# Hurricane Katrina Storm Surge Reconnaissance

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**Abstract:** Hurricane Katrina (August 23–30, 2005) was one of the costliest and deadliest hurricanes to ever strike the United States, impacting 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 survey covered both the impact on the built and the natural environments. The storm surge peaked to the east of Katrina's path exceeding 10 m 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. The storm surge measurements along New Orleans Lakeshore allowed the investigators to exclude overtopping as failure mechanism for the 17th Street outfall canal levee. Hurricane Katrina's storm surge distribution (Category 3 at landfall) is compared against Hurricane Camille's storm surge distribution (Category 5 at landfall). The land loss on the barrier islands and the increased vulnerability of the US Gulf Coast to future hurricane storm surges is discussed.

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**CE Database subject headings:** Hurricanes; Storm surges; Florida; Alabama; Mississippi; Louisiana; Reconnaissance; Surveys.

## Introduction

Hurricane Katrina (August 23–30, 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 exceeds 1,000 in Louisiana and 200 in Mississippi. Katrina made its first landfall as a Category 1 hurricane in southeastern Florida at 2230 UTC on August 25. Katrina attained its peak intensity of 280 km/h (central pressure 902 mb) at 1800 UTC on August 28 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 on August 29. 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 August 29 as it had been late on August 28, 2005.

The affected coastlines were particularly vulnerable to the storm surge because of the low-lying, coastal plain topography

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and the lack of effective barriers. The damage and performance of structures and the measurements of high water 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). 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 population (Sheikh 2005). Herein an independent storm surge data set is presented encompassing not only the built environment, but also mostly uninhabited Mississippi barrier islands forming the Gulf Islands National Seashore. Hence, this uniformly collected storm surge data set widely complements government agency reports and allows for independent verification, as well as a key benchmark data set for numerical models.

## Post-Hurricane Field Survey

The widespread failure of tide gauges along the Mississippi and Louisiana shores called upon reconnaissance crews to collect 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 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 were consistent in most cases. 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, August 14–22, 1969 (USACE 1970).

The storm surge peaked to the east of Katrina's path with consistent recordings between 7 and 10 m 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 decreased below 5 m along the Alabama coast. Nevertheless, more than 2 m 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 m along Lake Maurepas (80 km west of the track). Surge heights exceeding 6 m were only recorded in Shell Beach (Louisiana) a few km to the west of the track along Lake Borgne. Along Lake Pontchartrain, a significant storm surge gradient from east to west was observed with 5 m surge heights in Slidell and along the Chef Menteur Pass (LA) and a rapid surge height decay towards Lake Maurepas. 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.

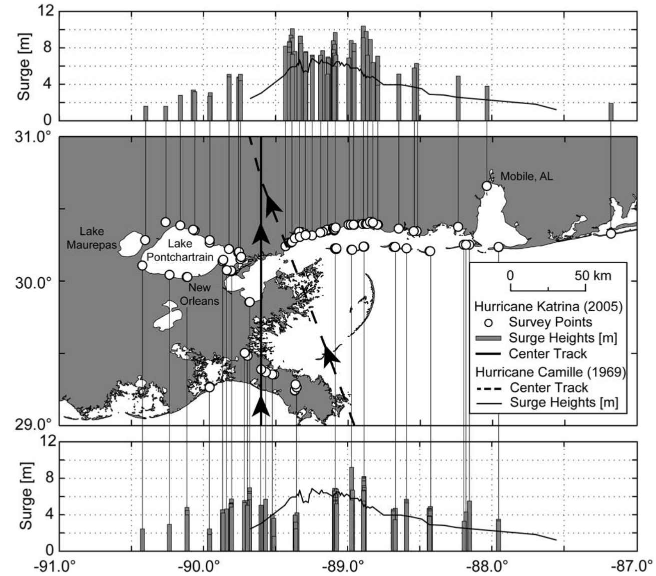


**Fig. 1.** Hurricane Katrina (2005) storm surge height measurements and Hurricane Camille (1969) high water mark profile (USACE 1970)

The systematic storm surge height measurements along the coastlines of Louisiana, Mississippi, Alabama, and Florida resulted in a unique high water mark data set of 153 data points with 56 on the barrier islands, revealing both the onshore and offshore storm surge distributions. Table 1 gives the full high water mark database gathered during the survey excluding additional transect and shoreline points. The overview map shown in Fig. 1 summarizes the database.

## Comparison of Hurricane Camille's and Katrina's Storm Surge Distributions

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 h prior to the main landfall. The massive storm surge produced by Katrina is primarily attributed to the huge size of the storm. On August 29, Katrina had a 50 km radius 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 its 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.

**Table 1.** Storm Surge Height Data Set Recorded by the Survey Team in the Immediate Aftermath of Hurricane Katrina

| Number | State | Location | Latitude °N | Longitude °E | Vertical survey [m] | Vertical survey Nature | Inland [m] | Survey Date | Survey Time |
|---|---|---|---|---|---|---|---|---|---|
| 1 | AL | Fort Morgan | 30.23145 | −87.95307 | 3.50 | MO | 74.5 | Sept. 29, 2005 | 17:41 |
| 2 | AL | Fort Morgan | 30.23283 | −87.95338 | 3.50 | MO | 230.6 | Sept. 29, 2005 | 18:11 |
| 3 | AL | Fort Morgan | 30.23283 | −87.95338 | 3.30 | MI | 230.6 | Sept. 29, 2005 | 18:11 |
| 4 | AL | Fort Morgan | 30.23374 | −87.95312 | 3.30 | RD | 329.5 | Sept. 29, 2005 | 17:54 |
| 5 | AL | Fort Morgan | 30.23374 | −87.95312 | 3.40 | RD | 329.5 | Sept. 29, 2005 | 17:54 |
| 6 | AL | Fort Morgan | 30.23374 | −87.95312 | 3.40 | RD | 329.5 | Sept. 29, 2005 | 17:54 |
| 7 | AL | Fort Morgan | 30.23374 | −87.95312 | 3.40 | RD | 329.5 | Sept. 29, 2005 | 17:54 |
| 8 | AL | Fort Morgan | 30.23374 | −87.95312 | 3.10 | RD | 329.5 | Sept. 29, 2005 | 17:54 |
| 9 | AL | Mobile | 30.65569 | −88.03317 | 3.80 | RD | 8.0 | Oct. 5, 2005 | 14:04 |
| 10 | AL | Dauphin Island | 30.25023 | −88.15542 | 5.50 | DT | 0.0 | Sept. 30, 2005 | 12:56 |
| 11 | AL | Dauphin Island | 30.24932 | −88.19169 | 3.30 | DT | 120.6 | Sept. 30, 2005 | 14:23 |
| 12 | AL | Dauphin Island | 30.25038 | −88.18017 | 4.30 | MI | 151.0 | Sept. 30, 2005 | 14:53 |
| 13 | AL | Camden | 30.37195 | −88.23352 | 4.90 | TB | 27.9 | Oct. 4, 2005 | 15:47 |
| 14 | MS | West Ship Island | 30.21213 | −88.97209 | 9.20 | RD | 417.0 | Oct. 1, 2005 | 10:30 |
| 15 | MS | West Ship Island | 30.21230 | −88.97227 | 5.60 | MI | 437.5 | Oct. 1, 2005 | 10:30 |
| 16 | MS | West Ship Island | 30.21262 | −88.96632 | 6.70 | RD | 59.8 | Oct. 1, 2005 | 11:11 |
| 17 | MS | East Ship Island | 30.23470 | −88.89082 | 5.50 | TB | 55.9 | Oct. 1, 2005 | 12:12 |
| 18 | MS | East Ship Island | 30.23517 | −88.88997 | 6.70 | TB | 53.9 | Oct. 1, 2005 | 13:22 |
| 19 | MS | East Ship Island | 30.23585 | −88.88815 | 8.10 | TB | 40.1 | Oct. 1, 2005 | 12:28 |
| 20 | MS | East Ship Island | 30.23584 | −88.88831 | 7.70 | TB | 49.9 | Oct. 1, 2005 | 12:29 |
| 21 | MS | East Ship Island | 30.23591 | −88.88845 | 6.60 | TB | 65.4 | Oct. 1, 2005 | 12:55 |
| 22 | MS | East Ship Island | 30.23663 | −88.88674 | 8.20 | TB | 37.5 | Oct. 1, 2005 | 12:51 |
| 23 | MS | East Ship Island | 30.23735 | −88.88557 | 7.00 | TB | 35.8 | Oct. 1, 2005 | 12:48 |
| 24 | MS | East Ship Island | 30.23735 | −88.88557 | 7.20 | TB | 35.8 | Oct. 1, 2005 | 12:48 |
| 25 | MS | East Ship Island | 30.23622 | −88.88956 | 8.00 | TB | 171.1 | Oct. 1, 2005 | 13:14 |
| 26 | MS | Ocean Springs | 30.38810 | −88.79090 | 6.30 | RD | 0.0 | Oct. 1, 2005 | 17:31 |
| 27 | MS | Ocean Springs | 30.38882 | −88.79118 | 7.10 | TB | 0.0 | Oct. 1, 2005 | 17:31 |
| 28 | MS | Ocean Springs | 30.38890 | −88.79143 | 3.90 | RD | 0.0 | Oct. 1, 2005 | 17:31 |
| 29 | MS | Lakeview | 30.23828 | −89.42984 | 8.20 | DT | 487.0 | Oct. 2, 2005 | 9:19 |
| 30 | MS | Buccaneer State Park | 30.26302 | −89.40391 | 8.70 | MO | 233.8 | Oct. 2, 2005 | 10:37 |
| 31 | MS | Buccaneer State Park | 30.26302 | −89.40391 | 8.60 | DT | 233.8 | Oct. 2, 2005 | 10:37 |
| 32 | MS | Buccaneer State Park | 30.26382 | −89.40324 | 8.10 | DT | 247.5 | Oct. 2, 2005 | 10:57 |
| 33 | MS | Buccaneer State Park | 30.26569 | −89.40468 | 7.50 | RD | 497.3 | Oct. 2, 2005 | 10:15 |
| 34 | MS | Waveland | 30.26440 | −89.39262 | 8.40 | TB | 92.3 | Oct. 2, 2005 | 11:05 |
| 35 | MS | Waveland | 30.26494 | −89.39298 | 9.40 | RD | 146.6 | Oct. 2, 2005 | 11:05 |
| 36 | MS | Waveland | 30.26891 | −89.38410 | 9.10 | DT | 99.8 | Oct. 2, 2005 | 11:19 |
| 37 | MS | Waveland | 30.26899 | −89.38372 | 10.10 | RD | 95.6 | Oct. 2, 2005 | 11:19 |
| 38 | MS | Waveland | 30.26904 | −89.38396 | 7.30 | RD | 107.0 | Oct. 2, 2005 | 11:19 |
| 39 | MS | Bay St. Louis | 30.31867 | −89.32418 | 8.50 | DT | 151.3 | Oct. 2, 2005 | 12:55 |
| 40 | MS | Bay St. Louis | 30.29215 | −89.36561 | 7.60 | MI | 692.4 | Oct. 2, 2005 | 15:54 |
| 41 | MS | Bay St. Louis | 30.33974 | −89.33723 | 6.35 | RD | 113.0 | Oct. 2, 2005 | 16:39 |
| 42 | MS | Bay St. Louis | 30.30623 | −89.32839 | 9.30 | RD | 45.7 | Oct. 2, 2005 | 17:13 |
| 43 | MS | Long Beach | 30.35296 | −89.13303 | 6.90 | MI | 201.4 | Oct. 3, 2005 | 9:42 |
| 44 | MS | Long Beach | 30.35046 | −89.13714 | 7.00 | DT | 128.5 | Oct. 3, 2005 | 10:28 |
| 45 | MS | Long Beach | 30.35249 | −89.14015 | 5.10 | DT | 494.8 | Oct. 3, 2005 | 10:05 |
| 46 | MS | Long Beach | 30.33904 | −89.17281 | 7.70 | TB | 313.6 | Oct. 3, 2005 | 11:02 |
| 47 | MS | Pass Christian | 30.33334 | −89.18897 | 7.20 | DT | 277.0 | Oct. 3, 2005 | 11:26 |
| 48 | MS | Pass Christian | 30.31534 | −89.24503 | 7.20 | DT | 217.9 | Oct. 3, 2005 | 12:12 |
| 49 | MS | Pass Christian | 30.31534 | −89.24503 | 7.10 | MI | 217.9 | Oct. 3, 2005 | 12:12 |
| 50 | MS | Pass Christian | 30.31732 | −89.29047 | 7.10 | TB | 7.7 | Oct. 3, 2005 | 13:21 |
| 51 | MS | Pass Christian | 30.31732 | −89.29047 | 7.50 | TB | 7.7 | Oct. 3, 2005 | 13:21 |
| 52 | MS | Pass Christian | 30.31655 | −89.29003 | 7.60 | TB | 25.0 | Oct. 3, 2005 | 13:29 |
| 53 | MS | Gulfport | 30.36216 | −89.10132 | 8.80 | DT | 0.0 | Oct. 3, 2005 | 15:31 |
| 54 | MS | Gulfport | 30.36034 | −89.09424 | 6.00 | DT | 0.0 | Oct. 4, 2005 | 14:21 |
| 55 | MS | Gulfport | 30.36282 | −89.09689 | 7.80 | DT | 405.4 | Oct. 3, 2005 | 15:53 |

**Table 1.** (*Continued.*)

| Number | State | Location | Latitude °N | Longitude °E | Vertical survey [m] | Vertical survey Nature | Inland [m] | Survey Date | Survey Time |
|---|---|---|---|---|---|---|---|---|---|
| 56 | MS | Gulfport | 30.35162 | −89.09016 | 8.40 | DT | 36.8 | Oct. 4, 2005 | 13:24 |
| 57 | MS | Gulfport | 30.35374 | −89.09288 | 7.40 | DT | 0.0 | Oct. 4, 2005 | 13:37 |
| 58 | MS | Gulfport | 30.35639 | −89.08685 | 9.70 | DT | 50.0 | Oct. 4, 2005 | 14:02 |
| 59 | MS | Gulfport | 30.36963 | −89.08227 | 7.20 | DT | 154.9 | Oct. 3, 2005 | 16:07 |
| 60 | MS | Biloxi | 30.38934 | −88.99214 | 6.90 | DT | 124.7 | Oct. 3, 2005 | 16:36 |
| 61 | MS | Biloxi | 30.39105 | −88.97612 | 8.80 | DT | 57.9 | Oct. 3, 2005 | 16:55 |
| 62 | MS | Biloxi | 30.39055 | −88.95620 | 8.50 | DT | 0.0 | Oct. 3, 2005 | 17:09 |
| 63 | MS | Biloxi | 30.39096 | −88.95507 | 7.60 | DT | 0.0 | Oct. 3, 2005 | 17:26 |
| 64 | MS | Biloxi | 30.39067 | −88.95586 | 8.50 | DT | 0.0 | Oct. 3, 2005 | 17:26 |
| 65 | MS | Biloxi | 30.39148 | −88.89053 | 9.10 | DT | 0.0 | Oct. 3, 2005 | 17:48 |
| 66 | MS | Biloxi | 30.39161 | −88.89362 | 10.40 | DT | 0.0 | Nov. 18, 2005 | 10:46 |
| 67 | MS | Biloxi | 30.39297 | −88.87193 | 9.80 | DT | 86.1 | Oct. 3, 2005 | 17:57 |
| 68 | MS | Biloxi | 30.39305 | −88.86223 | 7.20 | DT | 202.4 | Oct. 3, 2005 | 18:13 |
| 69 | MS | Pascagoula | 30.34175 | −88.52238 | 6.30 | DT | 92.2 | Oct. 4, 2005 | 8:34 |
| 70 | MS | Pascagoula | 30.34425 | −88.53822 | 5.80 | DT | 57.7 | Oct. 4, 2005 | 8:55 |
| 71 | MS | Gautier | 30.36112 | −88.64513 | 5.15 | MI | 97.7 | Oct. 4, 2005 | 9:49 |
| 72 | MS | Ocean Springs | 30.40768 | −88.84382 | 8.90 | DT | 379.0 | Oct. 4, 2005 | 10:44 |
| 73 | MS | Ocean Springs | 30.40429 | −88.82331 | 6.40 | DT | 49.5 | Oct. 4, 2005 | 11:01 |
| 74 | MS | Petit Bois Island | 30.20505 | −88.43348 | 3.90 | RD | 246.6 | Feb. 3, 2006 | 10:57 |
| 75 | MS | Petit Bois Island | 30.20419 | −88.43345 | 4.60 | RD | 339.3 | Feb. 3, 2006 | 11:04 |
| 76 | MS | Petit Bois Island | 30.20419 | −88.43345 | 4.70 | TB | 339.3 | Feb. 3, 2006 | 11:04 |
| 77 | MS | Petit Bois Island | 30.20457 | −88.43240 | 3.80 | TB | 295.0 | Feb. 3, 2006 | 11:13 |
| 78 | MS | Petit Bois Island | 30.20295 | −88.42802 | 3.80 | TB | 116.1 | Feb. 3, 2006 | 11:58 |
| 79 | MS | Petit Bois Island | 30.20386 | −88.42663 | 4.90 | TB | 213.0 | Feb. 3, 2006 | 12:21 |
| 80 | MS | Petit Bois Island | 30.20386 | −88.42663 | 4.60 | TB | 213.0 | Feb. 3, 2006 | 12:21 |
| 81 | MS | Petit Bois Island | 30.20404 | −88.42659 | 4.30 | TB | 232.5 | Feb. 3, 2006 | 12:14 |
| 82 | MS | Petit Bois Island | 30.20404 | −88.42659 | 4.40 | TB | 232.5 | Feb. 3, 2006 | 12:14 |
| 83 | MS | Horn Island | 30.22374 | −88.59161 | 5.30 | TB | 192.0 | Feb. 3, 2006 | 14:09 |
| 84 | MS | Horn Island | 30.22374 | −88.59161 | 5.50 | TB | 192.0 | Feb. 3, 2006 | 14:09 |
| 85 | MS | Horn Island | 30.22391 | −88.59285 | 5.70 | TB | 232.1 | Feb. 3, 2006 | 14:25 |
| 86 | MS | Horn Island | 30.23431 | −88.68197 | 4.40 | RD | 146.7 | Nov. 18, 2005 | 13:57 |
| 87 | MS | Horn Island | 30.23431 | −88.68197 | 4.60 | TB | 146.7 | Nov. 18, 2005 | 13:57 |
| 88 | MS | Horn Island | 30.23247 | −88.67136 | 3.40 | RD | 219.2 | Nov. 18, 2005 | 14:29 |
| 89 | MS | Horn Island | 30.23379 | −88.66912 | 4.70 | DT | 465.1 | Nov. 18, 2005 | 14:36 |
| 90 | MS | Cat Island | 30.22568 | −89.08950 | 6.60 | DT | 38.1 | Jan. 20, 2006 | 11:14 |
| 91 | MS | Cat Island | 30.22553 | −89.08951 | 6.90 | DT | 16.1 | Jan. 20, 2006 | 11:26 |
| 92 | MS | Cat Island | 30.22513 | −89.08777 | 5.60 | RD | 8.4 | Jan. 20, 2006 | 11:49 |
| 93 | MS | Cat Island | 30.22462 | −89.08581 | 5.50 | TB | 7.9 | Jan. 20, 2006 | 11:59 |
| 94 | MS | Cat Island | 30.22462 | −89.08581 | 5.60 | TB | 7.9 | Jan. 20, 2006 | 11:59 |
| 95 | MS | Cat Island | 30.22465 | −89.08522 | 6.30 | RD | 17.9 | Jan. 20, 2006 | 12:03 |
| 96 | MS | Cat Island | 30.22487 | −89.08524 | 6.90 | RD | 42.8 | Jan. 20, 2006 | 12:07 |
| 97 | MS | Cat Island | 30.22480 | −89.08502 | 6.50 | TB | 39.5 | Jan. 20, 2006 | 12:09 |
| 98 | MS | Cat Island | 30.22508 | −89.08528 | 6.70 | RD | 66.3 | Jan. 20, 2006 | 12:14 |
| 99 | MS | Cat Island | 30.22518 | −89.08548 | 6.70 | RD | 81.0 | Jan. 20, 2006 | 12:15 |
| 100 | MS | Cat Island | 30.22560 | −89.08530 | 5.90 | RD | 123.6 | Jan. 20, 2006 | 12:15 |
| 101 | MS | Cat Island | 30.22140 | −89.07941 | 5.60 | RD | 131.6 | Jan. 20, 2006 | 12:44 |
| 102 | MS | Cat Island | 30.22219 | −89.07888 | 5.20 | RD | 198.6 | Jan. 20, 2006 | 12:52 |
| 103 | MS | Cat Island | 30.22277 | −89.07834 | 6.80 | RD | 185.1 | Jan. 20, 2006 | 13:10 |
| 104 | MS | Cat Island | 30.22277 | −89.07834 | 5.90 | TB | 185.1 | Jan. 20, 2006 | 13:10 |
| 105 | FL | Pensacola | 30.32627 | −87.17912 | 1.90 | RD | 139.0 | Sept. 29, 2005 | 12:00 |
| 106 | LA | Venice | 29.23837 | −89.36441 | 3.96 | MI |  | Oct. 26, 2005 | 10:23 |
| 107 | LA | Venice | 29.24000 | −89.36461 | 3.90 | RD |  | Oct. 26, 2005 | 10:32 |
| 108 | LA | Venice | 29.26331 | −89.35313 | 4.20 | DT | 33.9 | Oct. 26, 2005 | 10:47 |
| 109 | LA | Venice | 29.28078 | −89.36013 | 2.40 | MO |  | Oct. 26, 2005 | 11:03 |
| 110 | LA | Venice | 29.28060 | −89.35936 | 3.20 | MI |  | Oct. 26, 2005 | 11:08 |

**Table 1.** (*Continued.*)

| Number | State | Location | Latitude °N | Longitude °E | Vertical survey [m] | Vertical survey Nature | Inland [m] | Survey Date | Survey Time |
|---|---|---|---|---|---|---|---|---|---|
| 111 | LA | Venice | 29.28060 | −89.35936 | 2.45 | MO | | Oct. 26, 2005 | 11:08 |
| 112 | LA | Buras | 29.34838 | −89.51062 | 1.60 | MI | | Oct. 26, 2005 | 11:51 |
| 113 | LA | Buras | 29.34838 | −89.51062 | 3.60 | DT | | Oct. 26, 2005 | 11:51 |
| 114 | LA | Buras | 29.34932 | −89.52148 | 4.00 | RD | | Oct. 26, 2005 | 12:18 |
| 115 | LA | Empire | 29.36657 | −89.56668 | 5.67 | MI | | Oct. 26, 2005 | 13:39 |
| 116 | LA | Empire | 29.38621 | −89.59976 | 5.00 | MI | | Oct. 26, 2005 | 13:17 |
| 117 | LA | Port Sulphur | 29.47964 | −89.69441 | 5.01 | MI | | Oct. 26, 2005 | 14:28 |
| 118 | LA | Port Sulphur | 29.47964 | −89.69441 | 5.51 | MO | | Oct. 26, 2005 | 14:28 |
| 119 | LA | Port Sulphur | 29.49802 | −89.71313 | 5.31 | TB | | Oct. 26, 2005 | 14:45 |
| 120 | LA | Port Sulphur | 29.49802 | −89.71313 | 5.51 | TB | | Oct. 26, 2005 | 14:45 |
| 121 | LA | Shell Beach | 29.85480 | −89.67839 | 6.90 | TB | 35.8 | Oct. 26, 2005 | 17:04 |
| 122 | LA | Shell Beach | 29.85179 | −89.68067 | 5.60 | RD | | Oct. 26, 2005 | 17:18 |
| 123 | LA | Shell Beach | 29.85125 | −89.67990 | 6.50 | DT | | Oct. 26, 2005 | 17:18 |
| 124 | LA | Shell Beach | 29.85191 | −89.68013 | 6.30 | TB | | Oct. 26, 2005 | 17:29 |
| 125 | LA | Shell Beach | 29.85376 | −89.67760 | 6.90 | DT | | Oct. 26, 2005 | 17:42 |
| 126 | LA | Chef Menteur Pass, NO | 30.06716 | -89.80640 | 5.16 | MI | 20.7 | Oct. 27, 2005 | 8:57 |
| 127 | LA | Chef Menteur Pass, NO | 30.06600 | −89.80501 | 5.70 | DT | | Oct. 27, 2005 | 9:06 |
| 128 | LA | Chef Menteur Pass, NO | 30.06565 | −89.80435 | 5.30 | DT | | Oct. 27, 2005 | 9:14 |
| 129 | LA | Chef Menteur Pass, NO | 30.06565 | −89.80435 | 4.80 | RD | | Oct. 27, 2005 | 9:14 |
| 130 | LA | Chef Menteur Pass, NO | 30.06900 | −89.80858 | 5.20 | DT | | Oct. 27, 2005 | 9:25 |
| 131 | LA | Chef Menteur Pass, NO | 30.07243 | −89.83909 | 4.60 | DT | 46.6 | Oct. 27, 2005 | 9:47 |
| 132 | LA | Irish Bayou Canal, NO | 30.13497 | −89.86595 | 4.50 | DT | | Oct. 27, 2005 | 10:13 |
| 133 | LA | Irish Bayou Canal, NO | 30.14410 | −89.86195 | 4.20 | DT | | Oct. 27, 2005 | 10:22 |
| 134 | LA | Lake St. Catherine Marina, NO | 30.14960 | −89.74075 | 5.10 | DT | 17.9 | Oct. 5, 2005 | 10:45 |
| 135 | LA | Lake St. Catherine Marina, NO | 30.16253 | −89.73963 | 4.40 | DT | 56.0 | Oct. 5, 2005 | 10:56 |
| 136 | LA | Slidell | 30.19652 | −89.75541 | 4.70 | DT | | Oct. 5, 2005 | 11:08 |
| 137 | LA | Slidell | 30.19891 | −89.75461 | 4.80 | DT | | Oct. 5, 2005 | 11:14 |
| 138 | LA | Slidell | 30.21831 | −89.82354 | 4.80 | DT | | Oct. 27, 2005 | 10:34 |
| 139 | LA | Slidell | 30.21934 | −89.82248 | 5.10 | DT | | Oct. 27, 2005 | 10:43 |
| 140 | LA | Lacombe | 30.26518 | −89.95647 | 2.70 | MI | | Oct. 27, 2005 | 11:40 |
| 141 | LA | Lacombe | 30.28161 | −89.95373 | 3.10 | DT | | Oct. 27, 2005 | 12:06 |
| 142 | LA | Mandeville | 30.34974 | −90.06025 | 3.20 | DT | 75.3 | Oct. 27, 2005 | 12:42 |
| 143 | LA | Mandeville | 30.35381 | −90.07047 | 3.35 | DT | 0.0 | Oct. 27, 2005 | 12:42 |
| 144 | LA | Madisonville | 30.38273 | −90.15940 | 2.80 | DT | | Oct. 27, 2005 | 13:15 |
| 145 | LA | Wallace Landing | 30.40588 | −90.26198 | 1.60 | MO | | Oct. 27, 2005 | 14:01 |
| 146 | LA | Galva | 30.28132 | −90.40018 | 1.60 | RD | | Oct. 27, 2005 | 14:46 |
| 147 | LA | Laplace | 30.10677 | −90.42276 | 2.40 | MO | | Oct. 27, 2005 | 15:13 |
| 148 | LA | Kenner | 30.03944 | −90.23476 | 2.90 | DT | 32.1 | Oct. 27, 2005 | 16:37 |
| 149 | LA | Lakeshore, NO | 30.02663 | −90.11218 | 4.75 | RD | 36.9 | Oct. 27, 2005 | 16:37 |
| 150 | LA | Lakeshore, NO | 30.02649 | −90.11207 | 3.95 | RD | 55.9 | Oct. 27, 2005 | 16:39 |
| 151 | LA | Lakeshore, NO | 30.02619 | −90.11184 | 4.45 | RD | 95.7 | Oct. 27, 2005 | 16:42 |
| 152 | LA | Grand Isle | 29.26381 | −89.95533 | 1.80 | RD | | Oct. 28, 2005 | 16:10 |
| 153 | LA | Grand Isle | 29.26335 | −89.95725 | 2.40 | DT | | Oct. 28, 2005 | 16:27 |

Note: DT=damage trimline; MI=mudline inside; MO=mudline outside; RD=rafted debris; and TB=tree bark.

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. Hurricane Katrina's storm surge exceeded Hurricane Camille's at all survey locations.

## Barrier Islands Field Observations

Coastal Mississippi and Alabama feature six nearly shore-parallel barrier islands located 15 to 20 km from the mainland coast [Fig. 2(a)]. 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

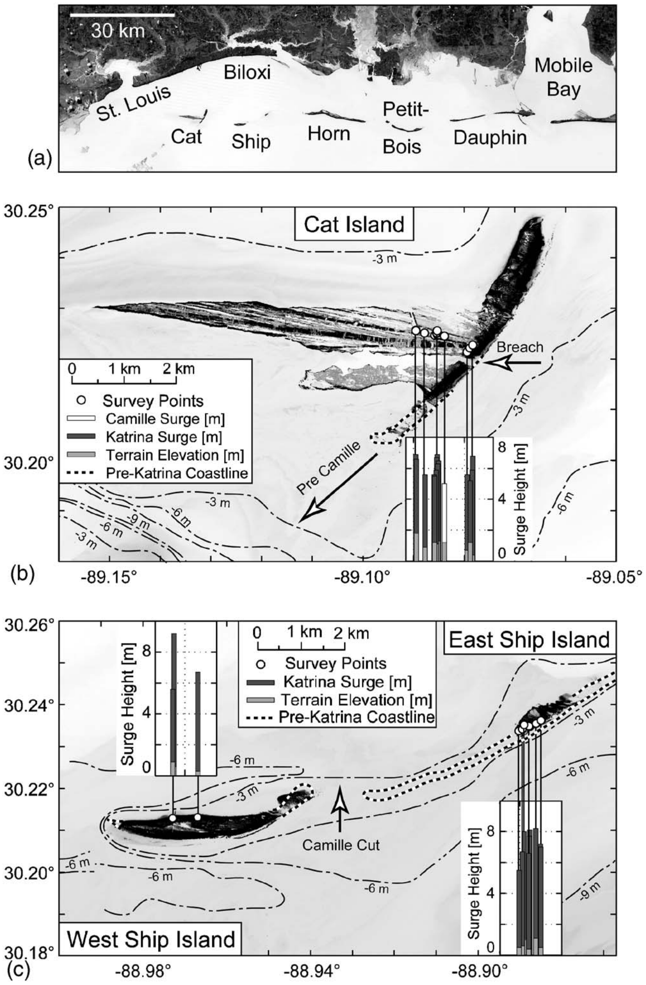


**Fig. 2.** Hurricane Katrina storm surge heights measured on the western Mississippi barrier islands with pre-Katrina shoreline and inverted post-Katrina IKONOS-satellite imagery (September 7, 2005): (a) location of barrier islands; (b) Cat Island (MS); and (c) West and East Ship Islands (MS)

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 (Nummedal et al. 1980; Schmid 2003). 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 overwashed 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 to 70 km east of Hurricane Katrina's track, storm surge water marks were recorded between 5.5 and 9 m (Fig. 2). Prior to Hurricane Katrina, the western most Cat Island featured five residential houses built on piles along a navigation channel at the center of the T-shaped island [Fig. 2(b)]. 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 together with two other houses. The frames of the two newest westernmost houses on Cat Island remained with severe washout damage and trimlines on the second floor, albeit being designed to the hurricane Camille storm surge height [Fig. 3(a)]. These two houses survived likely due to their location with several hundred meters of storm wave and current attenuating forest and marshland to the south and east. 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. 2(b)].

On West Ship Island, the historic brick Fort Massachusetts remained with minor damage. The south walls were severely battered by the storm waves superimposed on the storm surge. The earthwork on top of the fort was eroded and several cover stones collapsed. Wall overtopping filled the interior of the fort with half a meter of marsh grass and debris. Marsh grass was also caught in the hand rails on top of the fort. Most apparent were two scour holes at the corners of the semicircle-shaped fort. The largest scour hole with a diameter of 15 m was formed at the northeastern corner of the fort [Fig. 3(b)]. The fort completed in 1866 was built only 150 m from the west tip of the island, but westward migration of the island resulted in the fort's current location 1,400 m east of the west end and 550 m north of the south beach. Two towers were located 600 m east of the fort. The steel frame tower survived with marsh grass caught in the framework, while a wooden tower and its foundation collapsed due to scouring on the northeastern corner [Fig. 3(c)].

On the other Gulf Islands National Seashore barrier islands, high water marks were primarily based upon trimlines and scars in the bark of trees. 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. 3(d)]. 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. The amount of uprooted 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). 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 did not recover from the salt burn, while centuries old dwarf live oaks (*quercus geminata*) are recovering (George Boddie, co-owner Cat Island, MS, personal communication, 2007).

On the eastern Mississippi (Horn and Petit-Bois) and Alabama barrier islands (Dauphin Island) located 80 to 150 km to the east of Hurricane Katrina's track, the measured storm surge heights decreased to 3.5 to 5.5 m (Fig. 4). The variation of the high water measurements on the islands was in accordance with corresponding onshore recordings to the north. The breach in Dauphin Island was barely existent with 0.1 km before Hurricane Katrina and spanned 1.9 km in the immediate aftermath [Fig. 4(c)]. The 2 m overwash flow depth at the first house east of the breach was measured with a laser range finder [Fig. 3(e)]. Erosion levels such as the 0.7 m were determined based on revealed pipes and manholes [Fig. 3(f)]. The absence of a dense vegetation cover on


**Fig. 3.** (a) Cat Island, MS: one of the two only houses that survived with severe washout damage and trimline on the second floor; West Ship Island, MS: (b) Fort Massachusetts with 15 m diameter scour hole; (c) scour hole with collapsed tower foundation; (d) East Ship Island, MS: High water mark based on the bark stripped off a slash pine tree (note the 7.65 m long survey rod for scale); Dauphin Island, AL: (e) rapid surveying of a transect using a laser range finder (background: Offshore oil platform that broke loose and drifted from Louisiana to Alabama); and (f) massive 0.7 m overwash erosion revealing pipes

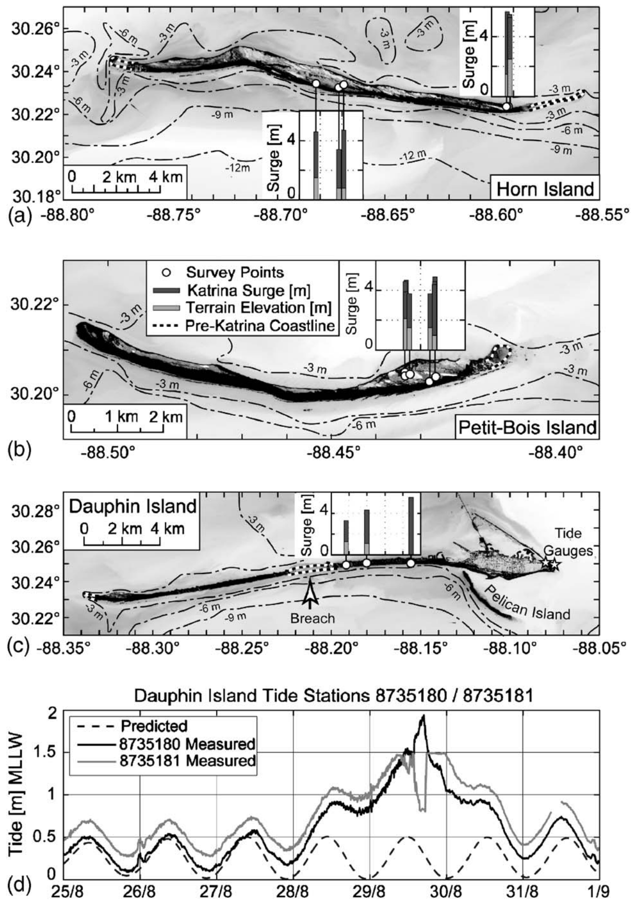


**Fig. 4.** Hurricane Katrina storm surge heights measured on the eastern Mississippi and Alabama barrier islands with pre-Katrina shoreline and inverted post-Katrina IKONOS-satellite imagery (September 7, 2005): (a) Horn Island (MS); (b) Petit-Bois Island (MS); (c) Dauphin Island (AL); and (d) Dauphin Island tide station recordings 8735180 and 8735181 (NWLON)

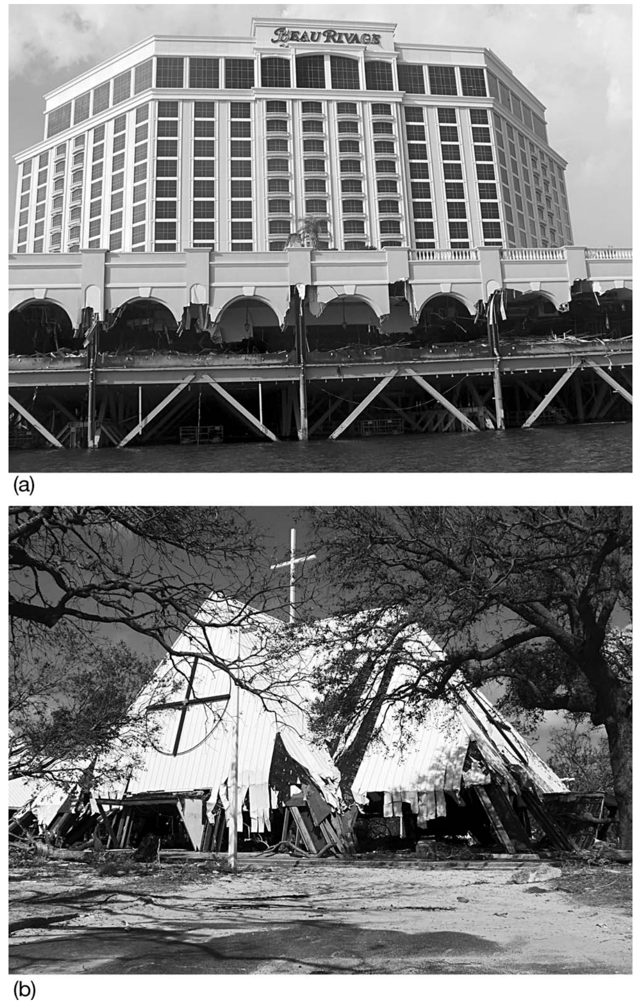


**Fig. 6.** Washout damage trimlines on massive steel frame structures designed to withstand hurricane Category 5 wind forces: (a) Beau Rivage Casino in Biloxi, MS, as seen from the reconnaissance boat; (b) Catholic church in Longbeach, MS

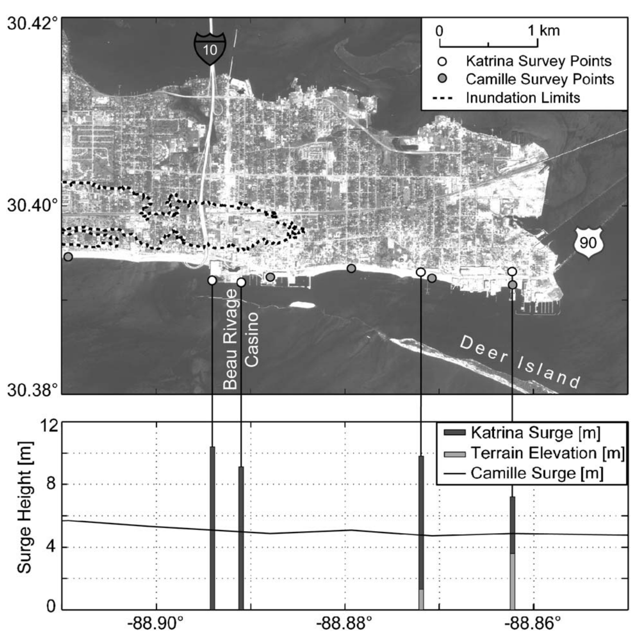


**Fig. 5.** Biloxi, MS, storm surge measurements combined with FEMA (2006a) inundation limits on post-Katrina IKONOS-satellite imagery (September 7, 2005)

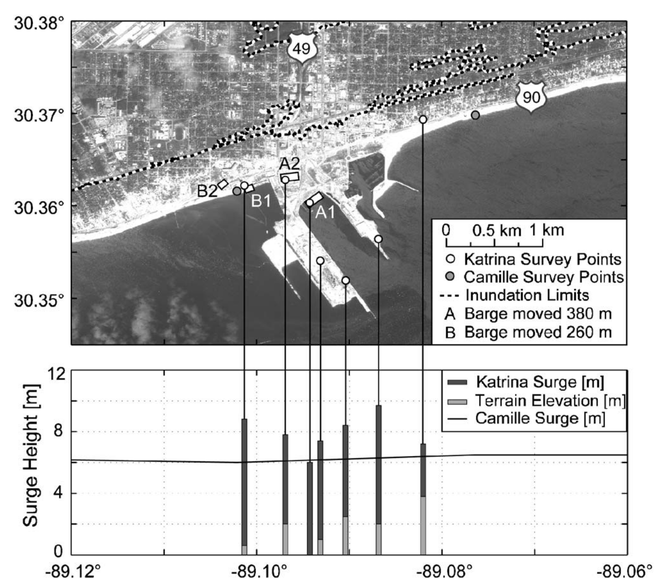


**Fig. 7.** Gulfport (MS) storm surge measurements and barge movements combined with FEMA (2006a) inundation limits on post-Katrina IKONOS-satellite imagery (September 7, 2005)

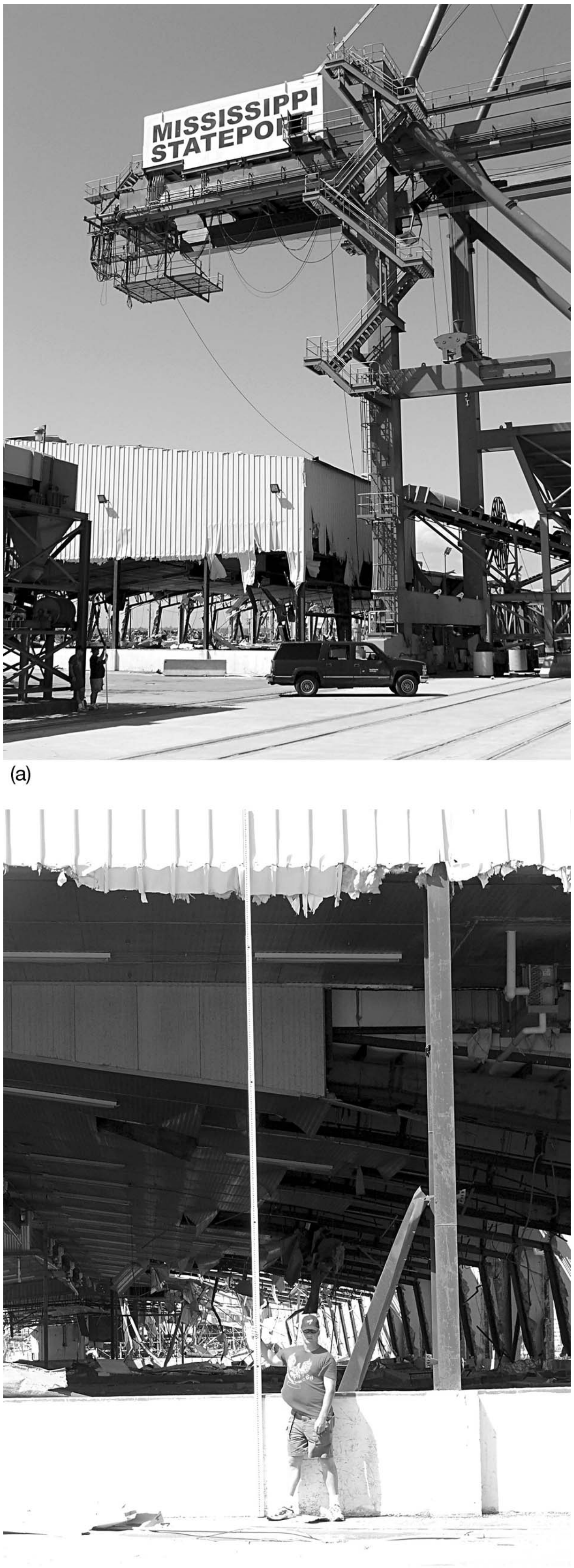


**Fig. 8.** Gulfport (MS) terminal: (a) intact container crane next to overwashed terminal with storm surge induced washout trimline on the storage building and intact upper siding and roof; (b) measurement of Hurricane Katrina storm surge height based on the washout trimline

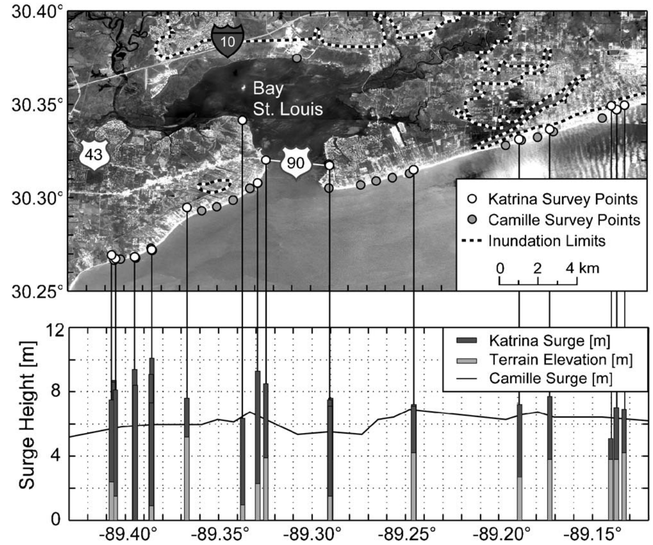


**Fig. 9.** Bay St. Louis, MS, storm surge measurements combined with FEMA (2006a) inundation limits on post-Katrina IKONOS-satellite imagery (September 7, 2005)

Dauphin Island increased its erosion vulnerability, illustrating the importance of coastal forests to reduce coastal erosion (Wolanski 2007).

Most tide stations broke down or delivered intermittent recordings during Hurricane Katrina. The tide stations on Dauphin Island are located inside the entrance to Mobile Bay somewhat protected by the offshore Pelican Island. The primary tide station 8735180 on the east tip of Dauphin Island continuously recorded the storm surge [Fig. 4(d)]. 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 northwest of station 8735180 prior to Hurricane Katrina (NWLON 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.

Hurricane Katrina's extreme storm surge induced currents and temporary flooding of the entire Mississippi barrier islands chain resulting in massive erosion and local accretion. The roughly perpendicular path of hurricane Katrina with respect to the barrier islands chain resulted in significant land loss. The significantly increased channel widths between the islands reduce the coastal protection provided to the mainland by the barrier islands. 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 (Fritz et al. 2007). 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). Beyond change brought about by natural forces, an important factor in the combined island's evolution primarily since 1948 has been maintenance of Ship Island, Pascagoula, and Mobile channels.


**Fig. 10.** Bay St. Louis, MS: (a) massive beach and shoreline erosion; (b) corresponding sand deposit 100 m inland submerging a backyard fence; Pass Christian, MS: (c) uplifted and northward collapsed sections of the Highway 90 bridge; and (d) surge height measurements along trees next to Highway 90

## Mississippi Gulf Coast Field Observations

The storm surge distribution peaked along a 60 km stretch of densely developed Mississippi coastline from Lakeshore to Ocean Springs. Coastal high water marks were primarily measured on structures that were damaged by combined effects of storm waves and storm surge, such as in Biloxi, MS (Fig. 5). Characteristic high water mark measurements are shown in Fig. 6. A typical view from the reconnaissance boat shows a sharp damage trimline along the entire ocean side 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. 6(a)]. Even along the hardest hit coastline buildings designed to resist peak hurricane winds were marginally damaged above the waterline, while classic washout failures marked the storm surge [Fig. 6(b)]. The storm surge is the primary cause of the high water marks. Height contributions due to storm waves were significant at the immediate shoreline, but decreased rapidly over the first 100 m inland.

The state port of Mississippi in Gulfport was the third busiest

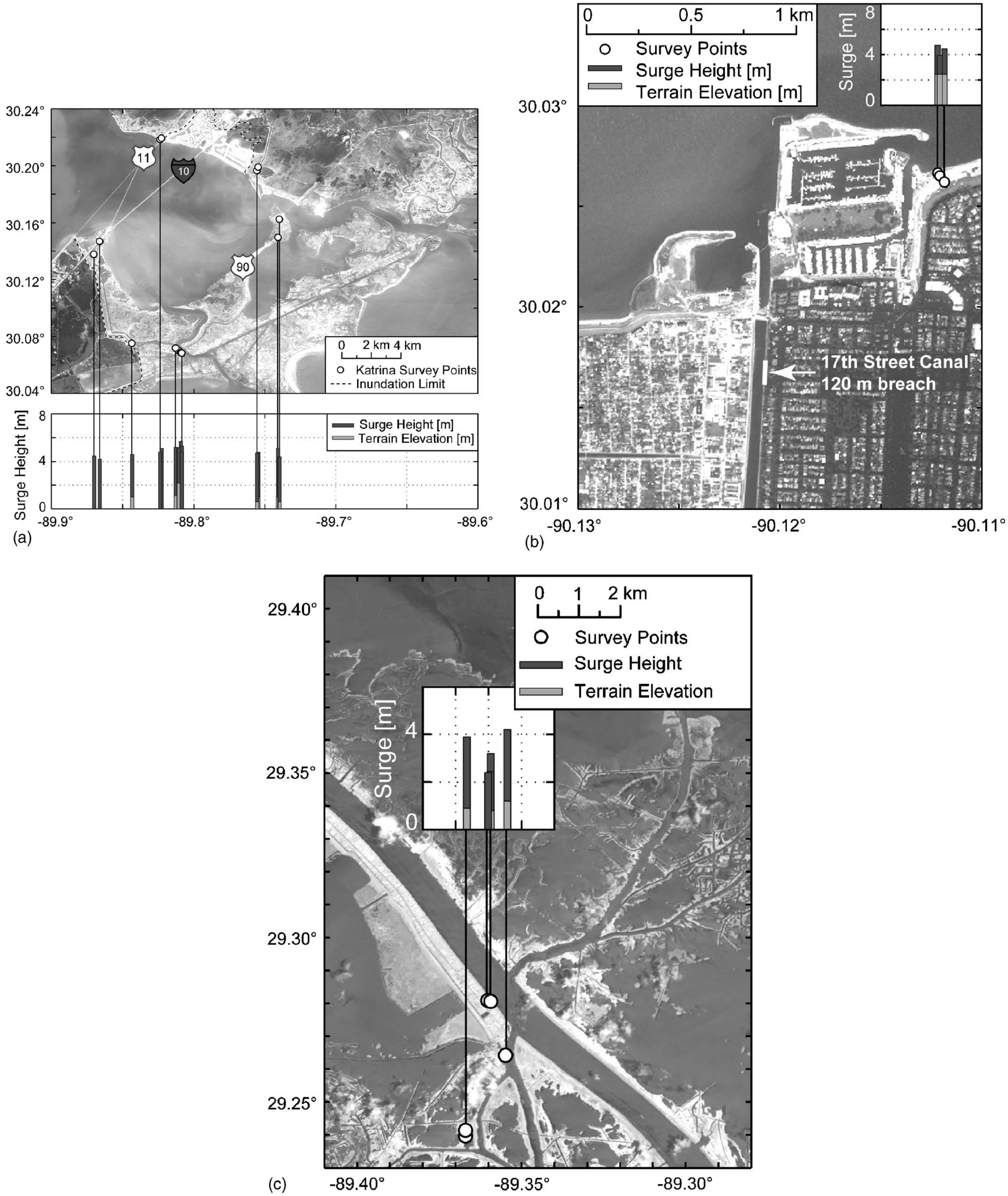


**Fig. 11.** Louisiana storm surge measurements combined with FEMA (2006c) inundation limits on post-Katrina IKONOS-satellite imagery (September 7, 2005): (a) Slidell and Chef Menteur; (b) New Orleans Lakeshore and 17th Street outfall canal; and (c) Venice at the mouth of the Mississippi river

container port on the U.S. Gulf of Mexico and the second importer of green fruit in the United States with 1,800 m of berthing space and a channel depth of 11 m (Fig. 7). Gulfport is located 50 km to the east of the hurricane center in the middle of the hardest hit stretch of coastline. The infrastructure damage was limited to classic washout damage on the warehouses at the loading terminal (Fig. 8). The combined height of the casino barge drafts and the pile heights at the docks provided minimal surge heights of 6 m necessary to mobilize and raft the barges several hundred meters ashore (Fig. 7). Similarly, sea containers became floating barges and scattered across the container storage and handling lots, as well as inland, up to the inundation limit. Detection, classification, and attribution of high resolution satellite image features in the aftermath of Hurricane Katrina in Gulfport were investigated for damage assessments and emergency response planning (Barnes et al. 2007).

The stretch of Mississippi coastline east and west of Bay St. Louis exhibited extreme storm surge heights between 7 and 10 m (Fig. 9). In Bay St. Louis, massive beach erosion occurred at the entrance to the Bay accompanied by the largest sand deposits a few hundred meters inland and northward [Figs. 10(a and b)]. All the beams of the Highway 90 bridge crossing from Bay St. Louis to Pass Christian were uplifted and tumbled northward [Fig. 10(c)]. Bark damage on trees along the bay and the highway embankment in Pass Christian allowed the research team to determine both the total surge height as well as the overflow depth (Fig. 10). The Highway 90 bridge was submerged by 3 m.

## Louisiana Field Observations

In Louisiana, surge heights exceeding 6 m were only recorded in Shell Beach facing Lake Borgne and the Mississippi Sound a few km to the west of the track. Along Lake Pontchartrain, a significant storm surge gradient from east to west was observed with the peak surge heights exceeding 5 m in Slidell and along the Chef Menteur Pass [Fig. 11(a)]. At the mouth of the Mississippi river in Venice, the storm surge height was limited to 4 m [Fig. 11(c)]. 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. The high water marks along the intact 5.5 m high Lakeshore levee system remained well below 5 m [Fig. 11(b)]. Facing directly Lake Pontchartrain, these high water marks were attributed to a combination of storm surge and storm waves. The storm waves and their runup likely contributed on the order of 1.5 m reducing the pure storm surge to 3 m. The nearby 17th Street outfall canal levee failed prior to reaching design capacity in early morning on August 29 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.

## 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 153 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 Lakeshore 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 resulted in an increased vulnerability of the US Gulf Coast to future hurricane storm surges, which depends on the duration and extent of barrier island recovery.

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