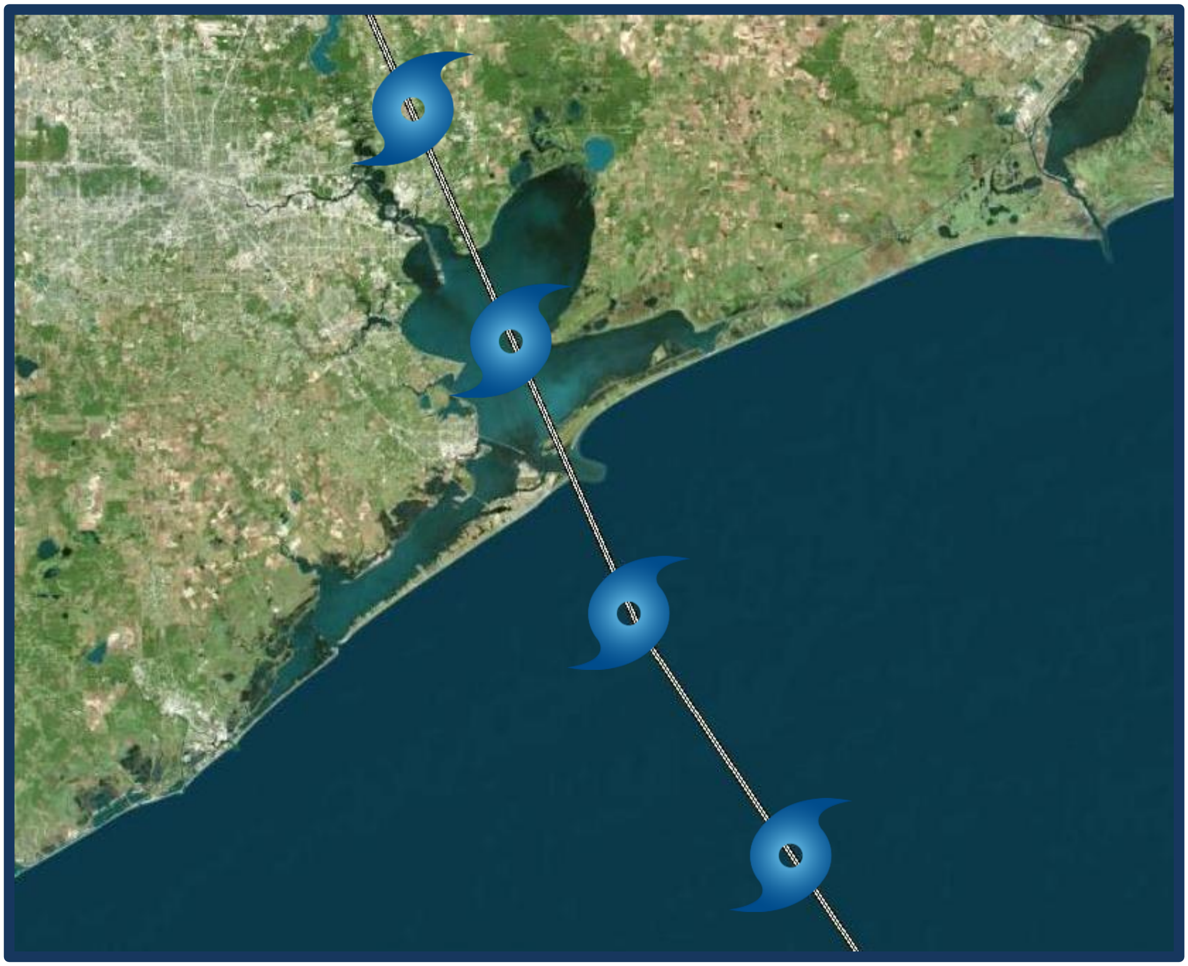
Beach and Shoreline Changes Along the Upper Texas Coast: Recovery from Hurricane Ike



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EXECUTIVE SUMMARY

Hurricane Ike made landfall at Galveston Island on September 13, 2008 as a Category 2 hurricane. Its low rating on the Saffir-Simpson scale does not reflect its massive size, with tropical storm force or greater winds cutting a swath 400 miles wide. Ike's storm surge reached 15 to 20 ft on Bolivar Peninsula and in parts of Chambers County with large waves present throughout the Gulf of Mexico. Large storm waves coupled with storm surge caused extreme erosion on the Texas coast. Peak shoreline erosion was over 400 ft with average values near 200 ft over much of the upper Texas coast. The storm, as reported by the National Oceanic and Atmospheric Administration (NOAA), is the second most costly in U.S. history (NOAA, 2011).

Preliminary impact assessments from Hurricane Ike have been updated as part of this study, and recovery of the beach/dune system has been reviewed through the analysis of LIDAR data along the Upper Texas coast. Site visits and limited beach profile data were also utilized to compare with the LIDAR results and help provide a clearer picture of beach and dune recovery. Based on shoreline and volumetric change analyses performed by Harte Research Institute at Texas A&M University -- Corpus Christi, much of the upper Texas coast had not fully recovered by 2012, four years after the passage of Ike. Tables E1 through E3 document the shoreline and volumetric (beach and foredune) changes. Considering the significant redistribution of sediment along the coast, full recovery is not expected for some of these areas due to a lack of natural sediment input and significant transport of sand away from critically eroding areas, such as along West Galveston Island. The Sabine to High Island area prior to the storm consisted of a thin veneer of sand overlaying clay outcroppings. Much of that sand veneer is gone and is not expected to recover, leaving this section of shoreline more susceptible to ongoing erosion.

Table E1 Average Shoreline Changes per Region (LIDAR Comparisons).

Region	**Net Shoreline Movement (ft)***				
	Epoch 1 2005-2008	Epoch 2 2008-2010	Epoch 3 2010-2011	Epoch 4 2011-2012	**2005-2012**
Sabine to High Island	-90.2	-19.4	-11.7	-19.9	-141.1
Bolivar Peninsula	-26.9	-12.5	9.6	-14.3	-44.0
East Galveston Island	-53.7	72.2	60.0	8.5	87.0
West Galveston Island	-51.0	40.2	50.3	-9.9	30.0
Follets Island	3.3	-10.2	55.2	-28.6	19.7
Quintana	-68.2	29.0	57.6	-35.2	-16.9

* Negative values indicate shoreline recession and positive values indicate shoreline advance.

Table E2 Average Volume Change Results of Sub-aerial Beach per Region (LIDAR Comparisons)

Region	Net Volume Change per Alongshore Length (cy/ft)		
	Impact of Ike (2005-2008)	Recovery (2008-2012)	Cumulative (2005-2012)
Sabine to High Island	-3.2	-0.6	-3.9
Bolivar Peninsula	0.3	-2.8	-2.5
East Galveston Island	2.2	-1.9	0.3
West Galveston Island	-2.7	2.6	-0.1
Follets Island	1.6	-2.1	-0.5
Quintana	-4.1	1.0	-3.1

Table E3 Average Volume Change Results of Foredune Zone – Dune Toe to 25 m landward, per Region (LIDAR Comparisons)

Region	Net Volume Change per Alongshore Length (cy/ft)		
	Impact of Ike (2005-2008)	Recovery (2008-2012)	Cumulative (2005-2012)
Sabine to High Island	-8.5	-2.9	-11.4
Bolivar Peninsula	-11.3	1.7	-9.6
East Galveston Island	-3.2	1.5	-1.7
West Galveston Island	-7.3	2.7	-4.5
Follets Island	-4.7	-0.2	-4.9
Quintana	-9.5	2.2	-7.3

ACKNOWLEDGEMENTS

Detailed shoreline and volumetric changes analyses for this report were performed by Harte Research Institute at Texas A&M University -- Corpus Christi. Determination of preliminary shoreline changes after the passage of Hurricane Ike was performed under the supervision of Dr. James Gibeaut. Further review of the impacts from Hurricane Ike and associated recovery were performed by Diana del Angel (shoreline change analyses) and Dr. Michael Starek (volumetric changes). Their analyses and insight into the coastal processes along the upper Texas coast were invaluable.

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1.0 INTRODUCTION

1.1 Authorization

This document was prepared for the Texas General Land Office (GLO) under Contracts No. 06-801-007 (Work Order Number 3585) and 10-103-005 (Work Order Numbers 4123 and 4661).

1.2 Project Location and Purpose

Hurricane Ike made landfall on the upper Texas coast at Galveston on September 13, 2008. The storm, as reported by the National Oceanic and Atmospheric Administration (NOAA), is the second most costly in U.S. history (NOAA, 2011), causing major erosion of the shoreline and vegetation line[1]. Substantial erosion has been observed along the entire Texas coast, as well as the coasts of other states bordering the Gulf of Mexico.

Phase 1 of this project provided a preliminary review of the storm's intensity and impacts, along with recommendations for future monitoring and analyses required to document recovery (HDR 2009). Phases 2 and 3 involved surveying and site visits along the upper Texas coast, along with analyses of shoreline and volumetric changes. The overall project documented herein reviews initial impacts to the coast and, in some areas, subsequent recovery. The analysis will provide information necessary to better understand hurricane impacts and plan for future storms. Although the initial assessment covered the entire Texas coast as well as adjacent Gulf states, the focus of this report is on the most heavily damaged areas of the upper Texas coast.

1.3 Site Overview

The Texas coastline is a mixture of moderately developed and natural beaches along deltaic headlands, peninsulas and barrier islands. Development is most dense in the Houston metropolis, with sporadic development near larger cities along the coast, most notably Galveston and its 10-mile long seawall. Texas coastal lands are mildly sloping and at very low elevation, leaving coastal property vulnerable to even moderate storm tides.

The Texas coast is microtidal with tide range generally less than 3 ft. However, the tides are mixed with irregular highs, lows and periods, which can also be influenced by meteorological factors that vary on a seasonal basis. As a result, higher average tides occur in the fall and spring, and lower average tides occur in the winter and summer.

In order to simplify this report, the Texas coast was broken up into three regions as shown in Figure 1.1. The Texas coast from Sabine Pass to the Brazos River (upper Texas coast) consists of barrier islands and two headlands (Morton and Peterson 2005). The dry beach width, the width of beach that is typically dry between the dune and water line, on the upper Texas coast is narrow, generally less than 100 ft with about 12 miles of beach regularly nourished along the approximately

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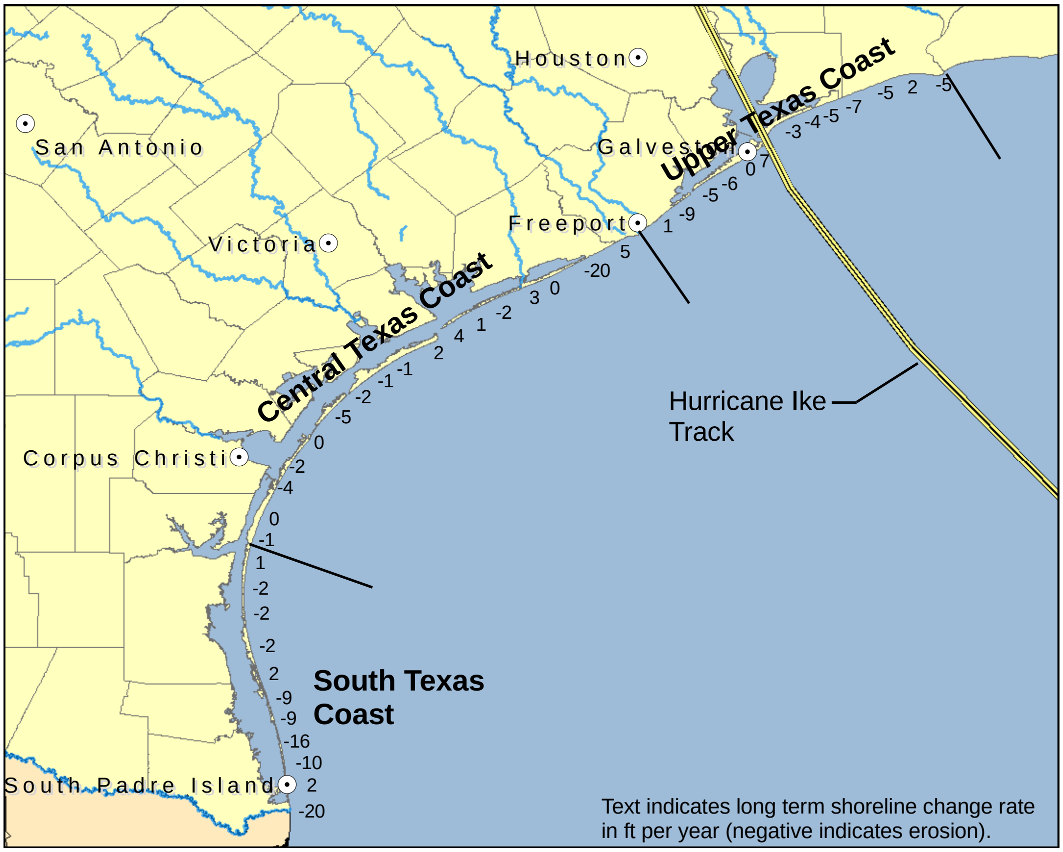
[1] Shoreline erosion within the context of this report is synonymous with shoreline retreat. See the Glossary for definitions of selected terms and abbreviations.

110-mile long upper Texas coast. Nourished beaches include various portions of Galveston Island, and beaches on Bolivar Peninsula around Rollover Pass. Dunes are not well developed along most of the upper Texas coast, leaving this reach highly susceptible to overwash from small tropical storms. Long-term shoreline erosion rates averaged over more than 60 years (Bureau of Economic Geology's Texas Shoreline Change Project shown in Figure 1.1) are on the order of 5 ft/yr along the upper Texas coast, with net longshore transport generally towards the southwest.



Text indicates long term shoreline change rate in ft per year (negative indicates erosion).

Figure 1.1 Annual long term shoreline change rate.

The central Texas coast extends from the Brazos River south to the Padre Island National Seashore near Baffin Bay. This reach includes Matagorda, San Jose, Mustang and part of North Padre Islands, which are all long sandy barrier islands fronting large bay areas. The beach along this reach is typically wide with a high, mostly continuous dune system (Morton and Peterson 2006A). Notable exceptions to the continuous dune system are found at washover and blowout areas (Morton and Pieper 1976). The shoreline orientation changes along North Padre Island at Big Shell Beach near Baffin Bay, a convergence zone for longshore currents, and the southern boundary of the central Texas coast. South of this convergence zone, net longshore transport is typically to the north. The opposite is true to the north of the convergence zone. Long term shoreline erosion rates are an average of 2 ft per year on the central Texas coast.

The south Texas coast extends from Padre Island south to the Rio Grande and consists of part of North Padre Island, South Padre Island and Brazos Island. Along the southern portion of North Padre Island, south of the convergence zone at Big Shell beach, the beach is wide with a high mostly continuous dune system. Beaches on South Padre and Brazos Islands have high but discontinuous dunes, except around the Town of South Padre Island where the dunes are smaller. Dunes in this region are sparsely vegetated due to an arid climate and have been periodically breached by many washover channels (Morton and Peterson 2006B). Long term shoreline erosion rates averaged over this section of the Texas coast are approximately 5 ft per year.

Strong winds and low pressure within a tropical storm act in concert to raise water levels, generally to the greatest extent within the right front quadrant of the storm. The area offshore of the Texas coast consists of a shallow continental shelf that widens from Brownsville north to Louisiana (Figure 1.2). As low pressure coupled with strong wind and large waves generated by a tropical storm raise water elevations, the shallow shelf tends to further increase the storm surge, especially when a storm's forward speed is relatively slow, as was the case with Ike.

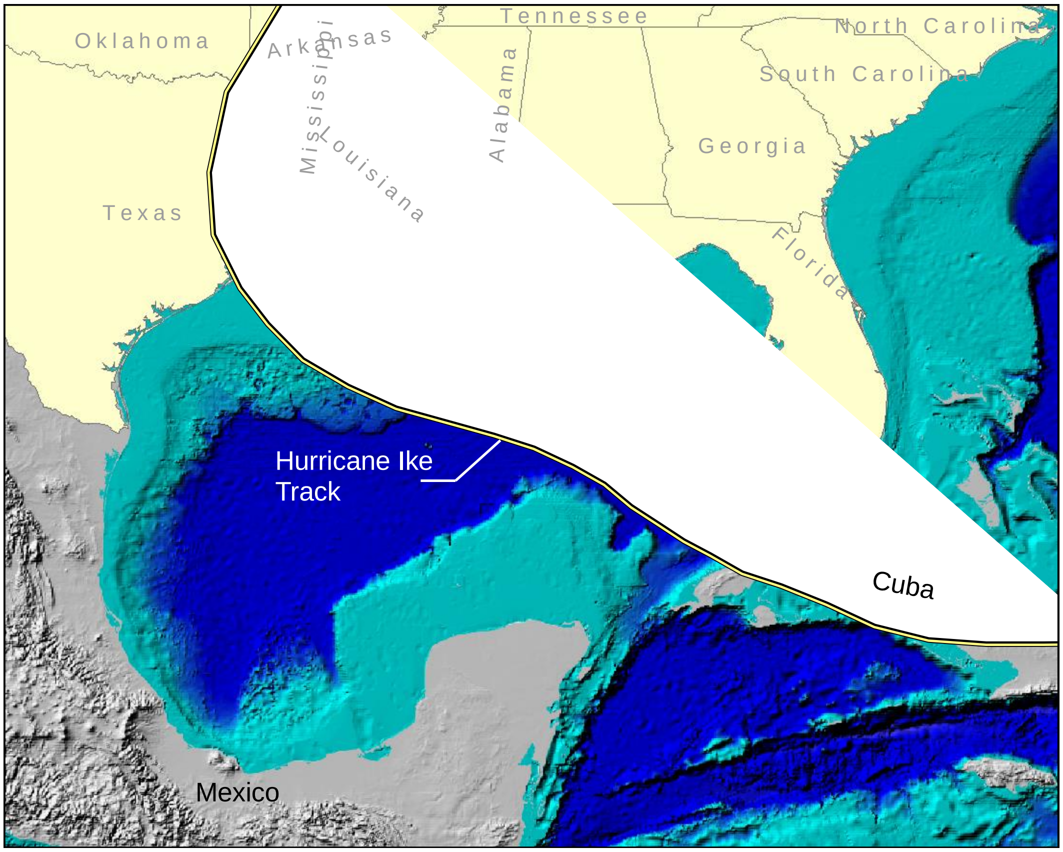


Figure 1.2 Stationing and CBI Monument Locations.

1.4 Previous Storms

Long term shoreline change on the Texas coast is generally the result of changes in relative sea level and/or the supply of sand (Gibeaut *et al.* 2000). However, the erosion, limited recovery, and changes to the littoral system caused by severe storms also influence these rates. Based on analysis of aerial photographs, surveys, and other data, most of the Texas shoreline is experiencing long term erosion. While a long term trend of 5 to 10 ft/yr is significant, shoreline erosion during a hurricane can be 100's of feet in a single day, equivalent to 10 to 20 years of long term shoreline erosion. After hurricanes, the beach usually recovers at least some of its pre-storm beach width because sand that moved into deeper water during the storm is transported back onto the dry beach. Some of the sand transported landward of the dunes or seaward of typical closure depth may not be recovered, meaning that the beach may never completely recover its pre-storm condition. Also, erosion of cohesive (silt and clay) sediments is generally irreversible, hindering recovery of beaches along portions of the Texas coast that are composed of little or no sand.

Hurricane Ike caused major damage to infrastructure and has been listed as the second costliest hurricane in U.S. history and by far the costliest hurricane in Texas history (Jarrell *et al.* 2001, Knabb *et al.* 2006, GLO 2009, NOAA 2011). Estimated cost of damage for Ike and other major storms is included in Table 1, followed by a brief description of Hurricane Alicia's and Carla's impacts on the Texas coast. Table 1.1 provides some statistics for the three most costly storms in U.S. history (Katrina, Andrew and Ike) as well as three storms that caused major shoreline change on the Texas coast (Ike, Alicia and Carla).

Table 1.1 Estimated cost of hurricane damage.

Hurricane/Year	Est. Damage (Billions)	Category at Landfall	Deaths
Katrina/2005	$87	3	1833
Andrew/1992	$49	5	26
Ike/2008	$29	2	103
Alicia/1983	$4.9	3	21
Carla/1961	$2.7	4	43

The slow forward speed of Carla exacerbated shoreline erosion from the storm by increasing the duration that the beach was subjected to erosive conditions. Along West Galveston Island, Hurricane Carla resulted in a vegetation line retreat of as much as 315 ft (Morton *et al.* 1985) with an average of 164 ft (Gibeaut *et al.* 2000). In most places along West Galveston Island the vegetation line, the extreme seaward boundary of natural vegetation which spreads continuously inland, never fully recovered after Carla (Gibeaut *et al.* 2000).

Hurricane Alicia made landfall along the upper Texas coast near San Luis Pass on August 18, 1983 as a Category 3 and was one of the costliest hurricanes in Texas history, causing extensive property damage along West Galveston Island. According to Morton *et al.* (1985), the storm eroded more than 2,000,000 cubic yards (cy) of sand from Galveston Island. Shoreline erosion during Alicia was reported (Savage *et al.*1984) for 70 miles of the upper Texas coast from High Island to Freeport with measured shoreline erosion greater than 100 ft over much of the area. Gibeaut *et al.* (2000) reported that it took four to five years for the beaches to recover from Alicia, but only about 55% of the eroded sand returned to the system.

As previously mentioned, following a storm there is typically shoreline recovery, but the amount will vary along the coast, as has been observed following past storms. Hurricane Carla in 1961 and Hurricane Alicia in 1983 caused similar magnitudes of shoreline erosion and profoundly altered patterns of shoreline change. Following the post-storm recovery period for Carla, there was an indication that average annual erosion rates accelerated, possibly because of the removal of sand from the littoral system. Following Alicia, beaches and dunes required four to five years to recover. Initial studies indicate that Hurricane Ike has caused changes to the littoral sediment system even greater than that of Carla or Alicia (Harte Research Institute (HRI) 2009).

2.0 HURRICANE IKE

2.1 Formation and Development

Hurricane Ike originated off the west coast of Africa on August 28, 2008 and was designated as a tropical depression on September 1, 2008. Ike grew to its peak intensity, Category 4 on the Saffir Simpson scale, on September 4, 2008 and nine days later came ashore as a Category 2 at Galveston, TX at 2:10AM CDT, September 13, 2008. Ike continued to travel north after making landfall with the post-tropical remnant low producing strong winds across the U.S. and into Canada. Figure 2.1, developed by the National Weather Service (NWS) (2008), shows Ike's track with satellite images of the storm overlaid.

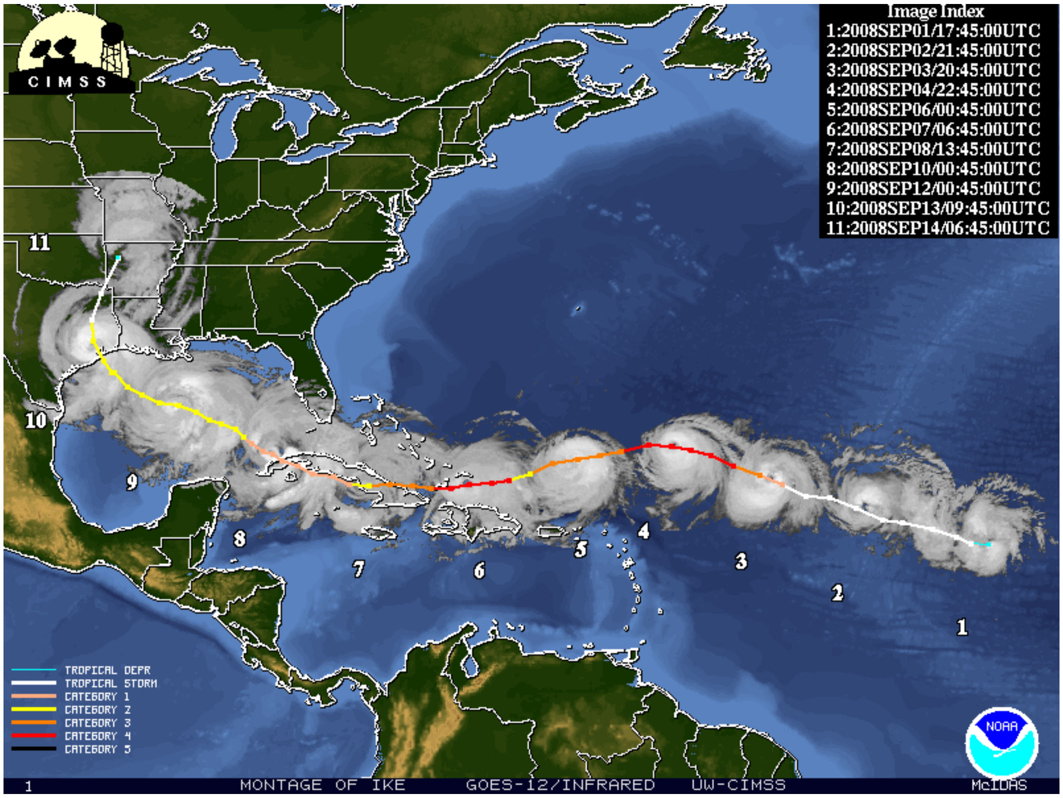


Figure 2.1 Hurricane Ike track (NOAA 2008).

2.2 Storm Conditions at Landfall

2.2.1 Winds

At landfall, the eye of the hurricane was approximately 46 miles wide with maximum sustained winds of 110 mph and a minimum central pressure of 950 mb. Ike's large size and relatively slow forward speed played a significant role in the devastation to Texas shorelines. Tropical storm force winds covered an area 400 miles wide and hurricane force winds covered an area 180 miles wide (NWS 2008). The shear scale of the storm is evident in Figure 2.2, which shows tropical storm force winds along half of the Texas coast and that the area from Sabine Pass south to Follets Island (NWS 2008) was subjected to hurricane force winds.

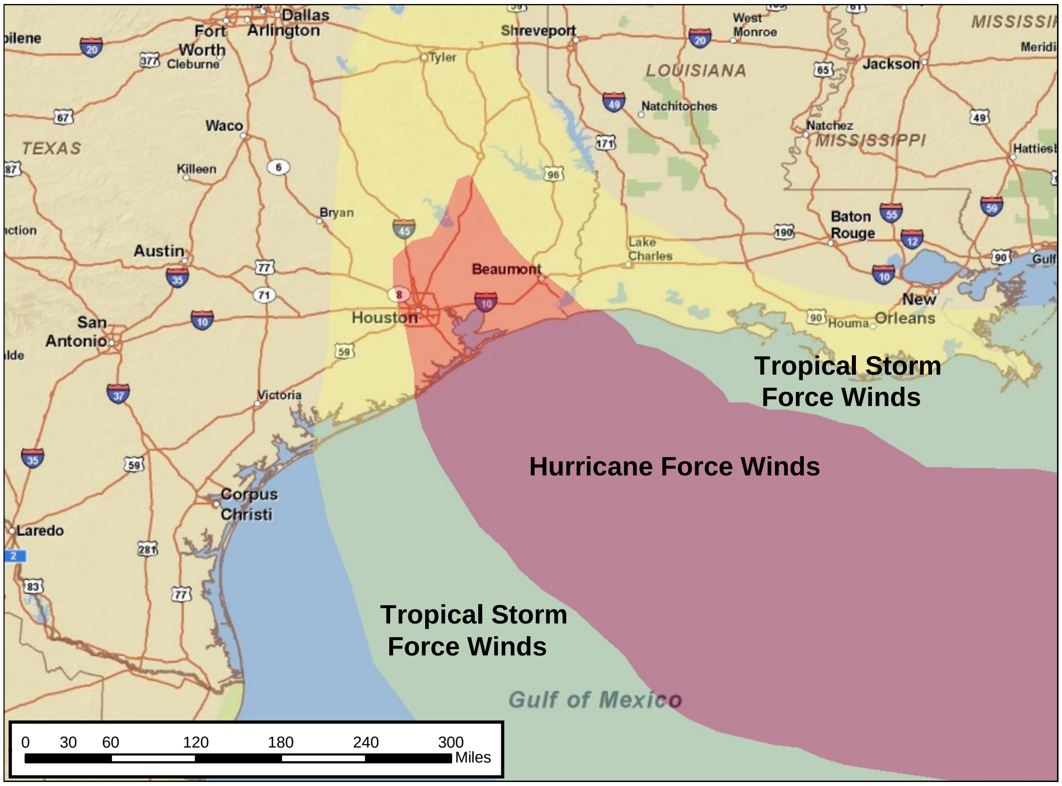


Figure 2.2 Spatial extent of hurricane and tropical storm force winds.

2.2.2 Surge

Storm surge is generated by wind, waves, and low atmospheric pressure acting on the water as the storm approaches the shoreline. Ike was predicted to make landfall at locations all along the western Gulf coast. However, as Ike approached Galveston, the shallow, gently sloping continental shelf in the northern Gulf of Mexico acted to further increase storm surge as described in Section 1.3. The highest storm surge on the coast was recorded on Bolivar Peninsula and in parts of Chambers County with elevated water levels reported in most of the Gulf of Mexico.

Waves and storm tides combine to reach extreme water levels along the open coast, but the highest storm surge is often found inland. Basin geometry of bays and estuaries combined with shallow bathymetry tend to trap and amplify surge between the storm and the shore, often resulting in surge much greater than at the open Gulf coast. Ike's massive size and relatively slow forward speed increased the duration over which the coast was subjected to high winds, waves and surge. Peak storm surge was estimated to be between 15 and 20 ft NAVD[2] along the worst impacted areas (Berg 2009). The highest still water level measured by FEMA during the storm was 17.5 ft located 10 miles inland in Chambers County (Berg 2009). Including wave height and runup, the absolute peak high water mark observed during Ike was over 19 ft on Bolivar Peninsula (East *et al.* 2008).

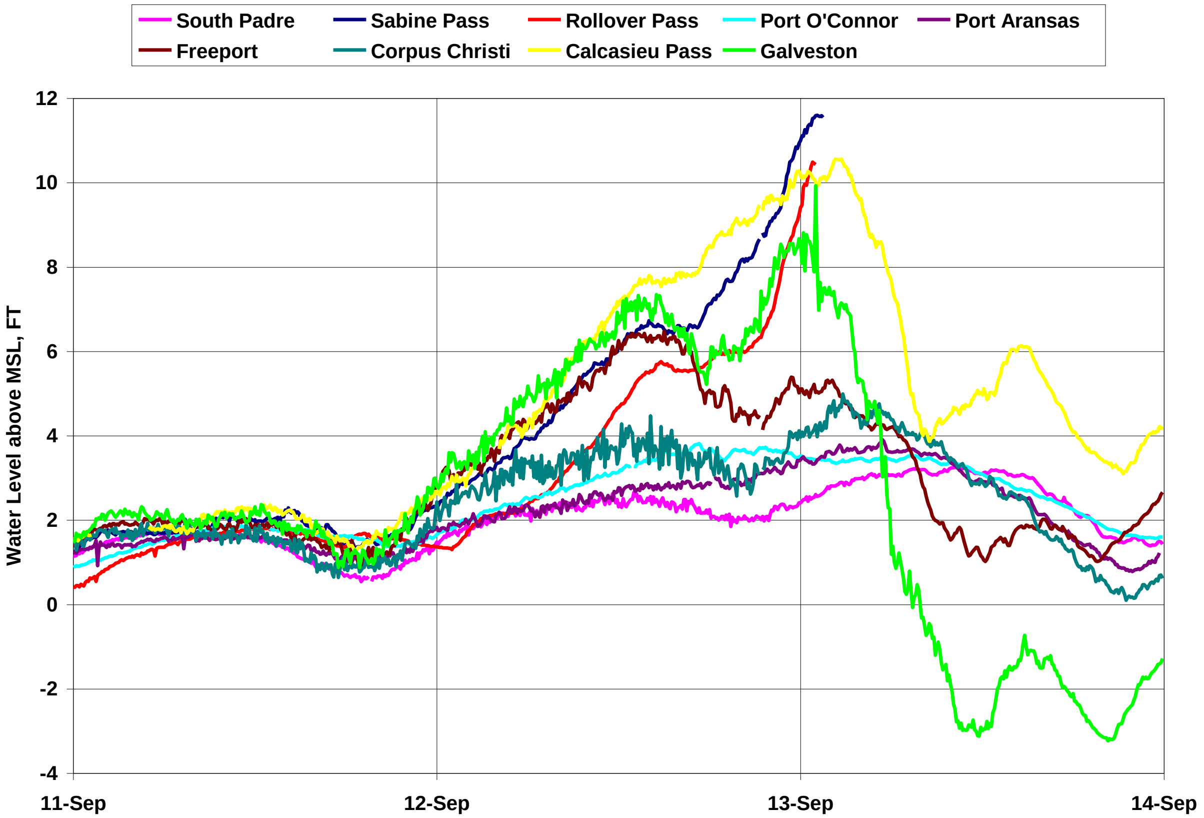


Figure 2.3 Water level measured at NOAA tide gauges during Ike.

2.2.3 Waves

The largest significant wave height measured during Hurricane Ike was 30 ft in open water near the middle of the Gulf of Mexico (NOAA NDBC 2008). Figure 2.4 shows significant wave height at four buoys in the Gulf of Mexico as Ike approached. Waves reaching the coast were likely depth limited, leading to large waves breaking on the shore during periods of high surge. Texas A&M University at Galveston maintains a wave forecasting model for the Gulf of Mexico (Panchang 2009) which they applied to calculate wave height during Hurricane Ike along the Texas coast and in the Gulf of Mexico. Calculated wave heights in the Gulf of Mexico prior to landfall are shown in Figure 2.5. Model simulations and NOAA data indicate that Ike caused large storm waves along the entire Texas coast for about three days.

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[2] All elevations herein will reference NAVD (North American Vertical Datum of 1988) unless otherwise noted.

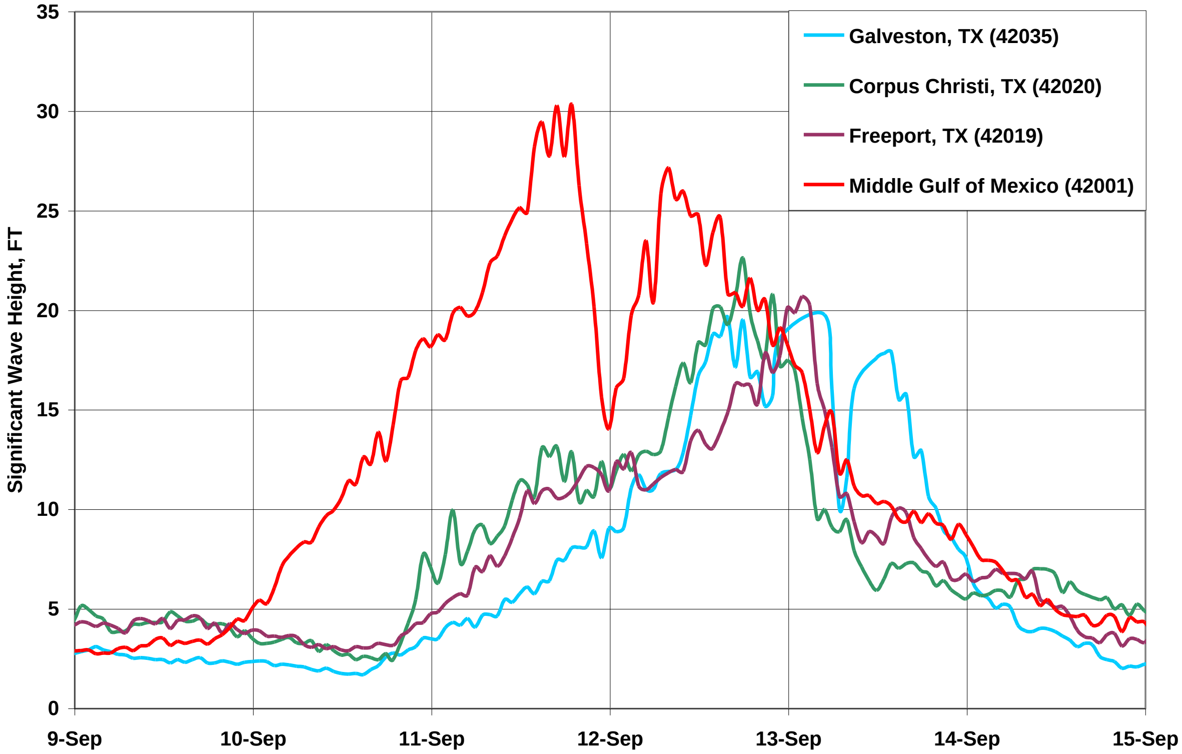

Figure 2.4 Wave height at buoys near the Texas coast during Ike.

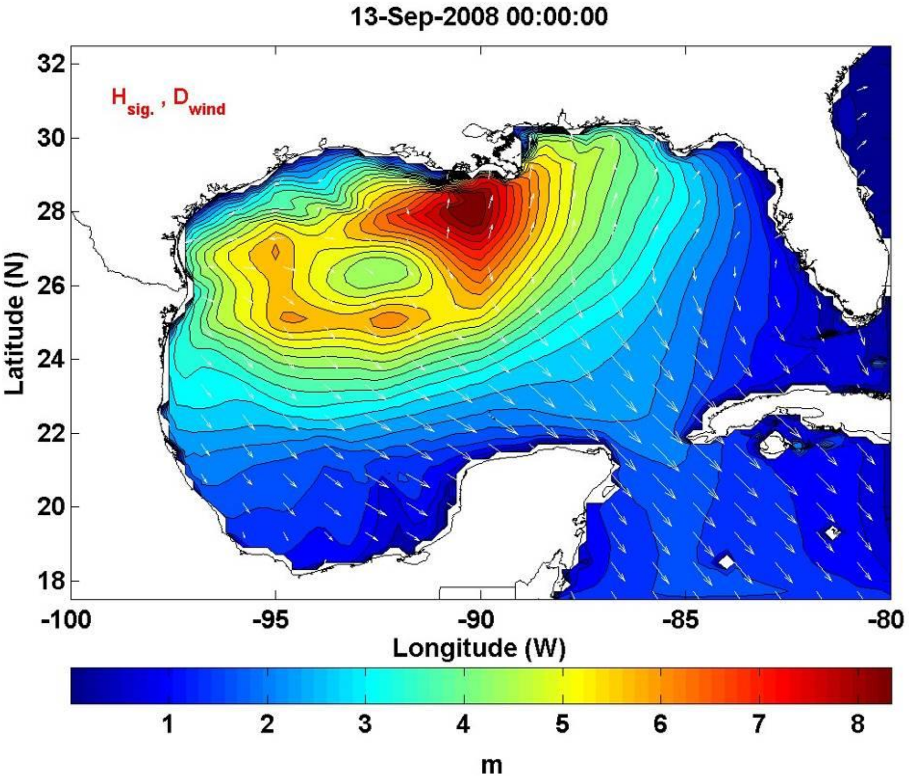

Figure 2.5 Calculated wave height, in meters, 7 hours prior to landfall (Panchang 2009).

3.0 PRELIMINARY DAMAGE ASSESSMENT

States bordering the Gulf of Mexico were subjected to large waves and high storm surge generated by Hurricane Ike. This section, organized by geographic region, discusses the data available immediately after the storm as well as preliminary shoreline change caused by Hurricane Ike. Further analysis of shoreline and volume changes along the upper Texas coast are provided in subsequent sections.

3.1 Methodology

Multiple sources of data were reviewed to estimate immediate changes of the Texas shoreline caused by Ike. Available data were limited and many were preliminary during the initial assessment of Ike impacts. This section describes the general types of data that were gathered and analysis methodologies utilized.

3.1.1 Aerial Photography

Aerial photography from July 29, 2008 (Texas General Land Office) was compared to photographs collected on September 19, 2008 (USGS/FEMA) to locate the shoreline from High Island south to Follets Island during Ike. The wet/dry line along the beach face was traced at 1:2000-6000 scale from pre and post-storm photography. Transects were created in 160 ft (50 m) intervals shore normal from a baseline located 330 ft (100 m) offshore from the pre storm shoreline. Shoreline change was calculated along each transect (HRI 2009). In the post-Ike photography, highly eroded, crenulated shorelines required generalization of the shoreline in some places, and often interpretation of the wet/dry line was somewhat subjective.

3.1.2 Beach Surveys

Beach survey data have been collected at various beaches on the Texas coast in recent history for beach nourishment design, monitoring and other purposes. Many engineered beaches (beaches that have been artificially nourished or structurally enhanced with geotextile tubes, seawalls, groins, etc.) were resurveyed after Ike to assess damage caused by the storm in order to qualify for government assisted reconstruction funds. Survey data collected by many different sources are available on Bolivar Peninsula, Galveston Island, Mustang Island, North Padre Island, South Padre Island and many other locations along the Gulf coast, but much of the data were limited to wading depths or only extended a short distance along shore. The limited spatial extent of the data makes accurate volume computations impossible to obtain from beach surveys alone. Instead, the data are used here to provide insight into the extreme erosion caused by Ike.

For the present analysis, change in shoreline position was determined by comparing pre and post-storm locations of the +2.3 ft contour, which is an approximation of the limit between the wet and dry beach along the upper Texas coast based on Gibeaut *et al.* (2002, 2003). Survey data were compared to determine change in shoreline position, change in volume of sand, and change in the shape of the beach.

3.1.3 LIDAR

LIDAR is a remote sensing technology that uses lasers to survey the surface of the earth and is capable of covering large areas very quickly. LIDAR was flown (USGS 2008) as soon as practical after Ike to assess change in shoreline and vegetation line position as well as change in volume and character of the beach.

Some preliminary LIDAR data have been analyzed by the USGS (2008) and are presented in Section 4.1.2 as an example of results that will be available later. LIDAR data collected September 17, 2008 were compared to LIDAR collected in 2005 to assess erosion and deposition on Bolivar Peninsula. The data allow comparison of elevation over large areas. Typical calculations include elevation change, shoreline position change and change in volume. The data are especially useful at estimating volume of washover.

3.1.4 Physical On-Site Investigations

Because of the scale of the storm, many groups and individuals independently conducted post-storm observations. Observations, photographs, measurements and other reports were compiled during the present assessment of Ike's impact. The Coasts, Oceans, Ports and Rivers Institute (COPRI) of the American Society of Civil Engineers sent two teams to assess the effects of Ike in the Galveston area[3]. Where observations, photographs, reports or personal knowledge was readily available, it was included in this analysis.

3.2 Upper Texas Coast Assessment

The upper Texas coast, for the purposes of this report, extends from Sabine Pass south to the Brazos River. The greatest damage to the Texas coast occurred in this region and is therefore covered in the greatest detail. Ike caused an average of 130 to 300 ft of Gulf shoreline erosion in Galveston and Brazoria Counties. Initial studies indicate that Hurricane Ike has caused changes to the littoral sediment system even greater than that of Hurricanes Carla or Alicia. HRI (2009) analyzed shoreline change along the upper Texas coast to determine immediate shoreline change due to Ike. HRI results are coupled with other data sources and discussed in more detail in the following subsections.

3.1.1 Sabine Pass to High Island

The beach along this segment of the Texas coast is characterized by a thin veneer of sand overlying mud and clay deposits. The beach serves as protection to a vast fresh water wetland and coastal prairie complex. Erosion caused by Ike stripped much of the sand from the beach and dune ridge, allowing saltwater to inundate the freshwater wetlands behind (Williams *et al.* 2009). Loss of this beach system has created a serious threat to the health of the ecosystem, including large portions of McFaddin National Wildlife Refuge and Sea Rim State Park.

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[3] Don Stauble, PhD, U.S. Army Corps of Engineers, personal communication, 2/25/2009.

Dr. Don Stauble[4] provided a comparison of shorelines traced from USGS Orthoimagery collected days after Ike and 2006 aerial photography. The comparison was used to estimate shoreline erosion during Ike from Sabine Pass to High Island. Average shoreline erosion from Sabine Pass to High Island was 180 ft with peak erosion over 300 ft. Figure 3.1 shows the shoreline at Sea Rim State Park with shoreline erosion of 200 to 300 ft evident in the photos.

Figure 3.1 Pre and post storm photo comparison at Sea Rim State Park.

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[4] Don Stauble, PhD, U.S. Army Corps of Engineers, personal communication, 2/25/2009.

3.1.2 Bolivar Peninsula

HRI (2009) analysis of aerial photography shows that the average shoreline erosion during Ike on Bolivar Peninsula south of High Island was 220 ft with peak erosion over 400 ft. Preliminary USGS (2008) results of elevation change, based on LIDAR data, are shown in Figure 3.2. In the figure, red indicates areas with greater than 3.3 ft of vertical erosion and blue indicates areas with greater than 3.3 ft of deposition. The many red squares represent houses lost to the storm. The data show that there was erosion on the beach and deposition landward.

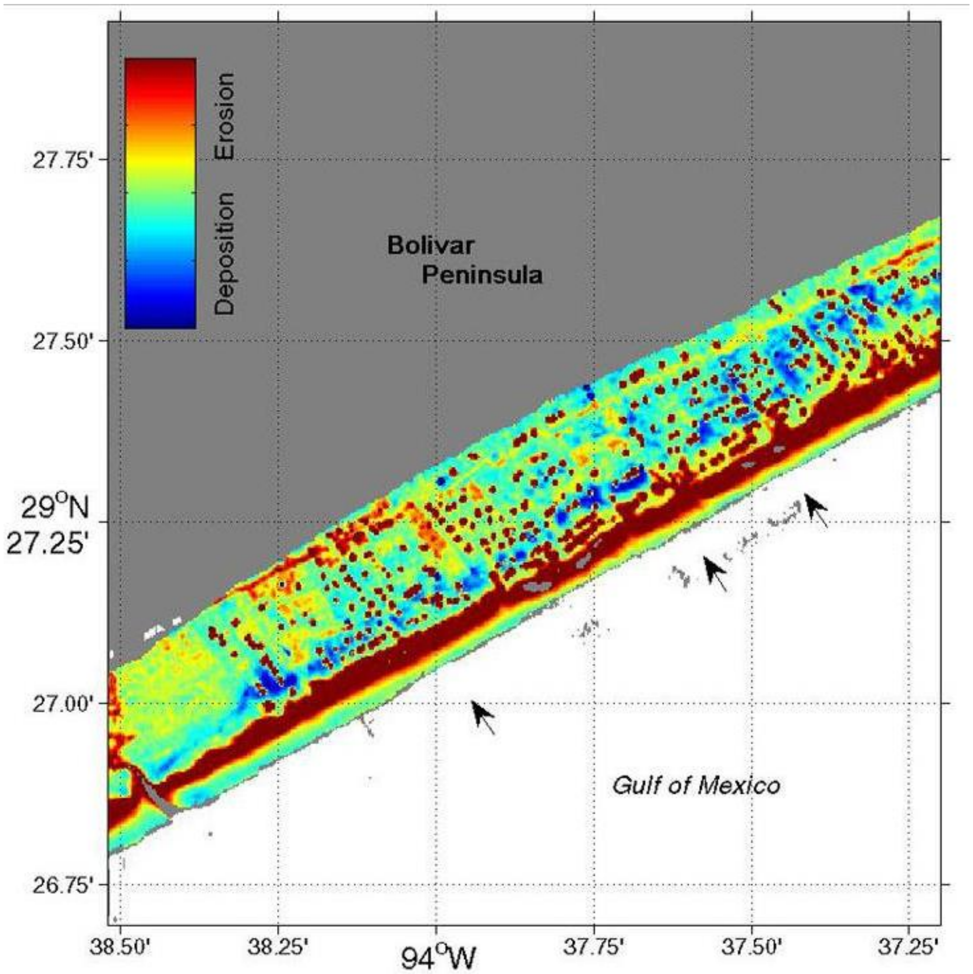

Figure 3.2. Comparison of LIDAR data on Bolivar Peninsula (USGS 2008).

In addition to the LIDAR and aerial photographs, beach surveys that extend approximately 6,000 ft southwest of Rollover Pass were conducted in June 2008 and February 2009 on Bolivar Peninsula. This beach received small scale beach nourishment in June of 2008; therefore, a post-Ike survey was performed to assess damage to the engineered beach. Survey results showed that the shoreline in February 2009 was 50 to 100 ft landward of its pre-Ike position. This segment of shoreline also contained geotextile tube shore protection projects. Visual assessment of the beach revealed loss of all dune cover, extensive damage to the geotextile tubes and over 4 ft of vertical erosion landward of the geotextile tubes. Figure 3.3 shows erosion under a house foundation landward of the previously existing geotextile tubes. Figure 3.4 is an aerial photo taken of damage along a section of beach on Bolivar, showing extreme damage to the geotextile tubes along this section of Bolivar Peninsula. Damage at Rollover Pass is shown in Figure 3.5.

The February 2009 post-Ike survey was not conducted until five months after the storm. Shoreline erosion in this area, based on aerial photography analyzed by HRI (2009), averaged 220 ft with peak erosion of about 300 ft. While it is not accurate to compare shoreline change based on surveys and photographs without more analysis, the magnitude of the difference between the shoreline position indicated in the February 2009 survey and the shoreline position in the post-Ike aerial photos indicates that substantial recovery has already occurred but that the beach may still need to advance another 50 to 100 ft to reach its pre-storm location.

Figure 3.3 Erosion under a house foundation south of Rollover Pass.

While conducting the beach survey in February 2009, overwash thickness and spatial extent was observed near Rollover Pass on Bolivar Peninsula. Overwash occurred here as the storm overtopped Bolivar Peninsula, destroying geotextile tubes and landward property. Many of the overwash deposits were quickly disturbed by reconstruction efforts, limiting accuracy of thickness measurements in developed areas. Figure 3.6 shows Crystal Beach on Bolivar Peninsula before and after Hurricane Ike (USGS 2008). Overwash in the post-Ike photo is the tan sand color in locations where green grass was evident in the pre-Ike photo.

Figure 3.4 Aerial photo of Bolivar Peninsula showing damage to geotextile tubes.

Figure 3.5 Aerial Photograph of damage at Rollover Pass.

Figure 3.6 Pre and post storm photo comparison at Crystal Beach (USGS 2008).

3.1.3 East Beach

HRI (2009) analysis of aerial photography shows that the average shoreline erosion during Ike at East Beach on Galveston Island was 315 ft with peak erosion over 700 ft immediately adjacent the south jetty. However, it is common for extreme shoreline change to occur adjacent to jetties during a storm because waves, currents and surge all tend to be amplified as they interact with the structure. Much of the sand from East Beach was likely transported over the jetty towards Big Reef and the Galveston Entrance Channel. Damage to the East Beach Pavilion (Figure 3.7) is indicative of the high surge and large waves during Ike. Figure 3.8 shows a comparison of the pre and post-Ike beach near high rise condominiums on the east end of Galveston Island.

Figure 3.7 Pavilion on East Beach damaged during Ike.

Figure 3.8 Pre and post storm photo comparison on Galveston East Beach (USGS 2008).

3.1.4 Galveston Seawall

Preliminary comparison of available beach survey data along the seawall was conducted as part of a post-Ike emergency seawall beach nourishment project. Surveys conducted by Vazquez in June 2006 and Naismith Marine Services in October – December 2008 were compared for the 3.75 mile long area from 10th Street to 61st Street. The results showed that the shoreline eroded completely to the seawall over much of the 3.75 miles. Figure 3.9 shows the area in front of the seawall near the Galveston Island Convention Center which was completely inundated after the storm during a mid-October 2008 high tide event

Figure 3.9 Beach near the Galveston Island Convention Center.

3.1.5 West Galveston Island

HRI (2009) analysis of aerial photography shows that the average shoreline erosion during Ike on West Galveston Island, west of the seawall to San Luis Pass, was 195 ft with peak values over 400 ft. Surveys by HRI staff along West Galveston Island one month after the storm revealed little beach recovery; the lack of natural beach recovery requires further study to better understand how long it will take for the beaches and dunes to re-establish. Some of the eroded sand was deposited on top of the barrier islands in layers up to and exceeding 2 ft (60 cm) thick, serving to raise the elevation of the Gulf edge (HRI 2009). Sand was also transported alongshore and offshore of the beaches to areas where it is not expected to return to the littoral system. Erosion during Ike was extreme on West Galveston Island, as evidenced by houses in the surf along much of the shoreline (Figure 3.10, 3.11, and 3.12). Figure 3.13 shows comparison of oblique aerial photographs of the Spanish Grant neighborhood before and after Ike on West Galveston Island (USGS 2008).

Figure 3.10 Houses in the Gulf after Hurricane Ike on West Galveston Island.

Figure 3.11 Damage in Spanish Grant on West Galveston Island.

Figure 3.12 Damage in Spanish Grant on West Galveston Island.

Shoreline erosion and beach volume change within 7.6 miles immediately west of the seawall were calculated based on surveys conducted in August and November 2008. As shown in Figure 3.14, shoreline erosion varied from a maximum of 280 ft, 4,140 ft west of the west end of the seawall where a small lagoon was breached, to a minimum of 50 ft, about 1,000 ft west of the seawall. Average erosion within the study area was 135 ft. Surveyed shoreline erosion appears to be less than observed in the aerial photographs. Note that the beach survey was performed several weeks after the aerial photography, allowing more time for beach recovery. In addition, survey comparison calculates changes at a specified elevation rather than differences in lines interpreted from aerial photographs. More detailed analysis to quantify shoreline change using a standard methodology based on LIDAR is presented in Section 4.

Based on the August and November 2008 survey data, the West Galveston Island beach within 7.6 miles west of the seawall lost in excess of 769,000 cy of sand above the 0 ft contour (HDR 2009). In contrast to erosion of the upper beach, the survey data show that the beach experienced significant deposition of sediment below the -10 ft contour. However, it is difficult to accurately quantify the amount of deposition due to the layer thickness being similar to the survey equipment tolerance of approximately 0.5 ft. While much of the sand deposited offshore will eventually be reworked into the upper beach profile, some sand was carried out to sea beyond the typical depth of closure and will not be recovered. In addition to sand lost seaward, overwash during the storm carried sand landward of the active beach, preventing recovery.

Figure 3.13 Pre and post storm photo comparison on West Galveston Island (USGS 2008).

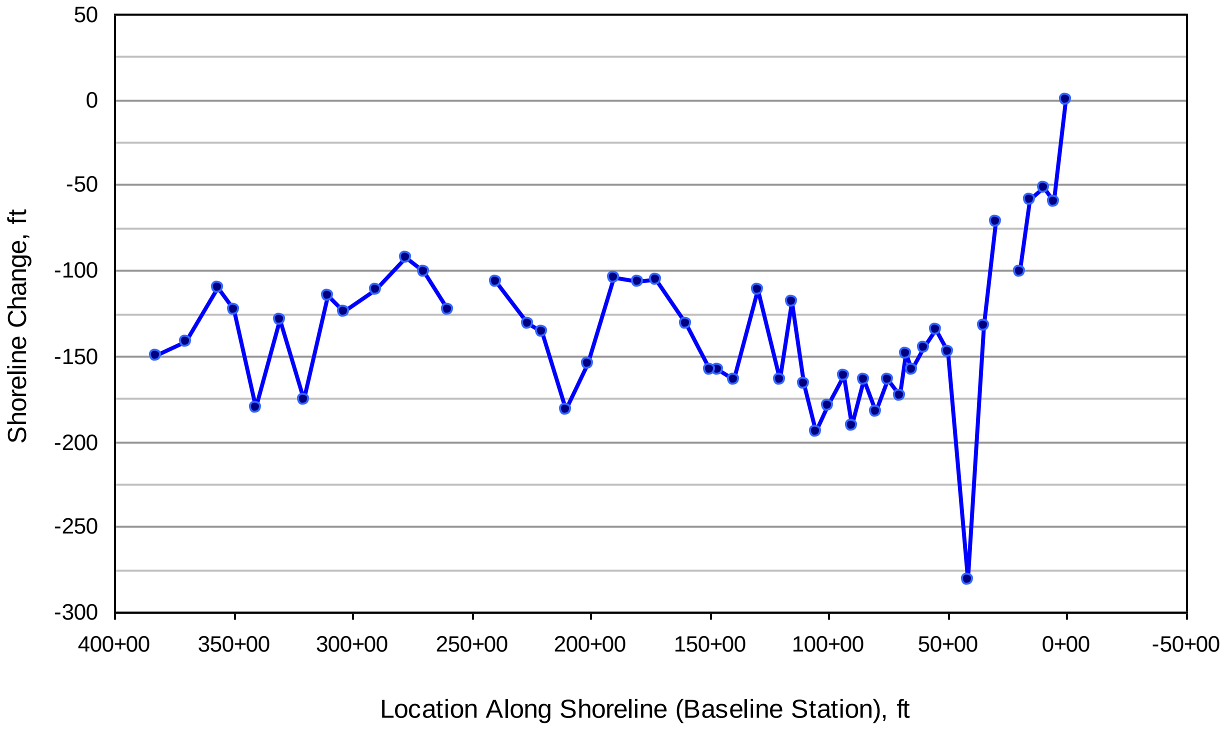

Figure 3.14 Change in shoreline position between August and November 2008 (HDR 2009).

3.1.6 Follets Island

Erosion in the town of Surfside, an area suffering from long term erosion, averaged about 180 ft during the storm with higher erosion at the northeast end of town. Figure 3.15 shows a home damaged in Surfside. HRI (2009) analysis indicates that Follets Island experienced average shoreline erosion of 215 ft with a peak of over 400 ft.

Damage was extreme along Blue Water Highway (CR 257) as shown in Figure 3.16. Much of this reach experienced significant scour of the beach and dune system, evident in the pre and post-Ike photo comparison in Figure 3.17. Much of the beach and dune scour likely occurred after passage of the storm as water from within the back bays of Christmas Bay and Drum Bay returned to the Gulf. The scour was the cause of significant damage to Blue Water Highway and complete destruction of some sections of the road.

Figure 3.15 Home damage in Surfside, TX.

Figure 3.16 Damage to Blue Water Highway on Follets Island.

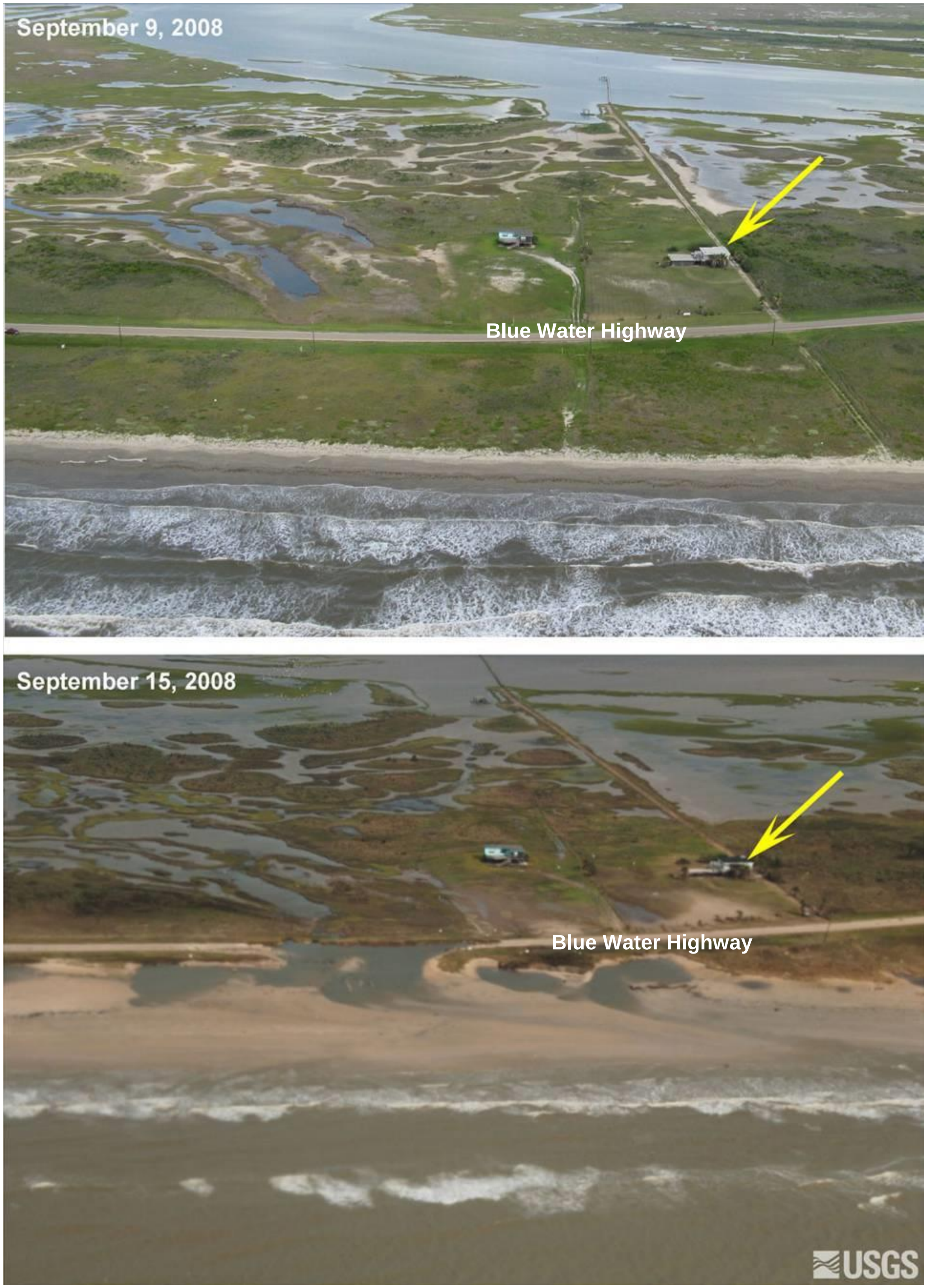

Figure 3.17 Pre and post storm photo comparison at Follets Island (USGS 2008).

4.0 TEXAS VIRTUAL MONUMENT SYSTEM

Data gathering for the preliminary assessment of impacts from Hurricane Ike highlighted several significant issues regarding beach profile survey data availability, reference monuments, collection methodology, and the cataloguing or archiving of the information. Surveys have historically been collected on a project by project basis and reference local or project specific baselines. In addition, transect spacing is often also project specific and may be non-uniform along the project baseline. Lastly, most of the survey data are held by project engineers or sponsors and there is no central location for archiving or acquiring data. As a result, compiling data across large geographic areas is challenging. In addition, surveys performed within the same areas may not reference the same baseline, making comparisons difficult. The most consistent set of survey data and use of reference monuments is for the City of South Padre Island as part of their monitoring regime that has been in place since 1995.

To address these issues, a Texas Virtual Monument System was developed for the GLO to provide a standardized set of locations at which beach profiles should be taken on Texas Gulf beaches, thus providing a framework for future coastal monitoring. No physical disc or survey monument would be placed for these monument locations, hence the “virtual” aspect of the monument system. The “monuments” include horizontal locations and an azimuth upon which beach profiles should be performed. This system was developed in a similar fashion to the R-Monument reference system utilized in Florida.

During the creation of the monument system and setting the monument locations, HDR worked with the GLO, coastal surveyors, and other coastal engineering consultants to document the location of existing beach profile transects along the entire Texas coast. The spacing of the monuments was established as approximately 1,000 ft but varies along the coast in order to re-occupy historical survey transects. As an example, in 2002 the U.S. Army Corps of Engineers performed beach profile surveys to the depth of closure from Sabine Pass in Jefferson County through Galveston County to San Luis Pass. These surveys were performed every ½ mile, or approximately every 2,600 ft. The locations of these surveys served as the basis for virtual monuments within Jefferson, Chambers, and Galveston County. Additional monuments were then placed between the existing USACE survey transects for an average spacing of approximately 1,300 ft. However, within Galveston County, there were several locations along Bolivar Peninsula (in the vicinity of Rollover Pass) and along Galveston Island (west of the seawall) where monitoring surveys and project design surveys had been performed. Therefore, the monuments between the USACE transects were selected to coincide with existing transects at monitoring or project survey locations, rather than just half way between the USACE transects. Figure 4.1 shows the location of virtual survey monuments within Galveston County.

This process was utilized for the entire coast of Texas and a GIS shape file was provided to the GLO. Recommendations on survey data collection and recording were also provided to assist with maintaining consistent data quality on future surveys. The GLO is utilizing this system on new coastal projects and is archiving beach profile survey data on their public GIS servers.

Figure 4.1 Virtual Monument locations within Galveston County.

5.0 SHORELINE CHANGE ANALYSIS OF UPPER TEXAS COAST - IMPACTS AND RECOVERY

Shoreline change analyses were performed for the upper Texas coast in order to provide a better understanding of shoreline impacts associated with Hurricane Ike, as well as to document ongoing recovery of the beach post-storm. The following sections describe various methodologies utilized to assess shoreline changes, an overall summary of shoreline changes, and assessments of local conditions.

5.1 Methods

5.1.1 Shoreline Mapping

Shorelines change analyses along the upper Texas coast were performed by the Harte Research Institute at Texas A&M University -- Corpus Christi. Shoreline locations for comparison were obtained from LIDAR-derived digital elevation models (DEMs) and represent the +2.3 ft (+0.7 m) contour based on Gibeaut et al. (2002, 2003). The data collected during the LIDAR surveys were recorded in SI units; therefore, the analyses were also performed in these units. As a result, the analysis methodology section below will document the work in SI units; however, the final results will be provided in English units.

The shorelines extracted from the LIDAR were smoothed in ArcMap (GIS) using the "Smooth Line" function (PAEK algorithm with a 2 meter smoothing tolerance). The number of vertices in the polyline were reduced by using ET Geowizards generalized polyline command tool with a 0.25 m tolerance. This retains the shape of the smoothed polyline while reducing the number of vertices. The lines were assessed and corrected for any topology errors. The DEM's used for shoreline extraction, as shown below, were obtained from The University of Texas at Austin Bureau of Economic Geology (BEG).

- 08/18/2005
- 12/13/2008
- 04/09/2010
- 04/13/2011
- 02/19/2012

The 2005 LIDAR survey was the closest available pre-storm LIDAR survey available for analysis. It should be noted that this survey was prior to Hurricane Rita and another weather event in the October 2006. However, the greatest impacts to shorelines from Rita were along the Louisiana coast, and the 2005 survey should provide a useful baseline for overall shoreline changes.

Shoreline Change Analysis

Shoreline change analysis was conducted using the Digital Shoreline Analysis System (DSAS) (Thieler, E.R.; et al, 2009). DSAS is a freely available ArcGIS application made available by the U.S. Geologic Survey, which computes rate-of-change statistics for a time series of shoreline data.

Data input for DSAS is a time series of shorelines aggregated into one GIS shapefile. Each shoreline segment has a date, uncertainty, length, shape, and object ID field. A second input is a set of shore-perpendicular transects extending from an off-shore baseline, landward to 1 km. Transect spacing for this analysis was set at 50 meters. Distance between shorelines and shoreline displacement is measured from a baseline, with seaward shoreline movements represented by positive (+) numbers and landward movements are represented by negative (-) numbers.

The analysis conducted for this project are the shoreline change rate (linear regression method) from 2005-2012 and the net shoreline movement from the epochs of 2005 (Pre-Rita)-2008, 2008-2010, 2010-2011, and 2005-2012. The linear regression method for the shoreline rate of change was determined using all available shorelines. This method fits a least-squares regression line to all shoreline points for a particular transect, and the linear regression rate (LRR) is the slope of the line. This process is similar to the shoreline change rate assessments performed by BEG for the entire Texas coast. Some sections of the study area were omitted from the analysis as the shoreline position had changed extremely over the time period of the analysis (e.g. near inlets and overwash channels), or due to the occurrence of coastal structures (groins, piers, houses or seawall segments).

5.1.3 Beach Survey Comparisons

Beach profile survey data is limited along the upper Texas coast study area, and typically occurs within shoreline segments that have had recent or ongoing beach nourishment/dune restoration projects. West Galveston Island, from the end of the seawall through Galveston Island State Park, has been surveyed multiple times for proposed beach nourishment projects, as well as for monitoring of geotextile tube projects. As a result, there is a relatively long section of shoreline (approximately sevan miles) that allows for comparison of impacts from Hurricane Ike as well as an assessment of recovery through 2010. Surveys were also performed in 2011 as part of this project at select locations along the upper Texas coast, with four transects located within the West Galveston Island project area. Lastly, a short section of beach (approximately 3,000 ft immediately west of the seawall) was surveyed as part of a proposed beach nourishment to be completed in winter 2013/2014. A summary of the surveys utilized in the analysis is provided in Table 5.1.

Table 5.1 Surveys Along West Galveston Island.

Date	Limits	Approx. Transect Spacing
8-2008 (Pre-Ike)	WGI STA 0+00 to 382+59 (G146 to G175)	500 ft
10-2008 (Post-Ike)	WGI STA 0+00 to 382+59 (G146 to G175)	500 ft
9-2009	WGI STA 0+00 to 382+59 (G146 to G175)	2,600 ft
9-2010	WGI STA 0+00 to 382+59 (G146 to G175)	500 ft
9-2011	WGI STA 67+65 (G151), 172+59 (G159), 251+34 (G165), 330+00 (G171)	7,900 ft
2-2013	WGI STA 0+00 to 30+00 (G146 to G148)	500 ft

5.1.4 Site Visits

Several site visits were performed along most of the upper Texas coast shoreline during the recovery period in June 2010 and in August 2011 (HDR, 2011). The area from Sabine to just west of Sea Rim State Park was not observed due to inaccessibility. During the field work, two coastal engineers from HDR visited a series of virtual monument locations to observe the conditions of the beach and dune system.

5.2 Results and Discussion

The shoreline change analyses along the upper Texas discussed herein will typically be based on the results of the LIDAR comparisons described above, unless otherwise noted. A summary of the overall changes are provided in Table 5.2 and Figures 5.1 and 5.2 below. Table 5.1 provides the average shoreline change between LIDAR surveys, as well minimum and maximum shoreline changes for each region. The minimum and maximum values are reported in terms of shoreline recession, with maximum values representing the maximum shoreline recession measured for a survey period, and minimum values indicating the most shoreline advance. In addition, the shoreline change rates per year for each section are listed. Figures 5.1 and 5.2 provide an overall graphical representation of the average shoreline changes along the study area. Further review of the changes per shoreline section (similar to the shoreline sections described in Section 3) are presented in subsequent sections.

Table 5.2 Shoreline Change Rates per Region (LIDAR Comparisons).

Region		**Net Shoreline Movement (ft.)***					**Shoreline change rate (ft/yr)**
		Epoch 1 2005-2008	Epoch 2 2008-2010	Epoch 3 2010-2011	Epoch 4 2011-2012	**2005-2012**	2005-2012
Sabine to High Island	**avg**	**-90.2**	**-19.4**	**-11.7**	**-19.9**	**-141.1**	**-20.1**
	min	81	387.5	127.6	95	74.4	14.4
	max	-367.1	-126.2	-84.1	-90.4	-358	-58.8
High Island to Bolivar	**avg**	**-26.9**	**-12.5**	**9.6**	**-14.3**	**-44.0**	**-4.4**
	min	109.5	166.0	79.3	178.1	121.5	17.6
	max	-441.8	-91.7	-117.0	-104.0	-369.0	-56.8
East Galveston Island	**avg**	**-53.7**	**72.2**	**60.0**	**8.51**	**87.0**	**12.4**
	min	28.9	364.5	229.1	174.7	182.0	26.0
	max	-422.0	0.6	-105.3	-27.2	46.1	6.6
West Galveston Island	**avg**	-51.0	40.2	50.3	-9.9	30.0	4.3
	min	-276.0	-84.8	-112.6	199.0	-114.5	-16.4
	max	196.3	264.3	172.8	470.2	344.1	49.1
Follets Island	**avg**	**3.3**	**-10.2**	**55.2**	**-28.6**	**19.7**	**6.3**
	min	101.8	356.4	118.9	37.2	77.0	15.7
	max	-355.6	-75.8	-26.8	-92.59	-125.3	-15.0
Quintana	**avg**	**-68.2**	**29.0**	**57.6**	**-35.2**	**-16.9**	**0.7**
	min	55.7	115.6	286.2	27.7	100.0	31.8
	max	-154. 8	-204.3	-0.5	-454.7	-103.9	-17.3

* Negative values indicate shoreline recession and positive values indicate shoreline advance.

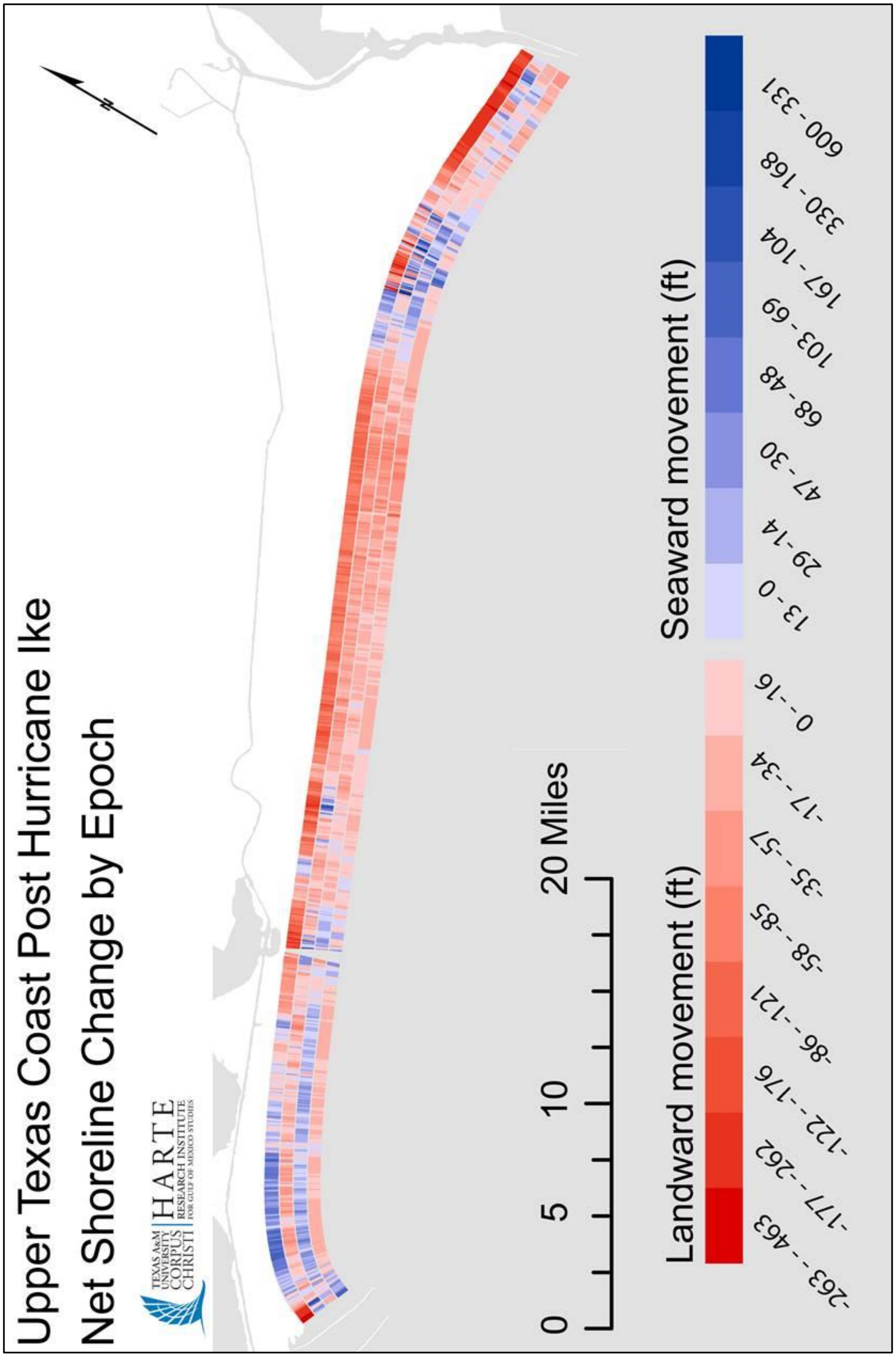

Figure 5.1 Shoreline Change Results – Sabine through Bolivar Peninsula (HRI).

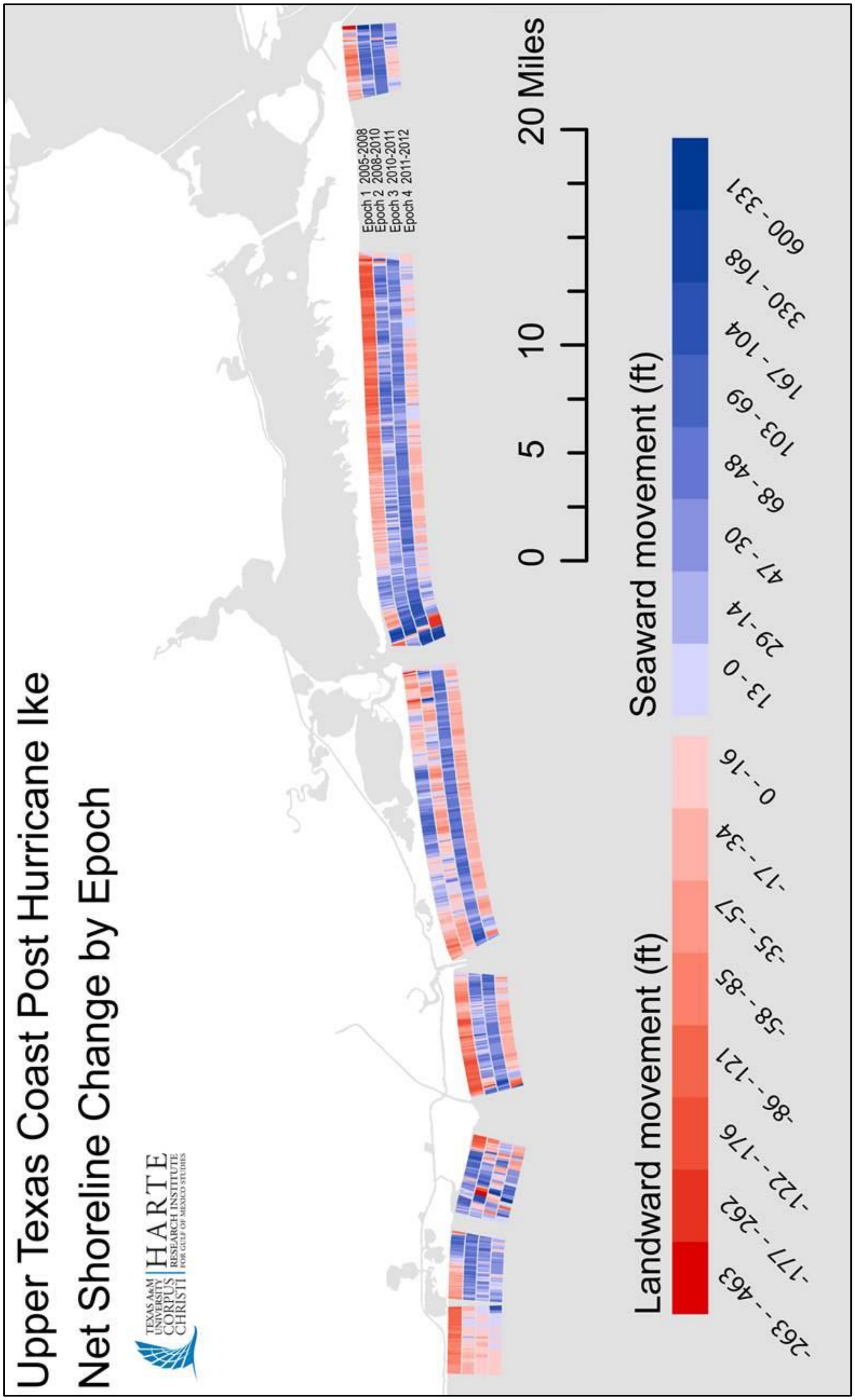

Figure 5.2 Shoreline Change Results – Galveston Island through Quintana (HRI).

5.2.1 Sabine Pass to High Island

The area from Sabine to High Island typically experienced a net shoreline retreat between each LIDAR survey as shown in Figure 5.3. This shoreline segment consists of clay outcropping shoreline features that become exposed during storms, and once the clay is eroded, the shoreline is not able to recover to pre-storm conditions as evidenced in the overall shoreline changes. However, the area between Texas Point National Wildlife Refuge and Sea Rim State Park appears to show some overall advance. Within this area, waves from Hurricane Ike created large washout channels as shown in Figure 5.4, which then experienced significant "recovery" as sediment moved back into these channel (Figure 5.5). Over the whole time period the average shoreline change rate for this section of the upper Texas coast has been an average of -141 ft, or -20.1 ft/yr (landward).

During a site visit in 2010, much of the area was eroded to the extent that the shoreline typically consisted of exposed clay (Figure 5.6) such as at monument J98 (approximately station 133000 in Figure 5.3). By the summer of 2011 (Figure 5.7), some sand had returned to shore; however, much of the clay was still exposed and no dunes were present. Figure 5.8 shows the 2011 condition of the shoreline near High Island, where much of the clay has been covered with a thin veneer of sand.

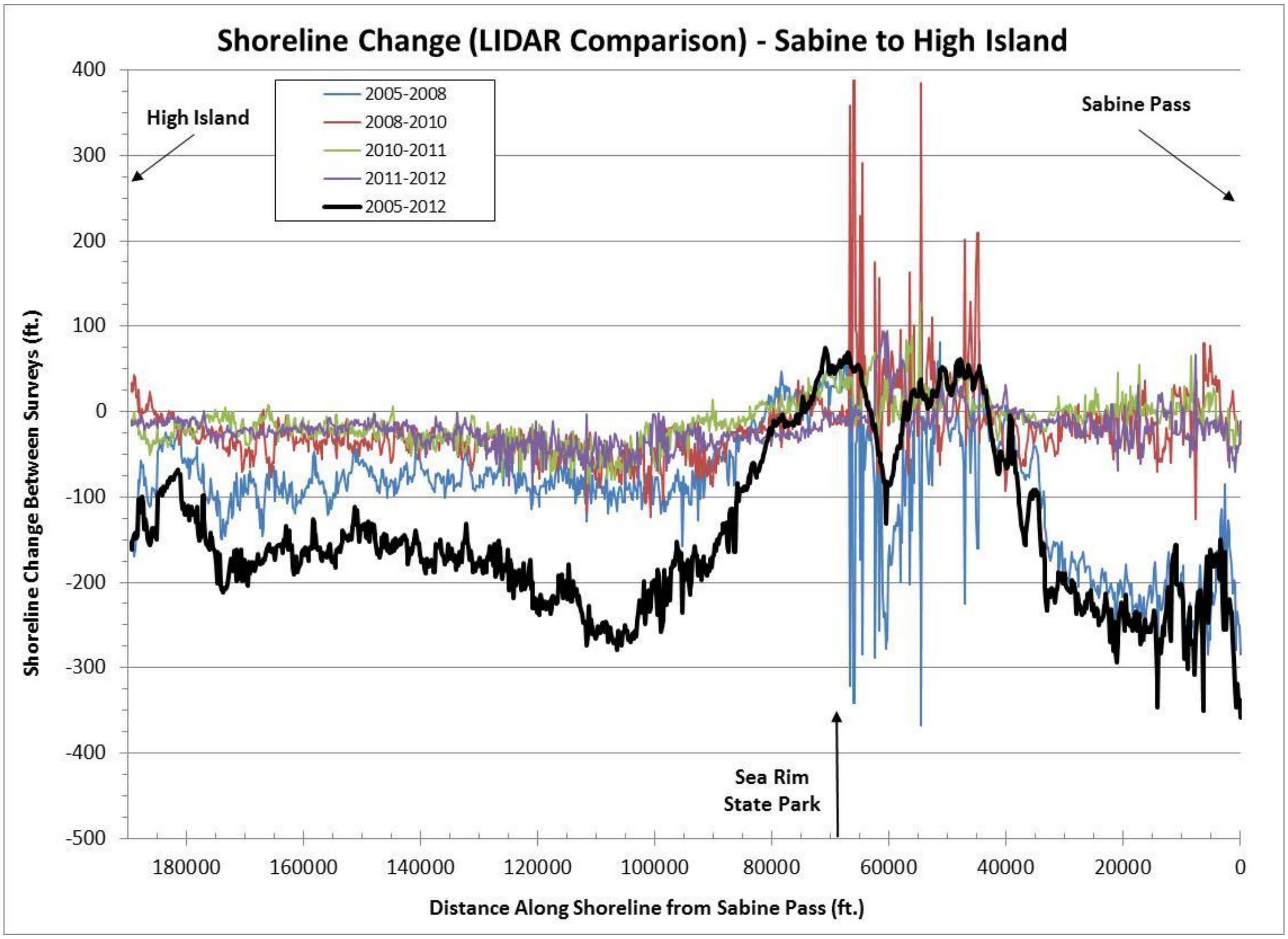

Figure 5.3 Shoreline Change from Sabine Pass to High Island.

Figure 5.4 Sea Rim park and eroded channels post Ike (Google Earth, 2008).

Figure 5.5 Sea Rim park and eroded channels post Ike (Google Earth, 2013).

Figure 5.6 2010 Shoreline near western edge of Jefferson County (Monument J98).

Figure 5.7 2011 Shoreline near western edge of Jefferson County (Monument J98).

Figure 5.8 End of Highway 87 at High Island, looking north (2011).

5.2.2 Bolivar Peninsula

Along Bolivar Peninsula much of the shoreline experienced erosion, or shoreline recession, due to Hurricane Ike, except for an area along the western end of the peninsula (Figure 5.9). This segment of shoreline has been stable to accretional even during typical conditions. Between 2008 and 2011, Bolivar beaches experienced some shoreline advance as profiles recovered from storm conditions. However, the overall shoreline recession trend returned between 2011 and 2012, with an overall shoreline recession of -44 ft or -4.43 ft/yr landward of the pre-Ike location.

Figures 5.10 and 5.11 show the immediate post-Ike and 2011 conditions (from site visit) east of Rollover Pass. Prior to Ike, this area consisted of narrow beaches with a geotextile core dune to provide protection to upland properties. The geotextile tubes and dunes were destroyed when the storm passed. The remnants of the tubes are observable in Figure 5.10. Survey results show that this area has not returned to pre-storm shoreline conditions; however, the photo in Figure 5.11 shows a fairly wide beach. This is due to a property buyout program implemented by Galveston County. The area around Rollover is not expected to fully recover due to sand being lost to washover into Rollover Bay and transported west as a result of wave action during Ike. In addition, the loss of sand from the areas east of Rollover (High Island and Sabine) has resulted in minimal sand being available for typical east to west transport.

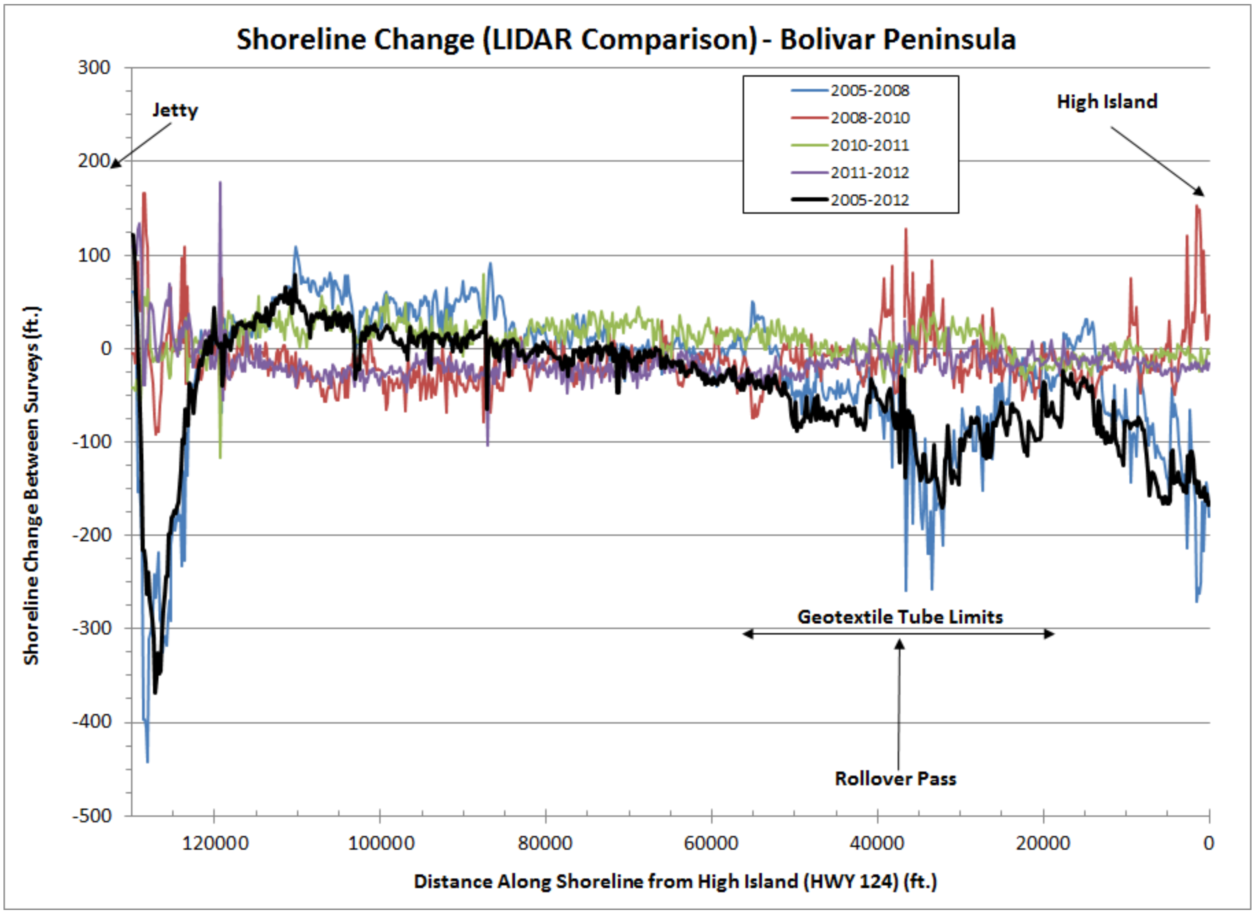

Figure 5.9 Shoreline Change along Bolivar Peninsula.

Further west along Bolivar Peninsula within Crystal Beach, the shoreline has nearly returned to pre-storm location and there is some dune structure reforming, though large dunes have not matched historical conditions (Figure 5.12). Much of the recovery along this section of the peninsula is likely due to the influx of sediment that was transported west during the storm.

Figure 5.10 Rollover Pass area Post-Ike looking east (2008, photo by AP).

Figure 5.11 Area just east of Rollover Pass (2011). Note yellow house shown in Figure 5.12.

Figure 5.12 Looking east at G72 (2011) towards Crystal Beach area shown in Figure 3.6.

5.2.3 East Beach

The area along the easternmost four miles of Galveston Island, between the jetty and 12th Street, experienced an average shoreline recession of -53.7 ft during Ike, with some areas moving up to 100 ft landward, and a maximum of over 300 ft near the jetty, as shown in Figure 5.13. Subsequent to the storm, these beaches recovered to, and in some cases seaward of, their pre-storm location. The overall average shoreline change between 2005 and 2012 was 87 ft seaward. This relatively large recovery may be due in part to sand transported into the area from along the seawall during Ike. In addition, a beach renourishment project was implemented along the seawall immediately after the storm (Section 5.2.4) and a majority of the sand for the project was dredged from the Galveston Entrance Channel and placed in a temporary dredged material placement area located on East Beach. After the sand had dewatered, trucks transported it to the seawall, but a significant amount of surplus material remained on East Beach and entered the littoral system.

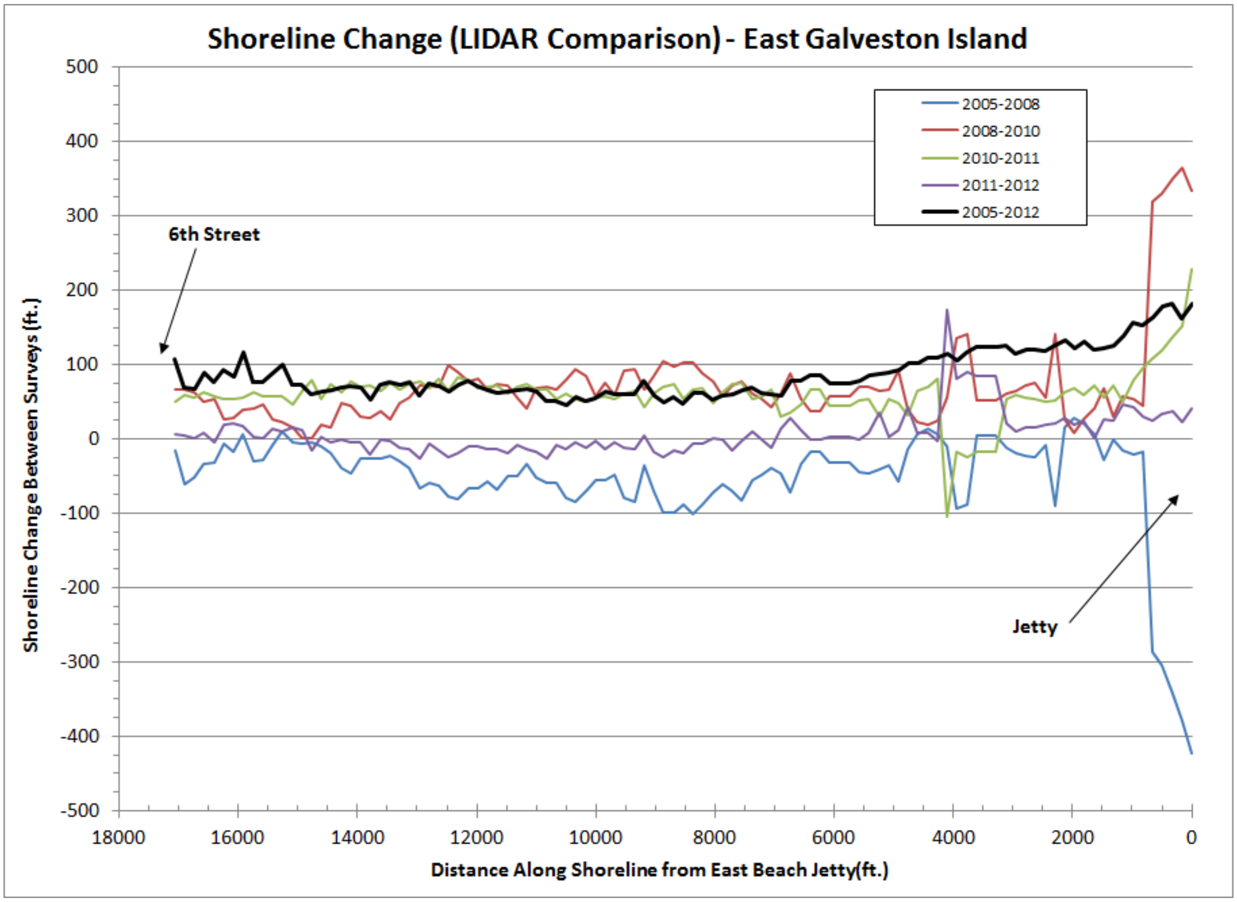

Figure 5.13 Shoreline change east of Galveston Seawall.

Figure 5.14 Eastern Galveston recovery (2011). Towers in background are those in Figure 3.8.

5.2.4 Galveston Seawall

Shoreline changes along the Galveston Seawall west of 10th Street were not calculated due to beach nourishment activities immediately following Ike influencing the shoreline position. As described in Section 3.1.4, the area along the seawall was significantly eroded during Ike and little, if any, beach remained after the storm passed. The loss of beach meant a loss to Galveston Island's primary economy (tourism) as well as increased concerns about potential scour of the seawall's foundation. Therefore, the Galveston Island Park Board of Trustees and the GLO implemented a beach nourishment project at the end of 2008 (only several months after the passage of Ike) that placed approximately 500,000 cy of sand to create a 70 to 100-ft wide beach, similar to what existed prior to the storm. Figures 5.15 and 5.16 show the post-storm and post-nourishment conditions of the seawall beach in front of the Galveston Island Convention Center.

Figure 5.15 Area fronting Galveston Seawall and Convention center immediately post-Ike.

Figure 5.16 Area fronting Galveston Seawall and Convention after beach nourishment.

5.2.5 *West Galveston Island*

The region west of the Galveston seawall typically experienced shoreline recession during Hurricane Ike, resulting in an average shoreline loss of 51 ft, with maximum values ranging from -100 to -276 ft near the end of the seawall as shown in Figure 5.17. The values near the end of the seawall compare well to pre- and post-storm beach profile surveys taken from the end of the seawall and extending 7 miles to the west. These measured survey shoreline changes indicate an average shoreline recession of -135 ft as shown in Table 5.3.

During the recovery period from 2008 to 2010, much of shoreline advanced as sand that had moved offshore during the storm was transported back to the upper beach face. However, typical shoreline processes eventually resumed and between 2010 and 2011 the shoreline receeded an average of 9.9 ft. The overall results from 2005 to 2012 show that the section of shoreline immediately west of the seawall did not return to its pre-storm conditions. Figure 5.18 shows the 2011 condition of the beach fronting Spanish Grant, located near the end of the seawall. A review of beach profile survey data shows that although there was recovery from post-storm conditions, by 2010 the six miles west of the seawall were still an average -56.4 ft from pre-Ike (August 2008) locations. The shoreline within 3,000 ft of the seawall was still -31.6 ft from pre-Ike locations in February 2013, more than five years after the storm.

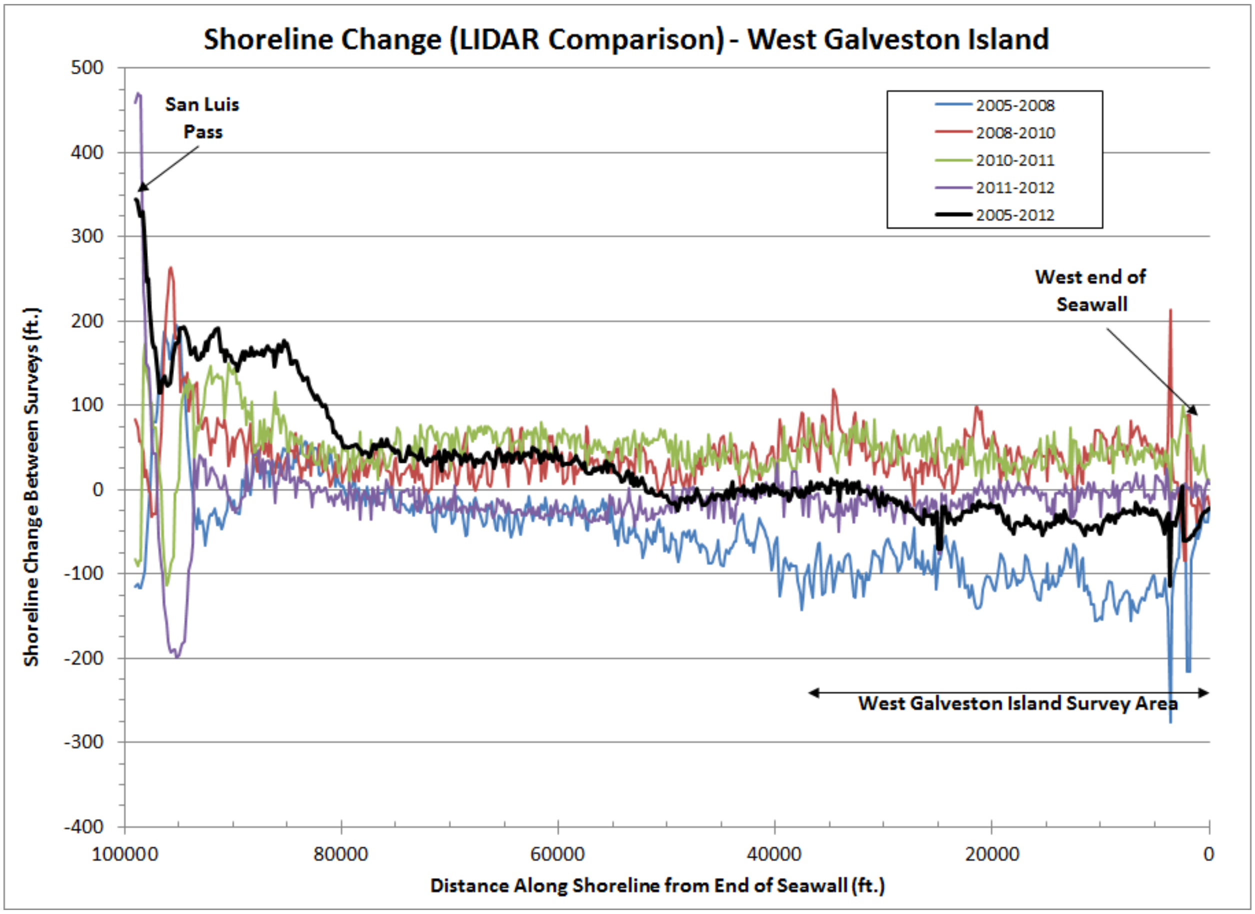

Figure 5.17 Shoreline change results for West Galveston Island.

Although a portion of the West Galveston Island shoreline did not fully recover, a significant length of the study area returned to, or advanced seaward of, the pre-storm locations. This is particularly evident at the western end of the island in the vicinity of San Luis Pass, as shown in Figure 5.17 and in the photos shown in Figures 5.19 and 5.20. Considering the path of Ike and the direction of waves impacting the island, much of the sand that was eroded on the eastern to middle section of the island (seawall to the area immediately west of the seawall) was likely transported west and has accumulated around the terminus of the island. The predominant east to west longshore transport pattern has also contributed to the western movement of sand during the recovery period. It should be noted that although some areas may have recovered to pre-Ike shoreline locations, much of the dune structure has been damaged and many of the shorelines were in narrow or recessed locations prior to the storm. Much of the western shoreline of Galveston Island remains in a critically eroded condition.

Table 5.3 Beach Profile Survey Analyses – West Galveston Island

	Station	8-2008 (pre) - 10-2008 (post)	10-2008 (post) - 9-2009	9-2009 - 9-2010	9-2010 - 7-2011	9-2010 - 2-2013		8-2008 (pre) - 9-2009	8-2008 (pre) - 9-2010	8-2008 (pre) - 9-2011	8-2008 (pre) - 2-2013
Seascape Condos	5+00	-62.3	-	-	-	40.8		-	-77.9	-	-37.1
	10+00	-56.6	-	-	-	46.2		-	-79.3	-	-33.1
Dellanera RV Park	15+00	-67.2	3.2	-2.9	-	39.8		-64.0	-66.9	-	-27.1
	20+00	-105.1	-	-	-	68.8		-	-94.2	-	-25.4
	25+00	-	-	-	-	-		-	-146.0	-	-
	30+00	-77.8	-	-	-	86.6		-	-121.8	-	-35.2
	35+00	-	-	-	-	-		-	-110.0	-	-
Sunny Beach	41+40	-287.0	176.2	16.5	-	-		-110.8	-94.3	-	-
	50+00	-146.9	-	-	-	-		-	-82.4	-	-
	55+00	-140.2	-	-	-	-		-	-77.0	-	-
	60+00	-145.9	-	-	-	-		-	-73.5	-	-
	65+00	-169.0	-	-	-	-		-	-69.4	-	-
	67+65	-154.0	62.9	22.8	30.6	-		-91.1	-68.3	-37.7	-
	70+00	-174.5	-	-	-	-		-	-68.3	-	-
	75+00	-168.0	-	-	-	-		-	-69.8	-	-
	80+00	-189.0	-	-	-	-		-	-69.6	-	-
	85+00	-167.0	-	-	-	-		-	-59.0	-	-
	90+00	-199.0	-	-	-	-		-	-73.9	-	-
	93+90	-164.0	81.0	22.0	-	-		-83.0	-61.0	-	-
Pocket Park #2	100+00	168.0	-	-	-	-		-	262.2	-	-
	105+00	-204.0	-	-	-	-		-	-70.2	-	-
Sands of Kahala	110+00	-167.0	-	-	-	-		-	-74.5	-	-
	115+00	-125.2	-	-	-	-		-	-78.2	-	-
	120+00	-171.0	93.0	7.6	-	-		-78.0	-70.4	-	-
W.B. Grand & Riviera	130+00	-113.4	-	-	-	-		-	-65.0	-	-
Hershey Beach	140+00	-186.0	-	-	-	-		-	-65.8	-	-
	146+36	-157.0	70.0	17.6	-	-		-87.0	-69.4	-	-
	150+00	-163.0	-	-	-	-		-	-69.3	-	-
	160+00	-136.0	-	-	-	-		-	-68.7	-	-
Bermuda	172+59	-118.3	58.6	5.2	27.6	-		-59.7	-54.5	-26.9	-
	180+00	-108.0	-	-	-	-		-	-44.6	-	-
	190+00	-110.0	-	-	-	-		-	-45.9	-	-
	201+34	-156.0	-	-	-	-		-	-51.5	-	-
	210+00	-186.0	-	-	-	-		-	-50.9	-	-
Pirates' Beach	220+00	-142.2	-	-	-	-		-	-64.0	-	-
	226+34	-132.0	79.6	10.8	-	-		-52.4	-41.6	-	-
	240+00	-111.0	-	-	-	-		-	-41.9	-	-
	251+34	-137.0	86.0	12.9	16.2	-		-51.0	-38.1	-21.9	-
	260+00	-129.0	-	-	-	-		-	-44.3	-	-
	270+00	-105.0	-	-	-	-		-	-38.5	-	-
	277+62	-95.1	-	-	-	-		-	-37.1	-	-
Pirates' Beach West	290+00	-118.5	-	-	-	-		-	-34.0	-	-
	303+80	-134.8	-	-	-	-		-	-47.4	-	-
Galveston Island State Park	310+00	-142.0	-	-	-	-		-	-42.7	-	-
	320+00	-189.0	-	-	-	-		-	-57.8	-	-
	330+00	-134.4	86.2	21.7	73.2	-		-48.2	-26.5	46.7	-
	340+00	-95.1	-	-	-	-		-	-20.0	-	-
	350+00	-128.6	-	-	-	-		-	-22.5	-	-
	356+30	-112.0	-	-	-	-		-	-41.6	-	-
	370+00	-146.0	-	-	-	-		-	-49.1	-	-
	382+59	-157.0	-	-	-	-		-	-49.2	-	-
	Average	**-135.0**	**79.7**	**13.4**	**43.8**	**60.6**		**-72.5**	**-56.4**	**-10.0**	**-31.6**

Figure 5.18 Spanish Grant area of West Galveston Island (2011).

Figure 5.19 Wide dune near San Luis Pass (2011).

Figure 5.20 Wide dune and beach near San Luis Pass (2011).

5.2.6 Follets Island

Follets Island also experienced areas of shoreline retreat and advance. Post-Ike the shoreline near San Luis Pass and Surfside experienced shoreline retreat, yet the mid-island stretch of beach experienced seaward movement. The following years were mixed between shoreline recovery and recession. These varying trends may be due to the fact that Ike eroded much of the foredune and upland complex between the beach and CR 257 (Bluewater Highway). Impacts included significant damage and scouring of Bluewater Highway both during the storm from wave attack and as water levels in the bays north of the island emptied and flooded across the island once the storm moved inland (Figure 5.22). This severe erosion of the dunes and uplands is expected to have contributed to the measured shoreline advance observed immediately following Ike in 2008. Between 2008 and 2010, most of Follets Island shorelines experienced some shoreline recession as the beaches sought equilibrium and recovered from the storm. However, the overall shoreline remains advanced of the pre-Ike location. It is believed that this is due to the slow rebuilding of the dunes along the island, causing the sand lost to the dunes to remain in the upper and active beach profile.

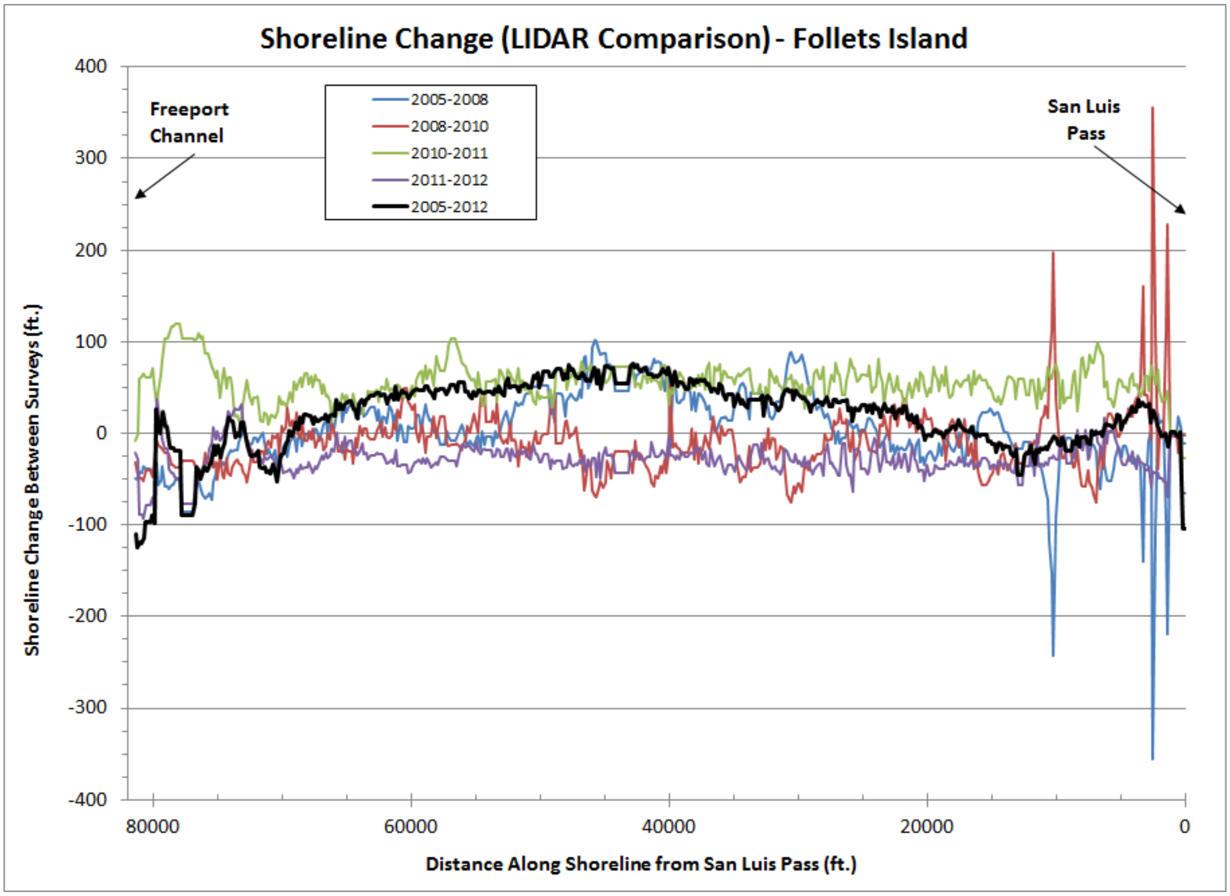

Figure 5.21 Shoreline change results along Follets Island.

Figure 5.22 Vertical Aerial in 2009 (Google Earth) of area in vicinity of Monument B26. Note erosion of dune and scour areas along Bluewater Highway.

Figure 5.23 Central section near Monument B26 of Follets Island (2011). Note dune beginning to recover, but still further landward of pre-storm locations.

5.2.7 Quintana

The Quintana section of shoreline extends from the west jetty at Freeport channel to the mouth of the Brazos River. Much of the area is undeveloped in regards to homes near the beach; however there are several leveed areas adjacent to, or immediately landward of, the beach. During Ike, much of the shoreline experienced recession, averaging -68.2 ft across the study area. As shown in Figure 5.24, some area receded over 100 ft. Between 2008 and 2011, the beach profile began recovering from the storm impacts as sand transported offshore moved back into the upper beach profile. One area of note is a 1,400 ft section east of the FM 1495 access road. This segment of shoreline is immediately adjacent to a leveed placement area and experienced significant erosion during Ike, and limited recovery, similar to a shoreline immediately downdrift of a coastal structure. Overall, the Quintana shoreline has not returned to pre-storm locations and is an average of -35.2 ft landward of the 2005 survey. The exception is the area west of the jetty where sand was likely deposited as waves transformed around the Freeport jetties.

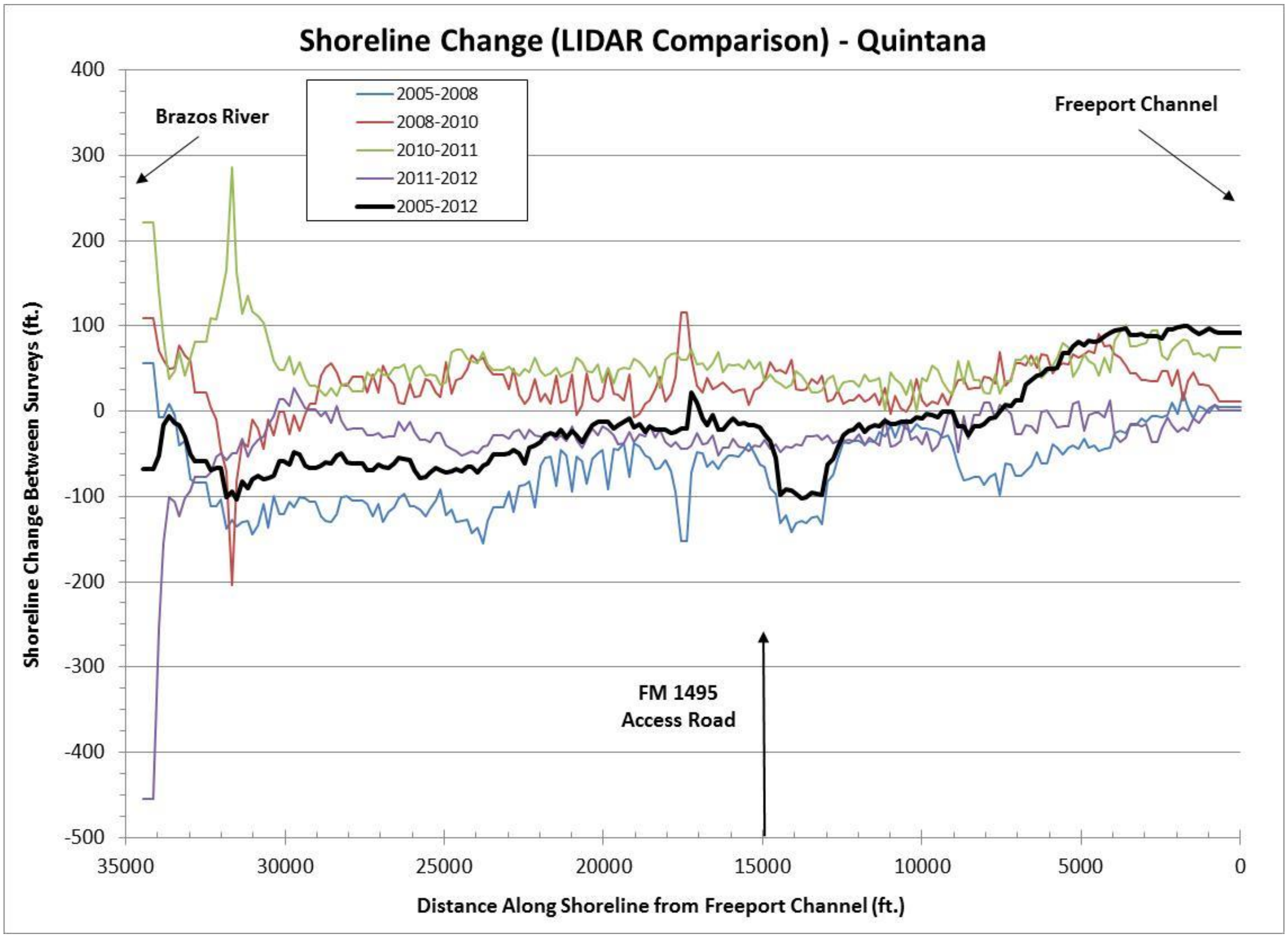

Figure 5.24 Shoreline change results for Quintana shoreline.

Figure 5.25 Quintana Beach (2011) looking east from FM 1495 access road

Figure 5.26 Quintana Beach (2011) looking west from FM 1495 access road.

6.0 VOLUMETRIC CHANGE OF UPPER TEXAS COAST – IMPACTS AND RECOVERY

Volume change analyses of impacts from Hurricane Ike and associated beach/dune system recovery along the upper Texas coast was performed by Harte Research Institute (HRI, 2012). The analyses utilized the five LIDAR surveys of the upper Texas coast that were part of the shoreline change analyses in Section 5:

- 8/18/2005 (pre-Rita)
- 12/13/2008 (post-Ike)
- 04/09/2010
- 04/13/2011
- 02/19/2012

Similar to the shoreline change analyses in Section 5, the data collected during the LIDAR surveys were recorded in SI units; therefore, the analyses were also performed in these units. As a result, the analysis methodology section below will document the work in SI units; however, the final results will be provided in English units. Further discussion on methodology and analysis results area available in Appendix A.

6.1 Methods

The raw LIDAR data consists of point clouds of irregularly spaced x,y,z values providing a three-dimensional representation of the ground and land cover. The raw points for each survey were tiled to form a contiguous sequence of 6 km (3.7 miles) tiles with 30 m (98 ft) buffer overlap along the coastline.

The last-return data for each survey were filtered using a progressive triangulated irregular network (TIN) densification algorithm (Axelsson, 2000) implemented with the LAStools software (Isenburg, 2011). The goal of filtering is to remove points that reflect from non-ground objects, such as from buildings, without altering the natural terrain surface. For this work, a multi-stage filtering process was applied whereby the data were filtered in stages by adjusting the parameters to optimize for non-developed and developed areas.

The ground points were then interpolated into 1 m (3.3 ft) resolution bare-earth digital elevation models (DEMs) using a TIN interpolation algorithm. The result is a series of LIDAR-derived bare-earth DEMs representing the beach surface and surrounding terrain at the time of each survey. Figure 6.1 shows an example of filtering results along a section of beach in the 2005 LIDAR-derived DEM. The filter performs well at removing buildings (e.g. homes) and objects on the beach (e.g. people and cars). Trees and tall vegetation are also typically removed by the filter. However, the short scrub vegetation that is common to the barrier island regions of Texas is very difficult to filter. This is not necessarily a limitation of the filter, but rather, the dense vegetation occludes the ground surface resulting in few points that actually reflect from the true ground surface. Additionally, the height of the vegetation above the ground is typically less than the LIDAR system pulse length causing a convolution of the return signal from the ground and vegetation. This makes it difficult for the receiver hardware to separate returns from the underlying surface.

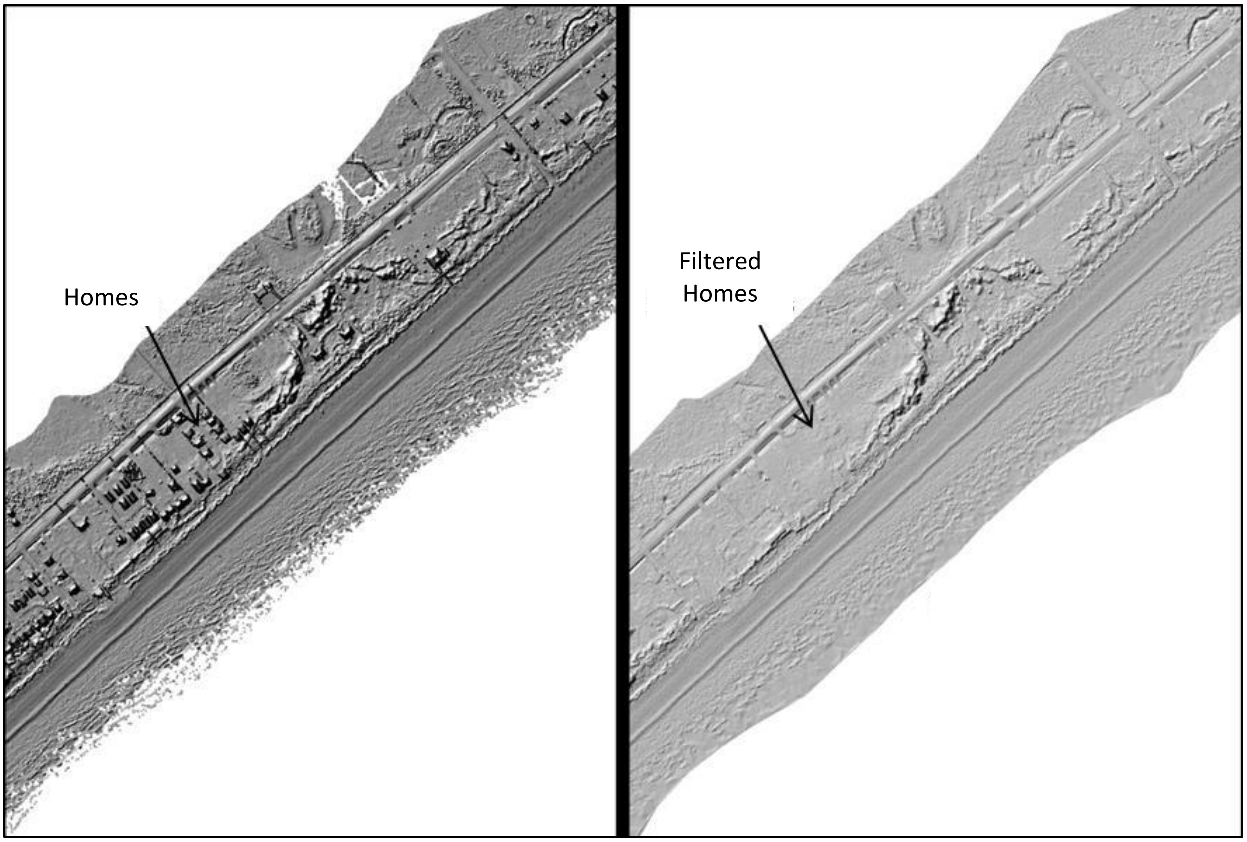

Figure 6.1 Shaded-relief of (left) unfiltered and (right) filtered DEMs generated from the 2005 LIDAR data (HRI, 2012b).

The DEMs were mosaicked in ArcGIS to form a contiguous DEM of the coastline for each survey. Because the project interest is in measuring the change in elevation between surveys, the DEMs were adjusted to correct for residual vertical bias between surveys. The 2010 DEM was selected as the baseline data set. The bias between a specific survey and the 2010 survey was measured based on the difference in elevation transects extracted from static road surfaces in the DEMs. The average difference in elevation was then used to vertically shift a specific survey's DEM relative to the 2010 DEM. The measured average bias ranged from a maximum absolute value of 8 cm (3.2 in) in the 2008 survey to a minimum of 1 cm (0.4 ft) in the 2012 survey.

Regions of the DEM where buildings had been removed were excluded in the analysis to avoid cases where filtering of the structures could potentially bias the volume change analysis. This is due to the interpolation of the surface causing an artificial rise or lowering of the elevation under the filtered structure. To mask out those grid cells, the set of "non-ground" points were classified into "building" or "non-building" points using a two stage process. First, the set of points that exceeded a 2 m (6.5 ft) height above the interpolated ground surface were segmented. Second, those points were then classified as building points based on an algorithm to determine whether or not each point meets certain planar criteria (Isenburg, 2011). A masking grid (‘No Value’ = building grid cell, ‘1’ = ground grid cell) was then generated for each survey from the set of building and ground points. The DEMs were then multiplied by their corresponding masking grid to remove building grid cells.

6.2 Volume Change Analysis

The DEMs described above were compared to measure the change in elevation between LIDAR surveys. The analysis was separated into two distinct zones: sub-aerial beach and foredune.

6.2.1 Sub-aerial Beach

The sub-aerial beach was defined based on the pre-Rita beach topography as represented by the December 2005 LIDAR-derived DEM. The region was delineated using a representative shoreline and dune toe contour line extracted from the 2005 DEM. The shoreline was represented by a 0.7 m (2.3 ft) elevation contour, as was developed for the shoreline change analyses in Section 5. The dune toe line was represented by the approximately 1.3 m (4.2 ft) elevation contour, which was determined to correspond well with the typical shoreward limit of the vegetation line along the upper Texas coast based on Gibeaut and Caudle (2009). A shaded relief image of the 2005 DEM was generated to ensure this elevation contour aligned well with the foredune edge. In certain regions, the contour was digitized to align more closely with the foredune edge (dune toe) to form a contiguous dune toe line. The shoreline and dune toe lines were kept static across the surveys for the analysis.

To compute volume change, a series of shore-normal transects spaced 50 m (165 ft) alongshore were extracted from a shore-parallel baseline. The baseline was generated by smoothing the 0.7 m shoreline contour using a 500 m (1,650 ft) length moving average window. The extracted transects were then segmented based on the pre-Rita shoreline and dune toe line as described above to form a series of bins (areas) covering 50 m alongshore distance (Figure 6.2). Net volume change was then computed for each alongshore bin by summing up the measured difference in elevation for each 1 m grid cell that falls within the bin.

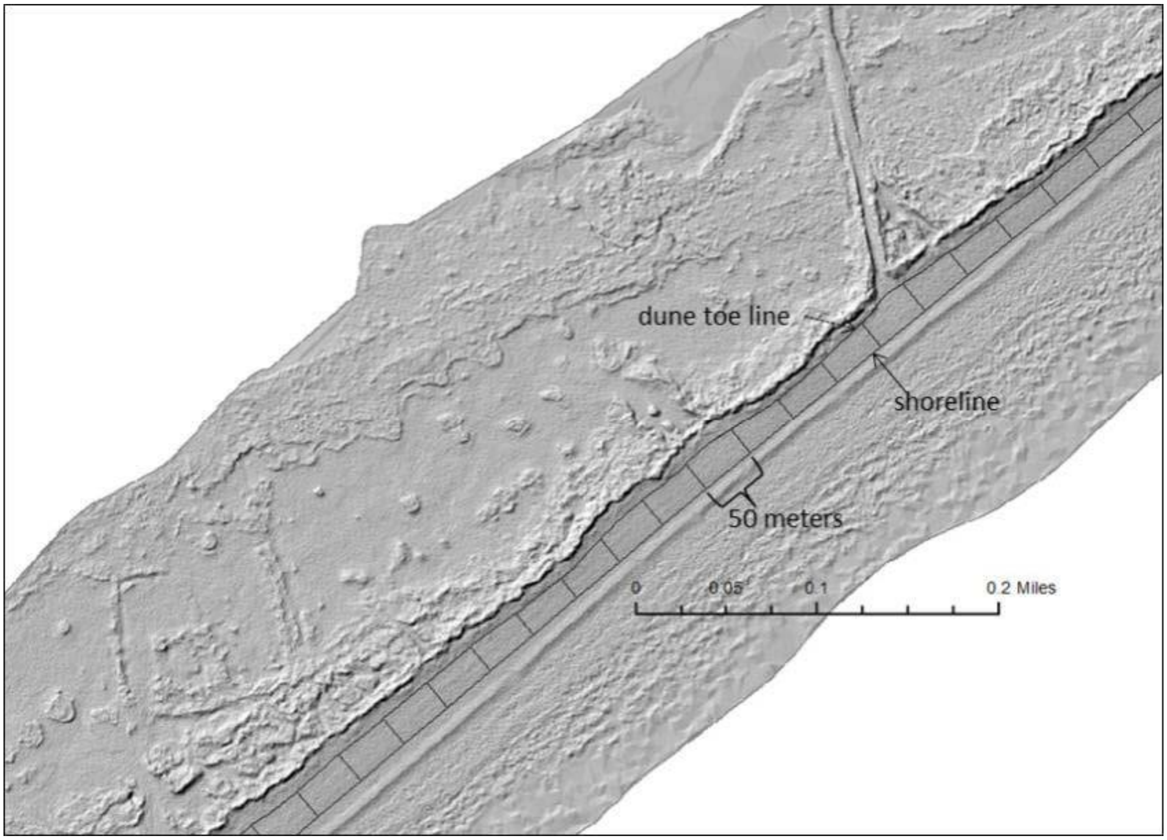

Figure 6.2 View of coast showing the sub-aerial beach 50 meter alongshore analysis bins overlaid on the pre-Rita DEM (HRI, 2012b).

6.2.2 Foredune Zone

The foredune zone of analysis was defined as the region extending from the pre-Rita dune toe line to 25 m (82 ft) landward. To compute volume change in this region, a grid structure was generated that consisted of shore-normal transects spaced 50 m alongshore with shore-parallel transects extracted every 5 m (16 ft) in the cross-shore direction. This formed a series of 50 m x 5 m bins extending from the shoreline landward (Figure 6.3). Net volume change was then computed at 50 m alongshore segments by summing up the difference in elevation for each 1 m grid cell that falls within the bins extending from the dune toe line to 25 m landward.

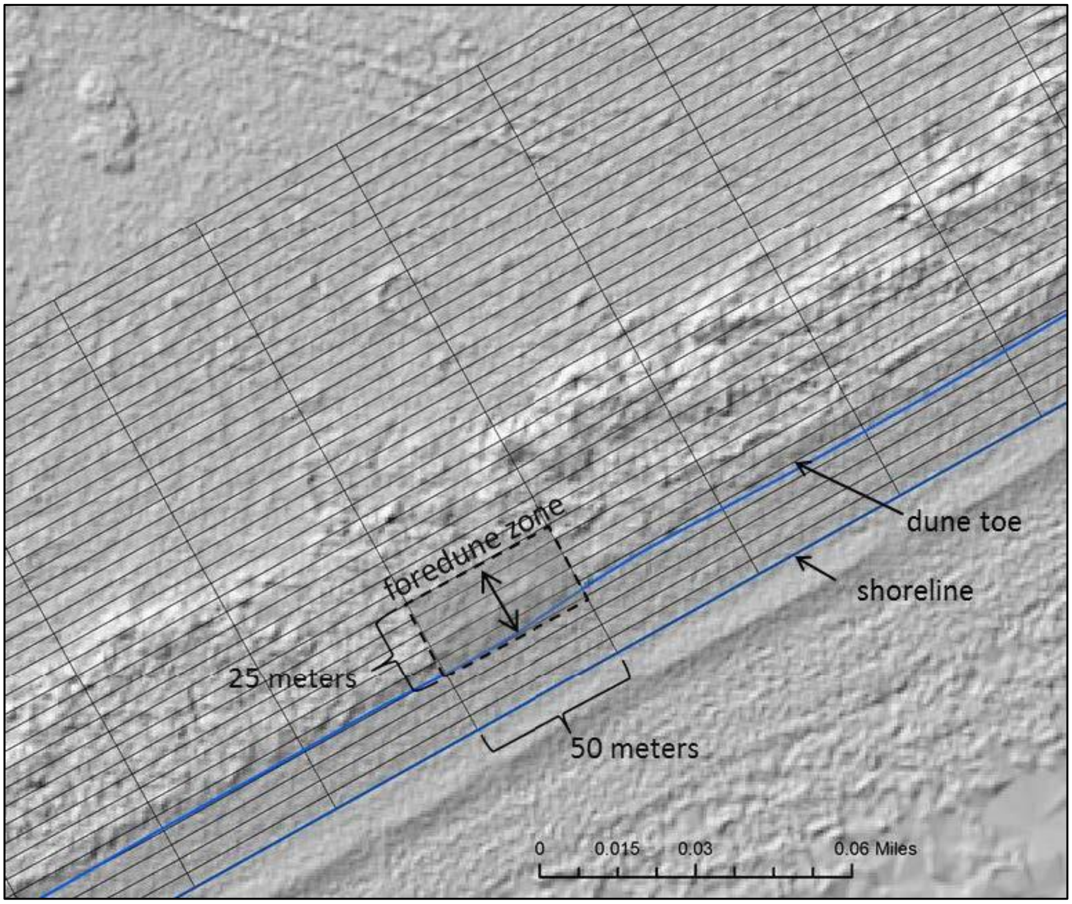

Figure 6.3 Zoomed in view of a region of the coast showing the 50 meter x 5 meter grid structure overlaid on the pre-Rita DEM. The foredune analysis zone is shown, which extends from the dune toe line to 25 meters landward (HRI, 2012b).

6.3 Results and Discussions

To visualize spatial and temporal patterns in volumetric sediment loss and post-storm recovery, Figures 6.4 and 6.5 present net volume change results for the beach and foredune analysis zones as color-coded maps and alongshore plots. Results are based on 50 meter alongshore bins and are presented by survey epoch. Figures 6.6 and 6.7 present the results cumulatively, based on the 2005 survey. Units of net change are in cubic yards and normalized net change (change per unit area of beach) in cy/sy. The normalized values compensate for differences in the area of each analysis bin, such as due to variation in beach width and regions where buildings may have been filtered and excluded. This enables relative comparisons of the magnitude of volumetric change between different regions.

Statistics for net volume change are presented in Tables 6.1 and 6.2 for the sub-aerial beach and foredune zone respectively. Statistics are based on 50 meter alongshore analysis bins. The results in the tables are normalized by the bin width (50 m) to derive volume change statistics per alongshore length of beach. The tables present results for three different survey epochs: Pre-Rita

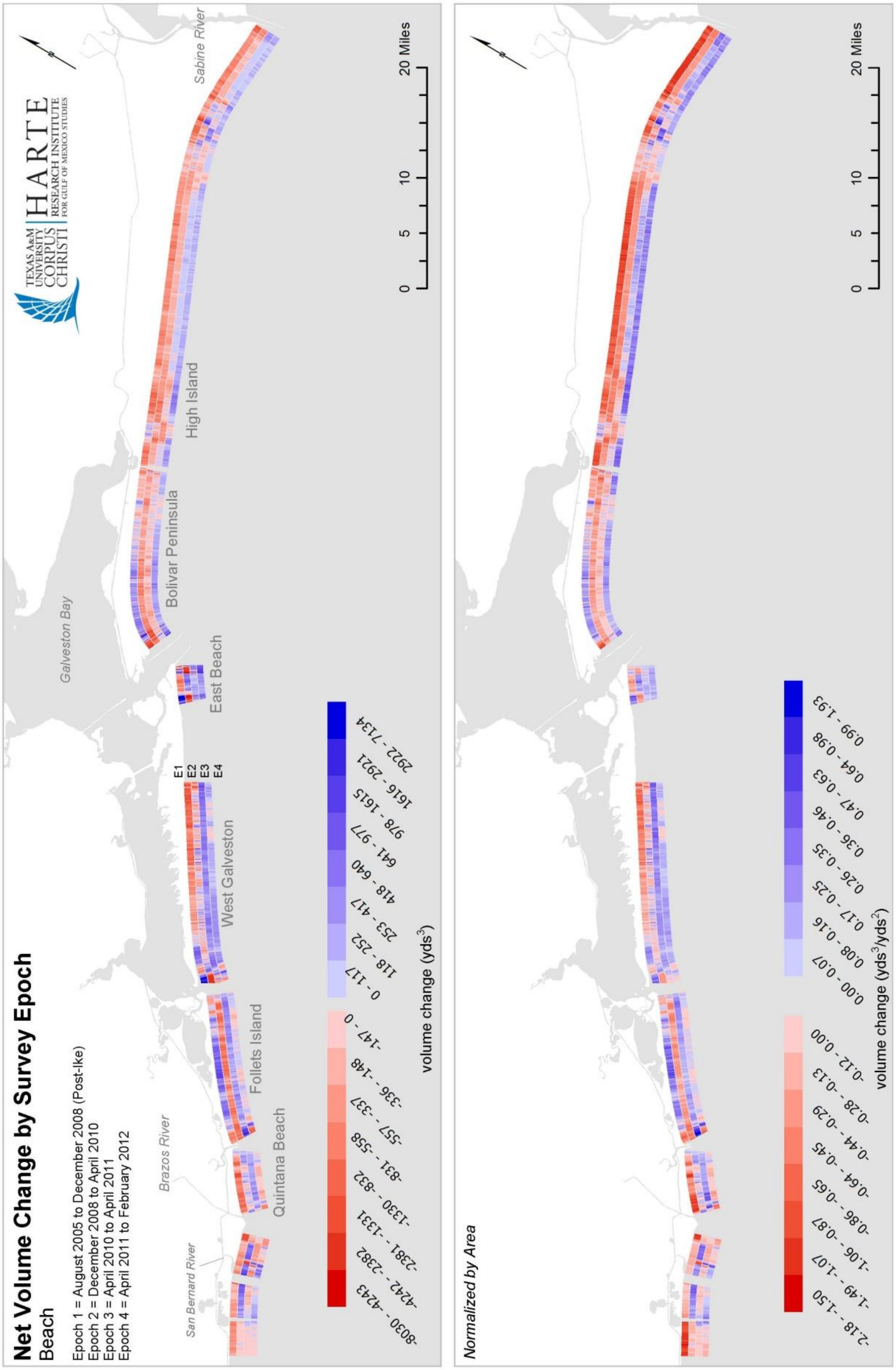

Figure 6.4 Net volume change for sub-aerial beach (HRI, 2012b).

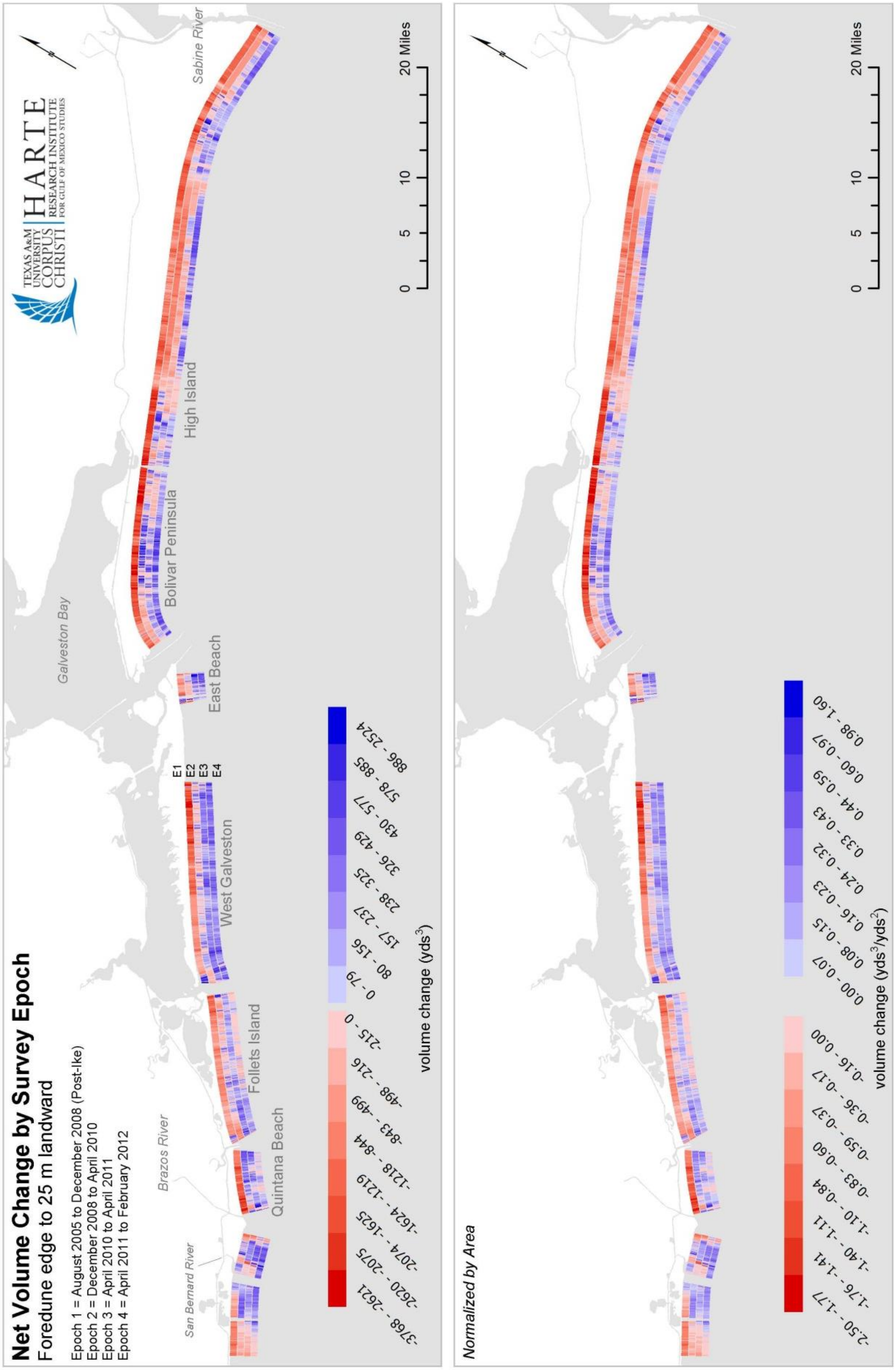

Figure 6.5 Net volume change for foredune zone (dune toe to 25 m landward) (HRI, 2012b).

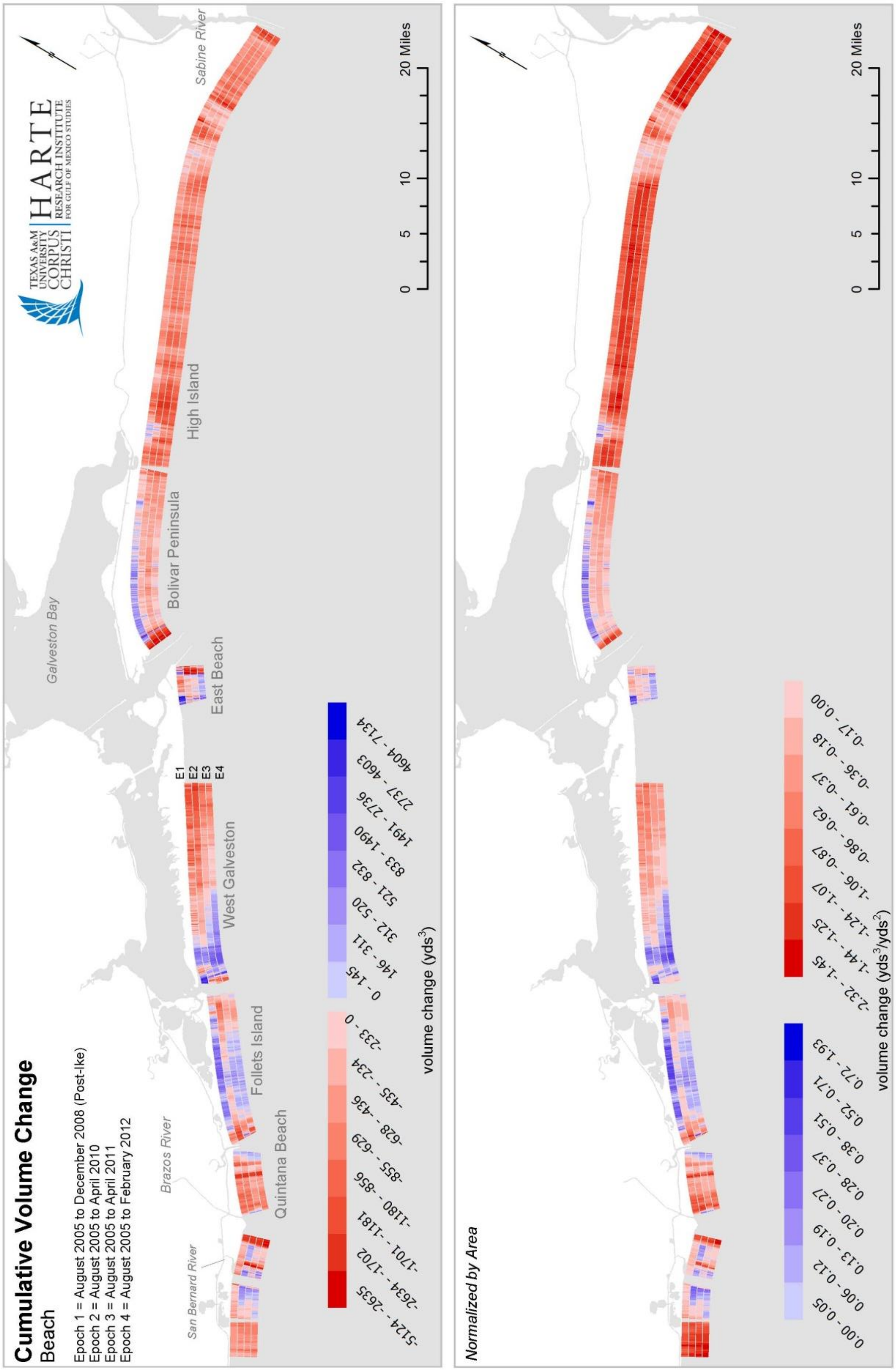

Figure 6.6 Cumulative volume change for sub-aerial beach (HRI, 2012b).

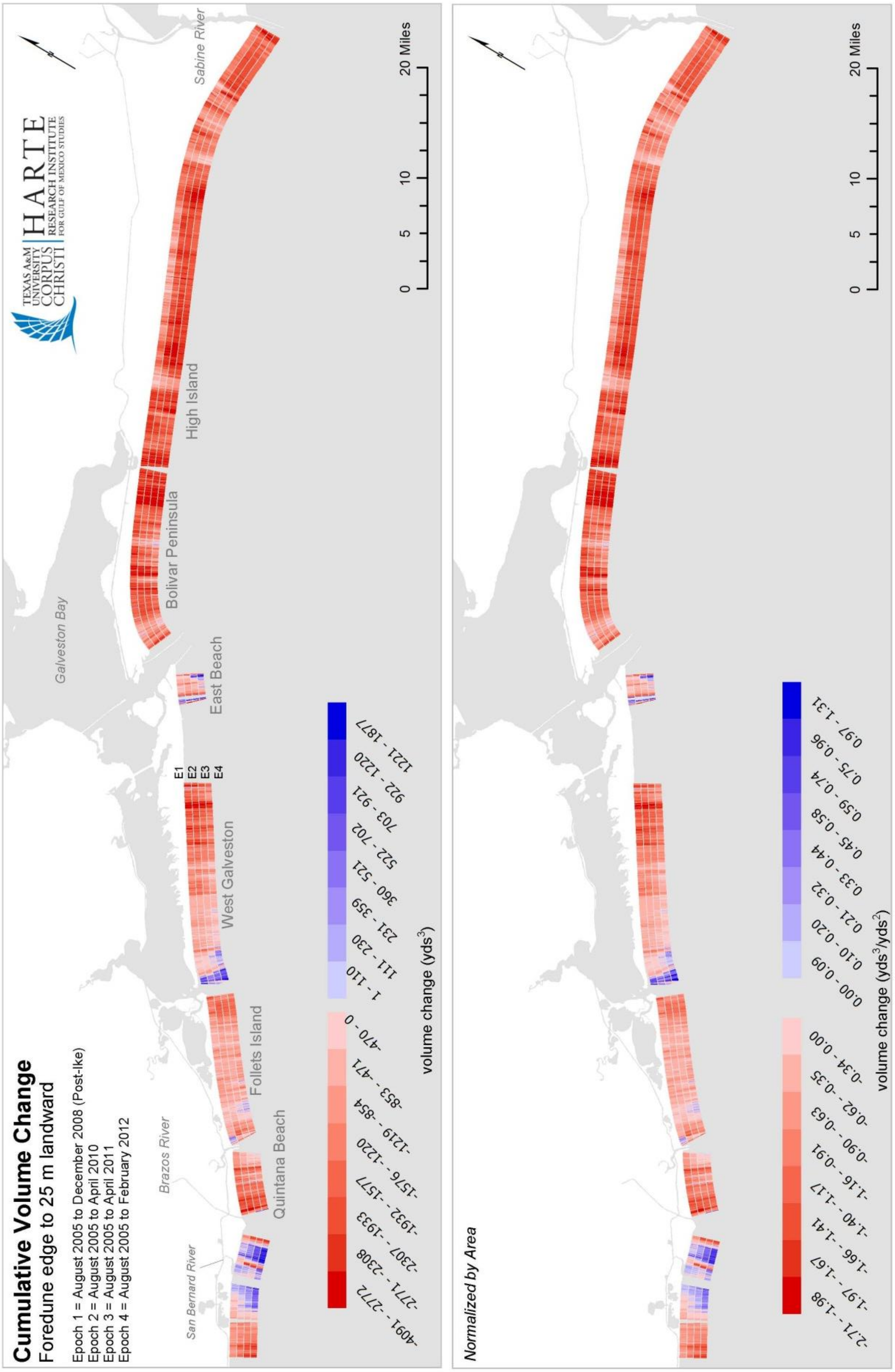

Figure 6.7 Net volume change for foredune zone (dune toe to 25 m landward) (HRI, 2012b).

2005 to Post-Ike 2008 (Impact), Post-Ike 2008 to 2012 (Recovery), and Pre-Rita 2005 to 2012 (Cumulative). Volume change maximum and minimum values are reported in terms of volume loss, such that maximum values in Tables 6.1 and 6.2 are maximum volume loss (erosion), and minimum values are volume increases (accretion).

Table 6.1 Volume Change Results of Sub-aerial Beach per Region (LIDAR Comparisons)

Region		Net Volume Change per Alongshore Length (cy/ft)		
		Impact of Ike (2005-2008)	Recovery (2008-2012)	Cumulative (2005-2012)
Sabine to High Island	**avg**	**-3.2**	**-0.6**	**-3.9**
	min	-20.3	-8.5	-14.3
	max	1.8	19.4	0.7
Bolivar Peninsula	**avg**	**0.3**	**-2.8**	**-2.5**
	min	-26.9	-20.1	-24.0
	max	16.6	2.9	9.0
East Galveston Island	**avg**	**2.2**	**-1.9**	**0.3**
	min	-15.2	-41.5	-14.2
	max	43.4	16.6	14.8
West Galveston Island	**avg**	**-2.7**	**2.6**	**-0.1**
	min	-14.1	-26.5	-9.6
	max	24.3	13.0	16.2
Follets Island	**avg**	**1.6**	**-2.1**	**-0.5**
	min	-7.9	-12.8	-15.1
	max	7.5	6.4	3.8
Quintana	**avg**	**-4.1**	**1.0**	**-3.1**
	min	-4.2	-3.3	-13.4
	max	1.3	10.2	1.9

Table 6.2 Volume Change Results of Foredune Zone – Dune to 25 m landward - per Region (LIDAR Comparisons)

Region		**Net Volume Change per Alongshore Length (cy/ft)**		
		Impact of Ike (2005-2008)	**Recovery (2008-2012)**	**Cumulative (2005-2012)**
Sabine to High Island	**avg**	**-8.5**	**-2.9**	**-11.4**
	min	-22.9	-10.2	-22.4
	max	0.2	13.8	-0.5
Bolivar Peninsula	**avg**	**-11.3**	**1.7**	**-9.6**
	min	-21.6	-11.8	-22.2
	max	3.1	14.4	3.6
East Galveston Island	**avg**	**-3.2**	**1.5**	**-1.7**
	min	-13.5	11.6	-18.4
	max	6.0	15.3	11.4
West Galveston Island	**avg**	**-7.3**	**2.7**	**-4.5**
	min	-21.5	-4.9	-19
	max	6.3	8.0	9.2
Follets Island	**avg**	**-4.7**	**-0.2**	**-4.9**
	min	-15.5	-10.7	-16.5
	max	3.0	6.9	4.0
Quintana	**avg**	**-9.5**	**2.2**	**-7.3**
	min	-19.9	-2.8	-17.8
	max	-2.1	11.5	7.8

6.3.1 Volumetric Changes from Ike: 2005 Pre-Rita to 2008

Quintana Beach, West Galveston, and High Island to Sabine Pass observed an average net loss in sub-aerial beach volume following the impact of Hurricane Ike (Table 6.1). The Quintana Beach segment experienced the largest average net loss in volume per unit length of beach (-3.1 cy/ft) compared to the other regions. Follets Island and Bolivar Peninsula, both observed an average net gain in sub-aerial beach volume following Ike with Follets Island experiencing an average gain of 1.6 cy/ft whereas Bolivar experienced a minor gain of 0.3 cy/ft. However, the foredune experienced significant losses in these areas as shown in Table 6.2. These patterns can also be observed in the color-coded volume change maps in Figures 6.4 and 6.5. As discussed in the shoreline changes analyses, redistribution of sediment during and following Ike, such as from return flow and alongshore transport, are potential factors. The 2008 LIDAR survey occurred approximately three months after the impact of Ike and berm formation was observed in the LIDAR-derived 2008 DEM within these regions.

In contrast to the sub-aerial beach, all regions experienced substantial volume loss within the foredune analysis zone (Table 6.2). Most notably is Bolivar Peninsula, which experienced the largest average net loss in foredune volume relative to the other study regions. It is important to mention that differences in unfiltered vegetation coverage between surveys can potentially impact the foredune volume change results in areas of dense vegetation cover. Quantifying the magnitude of such an effect would require high accuracy ground truth data, which is not available. However, the overall impact is expected to be minimal and should not alter the observed trends and patterns.

6.3.2 Recovery Period Volume Changes from Post-Ike to 2012

All regions experienced an average net loss in sub-aerial beach volume during the Ike recovery period except for two regions, Quintana Beach and West Galveston. This indicates that although shoreline positions showed recovery, there was still a net loss of volume to the beach system. The Quintana and West Galveston Island gains in sub-aerial beach were mainly near the large depositional area at San Luis Pass and near the jetty at Quintana.

All regions experienced an average net recovery in foredune sediment volume following the Ike impact except for two regions, Follets Island and High Island to Sabine Pass. Follets Island had a minor average net loss in volume per length of beach of approximately -0.2 cy/ft indicating a relatively stable period of foredune development (i.e. minimal recovery on average). However, this seems to contrast with observations along Follets Island during the site visits of 2010 and 2011. Local projects were implemented during this time to help rebuild the dunes that were mostly scoured out during Ike. These projects included placement of Christmas trees and sand fencing to help capture and promote dune development (Figure 6.8). The reason for the low foredune recovery measurement from this analysis may be due in part to the foredune calculation only extending 25 m (82 ft) from the 1.27 m (4.1 ft) elevation contour. Most of the dune formation projects were closer to Bluewater Highway and beyond the calculation area. It should noted that recent visits to this area in 2013 show that the dune and upland features are quickly developing with the help of these local projects.

Figure 6.8 Sand fencing along central portion of Follets Island to assist dune recovery.

Losses to the foredune between High Island and Sabine Pass are to be expected considering the makeup of the shoreline, as described in the previous section. This area contained minimal dune features and a thin veneer of sand over clay substrate along much of the shoreline prior to the storm. Once these areas were eroded and the clay exposed, significant rebuilding of dunes and event the sub-aerial beach is not expected to occur due to a lack of sediment.

6.3.3 Cumulative Volume Changes from 2005 to 2012

All regions, except for East Beach, experienced an average net loss in sub-aerial beach volume across the entire time period covered by the LIDAR surveys from August 2005 to February 2012. High Island to Sabine Pass and the Quintana Beach regions had the highest average net loss in beach volume per alongshore length. Overall, all regions had a total loss of sediment within the sub-aerial analysis zone except for East Beach. Anthropogenic modifications including the creation of a temporary dredged material placement area are a potential factor that resulted in the East Beach region exhibiting a net gain in sub-aerial beach volume.

Within the foredune analysis zone, all study regions experienced an average net loss. Bolivar Peninsula and the High Island to Sabine Pass regions experienced the highest average net loss in foredune volume. These regions were in the path of Ike’s right-front quadrant, which is notoriously the most destructive part of a hurricane. These results also show that dune formation lags significantly behind the sub-aerial beach in terms of recovery time. Dunes are typically created by plants trapping windblown sand, which is a process that can take many years compared to the fairly quick redistribution of sand within the active beach profile.

7.0 SUMMARY AND CONCLUSIONS

Hurricane Ike made landfall at Galveston Island on September 13, 2008 as a Category 2 hurricane. Its low rating on the Saffir-Simpson scale does not reflect its massive size, with tropical storm force or greater winds cutting a swath 400 miles wide. Ike’s storm surge reached 15 to 20 ft on Bolivar Peninsula and in parts of Chambers County with large waves present throughout the Gulf of Mexico. Large storm waves coupled with storm surge caused extreme erosion on the Texas coast. Peak shoreline erosion was over 400 ft with average values near 200 ft over much of the upper Texas coast.

Hurricane Carla in September 1961 and Hurricane Alicia in August 1983 both caused extreme shoreline erosion along the Texas coast. Following the post-storm recovery period after Carla, there is an indication that average annual erosion rates accelerated, possibly because of the removal of sand from the littoral system. Following Alicia, beaches and dunes required four to five years to recover (HRI 2009). Initial results indicated that Hurricane Ike has caused even greater impact to the Texas coast than Carla or Alicia and likely resulted in major impacts to the littoral system by removing a significant amount of sediment from some areas of the Texas coast. In addition to the extreme shoreline change, Ike caused over $29 billion in property damages and a total statewide economic loss of $142 billion.

Preliminary impact assessments from Hurricane Ike have been updated and recovery of the beach/dune system reviewed through the analysis of LIDAR data along the Upper Texas coast. Site visits and limited beach profile data were also utilized to compare the measured results and to provide a clearer picture of recovery efforts. Based on the analyses, much of the upper Texas coast had not fully recovered by 2012, four years after the passage of Ike. In addition, full recovery is not expected for some of these areas due to a lack of sediment input and significant transport of sand away from critically eroding areas, such as was seen along West Galveston Island.

Anthropogenic activities such as dune creation and preservation are helping areas such as Follets Island recover from severe erosion to the upland and dune system. Continued management and protection of the beach and dune system will help to protect upland property and infrastructure.

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GLOSSARY

Advance - a net seaward movement of the shoreline over a specified time

Alongshore - parallel to and near the shoreline

Barrier Island - a long, relatively narrow island running parallel to the mainland bordering on the Gulf of Mexico and entirely surrounded by water, built up by the action of waves and currents and serving to protect the coast from erosion by waves and tidal surges

Bathymetry - measurement of depths of water in oceans, seas, and lakes; also information derived from such measurements

Beach Profile - the intersection of the ground surface with a vertical plane; may extend from the top of the dune line to the seaward limit of sand movement

Beach System - a term used to describe the entire, inter-connected, dynamic system which composes a particular beach; the term incorporates all those parts of a beach between which sediment is regularly exchanged; as such, it includes the offshore sub-tidal regions of beaches and the frontal dune behind the beach.

Contour - a line on a map or chart representing points of equal elevation with relation to a datum

Cross-shore Transport - transport of sediment by waves and currents perpendicular to the shoreline

Deposition - the placement of beach material by wave action, tidal currents, littoral currents, or wind

Depth of Closure - the offshore depth beyond which beach profiles taken over time at a given site coincide; seaward of this depth net sediment transport tends not to result in significant changes in depth

Dune - ridges or mounds of loose, wind-blown material, usually sand

Erosion –the carrying away of beach material by wave action, tidal currents, littoral currents, or wind

Hurricane - an intense tropical cyclone in which winds tend to spiral inward toward a core of low pressure, with maximum surface wind velocities that equal or exceed 75 mph for several minutes or longer at some points

Landward - the direction towards the shore and away from the body of water bounded by the shore

LIDAR – **LI**ght **D**etection **A**nd **R**anging; an optical remote sensing technology used to perform topographic surveys over large areas

Longshore Transport - transport of sediment by waves and currents parallel to the shoreline

Nourishment - the process of replenishing a beach. It may be brought about naturally by longshore transport, or artificially by the deposition of dredged/excavated materials

Retreat - a net landward movement of the shoreline over a specified time

Seaward - the direction away from the shore and toward the body of water bounded by the shore

Shoreline - the intersection of a specified plane of water with the shore or beach

Shoreline Erosion - shoreline erosion, for the purposes of this report, refers to the landward movement of the shoreline, synonymous with shoreline retreat

Storm Surge - a rise above normal water level on the open coast due to the action of wind stress on the water surface; storm surge resulting from a hurricane also includes that rise in level due to atmospheric pressure reduction as well as that due to wind stress

Tropical Storm - a tropical cyclone with maximum winds less than 75 mph but greater than 39 mph

Vegetation Line - the extreme seaward boundary of natural vegetation which spreads continuously inland

APPENDIX A

POST-IKE SHORELINE CHANGE REPORT (HRI, 2012)

POST-IKE VOLUME CHANGE REPORT

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ABSTRACT

This document presents volume change results for the upper Texas coast stemming from the impact of Hurricane Ike in 2008. Results are based on five light detection and ranging (lidar) surveys acquired by the University of Texas at Austin's Bureau of Economic Geology (BEG): 2005 (pre-Hurricane Rita), 2008 (post-Hurricane Ike), 2010, 2011, and 2012. Differencing of lidar-derived digital elevation models (DEMs) is used to measure the change in surface elevation and subsequently compute change in sediment volume between surveys. Volume change is computed for the sub-aerial beach and foredune region at 50 meter alongshore bin spacing. The sub-aerial beach is defined as the region extending from the pre-Rita (2005) shoreline represented by a 0.7 m NAVD88 contour and the pre-Rita dune toe line represented by a 1.3 m NAVD88 contour. The foredune region is defined as the area extending from the pre-Rita dune toe line to 25 m landward. Results are arranged by nine geographic regions of the upper Texas Coast extending from Sargent Beach at the southern edge to Sabine Pass at the northern edge. Net volume change and normalized net volume change by survey epoch and cumulative epoch are presented for the sub-aerial beach and foredune region as color-coded maps and alongshore plots. Volume change statistics by region are summarized within tables in this document.

DELIVERABLES

- Net volume change and normalized net volume change by survey epoch displayed as color-coded maps (pdf) included at end of document (2 total); beach and foredune region
- Net volume change and normalized net volume change by survey epoch displayed as alongshore plots (pdf) included at end of document(2 total); beach and foredune region
- Net volume change and normalized net volume change by cumulative survey epoch displayed as color-coded maps (pdf) included at end of document (2 total); beach and foredune region
- Net volume change and cumulative net volume change by cumulative survey epoch displayed as alongshore plots (pdf) included at end of document (2 total); beach and foredune region
- Excel files of volume change statistics for beach and foredune region by survey epoch (2 total)
- Excel files of volume change statistics for beach and foredune region by cumulative epoch (2 total)

PURPOSE

This analysis was conducted to quantify the magnitude of sediment volume change after the impact of Hurricane Ike in 2008 and to assess post-Ike beach and foredune recovery. This analysis will provide increased information necessary to understand the post-hurricane Ike beach and foredune recovery along the upper Texas coast.

LIDAR SURVEYS

Volume change was computed using five lidar surveys of the upper Texas coast conducted by the University of Texas at Austin's Bureau of Economic Geology (BEG):

December 11, 2012

- 8/18/2005 (pre-Rita)
- 12/13/2008 (post-Ike)
- 04/09/2010
- 04/13/2011
- 02/19/2012

The data were acquired by the BEG's Optech ALTM 1225 topographic lidar system operating at a 25 kHz pulse rate and 1064 nm wavelength. The system is a discrete-return system that can record up to two returns per an emitted pulse, first and last. The BEG lidar data are provided in NAD83 UTM Zone 15 horizontal coordinates with the vertical coordinate (elevation) relative to NAVD88 converted using the GEOID99 model. Each survey covers a nominal strip approximately 300m wide of the Texas Gulf of Mexico shoreline, from Sabine Pass to the mouth of the Colorado River.

Vertical bias in the lidar observations stemming mostly from GPS induced trajectory errors are sometimes present (Starek et. al, 2012). The offsets between flights were removed by vertically shifting the lidar points to match higher accuracy kinematic GPS calibration lines acquired along static road surfaces within the survey area. For the lidar system, calibration method, and flight parameters utilized, the BEG reports average vertical RMS in the range of 5-10 cm relative to ground-survey measurements after bias adjustment. This accuracy will vary spatially and across the surveys due to differences in surface geometry, surface cover, sensor performance, and flight parameters among other factors.

METHODS

DATA PROCESSING

The raw lidar data consists of point clouds of irregularly spaced x,y,z values providing a three-dimensional representation of the ground and land cover. The raw points for each survey were tiled to form a contiguous sequence of 6 km tiles with 30 m buffer overlap along the coastline.

For multi-return data, the last (or single) return data are utilized to minimize the probability of land cover biasing the surface elevations. The last-return data for each survey were filtered using a progressive triangulated irregular network (TIN) densification algorithm (Axelsson, 2000) implemented with the LAStools software (Isenburg, 2011). The goal of filtering is to remove points that reflect from non-ground objects, such as from buildings, without altering the natural terrain surface. The TIN densification algorithm works iteratively by generating a TIN model from a sparse set of minimum elevation points as a first representation of the bare-earth surface. During each iteration, a point is added to the TIN if the point meets certain criteria in relation to the triangle that contains it. The criteria are that a point must be within a minimum distance to the nearest triangle node and the angle between the triangle normal and the line joining the point and node must be above a given threshold. New thresholds are computed and the process repeats until no more points are added. For this work, a multi-stage filtering process was applied whereby the data were filtered in stages by adjusting the parameters to optimize for non-developed and developed areas.

The ground points were then interpolated into 1 meter resolution bare-earth digital elevation models (DEMs) using a TIN interpolation algorithm. The result is a series of lidar-derived bare-earth DEMs representing the beach surface and surrounding terrain at the time of each survey. Figure 1 shows an example of filtering results along a section of beach in the 2005 lidar-derived DEM. The filter performs well at removing buildings (e.g. homes) and objects on the beach (e.g. people and cars). Trees and tall vegetation are also typically removed by the filter. However, the short scrub vegetation that is common to the barrier island regions of Texas is very difficult to filter. This is not necessarily a limitation of the filter, but rather, the dense vegetation occludes the ground surface resulting in few points that actually reflect from the true ground surface. Additionally, the height of the vegetation above the ground is typically less than the lidar system pulse length causing a convolution of the return signal from the ground and vegetation. This makes it difficult for the receiver hardware to separate returns from the underlying surface.

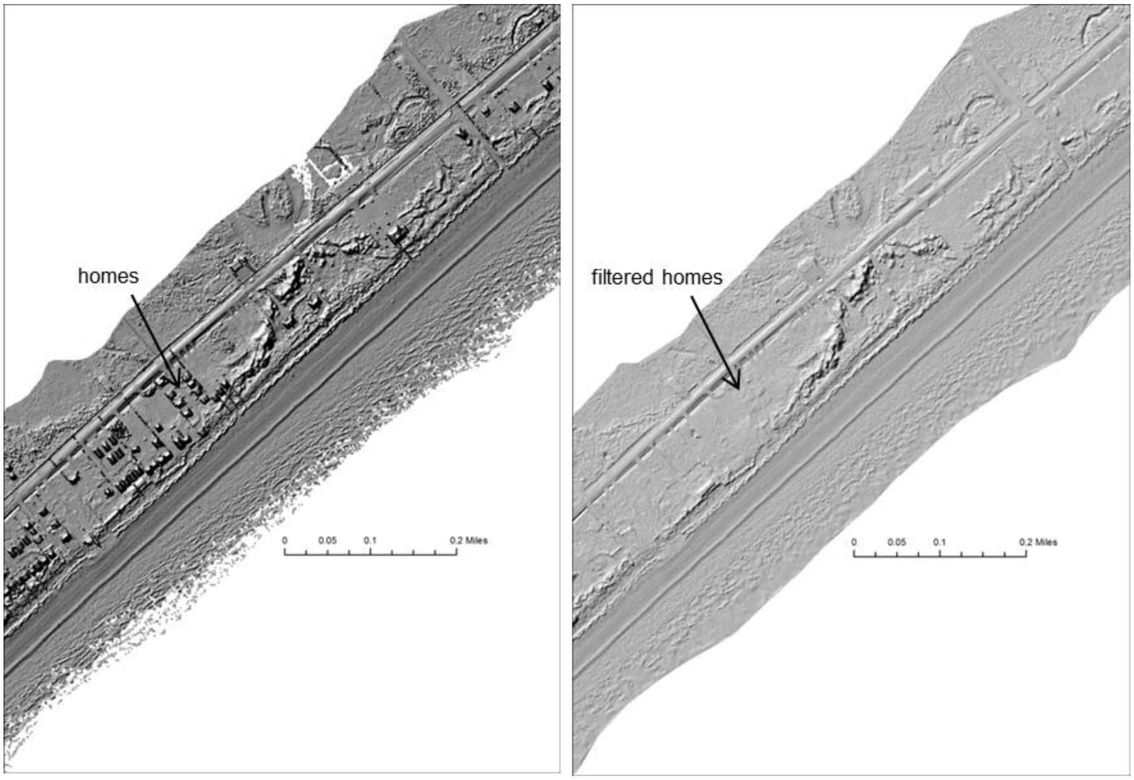

Figure 1. Shaded-relief of (left) unfiltered and (right) filtered DEMs generated from the 2005 lidar data. The filter performs well at removing homes behind the foredune as well as objects on the beach.

The DEMs were mosaicked in ArcGIS to form a contiguous DEM of the coastline for each survey. Because our interest is in measuring the change in elevation between surveys, the DEMs were adjusted to correct for residual vertical bias between surveys. The 2010 DEM was selected as the baseline data set. The bias between a specific survey and the 2010 survey was measured based on the difference in elevation transects extracted from static road surfaces in the DEMs. The average difference in elevation was then used to vertically shift a specific survey's DEM relative to the 2010 DEM. The measured average bias ranged from a maximum absolute value of 8 cm (2008) to a minimum of 1 cm (2012).

Regions of the DEM where buildings had been removed were excluded in the analysis to avoid cases where filtering of the structures could potentially bias the volume change analysis. This is due to the interpolation of the surface causing an artificial rise or lowering of the elevation under the filtered structure. To mask out those grid cells, the set of "non-ground" points were classified into "building" or "non-building" points using a two stage process. First, the set of points that exceeded a 2 m height above the interpolated ground surface were segmented. Second, those points were then classified as building points based on an algorithm to determine whether or not each point meets certain planar criteria (Isenburg, 2011). A masking grid ('No Value' = building grid cell, '1' = ground grid cell) was then generated for each survey from the set of building and ground points. The DEMs were then multiplied by their corresponding masking grid to remove building grid cells.

The data processing workflow is outlined in Figure 2 below.

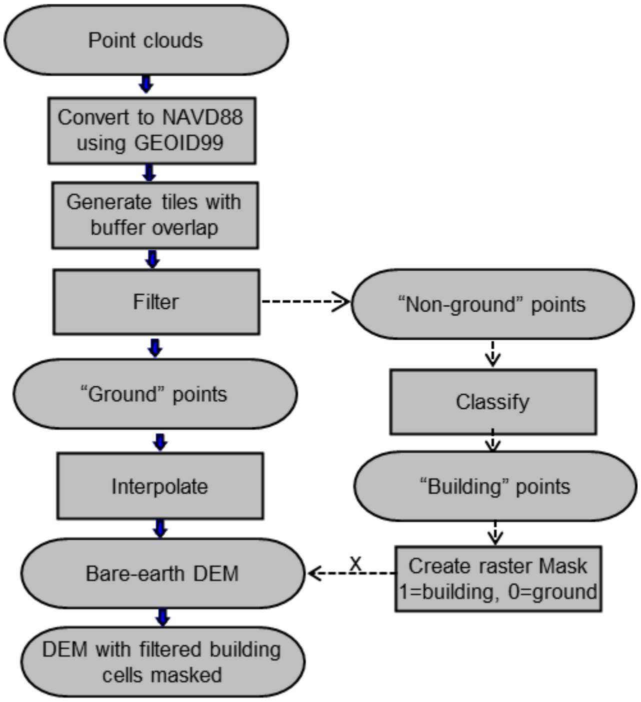

Figure 2. Lidar data processing flowchart

VOLUME CHANGE ANALYSIS

The DEMs were differenced to measure the change in elevation between sequential lidar surveys. The analysis was separated into two distinct zones: sub-aerial beach and foredune.

Sub-aerial Beach

The sub-aerial beach was defined based on the pre-Rita beach topography as represented by the December 2005 lidar-derived DEM. The region was delineated using a representative shoreline and dune toe contour line extracted from the 2005 DEM. Shoreline was represented by a 2.3 ft (0.7 m) NAVD88 elevation contour, which is defined as the limit between the wet and dry beach along the upper Texas coast based on Gibeaut et al. (2002, 2003). The dune toe line was represented by a ~4.2 ft (1.3 m) NAVD88 elevation contour, which was determined to correspond well with the shoreward limit of the vegetation line along the upper Texas coast based on Gibeaut and Caudle (2009). A shaded relief image of the 2005 DEM was generated to ensure this elevation contour aligned well with the foredune edge. In certain regions, the contour was digitized to align more closely with the foredune edge (dune toe) to form a contiguous dune toe line. The shoreline and dune toe lines were kept static across the surveys for the analysis.

To compute volume change, a series of shore-normal transects spaced 50 meters alongshore were extracted from a shore-parallel baseline. The baseline was generated by smoothing the 0.7 m NAVD88 shoreline contour using a 500 m length moving average window. The extracted transects were then segmented based on the pre-Rita shoreline and dune toe line as described above to form a series of bins (areas) covering 50 m alongshore distance (Figure 3). Net volume change was then computed for each 50 m alongshore bin by summing up the measured difference in elevation for each 1 m grid cell that falls within the bin.

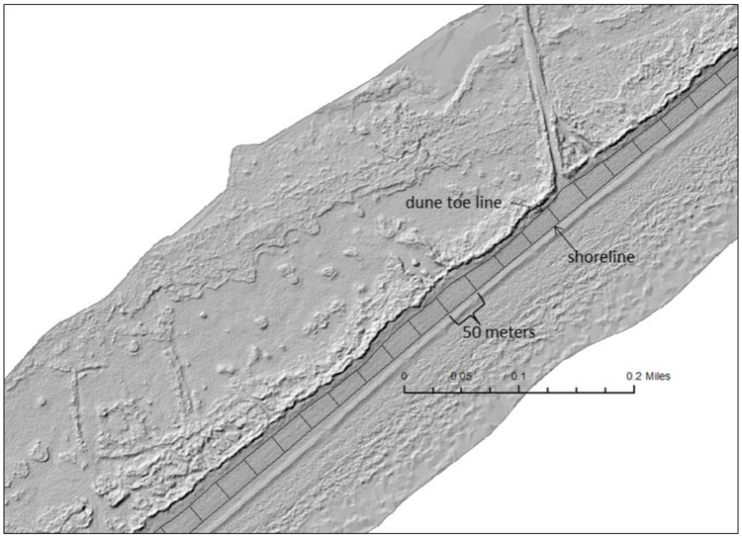

Figure 3. Zoomed in view of a region of the coast showing the sub-aerial beach 50 meter alongshore analysis bins overlaid on the pre-Rita DEM.

Foredune Zone

The foredune zone of analysis was defined as the region extending from the pre-Rita dune toe line to 25 m (82 ft) landward. To compute volume change in this region, a grid structure was generated that consisted of shore-normal transects spaced 50 meters alongshore with shore-parallel transects extracted every 5 meters in the cross-shore direction. This forms a series of 50 m x 5 m bins extending from the shoreline landward (Figure 4). Net volume change was then computed at 50 m alongshore segments by summing up the difference in elevation for each 1 m grid cell that falls within the bins extending from the dune toe line to 25 m landward (Figure 4).

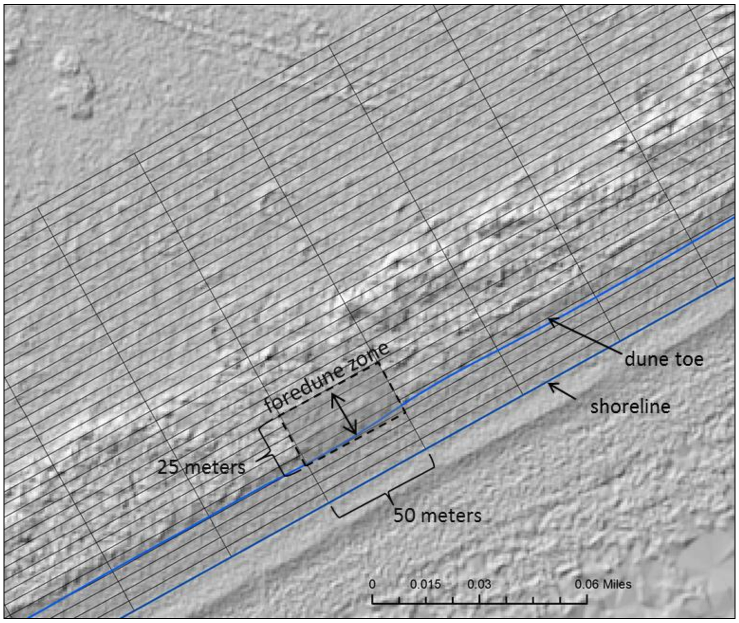

Figure 4. Zoomed in view of a region of the coast showing the 50 meter x 5 meter grid structure overlaid on the pre-Rita DEM. The foredune analysis zone is shown, which extends from the dune toe line to 25 meters landward.

RESULTS AND DISCUSSION

ANALYSIS REGIONS

Nine regions (Table 1 and Figure 5) of the upper Texas coast were analyzed extending from the north end of Sargent Beach (southern edge) to Sabine Pass (northern edge).

Table 1. Description of the nine regions examined in the volume change analysis

Region	Geographical Description of Areas
1	Sargent Beach to southern mouth of Cedar Lakes inlet area
2	Cedar Lakes inlet to mouth of San Bernard inlet
3	San Bernard inlet to mouth of Brazos
4	Quintana Beach
5	Follets Island
6	West Galveston
7	East Beach
8	Bolivar Peninsula to High Island
9	High Island to Sabine Pass

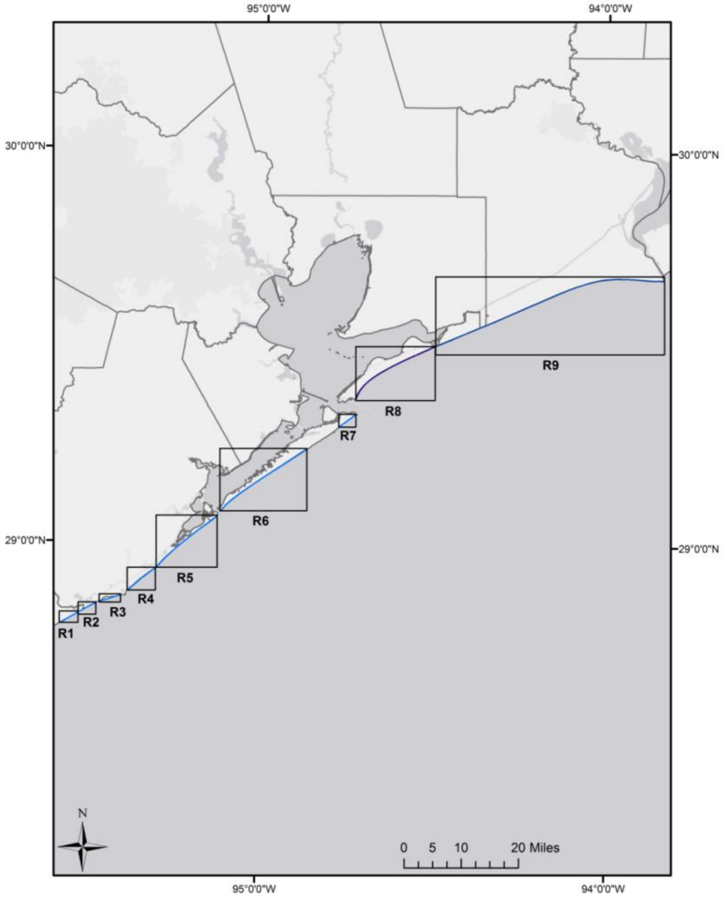

Figure 5. Map showing the nine regions along the coast examined in the analysis

VOLUMETRIC MAPS AND PLOTS

To visualize spatial and temporal patterns in volumetric sediment loss and post-storm recovery, Appendix A presents net volume change results for the beach and foredune analysis zones as color-coded maps and alongshore plots. Results are based on 50 meter alongshore bins and are presented by sequential survey epoch and by cumulative survey epoch. Units of net change are in yd^3 and normalized net change (change per unit area of beach) in yd^3/yd^2. The normalized values compensate for differences in the area of each analysis bin, such as due to variation in beach width and regions where buildings may have been filtered and excluded. This enables relative comparisons of the magnitude of volumetric change between different regions.

VOLUMETRIC STATISTICS

Statistics for net volume change are presented in Tables 2 and 3 for the sub-aerial beach and foredune zone respectively. Statistics are based on 50 meter alongshore analysis bins. The results in the tables are normalized by the bin width (50 m) to derive volume change statistics per alongshore length of beach. The tables present results for three different survey epochs: Pre-Rita 2005 to Post-Ike 2008 (Impact), Post-Ike 2008 to 2012 (Recovery), and Pre-Rita 2005 to 2012 (Cumulative). Only the results for Quintana Beach to Sabine Pass are presented in the tables below.

Table 2. Statistics for net volume change of the sub-aerial beach

		Net volume change per alongshore length (yd^3/yd)		
		Impact Pre-Rita 2005 to Post-Ike 2008	Recovery Post-Ike to 2012	Cumulative 2005 to 2012
Quintana Beach	min	-42.7	-9.8	-40.2
	max	3.9	30.7	5.7
	avg	-12.4 (8.7)*	3.0 (4.4)	-9.3 (8.8)
Follets Island	min	-23.8	-38.4	-45.4
	max	22.4	19.3	11.4
	avg	4.7 (8.3)	-6.2 (7.0)	-1.5 (7.4)
West Galveston	min	-42.4	-79.5	-28.7
	max	72.9	39.1	48.6
	avg	-8.1 (14.1)	7.8 (12.1)	-0.2 (10.4)
East Beach Galveston	min	-45.5	-124.6	-42.6
	max	130.2	49.8	44.3
	avg	6.6 (29.8)	-5.6 (30.5)	0.9 (13.4)
Bolivar Peninsula to High Island	min	-80.6	-60.2	-72.0
	max	49.9	8.6	27.1
	avg	0.8 (10.7)	-8.3 (6.9)	-7.4 (9.6)
High Island to Sabine Pass	min	-61.1	-25.5	-42.8
	max	5.5	58.1	2.0
	avg	-9.7 (5.5)	-1.9 (5.5)	-11.6 (5.4)

*standard deviation

Table 3. Statistics for net volume change of the foredune zone (dune toe to 25 m landward)

		Net volume change per alongshore length (yd^3/yd)		
		Impact Pre-Rita 2005 to Post-Ike 2008	Recovery Post-Ike to 2012	Cumulative 2005 to 2012
Quintana Beach	min	-59.7	-8.4	-53.9
	max	-6.2	34.4	23.4
	avg	-28.6 (10.0)	6.7 (5.6)	-21.9 (13.5)
Follets Island	min	-46.5	-32.2	-49.4
	max	9.0	20.7	11.9
	avg	-14.1 (7.7)	-0.5 (7.2)	-14.7 (10.0)
West Galveston	min	-64.5	-14.6	-57.0
	max	18.8	24.1	27.7
	avg	-21.4 (13.6)	8.0 (5.5)	-13.4 (13.0)
East Beach Galveston	min	-40.4	-34.9	-55.3
	max	17.9	46.0	34.2
	avg	-9.6 (11.1)	4.5 (13.7)	-5.0 (17.0)
Bolivar Peninsula to High Island	min	-64.8	-35.3	-66.5
	max	9.3	43.3	10.8
	avg	-34.0 (12.9)	5.2 (9.7)	-28.8 (15.1)
High Island to Sabine Pass	min	-68.8	-30.6	-67.3
	max	0.7	41.3	-1.6
	avg	-25.4 (10.7)	-8.7 (11.30)	-34.2 (10.5)

*standard deviation

Volume Change by Region

Tables 4 and 5 present the total net volume change within the sub-aerial beach and foredune analysis zones respectively. These results are computed by summing the net change measured for each 50 meter analysis bin within a study region. Only the results for Quintana Beach to Sabine Pass are presented in the tables below.

Table 4. Total net volume change in the sub-aerial beach

		Impact 2005 to 2008	Recovery 2008 to 2012	Cumulative 2005 to 2012	Area (yd^2)
Quintana Beach	Total (yd^3)	-130621	32482	-98140	
	Normalized (yd^3/yd^2)	-0.47	0.11	-0.35	273974
Follets Island	Total	114579	-151181	-36601	
	Normalized	0.13	-0.18	-0.04	831709
West Galveston	Total	-262890	253478	-9412	
	Normalized	-0.21	0.20	-0.007	1234753
East Beach Galveston	Total	40474	-34570	5903	
	Normalized	0.07	-0.06	0.01	575825

Bolivar Peninsula to High Island	Total	25117	-248274	-223157	
	Normalized	0.02	-0.27	-0.24	901984
High Island to Sabine Pass	Total	-719840	-143788	-863628	
	Normalized	-0.7	-0.13	-0.81	1072766

Table 5. Total net volume change in the foredune analysis zone

		Impact 2005 to 2008	Recovery 2008 to 2012	Cumulative 2005 to 2012	Area (yd^2)
Quintana Beach	Total (yd^3)	-300600	70393	-230207	
	Normalized (yd^3/yd^2)	-1.05	0.24	-0.80	285582
Follets Island	Total	-342108	-13854	-355962	
	Normalized	-0.52	-0.02	-0.54	654245
West Galveston	Total	-691894	258548	-433346	
	Normalized	-0.80	0.30	-0.50	855523
East Beach Galveston	Total	-44389	21067	-23321	
	Normalized	-0.37	0.17	-0.19	117613
Bolivar Peninsula to High Island	Total	-1015324	155085	-860238	
	Normalized	-1.26	0.19	-1.06	805062
High Island to Sabine Pass	Total	-1885153	-648832	-2533985	
	Normalized	-0.93	-0.32	-1.25	2016608

DISCUSSION

Impact: 2005 Pre-Rita to 2008 Post-Ike

Quintana Beach, West Galveston, and High Island to Sabine Pass observed an average net loss in sub-aerial beach volume following the impact of Hurricane Ike (Table 2). The Quintana Beach segment experienced the largest average net loss in volume per unit length of beach (-12.4 yd^3/yd) compared to the other regions. This does not necessarily imply that Quintana Beach underwent the most substantial beach erosion between the 2005 and 2008 lidar survey. Recall, that the results in Table 2 are normalized by the analysis bin length, not the total area of the bin, and as such, relative differences in beach width can still bias the results (e.g. larger width implies more erosion, all other factors being equal). When the net volume change is normalized by the area (volume change per unit area of beach), the region with the highest magnitude of volume loss is High Island to Sabine Pass (-0.7 yd^3/yd^2) followed by Quintana Beach (-0.5 yd^3/yd^2) (see Table 4).

Follets Island and Bolivar Peninsula, both observed an average net gain in sub-aerial beach volume following the impact of Ike (Table 2). Follets experienced an average gain of ~4.7 yd^3/yd whereas Bolivar experienced a minor gain of ~0.8 yd^3/yd. These patterns can also be observed in the color-coded volume change maps and plots of Appendix A. Redistribution of sediment during and following Ike, such as from return flow and alongshore transport, are potential factors. The 2008 lidar survey occurred approximately three months after the impact of Ike and berm formation was observed in the lidar-derived 2008 DEM within these regions. Anthropogenic effects are another factor affecting the results. This was apparent in East Beach, which also had an average net gain in beach volume. The high variation in volume change in East Beach (see standard deviation in Table 2) stems from the large differences in beach width alongshore as well as anthropogenic deposition. Sediment was deposited in the region to support a nourishment project and this was captured in the 2008 post-Ike survey subsequently biasing the results. Additional impacts from anthropogenic modifications must be accounted for when interpreting the post-Ike Impact.

In contrast to the sub-aerial beach, all regions experienced substantial volume loss within the foredune analysis zone (Table 3 and 5). Most notably is Bolivar Peninsula, which experienced the largest average net loss in foredune volume relative to the other study regions. This is in stark contrast to the volume change within the sub-aerial beach where it experienced a minor average net gain (Table 2). Similar patterns are observed for Follets Island whereby the foredune region experienced a substantial average net volume loss in contrast to the sub-aerial beach.

It is important to mention here that differences in unfiltered vegetation coverage between surveys can potentially impact the foredune volume change results in areas of dense vegetation cover. Quantifying the magnitude of such an effect would require high accuracy ground truth data, which is not available. However, the overall impact is expected to be minimal and should not alter the observed trends and patterns.

Recovery: Post-Ike to 2012

All regions experienced an average net loss (Table 2) in sub-aerial beach volume during the Ike recovery period except for two regions, Quintana Beach and West Galveston. Both of these regions experienced an average net loss in beach volume during the impact period indicating subsequent recovery of lost sediment. In contrast, both Follets Island and Bolivar Peninsula experienced an average net loss in sub-aerial beach volume during the recovery period indicating subsequent erosion of sediments that were gained during the impact period (Table 2).

All regions experienced an average net recovery in foredune sediment volume (Table 2) following the Ike impact except for two regions, Follets Island and High Island to Sabine Pass. Follets Island had an average net loss in volume per length of beach of approximately -0.5 yd^3/yd indicating a relatively stable period of foredune development (i.e. minimal recovery on average) although the standard deviation value (Table 2) indicates that there were relatively large fluctuations in volumetric recovery alongshore within the region. In comparison, the High Island to Sabine Pass region of the coastline experienced an average net loss in foredune volume of approximately -8.7 yd^3/yd. This indicates that there was continued erosion of foredune sediment within the region following Ike.

Cumulative: 2005 to 2012

All regions except for East Beach experienced an average net loss (Table 2) in sub-aerial beach volume across the entire time period covered by the lidar surveys: August 2005 to February 2012. High Island to Sabine Pass and the Quintana Beach regions had the highest average net loss in beach volume per alongshore length as shown in Table 2. Referring to Table 4, High Island to Sabine Pass followed by Quintana Beach and Bolivar Peninsula had the highest overall rate of beach volume loss per unit area (normalized change). Overall, all regions had a total loss of sediment within the sub-aerial analysis zone except for East Beach. Anthropogenic modifications are a potential factor that resulted in the East Beach region exhibiting a net gain in sub-aerial beach volume.

Within the foredune analysis zone, all study regions experienced an average net loss (Table 3) and total net loss (Table 5) in sediment volume. Bolivar Peninsula and the High Island to Sabine Pass regions experienced the highest average net loss in foredune volume. These regions also had the highest overall rate of foredune volume loss per unit area as observed in Table 5 (normalized change). Bolivar Peninsula to High Island were in the path of Ike's right-front quadrant, which is notoriously the most destructive part of a hurricane.

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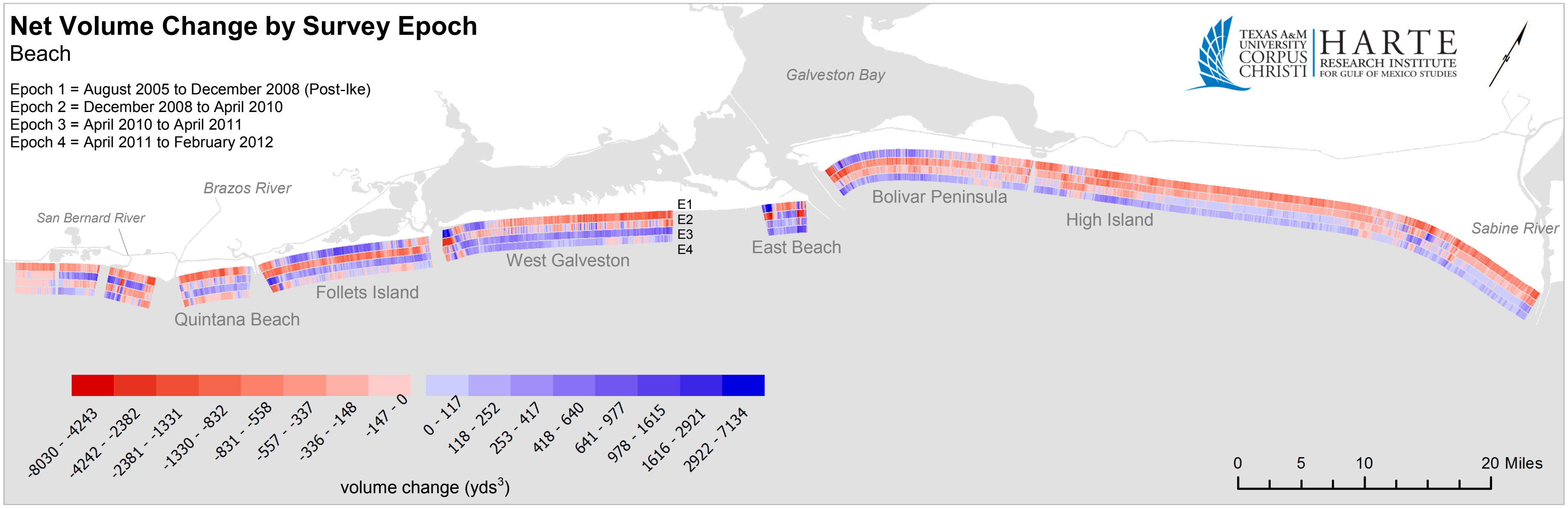
APPENDIX A

COLOR-CODED VOLUME CHANGE MAPS

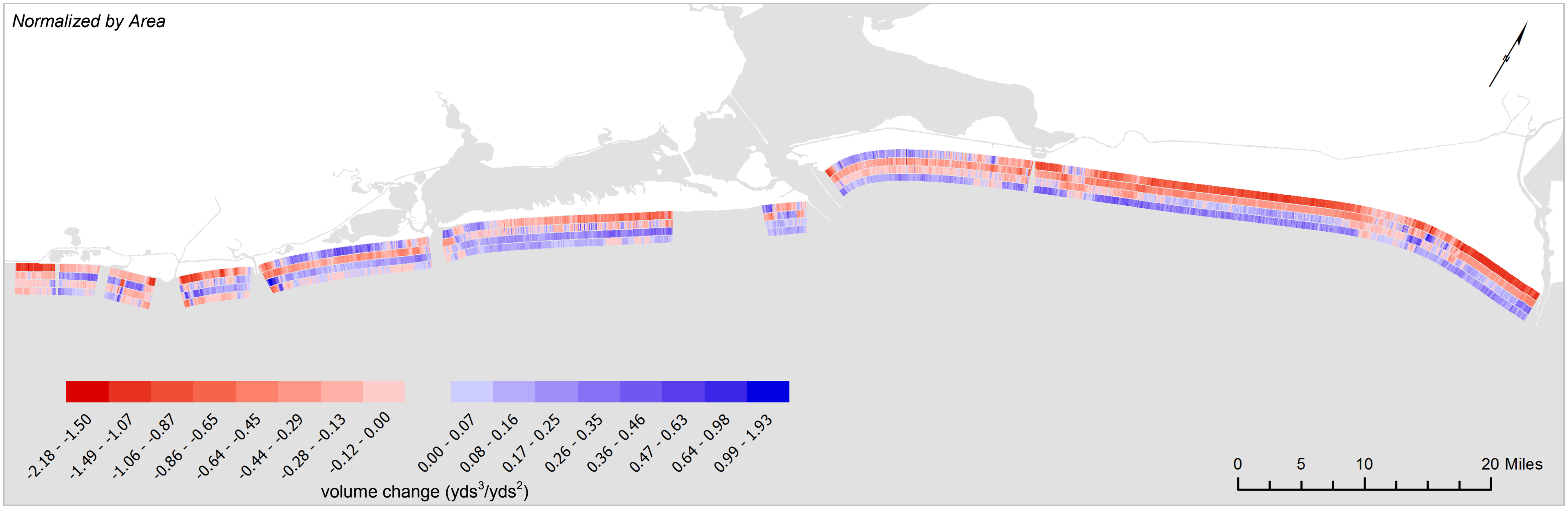
Net Volume Change by Survey Epoch

Beach

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = December 2008 to April 2010
Epoch 3 = April 2010 to April 2011
Epoch 4 = April 2011 to February 2012



Normalized by Area



Net Volume Change by Survey Epoch

Beach

Epoch 1 = August 2005 to December 2008 (Post-Ike)
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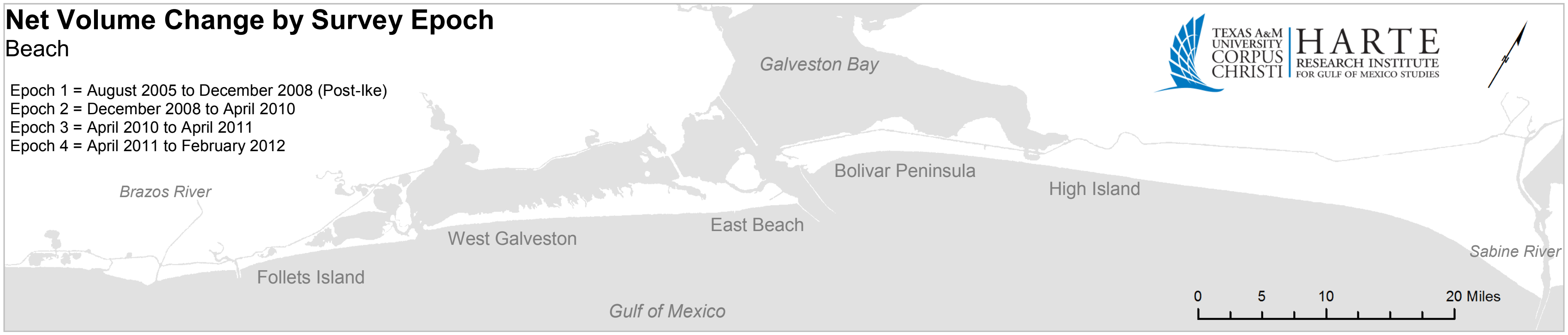

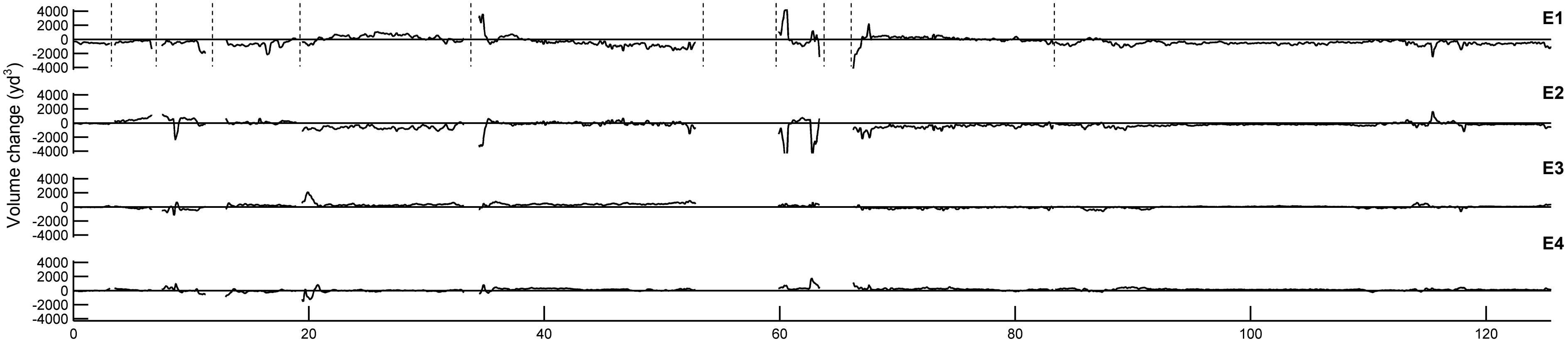

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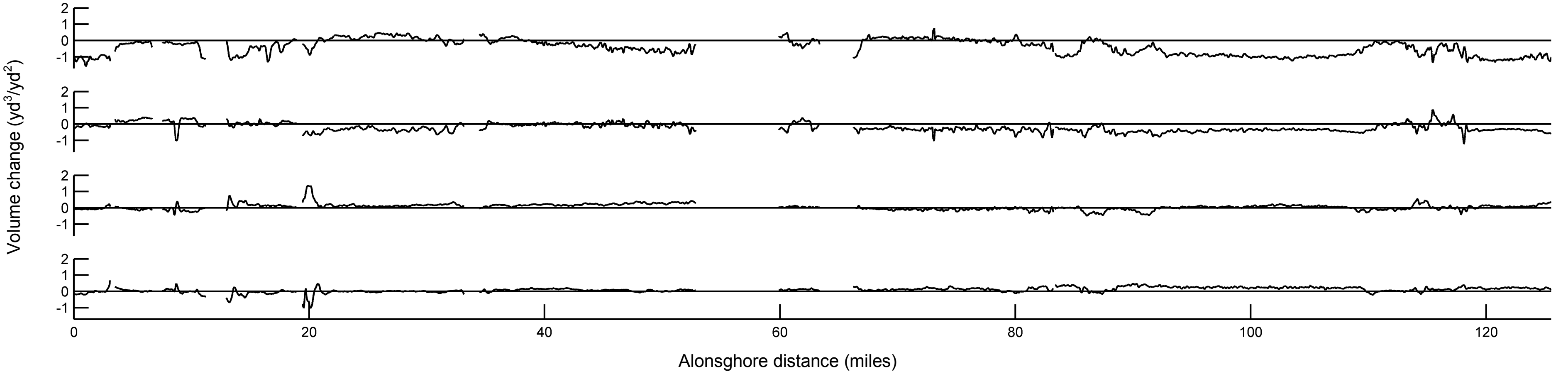
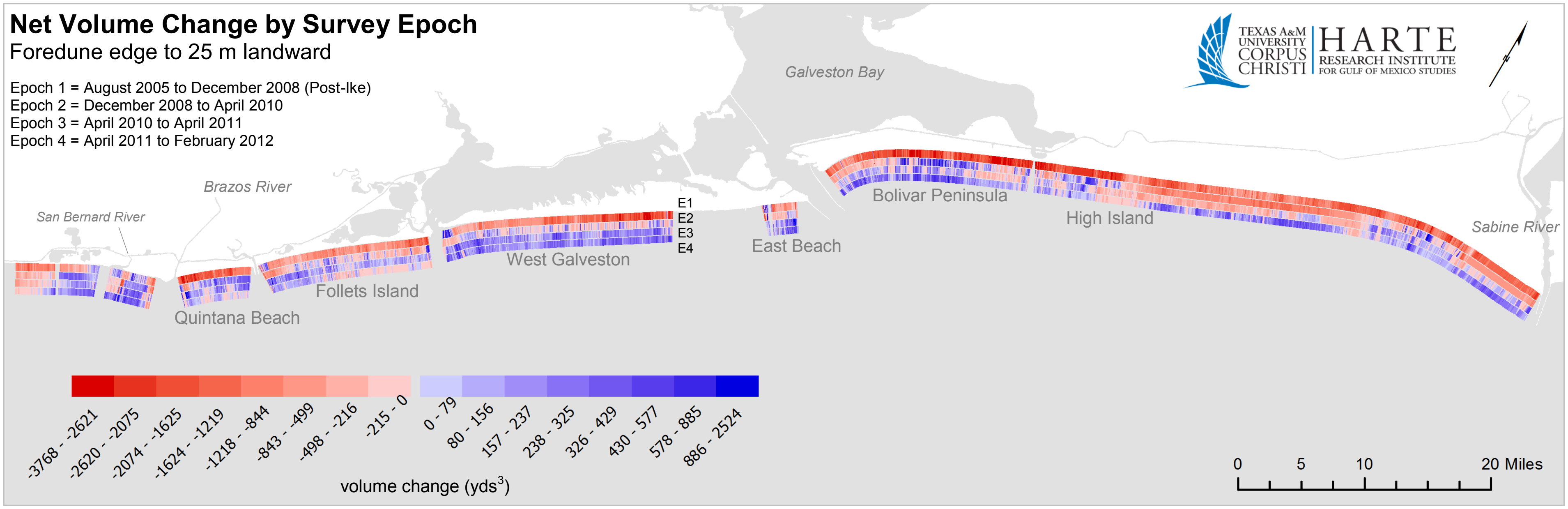
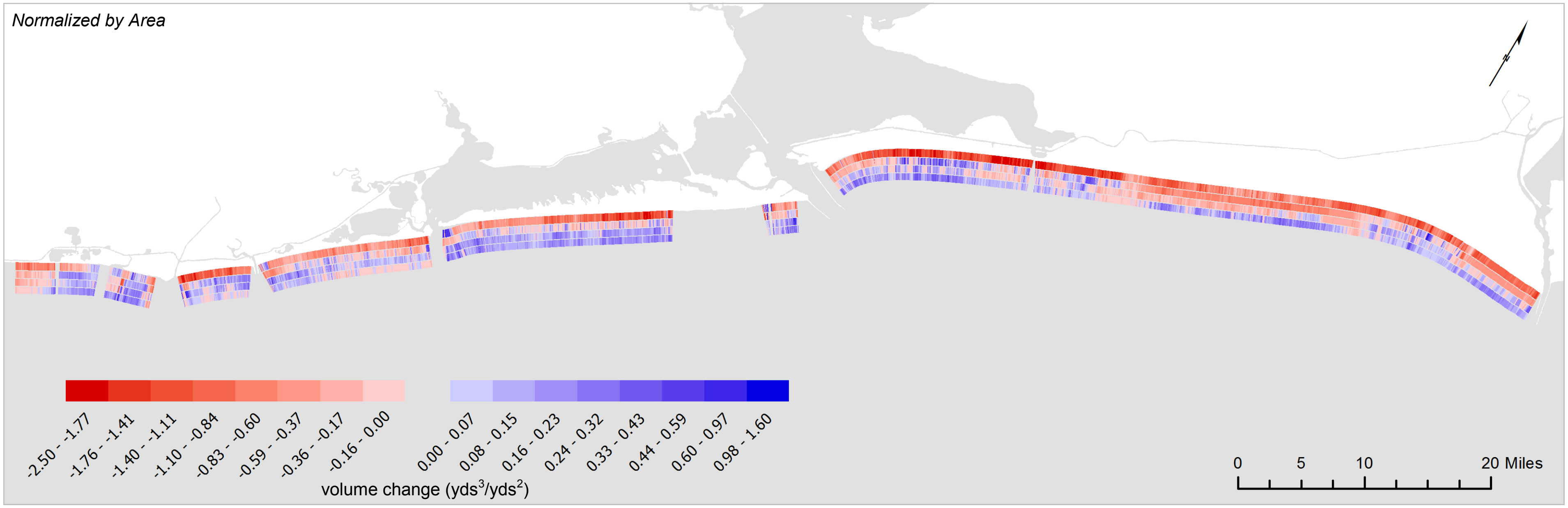




Net Volume Change by Survey Epoch

Foredune edge to 25 m landward

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = December 2008 to April 2010
Epoch 3 = April 2010 to April 2011
Epoch 4 = April 2011 to February 2012

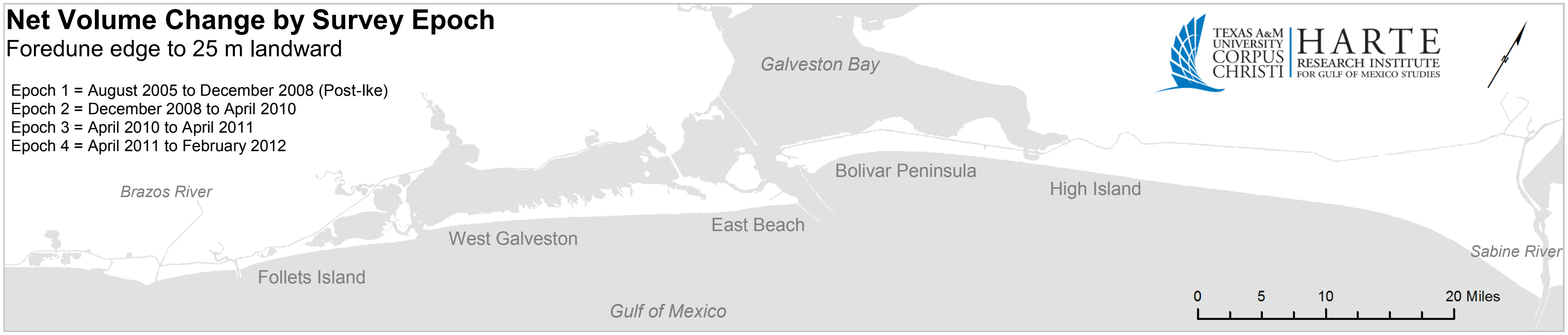


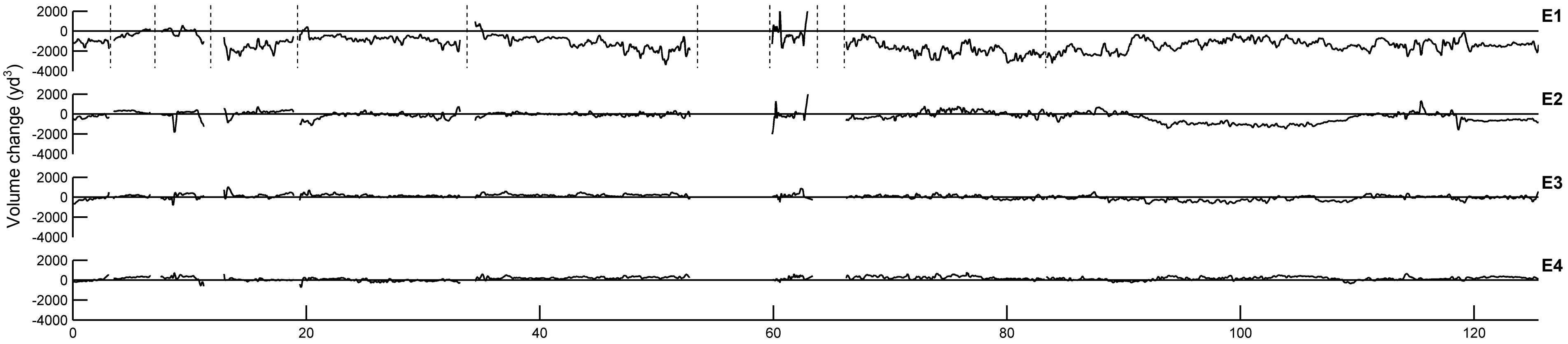
Normalized by Area

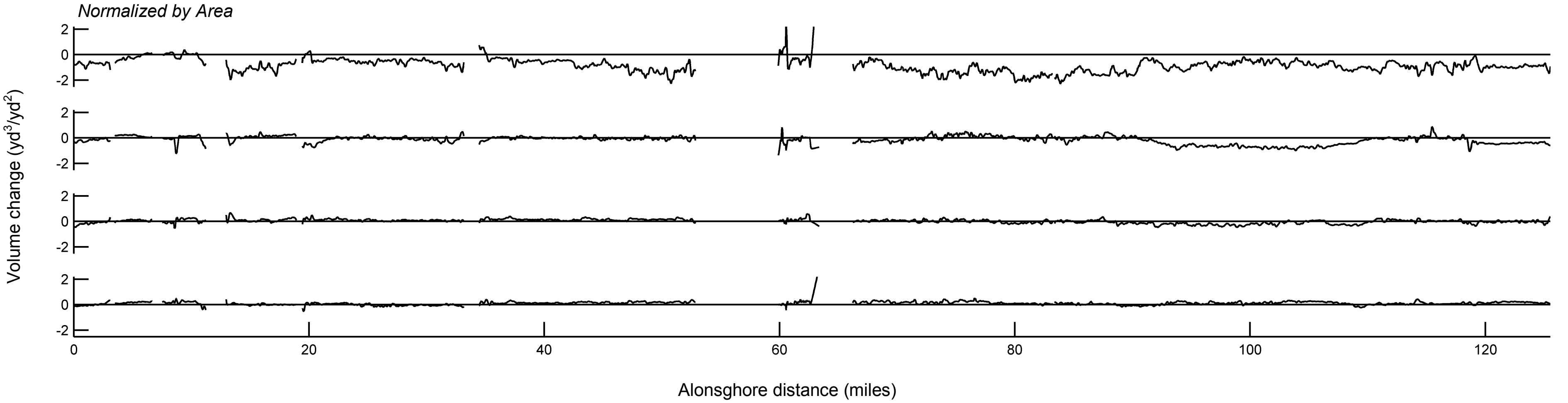
Net Volume Change by Survey Epoch

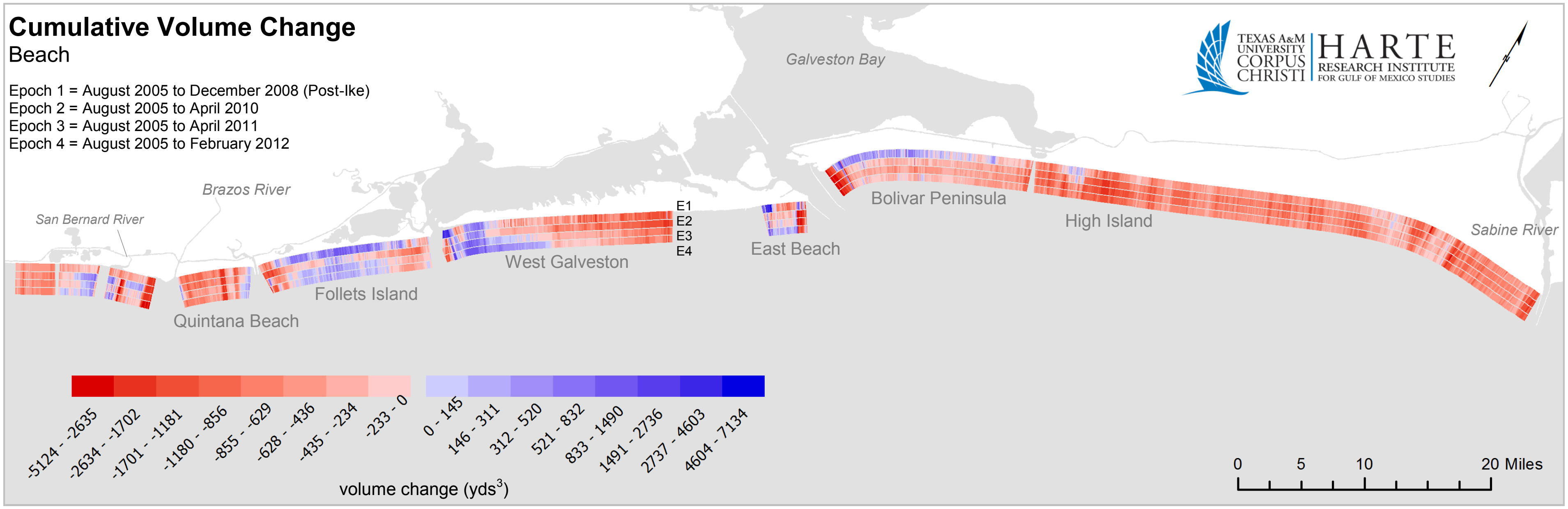
Foredune edge to 25 m landward

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = December 2008 to April 2010
Epoch 3 = April 2010 to April 2011
Epoch 4 = April 2011 to February 2012





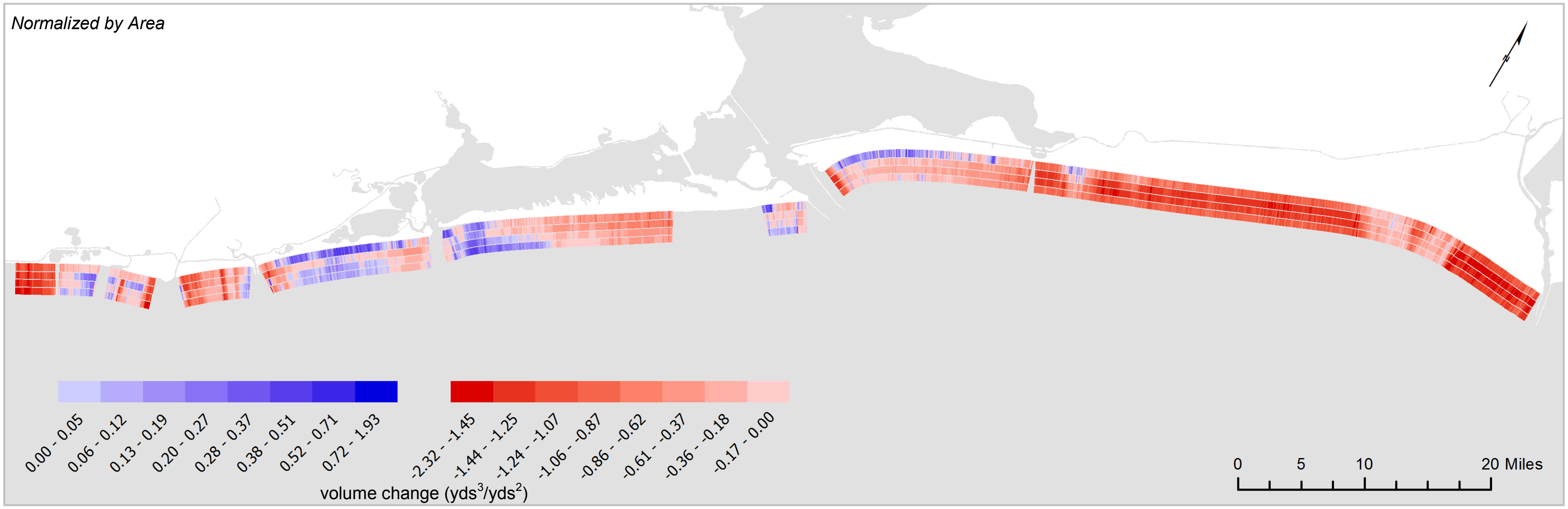




Cumulative Volume Change

Beach

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = August 2005 to April 2010
Epoch 3 = August 2005 to April 2011
Epoch 4 = August 2005 to February 2012

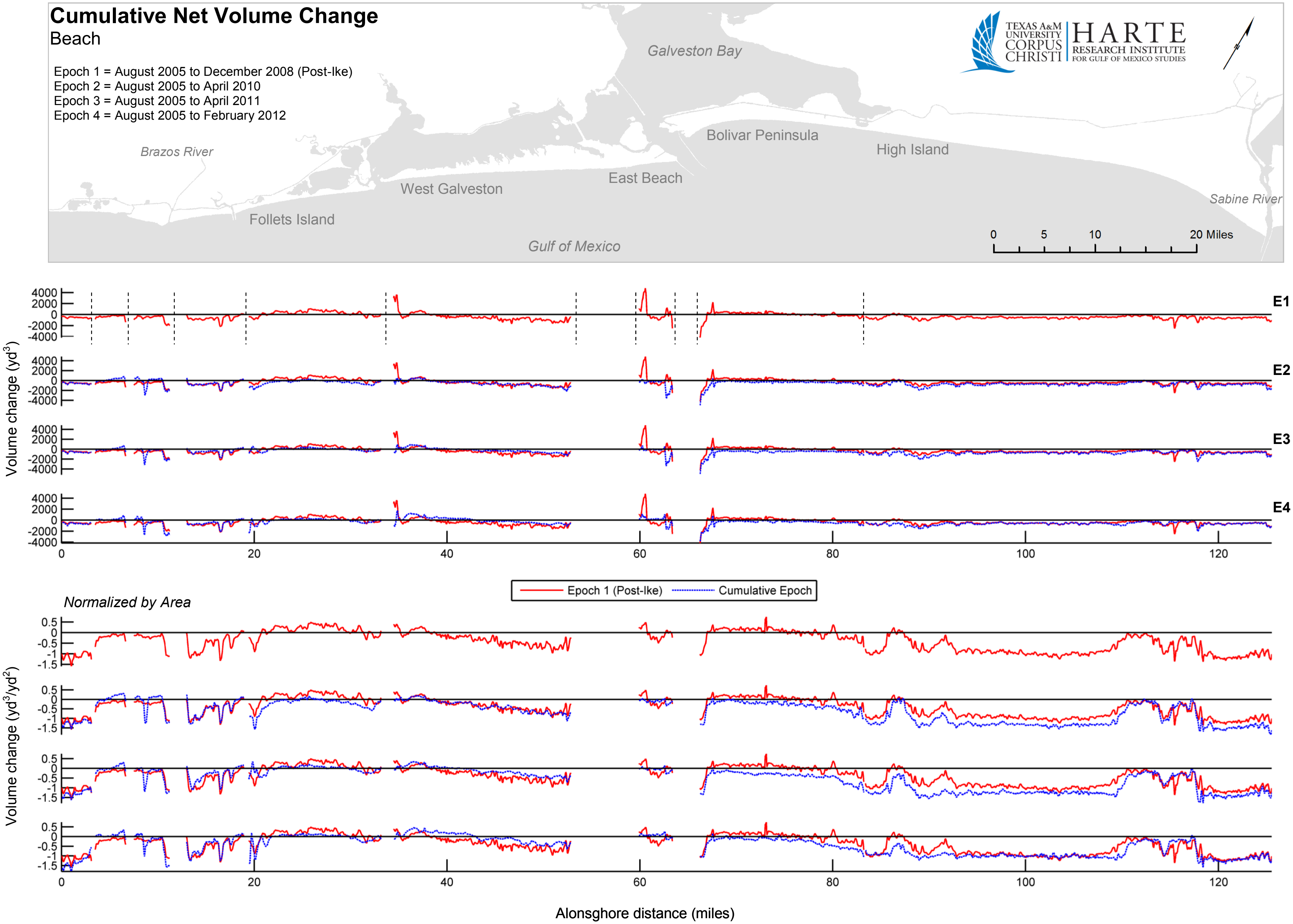


Normalized by Area

Cumulative Net Volume Change

Beach

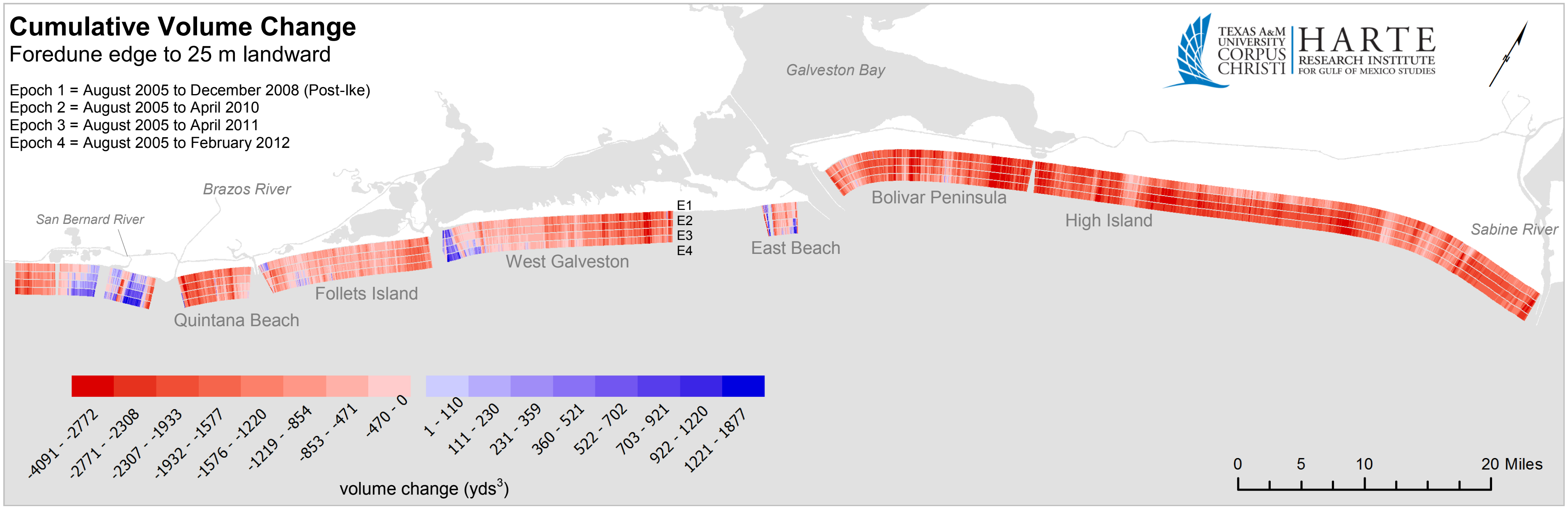
Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = August 2005 to April 2010
Epoch 3 = August 2005 to April 2011
Epoch 4 = August 2005 to February 2012



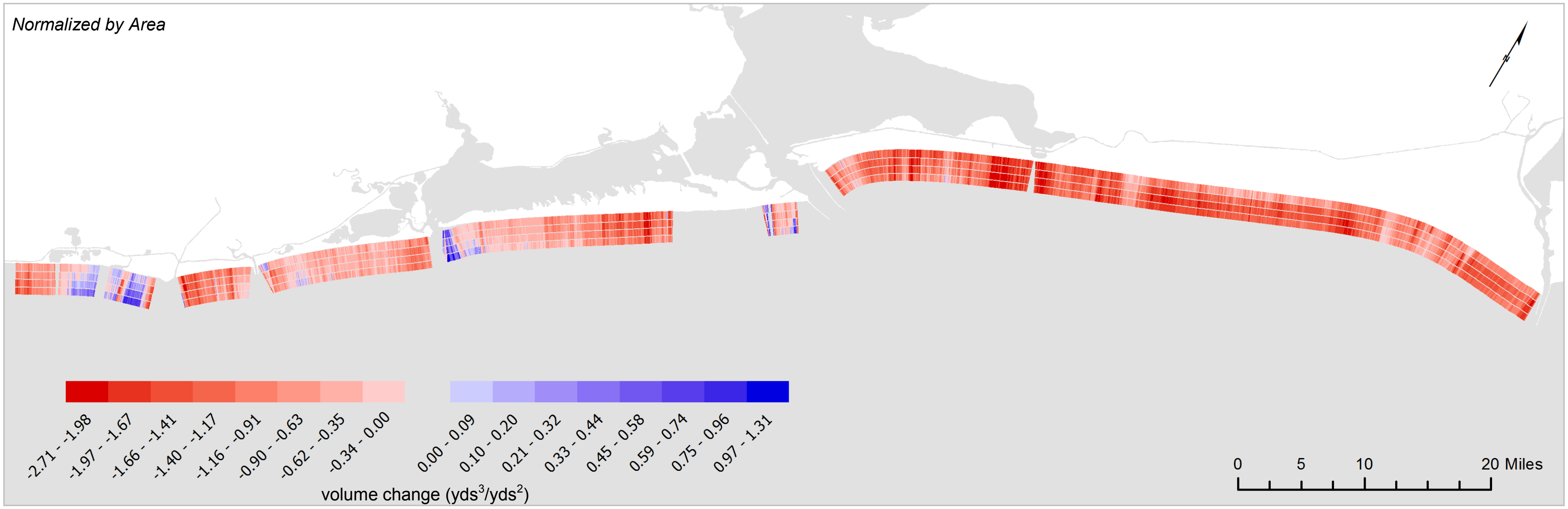
Cumulative Volume Change

Foredune edge to 25 m landward

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = August 2005 to April 2010
Epoch 3 = August 2005 to April 2011
Epoch 4 = August 2005 to February 2012



Normalized by Area



Cumulative Net Volume Change

Foredune edge to 25 m landward

Epoch 1 = August 2005 to December 2008 (Post-Ike)
Epoch 2 = August 2005 to April 2010
Epoch 3 = August 2005 to April 2011
Epoch 4 = August 2005 to February 2012