Area and Shoreline Changes: 2004 – 2016. Values adjusted to the area of greatest data availability of the 2004 dataset.

1300
1301   **Table 8**. Petit Bois Island's Subaerial Volume Changes: 2004 – 2016. Values adjusted to the
1302   greatest common area defined by shoreline overlap of the 2004 dataset.
1303
1304   **Table 9**. Petit Bois Island's Bathymetric Changes: 2007 – 2016. Values adjusted to the greatest
1305   common bathymetric area of the 2007 dataset.

Greatest common coverage area for volume

Missing coverage

2004 - Pre-Ivan

2005 - Post-Katrina

2007

2011

2016

degrees latitude

degrees longitude

meters above MHW
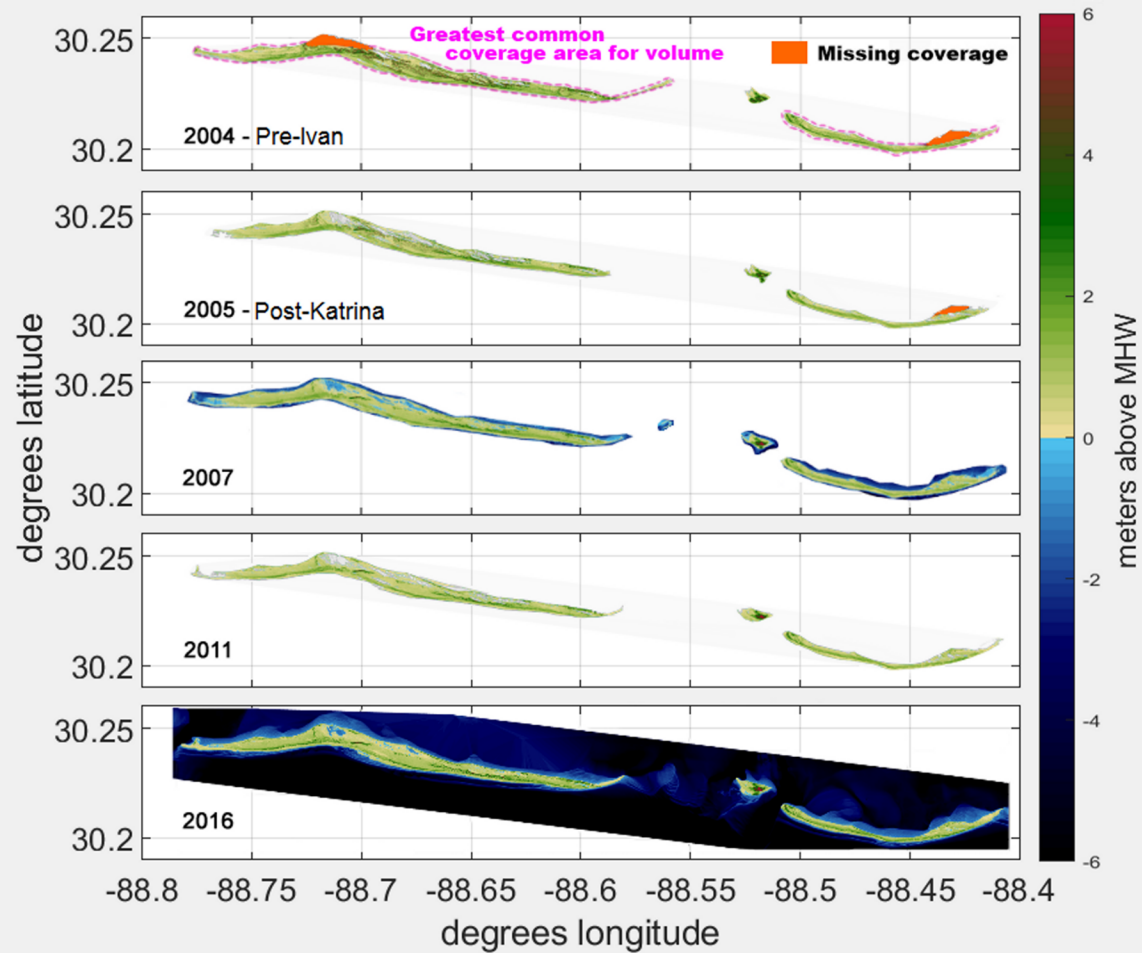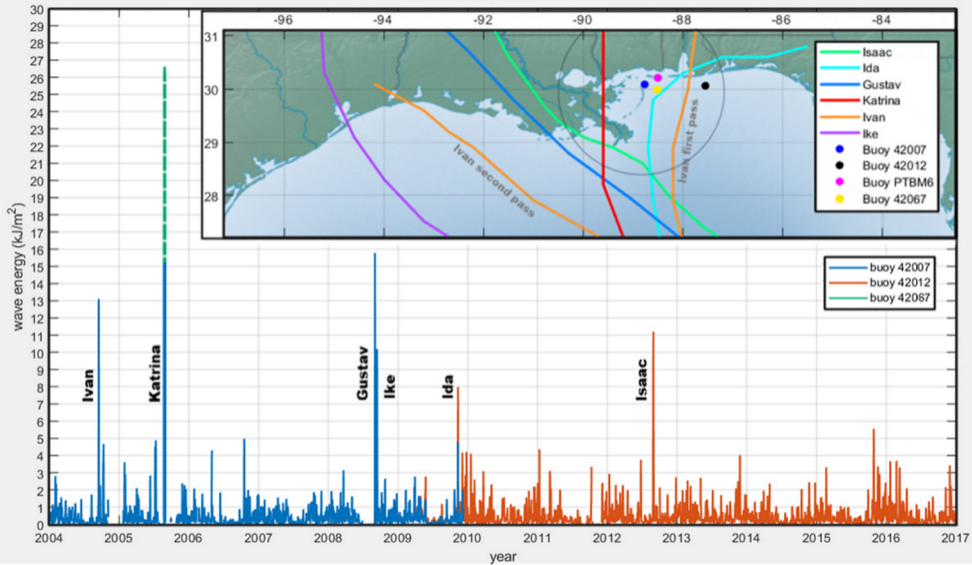
A. January 1, 2004 - December 31, 2016 (total study period)

B. July 1, 2011 - December 31, 2016 (anomalous period)

Wind Speeds (m/s)

- $W_s \geq 12$
- $10 \leq W_s < 12$
- $8 \leq W_s < 10$
- $6 \leq W_s < 8$
- $4 \leq W_s < 6$
- $2 \leq W_s < 4$
- $0 \leq W_s < 2$

Legend: 2004, 2005, 2007, 2011, 2016

Axis labels: elevation (m) versus cross-shore transect distance (km). MHW line marked at elevation 0. Inset labels: N, Vertical error, PB2, PB2.

Legend:
- 2004
- 2005
- 2007
- 2011
- 2016

N

Vertical error I

PB3
PB3'

A: 2004 to 2005
*Missing survey coverage

B: 2005 to 2007
*Missing survey coverage

C: 2007 to 2011

D: 2011 to 2016

E: Net 2004 to 2016
*Missing survey coverage

meters change

-6   -4   -2   0   2   4   6

degrees latitude

degrees longitude

April 2004: Pre-Ivan
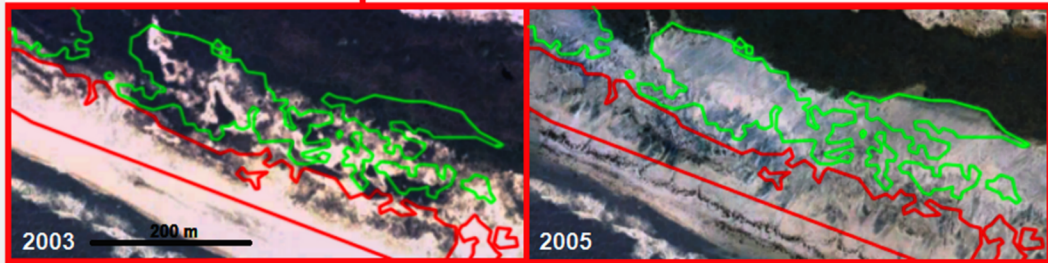
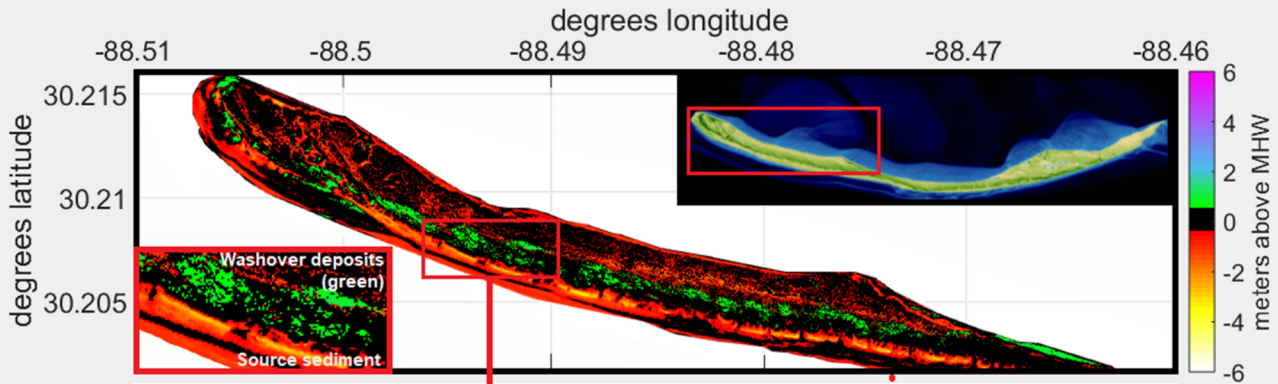**October 2004: Post-Ivan**

June 2005: Pre-Dennis

July 2005: Post-Dennis

August 2005: Pre-Katrina

September 2005: Post-Katrina

Washover deposits (green)

Source sediment

2003   200 m

2005
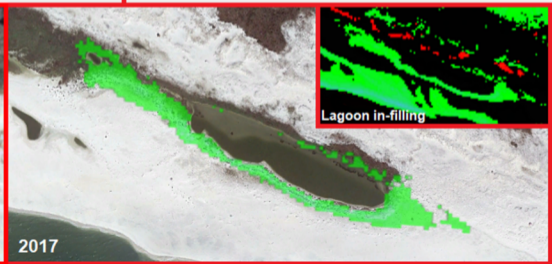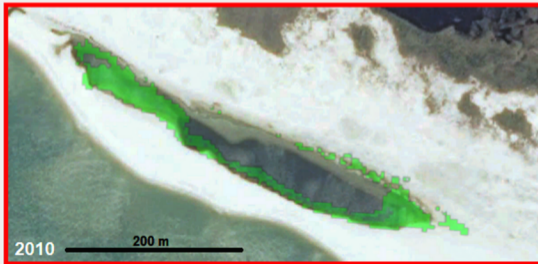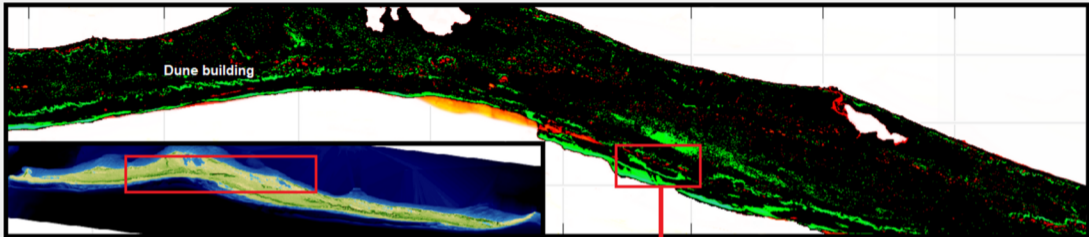
Horn Island Area Over Time
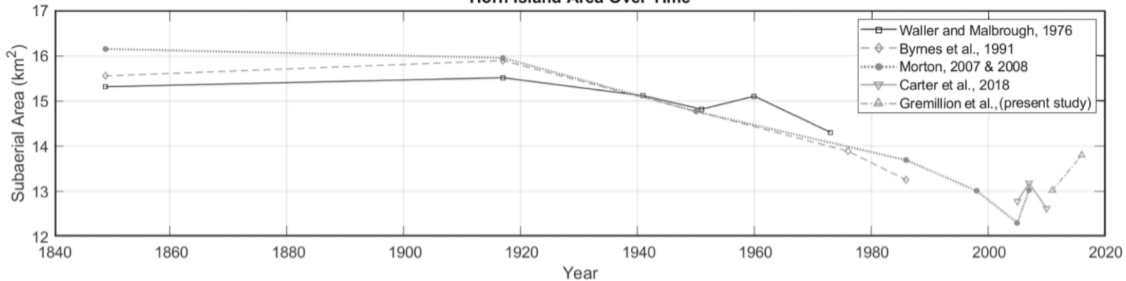
Petit Bois Island Area Over Time

MS Barrier Islands Subaerial Area

MS Barrier Islands Subaerial Volume

Wave Energy: 2004 to 2016

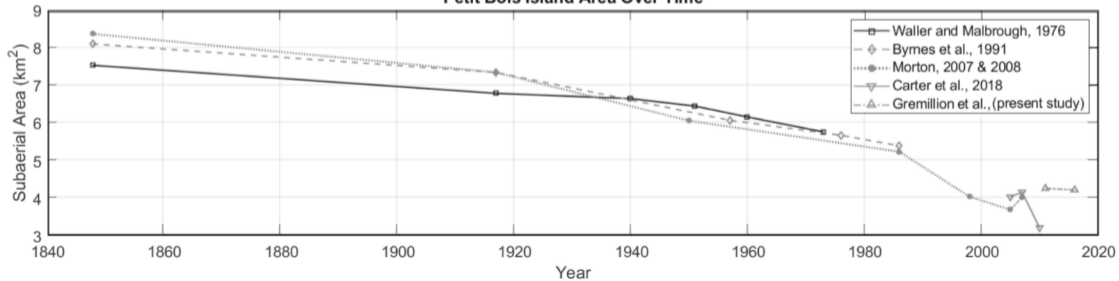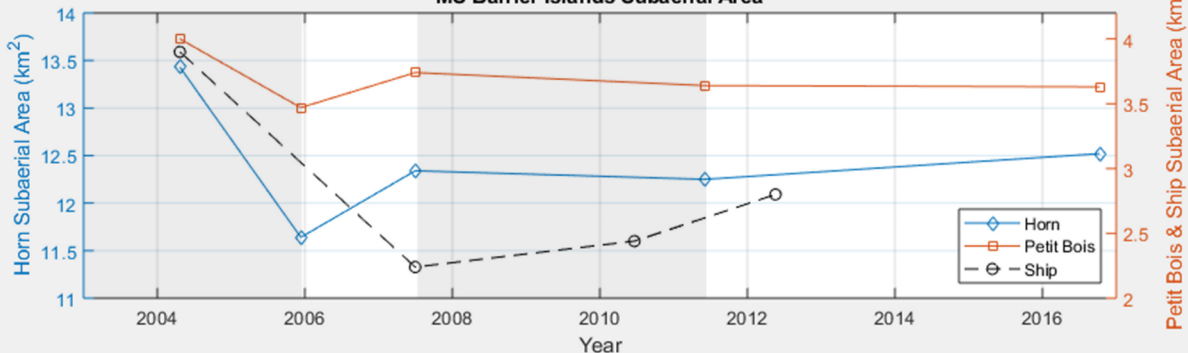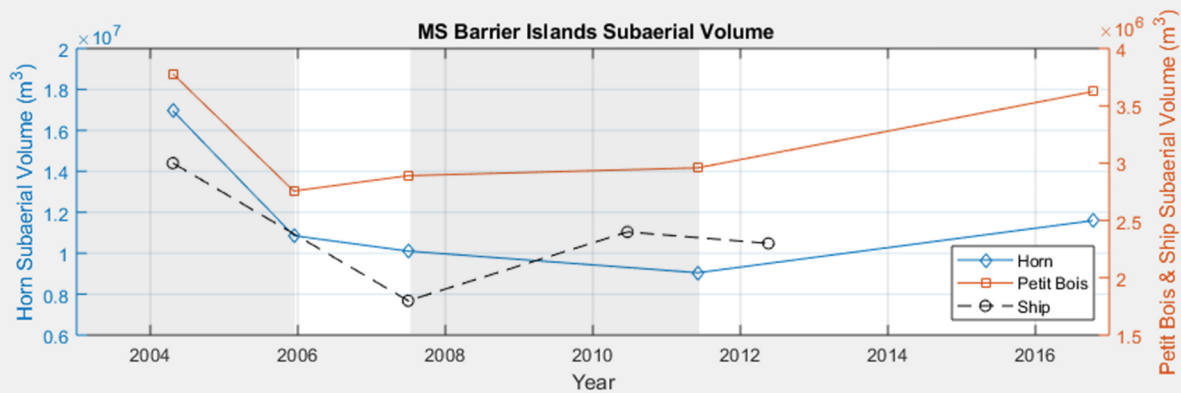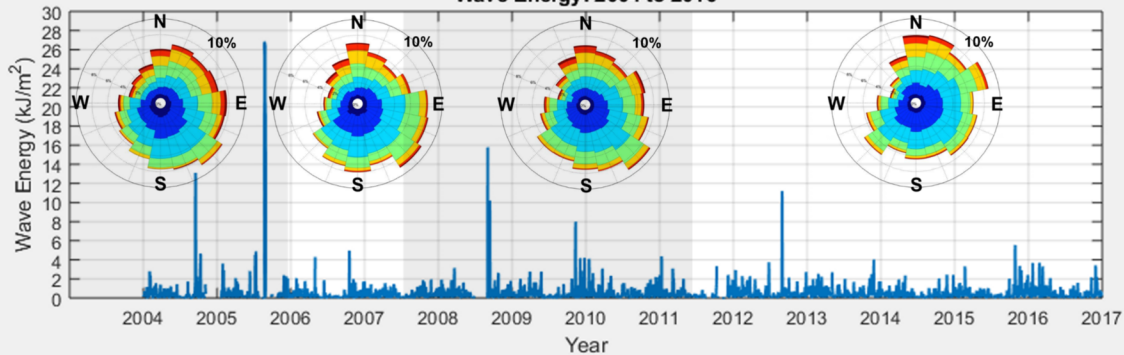| Year	Dates	Name	Category (Cat) at landfall	Tropical Cyclone Summary	Pre-/Post-Storm Datasets	Data Sources
2004	2-24 Sept	Ivan	Cat 3 Hurricane	Landfall west of Gulf Shores, AL on 16 Sept.; ~194 kph winds. Horn & Petit Bois sustained 1-2 m storm surge.	2004, 2005	Stewart, 2004
2005	8-14 June	Arlene	Tropical Storm (TS)	Landfall at AL-FL stateline on 11 June; ~93 kph winds. Storm tide of ~0.8 m reported at Dauphin Island, AL.	2004, 2005	Avila & Brown, 2005
2005	3-11 July	Cindy	Cat 1 Hurricane	First landfall as a Cat 1 at 0300 UTC on 6 July southwest of Grand Isle, LA. Second landfall as a TS (~75 kph winds) near Ansley, MS at 0900 UTC. ~2 m storm surge recorded in Ocean Springs, MS.	2004, 2005	Stewart, 2006
2005	4-13 July	Dennis	Cat 3 Hurricane	Landfall as a Cat 3 on Santa Rosa Island, FL on 10 July; maximum sustained winds ~195 kph. Storm surge of 0.7-0.8 m and TS-force wind gusts 62-74 kph affected the study area.	2004, 2005	Beven, 2005
2005	23-31 Aug	Katrina	Cat 3 Hurricane	Landfall as a Cat 1 in southeast FL on 25 Aug. Second landfall near Buras, LA, as a Cat 3; maximum sustained winds ~204 kph at 1110 UTC on 29 Aug. Third landfall 3 hours later near LA-MS stateline; winds ~194 kph. Storm surges along coastal MS were >10 m.	2004, 2005	Knabb et al., 2005; Fritz et al., 2007
2009	4-10 Nov	Ida	Extra Tropical Cyclone (ETC)	Landfall as an ETC on Dauphin Island, AL on 10 Nov. ~1200 UTC. The preceding 12 hours, Ida was a TS; sustained winds 74 kph and gusts up to 94 kph. Storm surge at Pascagoula, MS was 0.97 to 1.09 m.	2007, 2011	Avila & Cangialosi, 2010
2011	2-5 Sept	Lee	Tropical Storm (TS)	Landfall on 4 Sept., ~27.5 km southeast of Ester, LA; 74 kph winds. Tracking through central and southeastern LA, winds decreased to ~65 kph for 18 hours. As Lee moved across southern MS, winds accelerated to 74 kph. Storm surge along coastal MS was 0.9 to 1.9 m.	2007, 2016	Brown, 2011
2012	21 Aug - 1 Sept	Isaac	Cat 1 Hurricane	First landfall on 29 Aug. at 0000 UTC on MS River's Southwest Pass, then at 0800 UTC in Port Fourchon, LA; maximum sustained winds ~130 kph. Isaac caused up to 0.56 m of rainfall along coastal MS and storm surges up to 2.4 m.	2011, 2016	Berg, 2013

LIDAR Dataset*	Date	Agency	Horizontal Uncertainty	Vertical Uncertainty	Elevation Coverage
NCMP Topobathy Lidar: Gulf (AL, FL, MS) & Atlantic Coast (NC)	April 2004	USACE	100 cm	15 cm (RMSE)	Topographic
NCMP Topobathy Lidar: Post Katrina (LA to FL)	December 2005	USACE	75 cm	20 cm (RMSE)	Topographic
Coastal Lidar: Northern Gulf (LA to FL)	June 2007	USGS	100 cm	15 cm (RMSE)	Topographic, Bathymetric
NCMP Topobathy Lidar: Gulf Coast (AL, MS, LA)	June 2011	USACE	75 cm	20 cm (RMSE)	Topographic
NCMP Topobathy Lidar: Gulf Coast (TX, MS, AL, FL)	October 2016	USACE	100 cm	10 cm (RMSE)	Topographic, Bathymetric

	24-hour Mean Wave Energy (kJ/m^2)	Maximum Wave Energy (kJ/m^2)	Date of Max	Cause of Max
P1: Jan. 1, 2004 - Dec. 31, 2005	0.485 ± 1.44	26.6[A]	Aug. 29, 2005	Hurricane Katrina
P2: Jan 1, 2006 - Jul. 31, 2007	0.342 ± 0.48	4.97	Oct. 16, 2006	Squall Line
P3: Aug. 1, 2007 - Jun. 30, 2011	0.455 ± 0.76	15.79	Sept. 1, 2008	Hurricane Gustav
P4: Jul. 1, 2011 - Dec. 31, 2016	0.436 ± 0.60	11.2	Aug. 28, 2012	Hurricane Isaac
P5: Jan. 1, 2004 - Dec. 31, 2016	0.423 ± 0.80	26.6	Aug. 29, 2005	Hurricane Katrina

	Total Area (km^2)	Areal Change (km^2)	Total Average Shoreline Change Rate (m/yr)
2004	13.43		
		−1.79	−10.02
2005	11.64		
		+0.70	+4.16
2007	12.34		
		−0.09	−1.88
2011	12.25		
		+0.27	−0.83
2016	12.52		
Net Difference:	**−0.91**		
Average Rate of Change:	**−0.07 km^2/yr**		**−2.02 m/yr**

	Total Volume (m^3)	Volume Change (m^3)
2004	1.695×10^7	
		-6.09×10^6
2005	1.086×10^7	
		-0.76×10^6
2007	1.01×10^7	
		-1.05×10^6
2011	0.905×10^7	
		$+2.54 \times 10^6$
2016	1.159×10^7	
Net Difference:	-5.36×10^6	
Average Rate of Change:	$-4.29 \times 10^5 \, m^3/yr$	

	Bathymetric Water Volume (m^3)	Sediment Volume Change (m^3)
2007	9.065×10^6	
		-3.97×10^5
2016	9.462×10^6	

	Total Area (km^2)	Areal Change (km^2)	Total Average Shoreline Change Rate (m/yr)
2004	4.00		
		−0.53	−32.6
2005	3.47		
		+0.27	+5.15
2007	3.74		
		−0.10	−2.68
2011	3.64		
		−0.01	−1.47
2016	3.63		
Net difference:	**−0.37**		
Average Rate of Change:	**−0.03 km^2/yr**		**−3.14 m/yr**

	Total Volume (m^3)	Volume Change (m^3)
2004	3.778 x 10^6	
		−1.021 x 10^6
2005	2.757 x 10^6	
		+1.34 x 10^5
2007	2.891 x 10^6	
		+0.68 x 10^5
2011	2.959 x 10^6	
		+6.65 x 10^5
2016	3.624 x 10^6	
Net difference:	**−1.54 x 10^5**	
Average Rate of Change:	**−1.23 x 10^4 m^3/yr**	

	Bathymetric Water Volume (m^3)	Sediment Volume Change (m^3)
2007	9.236 x 10^6	
		+1.164 x 10^6
2016	8.072 x 10^6	