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Survey of the effects of Hurricane Katrina on the Gulf Coast

October 17-19, 2005

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Abstract

Hurricane Katrina devastated the Louisiana and Mississippi Gulf Coast region via a combination of storm surge, strong winds, and tornadoes. East of the eye (the scope of this survey), a 10 meter surge caused massive destruction. Most homes floated off their foundations or piles, and were destroyed in the process. The piles these homes were built upon survived intact in the cases where these piles were made of wood, but toppled when made of concrete, due to the stresses induced by the homes' buoyancy in the surge. Bridges decks were pushed off their piles by a combination of the surge and waves atop the surge, and some piles themselves toppled due to tidal-current-induced erosion of the soils they were sunk into. Roads and railroads collapsed when the soils and ballast supporting them were undercut. Hard structures (such as reinforced concrete and steel frame buildings) failed when either trees fell on them, buoyant debris collided with them, or the momentum of the surge and ocean waves battered them. Heavy sediments, such as gravel and sand, appeared to be eroded in a seaward direction, while large buoyant debris migrated landward in most cases. Reconstruction in the region may take some valuable lessons from the field of earthquake engineering, as well as from traditional Japanese bridge construction methods, but the most effective response will likely be to turn some of the shoreline into public access parks to create a buffer zone for storm surge, while moving residences further inland.

1. Introduction

The Gulf Coast of the southeastern United States is a region that occasionally experiences catastrophic hurricanes. The warm, shallow waters of the Gulf of Mexico tend to strengthen hurricanes that advect there from the east. Sometimes, these hurricanes continue advecting westward, and strike havoc on the coast of Texas, such as was the case in 1900, when an unnamed hurricane caused a storm surge that submerged and destroyed the resort city of Galveston, causing about 8,000 deaths (those were the days before advances in communications technology made hurricane warnings possible), making it the deadliest disaster ever to have hit the US. Other hurricanes, upon reaching the Gulf of Mexico, turn around completely, and advect back eastward, to land on the western coast of Florida. This was the case of Hurricane Wilma, which hit southwestern Florida on October 24, 2005 as a category 3 storm, but had at its peak, over the Gulf of Mexico, been the most powerful tropical cyclone ever recorded in the Atlantic basin. Due to precautions and evacuations in place before this storm landed, however, the death toll in Florida was only 35. Among these deaths, about 1/4 were direct deaths, due to flying debris and falling trees hitting residents, while the rest were indirect deaths, such as car accidents occurring during evacuation, and illness induced in elderly residents by lack of air conditioning during their three weeks without electric power following the storm. Yet other hurricanes turn north during their growth in the Gulf of Mexico. Hurricane Betsy of 1965 and Hurricane Camille of 1969 were two such storms, and swamped New Orleans and the Mississippi (MS) coast, respectively, with storm surge. Hurricane Katrina followed a similar path to that of Betsy and

Camille, but its much larger size and slower speed of propagation resulted in more destruction than either of the previous storms caused.

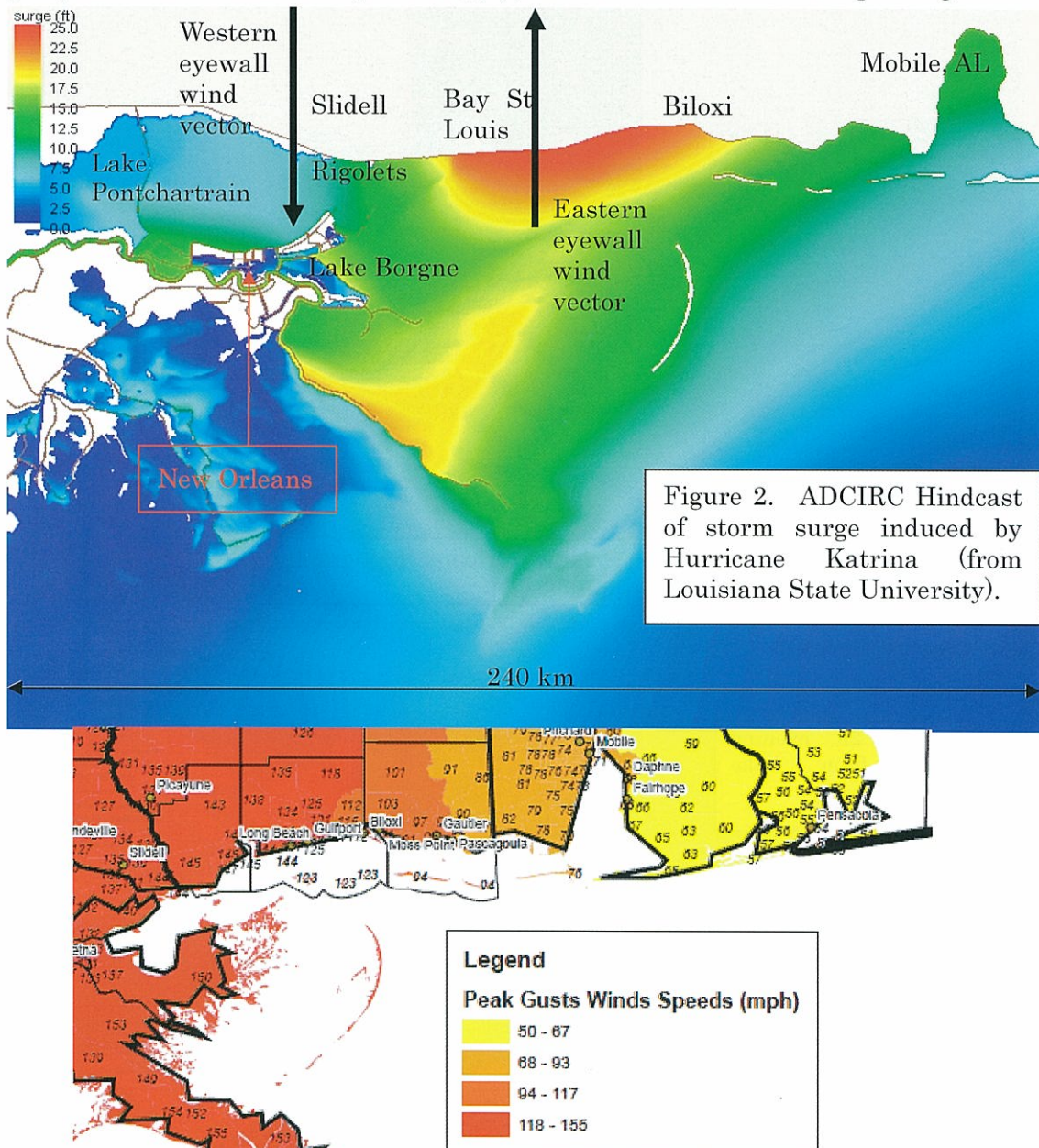
Hurricane Katrina struck the Gulf Coast region on Monday, August 29, 2005, as a category 4 hurricane, with sustained winds of 240 kph at landfall. The hurricane traveled northward through the region, with the eye passing through Pearlington, MS, near the border with Louisiana (LA) (figure 1). The western eyewall passed through Slidell, LA (a bedroom community for New Orleans), while the eastern eyewall passed through Waveland and Bay St. Louis, MS. The hurricane brought with it a storm surge of up to 10 m around the St. Louis Bay region (figure 2). The surge extended west to Slidell (via the Rigolets to Lake Pontchartrain) and east all the way to Mobile, Alabama (AL) (figure 2). This surge caused massive destruction along the entire coast, as well as inland, via bayous and overland flow. Along most of coastal MS, where residential land elevations are all at least 3 m above sea level, the flood lasted about 5 hours, and drained back into the ocean after the hurricane passed (a very different case than that of New Orleans, much of which is below sea level, resulting in flooding for over a week). In addition to the surge, the hurricane's high winds (figure 3) caused severe damage, and shear in the wind field near the eyewalls spawned many tornadoes.



The scope of this survey is the Gulf Coast, extending from Slidell, LA in the west, to Biloxi, MS in the east (encompassing the coasts of St. Tammany parish, and Hancock and Harrison counties). However, to compare the damage there with the much more publicized fate of New Orleans, I'll begin with a brief summary of what happened to that city in section 2 of this report. Section 3 is a narrative of the detailed survey of the Gulf Coast, explaining the photographs I took, in chronological order. Section 4 then summarizes the important findings of the survey, as well as makes some suggestions for a safer future.

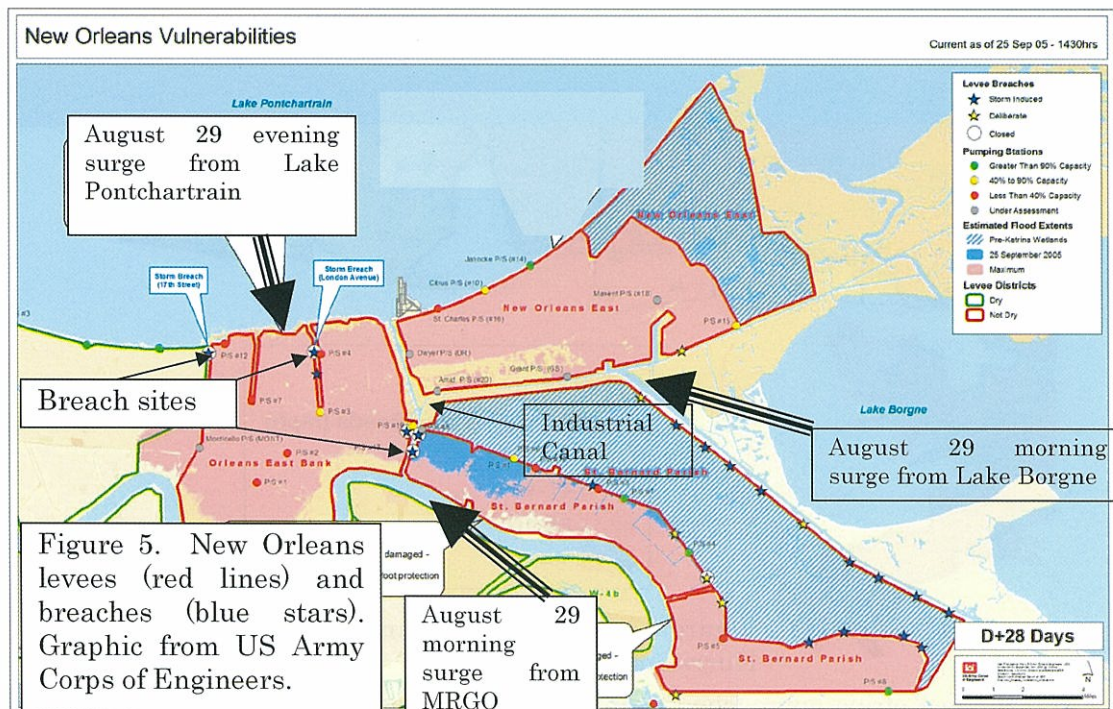
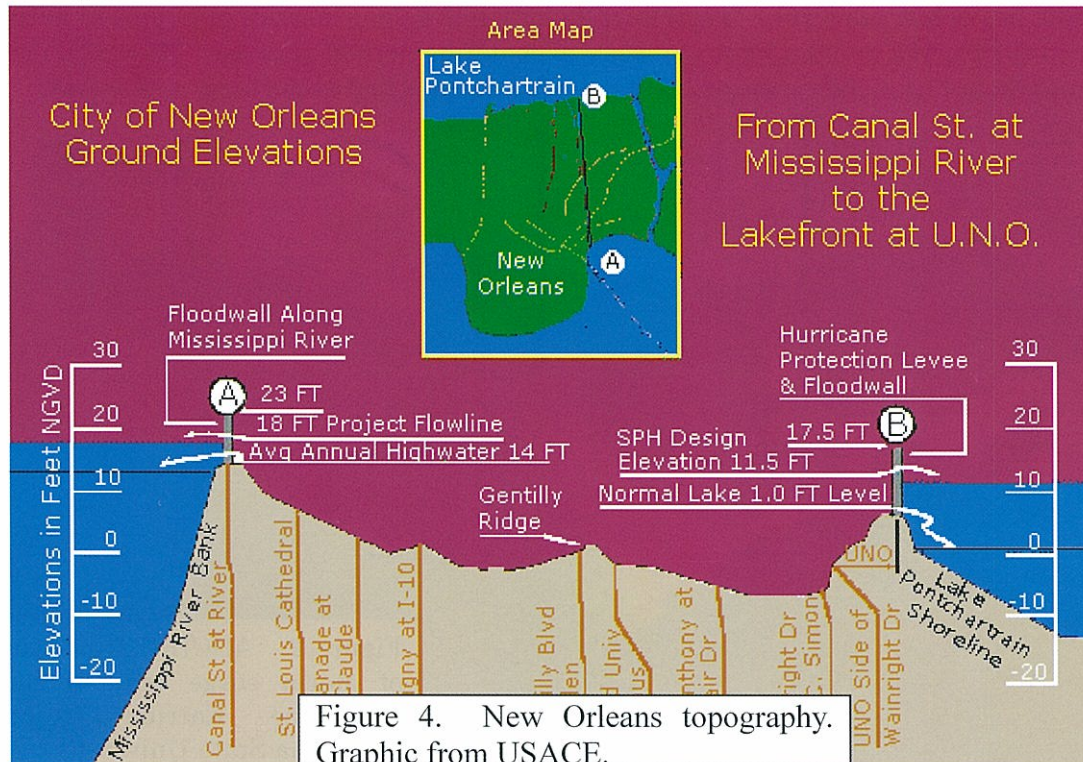
2. Summary of the storm's effects on New Orleans

The situation of New Orleans was much different from that of the Mississippi coast. New Orleans is built upon a historic marshland, which originally (during French administration of the region) served as a portage between the Mississippi River and Lake Pontchartrain. The banks of the river and lake are still relatively high in elevation (up to 5 m above sea level, see figure 4), though the drained marsh soils in the rest of the city have since subsided to the extent that most of the city now lies below the water surface level in the lake and river, and some of the city has subsided so much that it now lies below sea level. Therefore, the city relies upon a series of pumps to keep it dry in floods, and to drain its storm water even during normal periods. However, these pumps do not have their own power supply, but are attached to the local power grid.



When Katrina approached from the south, the easterly winds north of the eye pushed seawater into the Industrial Canal (figure 5) via Lake Borgne to the east and a shipping canal called the Mississippi River Gulf Outlet (MRGO) to the south. Due to the geometry of this region, the volume of water transported into the Industrial Canal

was massive, causing the water surface to top the levees on both sides of the canal, flooding levee districts in both Orleans East Bank, and St. Bernard Parish on the morning of August 29. After the concrete floodwalls atop the earthen levees were overtopped by the flood, water pouring down the unarmored landward faces of the levees scoured away the soils supporting the floodwalls atop the levees, causing the floodwalls to topple, followed by increased scouring of the levee soils. It's also possible that at one of these breach sites, a barge, which had broken loose from its moorings, caused the breach when it collided with the levee.



The 17th Street and London Avenue levee breaches (on the northern shoreline of New Orleans, along Lake Pontchartrain) are not thought to have occurred until after the hurricane had passed through the region, on the evening of August 29. During the

morning of August 29, the easterly wind north of the eye pushed a large volume of water westward, through the Rigolets, into Lake Pontchartrain. As the hurricane's eye passed east of the Rigolets, the northerly wind it caused in Lake Pontchartrain forced all this water to pile up on the southern shore of the lake (figure 2), impinging on New Orleans' northern levees. As the storm then passed to the north, the westerly wind in its southern quadrant pushed this water back toward the Rigolets, yet further adding to the pileup of water on New Orleans' levees, on the southeast shore of Lake Pontchartrain. This resulted in the 17th Street and London Avenue breaches. It's possible that the mechanism of failure was the same as it had been along the Industrial Canal, with overtopping followed by scouring and floodwall collapse. However, high water marks along the intact sections of New Orleans' Pontchartrain levees indicate that the lake level may not have risen high enough to top the levees there, intimating that "heaving" may have been the mode of failure in these sections. "Heaving" results when water pressure (due to an elevated free surface) squeezes soil out from underneath the concrete floodwalls, causing failure of the floodwall. Some of the failed embankments along Pontchartrain were observed to have moved up to 7 m, indicating that heaving may indeed have been the failure mode. However, heaving should not have occurred if design and construction had been carried out properly. Therefore, if heaving was indeed the failure mode, it's possible that they who had constructed these levees did not compact the soils under and around the floodwalls enough to meet the design specs.

In both cases, the floodwaters that reached New Orleans had to flow through narrow channels (the Industrial Canal, MRGO, and the Rigolets) in order to reach the levees around the city. Thereafter, these floodwaters poured through narrow sections of broken levee into the city. Within New Orleans, therefore, floodwaters rose very slowly (over the course of two days), and without substantial momentum, as if the city were a swimming pool being filled from a garden hose. Conversely, the floodwaters were drained equally slowly, because all the water had to be pumped out, and even some of these pumps were not operable, because they lost power along with the rest of the city. Therefore, much of the city remained flooded for over a week, and was flooded for a second time when Hurricane Rita landed on September 24, and caused a surge that flooded over the broken levees as they were under repair (and thus in a weakened state). This extended flooding is responsible for many of the structures in New Orleans having been rendered uninhabitable, because contaminated floodwaters permeated the walls of flooded structures, and caused mold to grow to levels unsafe for human health. The gradual flooding and drying of New Orleans stands in stark contrast to the major damage mode in Coastal Mississippi, where the rapidly rising and forceful surge ripped most structures off their foundations and piles, but the equally rapid retreat of the surge there prevented the growth of mold in flooded structures to the degree that New Orleans experienced.

The levees around New Orleans had been designed to protect the city from a category 3 hurricane, after Hurricane Betsy swamped the city in 1965. After that storm, Congress authorized and funded the US Army Corps of Engineers (USACE) to build the current levees and pumps over a 30 year period. Therefore, the levee system had been completed only recently. A large and slow-moving category 4 storm directed along the exact path that Katrina took had been thought to be a 300 year event, and the government had been hoping it would have ample time to build up the levees to sufficient height before such a storm struck. Despite this, the Federal Emergency Management Agency's former chief, Michael Brown, in 2001 had listed the threat of a large hurricane flooding New Orleans as one of the three most serious threats to national security (the other two threats were a terrorist attack on New York, and an earthquake in San Francisco).

In the wake of Hurricane Katrina, Congress is likely to authorize money for USACE to enhance the city's defenses to protect it from a category 5 storm. This will entail raising of the current levees and instillation of new, stronger pumps with the ability to operate off their own power supply. Some planners suggest digging drainage basins just inside the levees, while others advocate the abandonment of the city's lowest-lying areas for use as floodwater storage basins. The enhanced protection scheme may also entail the closure of MRGO, as the costs of maintaining this shipping channel in light of erosion, along with the flood risk it brings New Orleans, appear greater than the economic benefits gained by continuing its operation for the few shipping companies that use it (the vast majority of Mississippi River ship traffic uses the river mouth, rather than MRGO). Flood gates may also be constructed in the Rigolets and in the eastern reach of the Industrial Canal, as these are narrow straits that surge waters must funnel through before reaching the city (London and some cities in the Netherlands already rely on such gates for protection from regular high tides, while plans are underway for construction of high water gates at the inlets to Venice lagoon as well).

Before Hurricane Katrina struck, a coalition of Federal, State, and local agencies had compiled a well-formulated, though expensive, plan (known as "Coast 2050") for comprehensive protection of New Orleans through a combination of the measures described above with restoration of marshes throughout the region. In light of Katrina, this plan may now gain more support in Congress than it had previously. Marshes offer protection from storm surge by effectively moving the coastline further seaward, creating a buffer zone of increased frictional drag which the wind must counter in order to push surge waters onshore. By the time surge waters reach inhabited areas, they therefore don't rise as high, and carry less momentum than they would otherwise. Over the last century, though, a variety of anthropogenic causes have resulted in the loss of 70-100 square kilometers of marsh each year. 1927 river floods prompted construction of levees along the lower reaches of the Mississippi River, which since have prevented occasional river floods from supplying marshes in the river delta with the sediment they need in order to build up. These marshes, being exposed to oceanic and atmospheric forces, thus erode instead of accreting, while all the sediment carried by the Mississippi River flows between levees all the way to the Gulf of Mexico, and is then lost to waters too deep to support marsh building. To mitigate this effect, Coast 2050 proposes a series of controlled diversions of the Mississippi River onto its surrounding floodplains to deposit sediment and thereby build marsh throughout the foreseeable future. Diverted sediment not deposited in coastal marshes will then flow to the shallow waters of Mississippi Sound via local rivers, and replenish the barrier islands which are also essential in protecting the coast from storm surge (without a sediment supply, the barrier islands off the coasts of Louisiana and Mississippi are, like the coastal marshes, in a state of gradual erosion). However, this is a case where the safety and environmental objectives of the project conflict with other environmental concerns, as pilot projects have succeeded in building marsh through river diversions, but the resulting sediment-laded bayous have choked out commercial oyster beds in some areas, bringing fishermen to litigate against the government. Much of the money required for the government to undertake the large-scale diversions of the Mississippi needed to restore the marshes that protect New Orleans is earmarked for compensation of these fishing interests.

3. Narrative of survey

The modes of destruction in St. Tammany Parish (the northeast shore of Lake Pontchartrain) and Hancock and Harrison counties (the Mississippi coast) were much different than those in New Orleans. Instead of a gradually rising, long-standing flood,

these areas experienced a rapidly rising surge of catastrophic scale, which then receded as quickly as it rose (flooding lasted for about four hours). In unsheltered areas, this surge was accompanied by rapid tidal currents and topped by large wind waves, causing devastation reminiscent of the Indian Ocean tsunami of December 2004. In areas such as Slidell, which is many kilometers inland, the surge rose more slowly than it did on the coast, but also receded more slowly, leaving homes flooded for about a day.

To survey the effects of the hurricane along the MS gulf coast, I met with scientists and engineers of the US Geological Survey's Hydrologic Instrumentation Facility, located at Stennis Space Center, LA (near Picayune), many of whom had lost their own homes to the storm, and who were living in trailers on site until they could repair or rebuild their homes. They lead me on a tour of the region as shown in figure 1.

The first stop on this tour was the town of Pearlinton (stop #1 on figure 1), on the Pearl River, which serves as the border between LA and MS. Here, the surge rose to about 5 m. According to the resident who owned the restaurant pictured in photo #1, the structure was intact until another home came floating by and rammed it (left). The photo on the right side of photo #1 shows marsh grass deposited on a telephone cable by the surge. As with many of the other Mississippians who chose to stay and brave out the storm, this resident said her reason for doing so was that she survived Hurricane Camille in 1969. Hurricane Camille was a category 5 storm, and it wrecked havoc on the Gulf coast. However, Camille was a small, fast-moving storm, with a radius (for hurricane-force winds) of only 100 km. Katrina was only category 4 upon landfall, but its radius was 210 km, and it moved much more slowly. This resulted in Katrina's storm surge rising much higher than Camille's, and therefore causing significantly more devastation. After her near-death experience inside her restaurant during Katrina, this resident said that, henceforth, she'll evacuate from even a category 1 hurricane. Her house, which had been located beside the restaurant, was uprooted by the surge, and advected about 2 km inland. Since the restaurant survived, to some extent, intact, she had to spend the days after the flood clearing fish from the upper floor of the restaurant. In addition to structural damage, she found a wake of devastation on the local fauna after the floodwaters receded; raccoons, possums, seagulls all died in large numbers. Along with rotten food (since power infrastructure was destroyed, refrigerators no longer worked), the dead fauna attracted flies, making life even harder for the now-homeless residents. On the brighter side, she said, authorities in Mississippi responded to the disaster quickly and efficiently, deploying to the area the day after the flood. Police, firemen, medics, and rescuers arrived en masse from all over the nation to assist. Police from Miami even assisted her in cleaning salt off her rifle, and instructed her that, if looters came to steal her property, she should shoot to kill, as that would entail less paperwork than would be necessary otherwise! Luckily, she didn't need to use that advice; part of the reason for this was that the Highway 90 bridge over the Pearl River, connecting Pearlinton with neighboring Louisiana, was rotated open (to boat traffic, or closed to vehicle traffic) during the flood, and could not be closed again until power was restored to the motors used for rotation. This prevented looters from entering Mississippi from Louisiana.

We next drove to a small community of fishing camps (weekend homes), labeled as stop #2 on figure 1. On the way there, we passed over a railroad, whose gravel ballast had been scoured to a large extent by the flood (photo #2). This cargo railway runs along the extent of the MS coast, about 1 km inland. Since most of the gravel debris was on the shoreward side of the tracks, the scouring appeared to have been an effect of the receding flood. We saw identical scouring along the whole coast, as far east as Biloxi (the eastern terminus of our tour). In many places, however, the railway acted as a levee, offering some protection to the homes landward of it.

At the fishing camps themselves, we found complete destruction (photo #3). Homes there had been built on piles of 3 m in height, but this was not enough to protect them from a surge of over 6 m. The surge caused homes to lift off of their pilings, and float away, some to be destroyed in the flood, and some to be deposited intact elsewhere. The church in photo #4 is a striking example of a building that floated off its foundation, and was then deposited elsewhere, largely intact. Homes were not the only victims of the surge. Flora was devastated as well. Softwoods were snapped by the wind, while hardwoods were uprooted (photo #5). Among trees that were not immediately toppled, many died due to inundation with salt water as well. As we drove to Waveland (stop #3), the devastation continued. Photo #6, an aerial photo courtesy USGS, gives an idea how complete the destruction of Waveland was, from the coast and extending inland past the railway, over 1 km away from the shore. It also shows extensive beach erosion, with sands pulled seaward by the receding surge. Homes upon bluffs or hills were built without piles, but directly upon concrete slab foundations. Since the surge rose to 10 m here, neither local topography nor piles were sufficient to protect these structures.

The tent in photo #7 stands on the foundation of a church that was destroyed in the flood. Photo #8 is Coleman Ave, downtown Waveland, where the town hall, police department, other municipal buildings, and many shops stood before the flood. The tents in photo #9 stand upon the city hall's foundation, as the building was destroyed by the surge. Of the brick home in photo #10, which stood on a bluff near the beach, nothing is left standing except the toilet. We often found this same situation in homes built on concrete slab foundations, where the only fixture left standing inside a wrecked home was the toilet on the first floor. The cars and tractors in photo #11, which had been in another nearby brick home, were tossed around by floodwaters as the building around them was destroyed.

Photo #12 shows another case where the gravel around the railway was scoured seaward, meeting larger buoyant debris that appeared to have been advected here in a landward direction (from homes that had stood seaward of the tracks). There were many instances of roofs left intact, either displaced from the home they had belonged to, or sitting atop a home that had been pancaked under them (photo #13). This may reflect tornado-induced damage. Since most residents of coastal Mississippi lived in homes on grounds at least 6 m above sea level, or in homes on piles at least that high, they had no flood insurance. Therefore, they want to believe that their homes were destroyed by wind, and not by water. It's likely that a combination of these elements caused most of this type of destruction. Also evident in this photo was information written by the residents of that house on the front face of the roof. This included the name of the insurance company they prescribed to (in this case, State Farm) accompanied by the words "don't remove!", as the insurance companies had agents touring the region to verify claims.

At the location of photo #14, about 2 km inland, wooden and brick homes were destroyed by the surge. Much debris landed upon the flattened roof pictured. Debris removal was, by this time, proceeding in full force. Debris removal was coordinated by USACE, which hired contractors from around the country for this task. Residents were responsible for moving debris from their property to within 3 m of a road, within which distance the contractors were authorized to remove the debris, as shown in the photo.

Our next stop was Bay St. Louis (site #4 on figure 1). The surge reached 10 m here, so destruction was similar to that in Waveland. The coastal road was undercut and then washed away (photo #15). On the beach, steel-frame, reinforced-concrete restaurants were destroyed by the surge (photo #16). The striking structural damage to these shoreline structures may have been due to battering by windwaves atop the surge,

the momentum of tidal currents due to the surge, or the impact of large debris carried by the surge.

The cargo railway bridge over St. Louis Bay lost its deck and rails to the surge (photo #17). The likely cause was that the rising water reached the bridge level, and then waves incident on the decks pushed them landward, until they fell off the pilings and into the bay. As you can see in the photo, work was already proceeding from both sides of the bridge to repair it. The highway 90 automobile bridge over St. Louis Bay also lost all its decks to the surge (photo #18). These decks were not fixed rigidly to the piles, but rather were held to the piles via their weight. As with the railroad bridge just south of the highway bridge, decks were pushed northward and fell into the bay. Due to the strong tidal currents generated by the incident and receding surge, many of the bridge's pilings failed as well (photo #19). This was probably due to scouring of the earth into which these piles were sunk.

Inland, in Diamondhead (site #5 on figure 1) homes on piles were swept away. Some piles failed as well. The piles in photo #20 were attached to the foundation via only a short piece of rebar, and toppled. Other concrete piles (photo #21) failed in either tension or shear, when the house which they were supporting was lifted up by the surge and then pushed laterally by tidal currents, waves, debris, and wind.

The second floor of the home in photo #22 was flooded to about 1.5 m, and all drywall under that height was destroyed. The floor in photo #23 was floated off its blocks, and the rest of the house was destroyed. An interesting point is that the homes in photo #22 (which partially survived) and photo #23 (which was destroyed) stood beside each other. A grove of trees stood between the bayou and the home of photo #22, while the wrecked home of photo #23 was directly exposed to the momentum of the surge. Within Diamondhead, many homes, which had been built on piles, were also destroyed, especially in the cases where no physical barriers (such as woods) existed between the homes and the bayou.

On to Pass Christian (site #6), the only portion of the bank in photo #24 remaining after the surge was the vault. Scenic Drive, a road on a coastal bluff about 6 m above sea level, was washed out by the 10 m surge. The water pipeline in photo #25, under the road, broke during the washout, but had recently been fit with a steel sleeve, as a temporary fix in order to allow the system to be repressurized. The gas pipeline beside it seemed to be undamaged at this location.

Photo #26 was taken about 2 km inland, in Pass Christian, and shows wrecked vehicles deposited near the railroad tracks by the surge. The flow induced by the surge caused scour around the foundations of buildings built on piles, causing failure in some cases (photo #27). The surge also caused much scour of roadways and slopes along the coastal bluff (photo #28). Manholes were often more sturdy than the pavement around them, and survived the surge (photo #29). As in Waveland and Bay St. Louis, all that was left of many structures were their foundations (photo #30). Fire hydrants proved to be quite sturdy, and often remained in place, even when the roads around them were scoured away. The structure in photo #31 was destroyed by either trees falling upon it, or waves atop the surge battering it.

Driving towards Long Beach (site #7 on figure 1), we found national guardsmen and police checkpoints at intersections along the coast, to stop looters from operating there. At locations other than intersections, razor wire prevented the entry of looters on foot (photo #32).

In Biloxi (site #8 on figure 1), the seafood industry was hit hard by the 9 m surge. Boats which didn't escape to a distant harbor were destroyed, as were ice-making plants, and the packaging and shipping infrastructure. In photo #33, a processing plant, on the north side of the peninsula, was destroyed by surge. Boats in Biloxi's harbor were either battered in the water, or grounded by the receding surge.

The boat in photo #34 rests on a road about 5 m above sea level. A nearby casino, though its structure survived, had been flooded by the surge. In photo #35, it's shown with large dehumidifying ducts running up to its second floor, in an attempt to clear the building of mold induced by the floodwaters. The boat in photo #36 was deposited about 9 m above sea level, upon concrete spans at a bridge-deck manufacturing plant.

The structure in photo #37 is one of Biloxi's massive casino barges, floated ashore by the surge. This barge shows structural damage near its far end because that part of the barge is resting on lower ground than its near end. Mississippi's tourist economy relies heavily upon its gambling industry, and this industry was destroyed by the storm, because gambling had been allowed only on the water, not on land. This was a compromise between the government, which values the income it receives in taxes from the casinos, and the conservative Christians who live in abundance in Mississippi and want gambling to be outlawed. A compromise between these parties resulted in the rule that gambling could only be conducted on the water (barges on Mississippi Sound or steamboats on the Mississippi River), not on land. Because of the destruction incurred by Katrina, however, the state changed this law to allow gambling up to 1/4 km inland from the water. This is likely to be challenged in time to come, but the state hopes it will help revive the tourist economy more quickly.

As was the case in Bay St. Louis, the highway 90 bridge over Biloxi Bay was destroyed by the surge (photo #38). Bridge decks, held to their piles by gravity, were lifted and pushed, thereafter falling off their pilings. The photo clearly shows that all decks were pushed northward (landward) by the incoming surge and waves. Also akin to Waveland and Bay St. Louis, destruction of residential areas in Biloxi was near total (photo #39).

The next stop on my tour was Slidell, LA (site #9 on figure 1), a residential community across Lake Pontchartrain from New Orleans. Even though Slidell was where the western eyewall of the hurricane passed (with winds blowing away from shore), the initial easterly winds of the northern quadrant of the storm pushed a large mass of seawater through the Rigolets, and into Lake Pontchartrain, flooding Slidell in the process. The waters rose more gradually here than they did along the MS coast, and also subsided more slowly, leaving homes flooded for about 1 full day. In Slidell proper (inland), the surge rose to about 4 m above sea level. Since this region of LA is lower-lying than coastal MS, most homeowners here had flood insurance. Homes in inland Slidell are located at about 2 m above sea level, and there are not many levees for protection from storm surge. In photo #40 (courtesy Kirk Thibodeaux), a Slidell resident's garage, the flood line is easily seen on the wall and curtains. Photo #41 shows this same resident's garage door. According to him, its bottom panel buckled due to the pressure of water rising outside. This caused the seal between the door and the floor to break, allowing flood waters to pour in under the door. This resident has since gutted his home (removed all drywall), and is running a dehumidifier around the clock, in an attempt to remove harmful mold from the wood. If he cannot remove the mold, then he will have to demolish the house, and rebuild from anew. In either case, he will be required to raise the living quarters of his home, by either raising his home onto piles, jacking the foundation up onto blocks, or abandoning the first floor of his house and building upward. Since many kilometers of marsh lie between Slidell and the lake, the surge did not carry much momentum by the time it reached inhabited areas, nor did large wind waves still exist atop the surge; therefore, the damage in Slidell is more reminiscent of that in New Orleans, where standing floodwaters caused mold to grow to unsanitary levels in homes, than of the Mississippi coast, where the catastrophic surge reduced most homes to rubble and debris.

Further south, on the northern shore of Lake Pontchartrain (site #10 in figure 1), the scene was again similar to that in Mississippi. The surge lifted and destroyed

homes and restaurants which were built on piles above the water surface, along with the piers alongside them (photo #42). Further east, near the Rigolets (site #11 in figure 1), marsh grasses, which had been torn up by the storm and then pushed inland by the surge, were piled up amongst debris along the road (photo #43). As in other areas, even homes built on piles were swept away (photo #44).

4. Conclusions

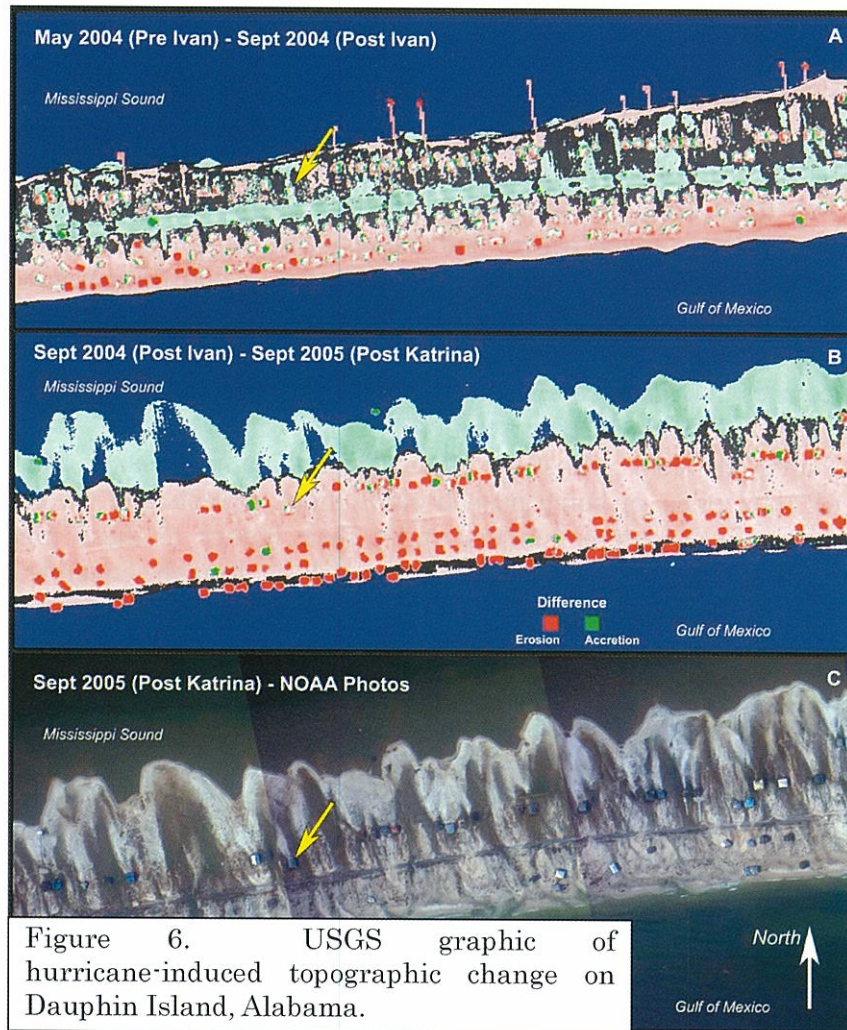
Despite the chaos that ensued after the onslaught of Katrina, the mandatory evacuations that were ordered along the Mississippi coast, as well as relatively rapid response by local and state authorities and the national guard, prevented many deaths. The total death toll from the storm was about 1,300, with only about 300 of these deaths occurring in Mississippi. Most residents along the Mississippi coast plan to rebuild, but are waiting for the Federal Emergency Management Agency (FEMA) to redraw their flood maps, in order to determine how much higher they must raise the living quarters of their homes, in order to bring them above the FEMA-required flood level. Many residents are also waiting for FEMA safety authorities to tell them whether or not their homes, if not destroyed, are livable, based on safety (structural) and health (mold) concerns; if not safe, these homes will be demolished, and new ones constructed from scratch. In the meantime, these residents are living in tents and trailers on their property, in nearby refugee camps and trailer parks, in hotels in the region, and with family scattered around the country. Debris removal and infrastructure repair (water supply, sewage, and power) are furiously underway, so that residents can return to their property and receive a FEMA trailer to live in until they begin to rebuild their structures (FEMA requires that a site have active water supply, sewage, and power connections for the resident of that site to receive a trailer).

Along the coast, most of the residential damage came from raised homes floating off their piles, or being pushed off by tidal currents and waves atop the surge. This might motivate future builders to fix their homes to these piles more firmly. Since this would put the piles in tension and shear, though, concrete piles would be likely to fail, while wooden piles would work better; during the survey, we saw many failed concrete piles, while wooden piles were almost all intact, even if the homes that they had supported were gone. Applying knowledge of reinforced concrete from earthquake engineering, however, might make concrete piles more viable than they currently are, as this could increase their strength in shear and tension.

The bridge damage we observed seemed to have the same cause, due to buoyancy of the decks when submerged. Likely solutions seem to be to either fix the decks to the piles more rigidly, or to raise the decks higher above the water surface. Since bridge damage doesn't incur loss of life, however, economics would govern this choice. A lesson may be learned from the submerging bridges on Shikoku's Yoshino and Shimano Rivers, which are designed to withstand strong currents during floods. However, these river bridges aren't built to withstand the waves that the Highway 90 bridges were subjected to during the hurricane. Furthermore, the kind of storm surge caused by Katrina is expected to hit the region only once every 300 years, while the bridges on Shikoku are submerged by floods almost every year. Therefore, it may be economically more viable to repair, or rebuild, the Mississippi bridges after each such rare event, than it would be to strengthen them to survive these events (the return time of such a storm is likely longer than the designed lifespan of the bridge).

Most of the structural damage we saw appeared to have been directed inland, pushed inland by the onshore wind and waves or by the approaching flood. Fallen trees all fell inland, and wrecked homes, which had floated away from their piles or foundations, were mostly found inland. However, we found some house and tree debris on the beach, and these were advected there by the receding floodwaters. Most

soil erosion seemed to have been dominated by the receding flood, as this erosion was directed seaward. The railroad's gravel ballast and the washout of coastal roads, all indicate that scouring was stronger during the receding flood than during the incoming flood. This may simply be because the receding flood was flowing downhill (according to the land slope), and was therefore assisted by gravity, while the incoming flood was flowing uphill. It may also be related to the amount of time which the onshore winds took to blow the surge onto land, compared to the suddenness with which these winds shut off, and allowed the surge to recede. It's interesting to note that the Gulf coast's barrier islands were eroded in the other direction, with sands eroded from their seaward side and deposited in the ocean on their landward side, effectively migrating landward. Figure 6 (courtesy USGS) shows the hurricane's effect on Dauphin Island, a barrier island southwest of Mobile, AL. North is landward, towards the coast.



Barrier islands such as Dauphin Island, though eroded severely by the storm, played an important role in protecting the coast from the full might of the storm surge (see section 3 of this report). One of the strategies of Coast 2050, mentioned in section 3 of this report, is to use controlled diversions of the Mississippi River to replenish coastal marshes and barrier islands with sediment. Some regions of the Mississippi coast, such as the areas around Pearlington and St. Louis Bay, are home to vast marshes, and thus would benefit from the flood protection of both expanded marshes and barrier islands. Much of the Mississippi coast, though consisting of sandy beaches without marshes, would still experience benefits in flood protection from replenished barrier islands.

Apart from structural concerns, Katrina also teaches us that hurricane education

for residents and tourists in hurricane-prone areas is essential. The reason that many residents didn't evacuate the Mississippi coast before Katrina landed was because they had survived Hurricane Camille in 1964 (see the discussion with the resident of Pearlinton at the beginning of section 3 of this report). Since hurricanes are widely viewed in terms of category, which is a function of maximum wind speed, residents often don't pay enough heed to other effects, such as storm surge, which are often much more damaging than winds alone (as was the case with Katrina). Because of such stubborn residents, local police and firefighters could not evacuate themselves, because it was their job to remain in their towns to rescue those who needed rescuing. These public servants were thus put in great danger as well, as was evidenced by the experience of Waveland's police force, whose station and vehicles were swept away by the surge; many officers survived (miraculously, the entire force survived) only because they clung to a large tree beside the station for four hours, until the ocean returned to its proper location.

Most residents of the Mississippi and Louisiana coasts love their land, and so will return to their homes there, and rebuild. The government can motivate a safer future for the region by enacting the measures stated in Coast 2050, and by buying coastal lands from private landholders for the creation of public parks and beaches to serve as buffer zones along the coast. Furthermore, new knowledge of storm surge effects as a result of Katrina will help FEMA will redraw its flood maps to specify how high homes must be raised off the ground for safety. Nature's fury cannot be contained, but application of knowledge gained from experiences like this will help the government and residents gradually learn how to build communities as safe as possible in such a disaster-prone region.

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References

Sections 3 and 4 of this report consist of a mix of my own ideas and data, as well as the expert knowledge, theories, and observations of my guides from the USGS: Janice and Jim Fulford, Jim Jilenski, and Kirk Thibodeaux. Sections 1 and 2 are compiled from background research based on a variety of sources. The websites of NOAA and the USGS contain a wealth of hydrologic, meteorological, and historical data, while the website of the US Army Corps of Engineers explains the hydrology of New Orleans in detail. The FEMA website, as well as those of its state-level counterparts in Mississippi and Alabama, are valuable sources to learn about the current status of infrastructure throughout the region. The text of "Coast 2050" contains a wonderfully informative natural history of the Louisiana coast, together with the challenges induced by anthropogenic changes, and ideas for protection of this coast in the future. The websites of CNN and the New York Times provide intelligent opinions and explanations of the storm's effects on the region's industries, while the website of Mississippi's major newspaper, the Clarion Ledger, is full of detailed information and personal stories regarding the hurricane. Other internet sites, such as Wikipedia, are also very helpful.

Photos



Photo #1. Pearlington, MS. Restaurant damaged by the surge (left) and marsh grass deposited by the surge on telephone lines (right).



Photo #2. South of Pearlington, MS. Railway damaged by the surge and associated debris, and gravel ballast scoured seaward by the surge.



Photo #3. South of Pearlington, MS. Piles that had supported homes, which floated away (landward) in the surge. The bayou off which the surge entered the region is visible on the left.



Photo #4. South of Pearlington, MS. A church which had floated off its foundation during the surge, and landed in this spot when the floodwaters receded. Spray painted on the siding on the left-hand side of the photo are the words "Do not destroy. Historical building. Built 1868 by C LaFontaine."



Photo #5. Waveland, MS. Softwood (left) and hardwood(right) trees destroyed in the storm.



Photo #6 (USGS). Aerial photo of Waveland, MS on the day after the storm landed.



Photo #7. Waveland, MS. Tent sitting on the foundation of a wrecked brick church.



Photo #8. Waveland, MS. Restaurants, shops, and homes devastated by the surge.



Photo #9. Waveland, MS. Tents sitting atop the site of Waveland's city hall, which had been destroyed in the surge.



Photo #10. Waveland, MS. Brick home destroyed by the surge. Only the toilet was left standing.



Photo #11. Waveland, MS. Garden items, vehicles, and trees amidst the debris of a wrecked brick home.



Photo #12. Waveland, MS. Railroad ballast scoured seaward by the surge, along with large, buoyant debris which had been advected landward by the surge and then deposited on the seaward side of the railroad.



Photo #13. Waveland, MS. Roof sitting atop a wrecked home.



Photo #14. Waveland, MS. Debris removal underway by contractors.



Photo #15. Bay St. Louis, MS. Coastal road and buildings destroyed by the surge.



Photo #16. Bay St. Louis, MS. Steel-frame and reinforced-concrete restaurant on the beach, destroyed by the surge.



Photo #17. Railway bridge across St. Louis Bay, destroyed by the surge, and now under repair from both directions.



Photo #18. The US Highway 90 bridge over St. Louis Bay, MS. Decks were pushed off their piles by the surge and waves.



Photo #19. Piles supporting the US Highway 90 bridge over St. Louis Bay, MS. Some piles failed in the strong tidal currents induced by the surge.



Photo #20. Diamondhead, MS. Pilings from atop which a home had been carried away by the surge. These concrete piles, very weakly attached to the foundation below them (by only a single piece of rebar), toppled.



Photo #21. Diamondhead, MS. Piles from atop which a home had been carried away by the surge. These concrete piles, though fixed strongly to the foundation by pouring the foundation around the piles, as well as by running many pieces of rebar from the foundation to the piles, failed.



Photo #22. Diamondhead, MS. 2nd floor of a flooded home. All soft materials were destroyed.



Photo #23. Diamondhead, MS. Floor of a home which had floated off its foundation blocks in the surge.



Photo #24. Pass Christian, MS. Vault of a bank. The rest of the building was destroyed in the surge.



Photo #25. Pass Christian, MS. Water and gas pipelines under a road which had been washed out in the surge. The steel sleeve on the water main is a temporary repair, to allow the system to be repressurized.



Photo #26. Pass Christian, MS. School bus and pickup truck advected inland by the surge, and resting just seaward of the railroad tracks.



Photo #27. Pass Christian, MS. Earth scoured away from around a building's pile by the surge.



Photo #28. Pass Christian, MS. Road on a coastal bluff, washed away by the surge.



Photo #29. Pass Christian, MS. Manhole intact despite the road around it having been destroyed by the surge.



Photo #30. Pass Christian, MS. Home and road were destroyed, but foundation and fire hydrant remain.



Photo #31. Pass Christian, MS. Wrecked building near the beach.



Photo #32. Long Beach, MS. Razor wire keeping looters out of the coastal area of Long Beach.



Photo #33. Biloxi, MS. Fishing industry warehouse destroyed by the surge.



Photo #34. Biloxi, MS. Tour boat floated inland by the surge.



Photo #35. Biloxi, MS. Casino with dehumidifying ducts running out of its 2nd story windows, in an attempt to clear the place of mold.



Photo #36. Biloxi, MS. Boat deposited about 10 meters above sea level.



Photo #37. Biloxi, MS. Casino barge deposited in a parking lot.



Photo #38. US Highway 90 bridge over Biloxi Bay. Decks were pushed off their piles by surge and waves.



Photo #39. Biloxi, MS. Typical scene of the destruction caused by the surge in residential areas.



Photo #40. Slidell, LA. Debris line in this garage indicates the maximum flood level. Photo courtesy Kirk Thibodeaux.



Photo #41. Slidell, LA. Garage door of a home, with its bottom panel buckled and seal broken by surge waters.



Photo #42. South of Slidell, LA. Massive destruction of homes and restaurants along the north shore of Lake Pontchartrain.



Photo #43. Rigolets, LA. Marsh grass deposited by the surge.



Photo #44. Rigolets, LA. Piles on which sat homes that the surge carried away.