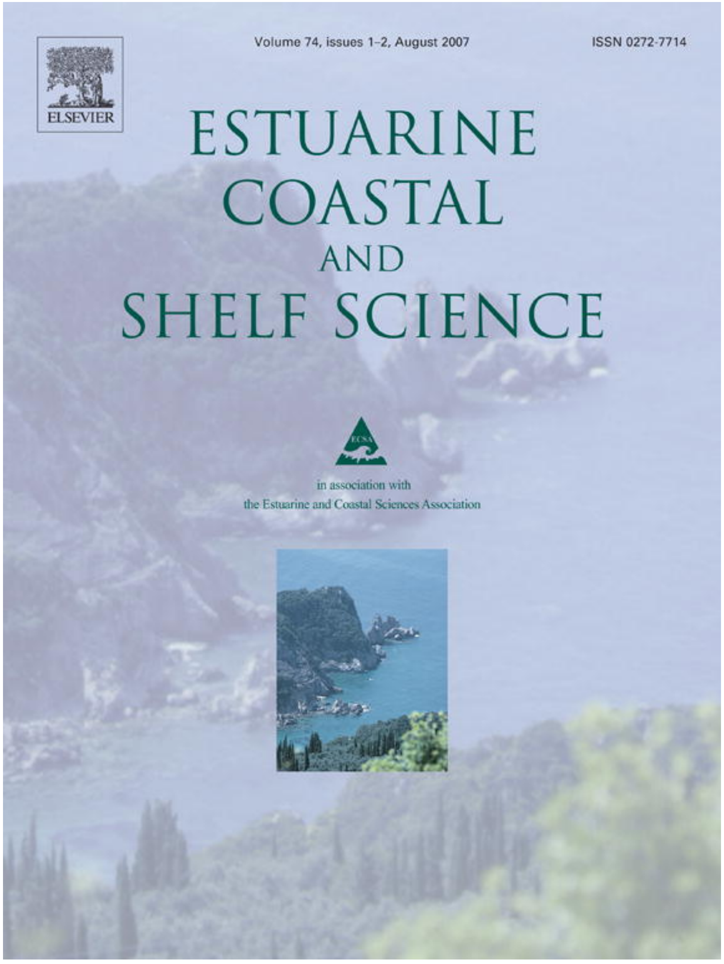
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Hurricane Katrina storm surge distribution and field observations on the Mississippi Barrier Islands

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Abstract

Hurricane Katrina (23–30 August 2005) struck low-lying coastal plains particularly vulnerable to storm surge flooding. Maximum storm surges, overland flow depths, and inundation distances were measured along the Gulf Coast of Florida, Alabama, Mississippi and Louisiana. The vehicle based survey was complemented by inspections with the reconnaissance boat along the Gulf Coast and the Mississippi Barrier Islands. The storm surge peaked to the East of Katrina's path exceeding 10 meters in several locations along the Mississippi coastline. The storm surge measurements show that the lower floors of specially designed buildings were damaged by the surge of seawater and associated wave action, while the upper floors sustained minimal wind damage. Furthermore, the storm surge measurements along New Orleans's Lake shore indicate that the 17th Street Canal levee failed prior to overtopping. The land loss on the barrier islands resulted in an increased vulnerability of the US Gulf Coast to future hurricane storm surges.

Keywords: Hurricane Katrina; storm surge; barrier islands; Mississippi; Alabama; Louisiana; Florida; pinus; beach erosion

1. Introduction

Hurricane Katrina (23–30 August 2005) was the costliest and one of the five deadliest hurricanes to ever strike the United States. The total number of fatalities directly related to the forces of Katrina exceeded 1000 in Louisiana and 200 in Mississippi. Katrina made its first landfall as a Category 1 hurricane in southeastern Florida at 22:30 UTC 25 August. Katrina attained its peak intensity of 280 km/h (central pressure 902 mb) at 18:00 UTC 28 August about 310 km southeast of the mouth of the Mississippi River (Knabb et al., 2005). The tropical storm-force winds extended 370 km from the storm's center and hurricane-force winds extended 170 km from the storm's center, making Katrina not only extremely intense but also exceptionally large. The hurricane then made landfall, at the upper end of Category 3 intensity (central pressure 920 mb) with estimated maximum sustained winds of 200 km/h, near Buras, Louisiana at 11:10 UTC 29 August. Katrina continued northward and made its final landfall near the mouth of the Pearl River at the Louisiana/Mississippi border, still as a Category 3 hurricane with estimated wind speeds of 190 km/h (central pressure 928 mb). Katrina remained very large as it weakened, and the extent of tropical storm-force and hurricane-force winds was nearly the same at final landfall on 29 August as it had been late on 28 August 2005.

The affected coastlines were particularly vulnerable to the storm surge because of the low-lying, coastal plain topography and the lack of effective barriers. The damage and performance of structures and the measurements of high water

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marks due to Katrina have been outlined in several government and interagency reports (Link et al., 2006; Gutierrez et al., 2006; FEMA, 2006a,b,c; Seed et al., 2006). However, these reports focus primarily on the built infrastructure along the mainland and lack the mostly uninhabited Mississippi barrier islands forming the Gulf Islands National Seashore. Hurricane Katrina also served as a major influence on the natural environment with many effects on biological resources including wetland and timber loss, and declines in fisheries and wildlife populations (Sheikh, 2005).

2. Post-hurricane field survey

The widespread failure of tide gauges along the Mississippi and Louisiana shores called upon reconnaissance crews to collect elevations from high water marks. The teams surveyed the coastlines of Florida, Alabama, Mississippi and Louisiana during two, one-week-long periods in September and October, 2005. The surveys extended 240 km to the east and 80 km to the west of the hurricane path, including Lake Pontchartrain, Grand Isle (Louisiana) and Dauphin Island (Alabama). In addition, four separate boat expeditions covered the Gulf Islands from Petit-Bois Island to Cat Island (Mississippi). The teams measured the maximum storm surge elevation (the height of the water level), overland flow depth (depth of the water above the ground), inundation distance (the straight-line distance between the coastline and the maximum extent of saltwater intrusion), and areas of inundation. Further, soil samples from storm deposits were collected and erosion documented. Ephemeral infrastructure damage was recorded at various scales. The elevations of water marks on buildings, scars on trees, and rafted debris were measured as indicators of the maximum storm surge elevation. The high water measurements, based on different indicators at corresponding locations, tended to be consistent. High water marks were photographed and located using GPS. Transects from the beach to the high water marks were recorded with a laser range finder. Fig. 1 shows the measured Katrina high water marks and a superimposed high water line recorded in analogous manner after Hurricane Camille, 14−22 August 1969 (USACE, 1970).

The storm surge peaked to the east of Katrina's path with consistent recordings between 7 and 10 meters along a 60 km stretch of Mississippi coastline from Lakeshore (20 km east of center) to Ocean Springs (80 km east of center). The surge penetrated at least 10 km inland in many portions of coastal Mississippi and up to 20 km inland along bays and rivers. The surge heights dropped below 5 meters along the Alabama coast. Nevertheless, more than 2 meter surge heights were measured 240 km east of the Katrina's track along Florida's panhandle. The surge heights dropped quicker to the west of Katrina's path, attaining 2 meters along Lake Maurepas (80 km west of the track). Surge heights exceeding 6 meters were only recorded in Shell Beach, a few kilometers to the west of the track. Along Lake Pontchartrain a significant storm surge gradient from east to west was observed, with surge heights exceeding 5 m in Slidell and along the Chef Monteur Pass (LA). The storm surge, pushed ashore on Lake Pontchartrain‘s south coast by the northerly wind direction, severely strained the levee system along New Orleans's Lakeshore. However the high water marks along the intact levee system on the Lakeshore adjacent to the 17th Street outfall canal did not exceed 5 m. Hence, the 17th Street outfall canal levee failed prior to reaching its design capacity on the early morning of 29 August 2005 without any forensic evidence of overtopping. This study could not determine whether the other levee breaches—flooding 80% of New Orleans—were due to overtopping.

The high water marks were measured on structures that were damaged by waves on top of the storm surge and the surge itself. Characteristic high water mark and erosion measurements are shown in Fig. 2. A typical view from a survey boat shows a sharp damage trimline along the entire oceanside of the Beau Rivage Lighthouse and Casino in Biloxi with only the steel frames remaining at the lower floors, while at the upper floors not a single window was broken (Fig. 2a). Even along the hardest hit coastline, buildings designed to resist peak hurricane winds were marginally damaged on the upper floors, while classic wash-out failures marked the lower floors. In uninhabited areas, such as the Gulf Islands National Seashore barrier islands, high water marks were based upon trimlines and scars in the bark of trees. In rare cases heavy debris rafted into trees, such as a full size 180 kg refrigerator deposited in a tree that was used as a surge height indicator (Fig. 2b). The storm surge is the primary cause of the high water marks. However, wave action and, to a lesser extent, astronomical tides also contribute. Unfortunately the final landfall occurred on top of an astronomical high tide (up to 0.6 m).

3. Barrier Islands field observations

Coastal Mississippi and Alabama feature six nearly shore-parallel barrier islands located 15−20 km from the mainland coast (Fig. 3a). The barrier islands are an elongate chain stretching 105 km to the west of the constricted entrance of Mobile Bay (Alabama). From east to west the islands confining the Mississippi Sound are: Dauphin Island (Alabama), Petit Bois, Horn, East Ship, West Ship and Cat Islands (Mississippi). The Mississippi Barrier Islands are part of the Gulf Islands National Seashore with only part of Cat Island remaining privately owned. It is the eastern portion of the original Ship Island that was separated into East and West Ship Islands during Hurricane Camille. Historically, within the last 150 years, the Petit Bois and Horn Islands have had a dominantly translational—longshore westward-migration, whereas Cat Island and, to a lesser extent, the Ship Islands are typified by erosion over westward migration (Schmid, 2000).

The barrier islands were completely inundated and over washed by Hurricane Katrina's storm surge and waves. On the open Gulf Coast of the western Mississippi barrier islands (Cat, East and West Ship Islands) stretching 40−70 km east of Hurricane Katrina's track, storm surge water marks were

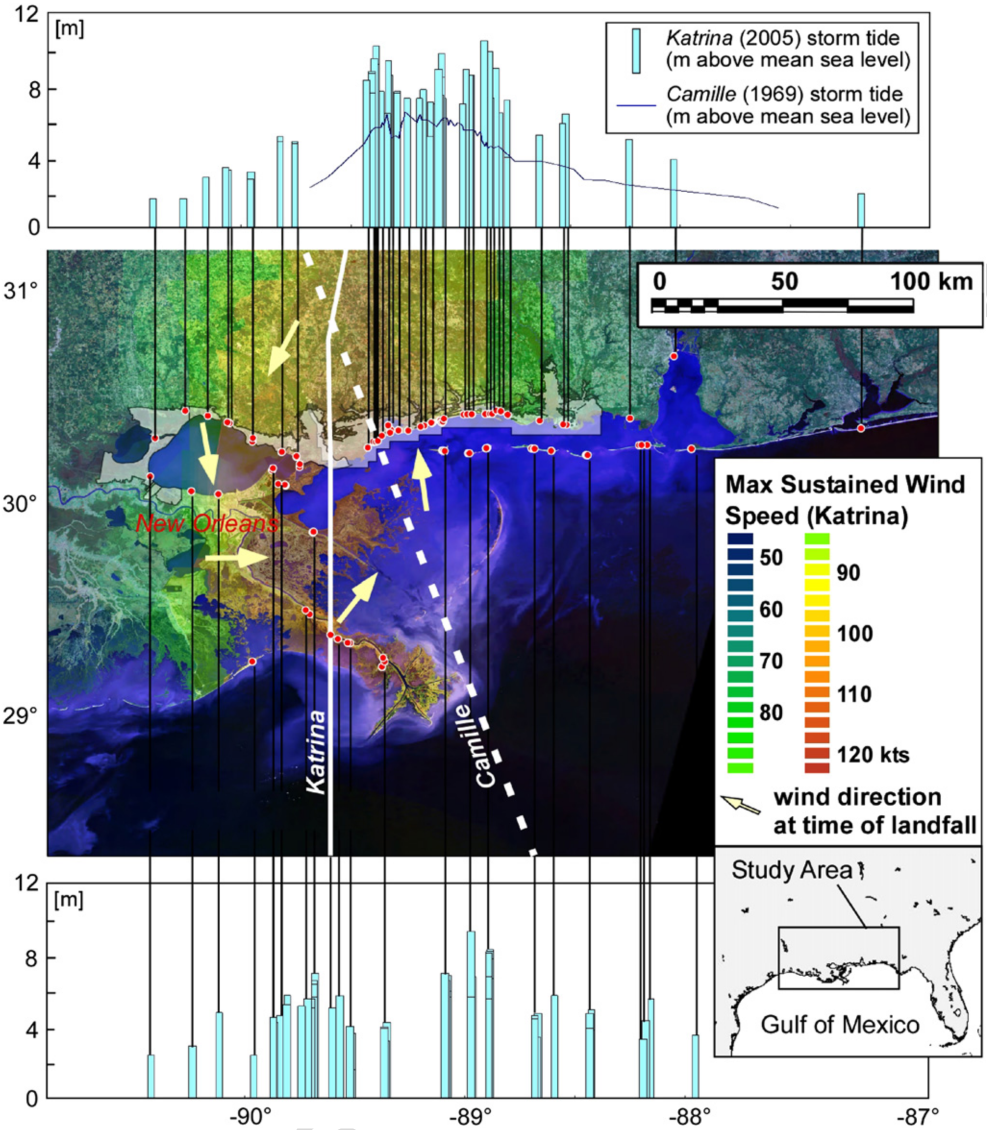

Fig. 1. Hurricane Katrina (2005) storm surge height measurements and Hurricane Camille (1969) high water mark profile (USACE, 1970).

recorded between 5.5 and 9 m (Fig. 3). On the Gulf Islands National Seashore barrier islands, high water marks were primarily based upon trimlines and scars in the bark of trees. Besides the tree marks the following structures served as high water marks: residential buildings (Cat and Dauphin Islands), historic brick Fort Massachusetts (West Ship Island), and steel frame communication towers (West Ship and Horn Islands). The house on Cat Island that survived Hurricane Camille in 1969 to record a storm surge of 5 m was completely destroyed by Hurricane Katrina together with two other houses. Only 2 out of the 5 houses on Cat Island pre-Katrina remained with a severe wash-out damage trimline on the second floor. The forest vegetation coverage on the barrier islands is dominated by well developed slash pine forests (*Pinus elliotii*) with the exception of Dauphin Island (Stoneburner, 1978). The forest on East Ship Island was by far the hardest hit due to the low terrain elevations. The trees along the entire south beach were either snapped above ground or their bark ripped off cleanly to heights of 8 m (Fig. 4a). Bark cleanly ripped off trees from the ground to the storm surge level was observed up to 300 m from the shoreline. The closest upright tree trunks were encountered 30 m from the post-event shoreline in areas with peak storm surge heights and wind speeds (Fig. 4b). Similarly the amount of up-rooted and snapped trees decreased rapidly within 100 m of the shoreline, illustrating the effectiveness of coastal forests in reducing the impact of hurricane force winds and storm waves while their effect on the storm surge height remains marginal (Fritz and Blount, 2007; Barnes et al., in press). The size of the storm surge and the duration resulted in forests being submerged in salt water for the duration of roughly an entire day resulting in salt burn damage on otherwise intact trees. Salt concentrations in the soil remain to be determined for an in depth analysis as measured after Hurricane Hugo (1989) in South Carolina (Gardner et al., 1992). A year after the hurricane, the slash pine trees on Cat Island had not recovered from the salt burn, while centuries old dwarf live

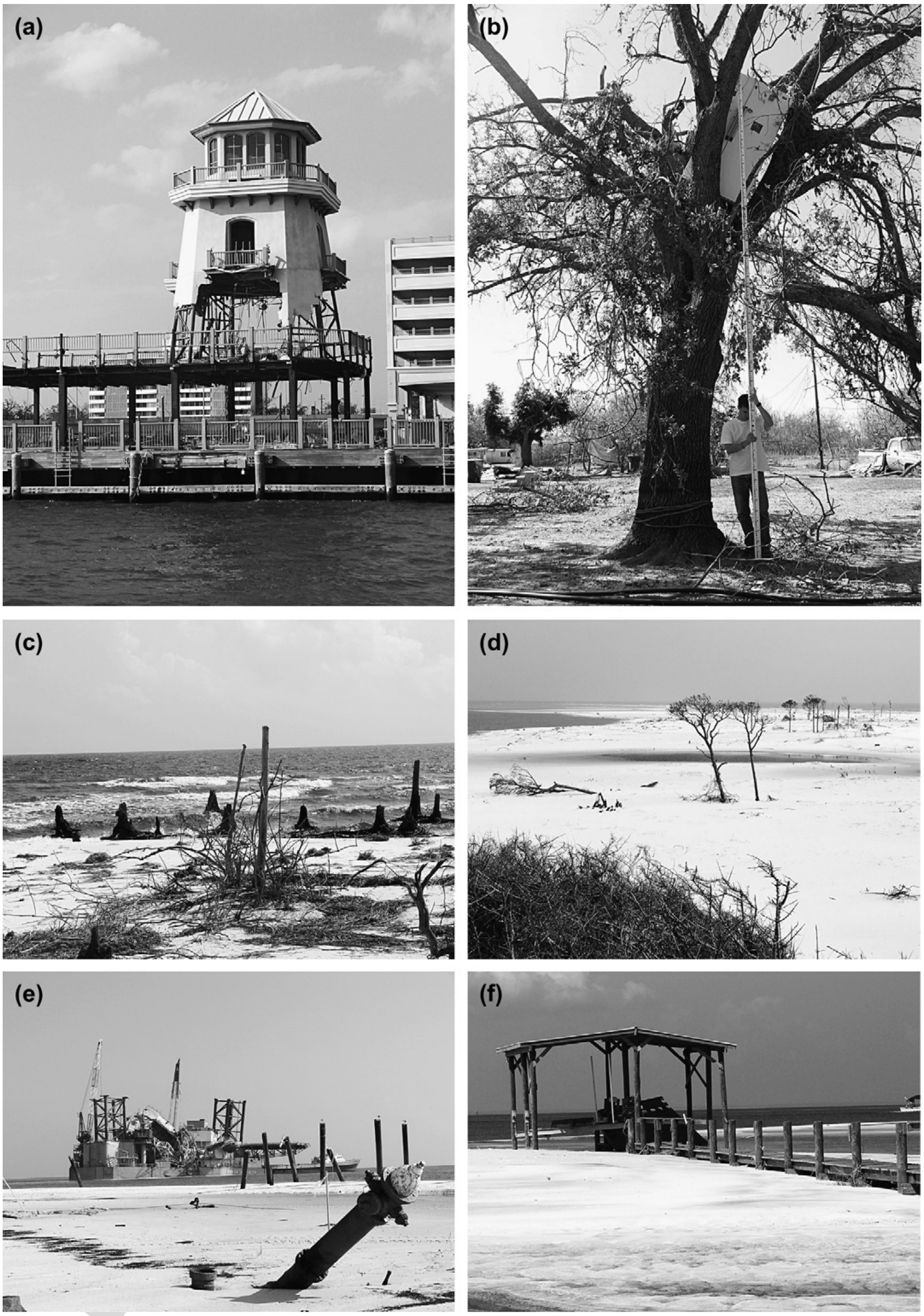

Fig. 2. (a) Wash-out damage trimline on steel frame structure of the lighthouse at Beau Rivage Casino in Biloxi, Mississippi (USA); (b) rafted refrigerator, with a net weight of 180 kg, deposited on a tree in Buras, Louisiana (USA); (c) tree trunks piercing the water surface in the surf zone along East Ship Island's south coast after massive erosion; (d) east tip of Horn Island with massive land loss due to erosion; (e) erosion on Dauphin Island's south beach measured 0.7 m on a fire hydrant (background: offshore oil platform that broke lose and drifted from Louisiana to Alabama); (f) sediment accretion that migrated Dauphin Island's north beach between 80 and 150 m northward and setting a boat dock dry.

oaks (*Quercus geminata*) were recovering (personal communication in 2007 from George Boddie, co-owner Cat Island, MS).

On the eastern Mississippi (Horn and Petit-Bois) and Alabama Barrier Islands (Dauphin Island) located 80–150 km to the east of Hurricane Katrina's track the measured storm surge heights decreased to 3.5–5.5 m (Fig. 5). The variation of the high water measurements on the Islands was in accordance with corresponding onshore recordings to the north. Most tide stations broke down or delivered intermittent recordings

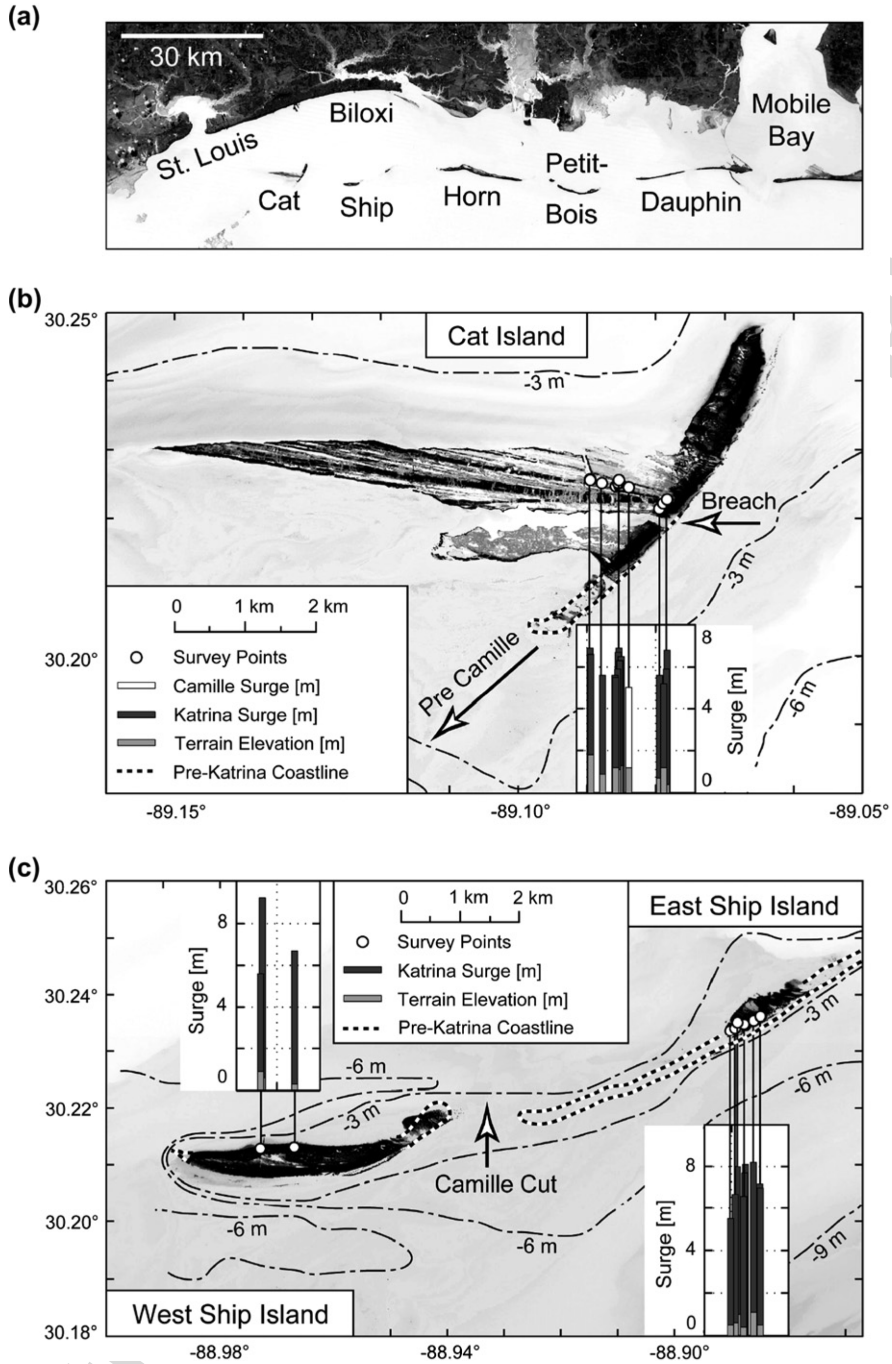

Fig. 3. Hurricane Katrina storm surge heights measured on the western Mississippi barrier islands with pre-Katrina shoreline and inverted post-Katrina IKONOS-satellite imagery (7 September 2005): (a) location of Barrier Islands; (b) Cat Island (MS); (c) West and East Ship Islands (MS).

during Hurricane Katrina. The tide stations on Dauphin Island are located inside the entrance to Mobile Bay somewhat protected by the off-shore Pelican Island. The primary tide station 8735180 on the east tip of Dauphin Island continuously recorded the storm surge (Fig. 5d). However, the latest inspection report lists damage to the station due to hurricanes and skipped routine maintenance, resulting in the installation of the temporary tide station 8735181 some 500 m to the north-west of station 8735180 prior to Hurricane Katrina (Chapin, 2006). The storm surge records of the two stations are in phase during the ascent and descent but diverge during the peak hours. The time-averaged tide gauge records measured storm surge peaks of less than 2 m.

4. Barrier Islands evolution

Hurricane Katrina's extreme storm surge induced currents and temporary flooding of the entire Mississippi Barrier Islands chain resulted in massive erosion and local accretion. The beach and over wash erosion along East Ship Island's

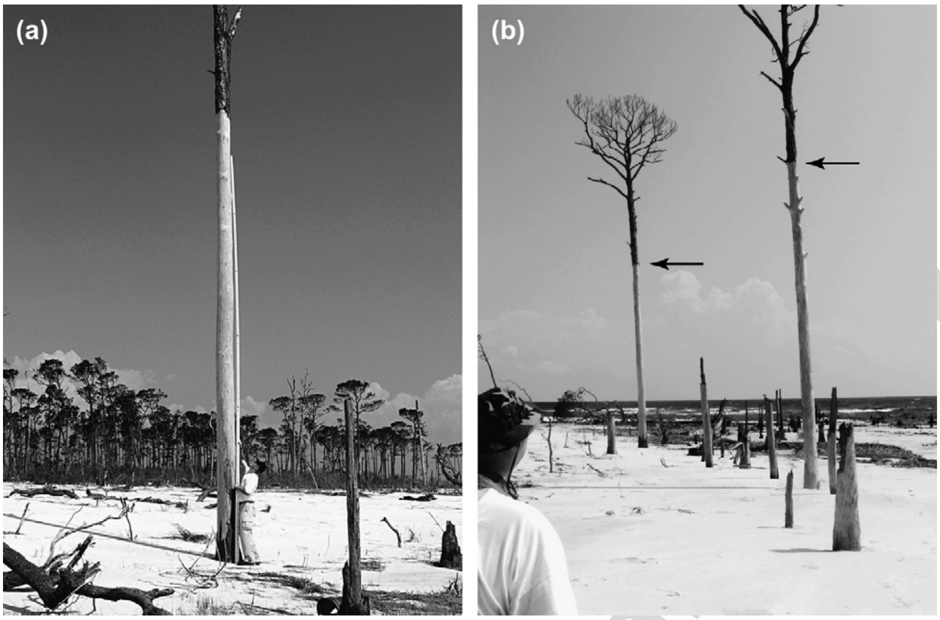

Fig. 4. East Ship Island high water marks: (a) bark stripped off a tree with salt-burned pine trees in the background (note the 7.65 m long survey rod for scale); (b) massive beach and over wash erosion illustrated by damaged and snapped pine trees along the beach.

south coast resulted in damaged tree trunks standing along the beach and even piercing the water surface inside the surf zone (Fig. 2c). The shoreline retreat along East Ship Island's south coast was in the order of 100 m. The roughly perpendicular path of Hurricane Katrina with respect to the barrier islands chain resulted in significant land loss, such as at the east tip of Horn Island (Fig. 2d). The land loss significantly increased the channel widths between the islands, thereby reducing the coastal protection provided to the mainland by the barrier islands. The evolution of the individual and total channel widths, based on the T-sheets (US Coast and Geodetic Survey) from 1910 to 1922, 1950, 1986 and pre- and post-Hurricane Katrina Imagery, is shown in Fig. 6. Satellite imagery, recorded a few months before and within 2 weeks after Hurricane Katrina, shows a significant erosion and land loss in the immediate aftermath. The sum of the channel widths between the islands from Cat to Dauphin Islands added to 29.7 km before and 40.6 km after Hurricane Katrina, which corresponds to a 37% increase in total channel widths. The recovery in the years after Hurricane Katrina will show how much of the land loss is temporary. Similarly, East Ship Island lost 25% of its area during the much smaller Hurricane George (1998, Category 2) and almost completely recovered by the second year. However each hurricane or storm is unique and its effect on individual barrier islands produces a distinct result (Sallenger, 2000; Morton, 2002; Morton and Sallenger, 2003). Cat Island was breached at the head of the T-shape. The shallow 350 m wide breach reduced the main island to an L-shape (Fig. 3b). The breach in Dauphin Island was barely existent (0.1 km) before Hurricane Katrina and spanned 1.9 km in the immediate aftermath (Fig. 5c). The measured 2 m over wash flow depth at the first house east of the breach on Dauphin Island, resulted in 0.7 m vertical erosion on the south beach (measured on a fire hydrant) and 80–150 m northward sediment accretion on the north beach, setting the boat dock on dry land (Fig. 2e,f). The absence of a dense vegetation cover on Dauphin Island increased its erosion vulnerability and illustrates the importance of coastal forests to reduce coastal erosion (Wolanski, 2007). Similarly Ship Island has been breached five times since 1850 and then permanently in 1969 by Hurricane Camille (Nummedal et al., 1980; Schmid, 2003). Hardest battered were the Chandeleur Islands with more than 200 cuts reported after Hurricane Katrina (personal communication by George Boddie, Pass Christian, MS).

Beyond change brought about by natural forces, an important factor in the combined evolution of the barrier islands has been maintenance of navigation channels. There are four navigational channels that pass through the north Gulf of Mexico that affect the barrier islands (Pensacola, FL; Mobile, Pascagoula, and Gulfport, MS). The Pensacola shipping channel was constructed in 1878 and deepened and/or widened in 1883, 1959, and 1991 (KellerLynn, 2007). The last project on the channel (244 m wide and 14.6 m deep) was the major influence on the recent shoreline change around Pensacola Pass (Browder and Dean, 1999). Disposal of the spoil material from the Mobile ship channel may be the cause of significant decrease (or termination) of the westward littoral drift by the Mississippi barrier islands (KellerLynn, 2007). The Pascagoula shipping channel passes between Horn and Petit Bois Islands. As Petit Bois Island migrates westward into the channel, the dredged material is placed on the western side of the channel creating a new island. If this continues Petit Bois Island will not exist in 75 years (Shabica et al., 1993). The Gulfport channel was created in 1899 (KellerLynn, 2007) between Ship and Cat Island, and it has undergone periodic dredging since 1918 (Shabica et al., 1993). The current widths of the channel are 122 m in Ship Island Pass and 91.5 m in the Mississippi Sound (Zender et al., 2007). This dredging was suspected to

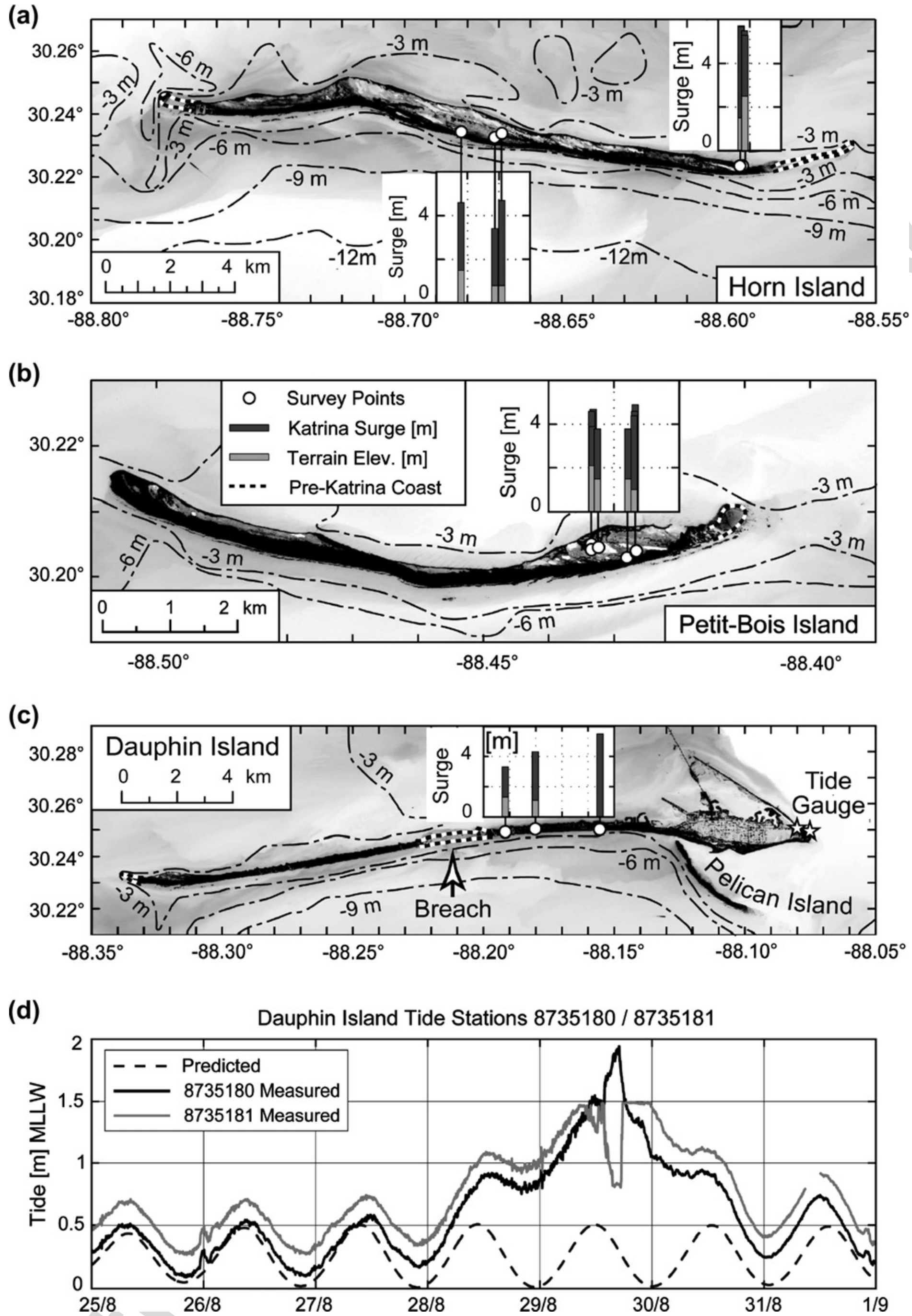

Fig. 5. Hurricane Katrina storm surge heights measured on the eastern Mississippi and Alabama barrier islands with pre-Katrina shoreline and inverted post-Katrina IKONOS-satellite imagery (7 September 2005): (a) Horn Island (MS); (b) Petit-Bois Island (MS); (c) Dauphin Island (AL); (d) Dauphin Island tide station recordings 8735180 and 8735181 (NWLON).

have stopped the westward migration of West Ship Island and so the USACE moved the channel 579 m west in 1993 (without backfilling the old channel) to allow the island to migrate for 50 more years (Shabica et al., 1993). However, since the old channel has been used as a source for beach nourishment, the westward migration is still impeded (Toscano, 2004). Disposal of dredged material from these channels onto deepwater remote sites in the Gulf of Mexico, can permanently remove the sands from the littoral sand transport system (Douglass, 1994; Otvos and Carter, in press).

5. Storm surge comparison between Hurricane Camille and Katrina

The similar tracks of Hurricane Katrina (Category 3 at landfall) and Camille (Category 5 at landfall) enable a direct comparison of the induced storm surges shown in Fig. 1. Both hurricanes moved at similar speeds of 20 km/h within the last 24 hours prior to the main landfall. The massive storm surge produced by Katrina is primarily attributed to the huge size of the storm. On 29 August, Katrina had a 50 km radius

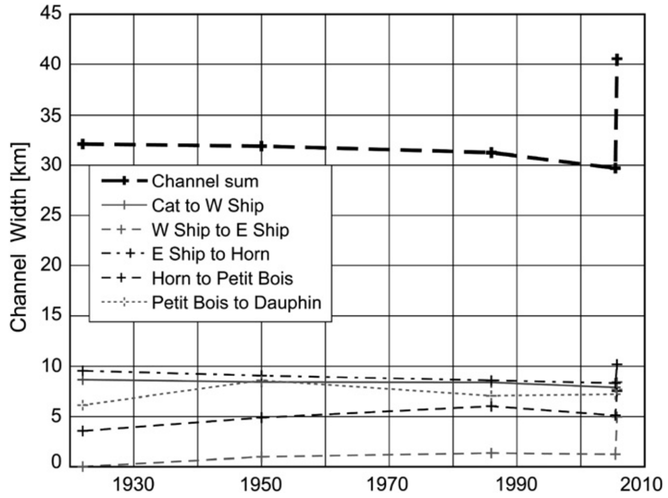

Fig. 6. Channel widths evolution based on T-sheets (1910-1922, 1950, 1986 from US Coast and Geodetic Survey), pre- and post-Katrina satellite imagery (7 September 2005).

of maximum sustained winds and a very wide swath of hurricane force winds that extended 140 km (from the center to Dauphin Island, AL). In addition Katrina had already generated large northward-propagating swells as a Category 5 storm in the hours before landfall, leading to substantial wave setup along the northern Gulf coast. Hurricane Camille (1969) was more intense than Katrina at landfall in terms of peak wind velocities. However Camille was far more compact, with hurricane force winds extending only 100 km to the east of the center resulting in a narrower storm surge distribution (ESSA, 1969). The 6.9 m maximum high water mark recorded in the aftermath of Hurricane Camille was likely exceeded in the Richelieu apartment complex in Pass Christian (MS) prior to their collapse, according to eyewitness estimates of 8.5 m (Hearn, 2004). Summarizing, Katrina's high water levels were due to the size of the Category 3 storm enhanced by waves generated in the hours prior to landfall by a Category 5 strength storm. The comparison between the storm surges induced by Hurricanes Katrina and Camille illustrates that the storm surge is not solely determined by the wind velocity-based Saffire–Simpson scale. Several Camille survivors became victims misled by the assumption that their properties would not be inundated by the Category 3 Katrina storm surge since the Category 5 Camille storm surge spared them. Even the house on Cat Island that survived Hurricane Camille in 1969 to record a storm surge height of 5 m, was completely destroyed by Hurricane Katrina's storm surge (Fig. 3b). Hurricane Katrina's storm surge exceeded Hurricane Camille's at all survey locations.

6. Conclusions

The rapid response of the survey team led to the recovery of important ephemeral data on the characteristics of hurricane impact on large low-lying coastal plains and barrier islands particularly vulnerable to storm surge flooding. The systematic storm surge height measurements along the coastlines of Louisiana, Mississippi, Alabama and Florida resulted in a unique data set of 152 data points with 56 on the barrier islands, revealing both the onshore and offshore storm surge distribution. The peaks in the measured storm surge height distribution exceeded 10 m along the Mississippi coastline. At every survey location Hurricane Katrina's storm surge (Category 3 at landfall) surpassed Hurricane Camille's storm surge heights (Category 5 at landfall). The wind velocity-based Saffire—Simpson scale is limited in categorizing storm surge heights. The lower floors of specially designed buildings were damaged by the storm surge and storm wave impact, while the upper floors sustained minimal wind damage. Similar damage patterns were recorded on the forests of the barrier islands. The measured storm surge heights along New Orleans's Lake shore indicate that the 17th Street Canal levee failed prior to overtopping. The massive land loss on the Mississippi and Alabama barrier islands due to Hurricane Katrina's storm-surge-induced currents is illustrated by the 37% increase in the cumulated channel widths between the islands. The significant reduction of the barrier islands increased the vulnerability of the US Gulf Coast to future hurricane storm surges. Rapid recovery of the barrier islands is necessary to partially reduce the numerous breaches and widened channels in order for the barrier islands to resume their protective function.

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