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Development of storm surge which led to flooding in St. Bernard Polder during Hurricane Katrina

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ABSTRACT

Hurricane Katrina caused devastating flooding in St. Bernard Parish, Louisiana. Storm surge surrounded the polder that comprises heavily populated sections of the Parish in addition to the Lower 9th Ward section of Orleans Parish. Surge propagated along several pathways to reach levees and walls around the polder's periphery. Extreme water levels led to breaches in the levee/wall system which, along with wave overtopping and steady overflow, led to considerable flood water entering the polder. Generation and evolution of the storm surge as it propagated into the region is examined using results from the SL15 regional application of the ADCIRC storm surge model. Fluxes of water into the region through navigation channels are compared to fluxes which entered through Lake Borgne and over inundated wetlands surrounding the lake. Fluxes through Lake Borgne and adjacent wetlands were found to be the predominant source of water reaching the region. Various sources of flood water along the polder periphery are examined. Flood water primarily entered through the east and west sides of the polder. Different peak surges and hydrograph shapes were experienced along the polder boundaries, and reasons for the spatial variability in surge conditions are discussed.

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1. Introduction

In August 2005, extremely high storm surge and energetic waves during Hurricane Katrina caused massive flooding, devastating loss of life, and widespread damage throughout south-eastern Louisiana and Mississippi. The immense size of Hurricane Katrina, in relation to the entire northern Gulf of Mexico coastline from western Louisiana (left side of the figure) to the Florida panhandle (right side), is shown in Fig. 1. The Interagency Performance Evaluation Task Force (IPET) thoroughly investigated and documented this extraordinary event and its consequences (IPET, 2008). Flooding caused by Katrina was particularly severe in the polder that comprises part of St. Bernard and Orleans Parishes in New Orleans, Louisiana, referred to here as the St. Bernard Polder (see Fig. 2). This polder is located within the small rectangular box shown in Fig. 1.

The St. Bernard Polder is surrounded by a perimeter of levees and floodwalls. There was considerable variability in levee/wall crest elevation along each of the various segments that form the perimeter. A small segment of the western boundary of the polder extends along the Inner Harbor Navigation Canal (IHNC); this section of levee/wall had crest elevations that ranged from approximately 3.7 to 4.6 m NAVD88 2004.65, with a few isolated low spots having crests of 3.5–3.7 m. NAVD88 2004.65 is the vertical datum that was developed for the region as part of the IPET investigation. The rest of the western boundary of the polder is formed by the much higher Mississippi River levee. The northern polder boundary runs along the south side of the co-located Gulf Intracoastal Waterway (GIWW) and Mississippi River Gulf Outlet (MRGO) channels, referred to as the GIWW/MRGO Reach 1; levee/walls along this segment had crest elevations in the range of 4.6–5.5 m, with a few isolated low spots of 3.5–4.6 m. The eastern polder boundary parallels the MRGO Reach 2 navigation channel from Bayou Bienvenue to a point southeast of Bayou Dupre; wall/levee crest elevations generally ranged from 4.6 to 5.8 m with isolated low spots of 4.3–4.6 m. The southern boundary of the polder, the Chalmette Extension Levee, extends from the MRGO Reach 2 to the Mississippi River levee at Caernarvon and is fronted by the extensive Caernarvon marsh. Levee/wall crest elevations along this section ranged from 4.6 to 5.8 m, with isolated low spots of 4.0–4.6 m.

Unique dynamics of storm surge development and propagation into the region caused different surge conditions to occur along the polder's periphery. Spatial differences in the surge hydrograph and variability in levee/wall crest elevation led to highly complex and variable (in space and time) overtopping and overflow conditions. This paper examines the development of the storm surge in this local region, causes for its temporal

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and spatial variability, and it discusses how that variability contributed to different sources of floodwater that entered the polder.

High surge levels led to two breaches in the floodwall located just north of the IHNC lock along the western boundary of the polder (IPET, 2007b). Both led to early inundation of the Lower 9th Ward, the heavily populated western most portion of the polder, with interior water elevations initially rising to approximately +0.6 to +1.2 m NAVD88 2004.65 (IPET, 2007a). Along the MRGO Reach 2 channel, high storm surge and energetic waves led to widespread overtopping and overflow, which caused erosion and degradation of much of the levee immediately adjacent to the waterway (IPET, 2007b). As this levee degraded, a large volume of water entered the Central Wetlands which lie within the polder, fully inundating them. The advancing surge overwhelmed the much lower local interior 40 Arpent levee (see Fig. 2) within the polder, which separates the wetlands from most of the population. Crest elevations along the 40 Arpent levee generally ranged from 1.8 to 3 m. Flow over this interior levee caused substantial inundation throughout the populated areas of the polder, raising water levels everywhere to elevations of approximately +3.3 m NAVD88 2004.65. The northern and southern boundaries of the polder experienced less overtopping and overflow. Levees and walls had crest elevations that generally exceeded peak surge levels along these two segments.

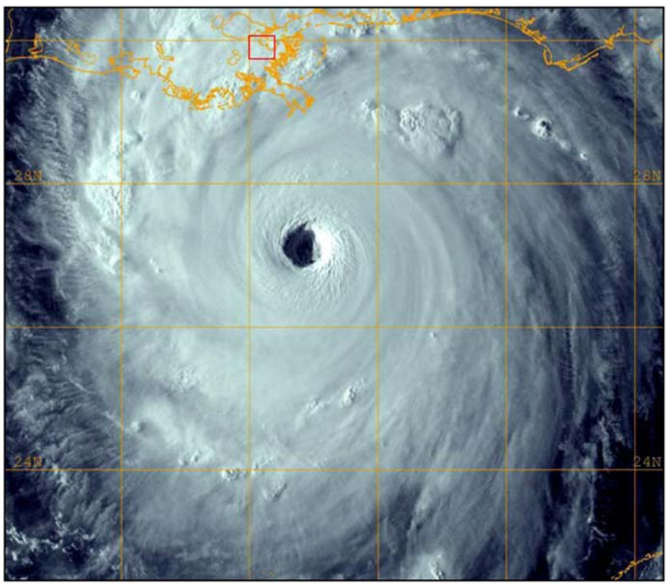

Fig. 1. Satellite image of Hurricane Katrina cloud cover as the storm approaches landfall along the northern Gulf of Mexico coastline.

2. The storm surge model

The regional storm surge and waves team of the IPET performed extensive technical analyses of measured data and applied state-of-the art computer models of hurricane winds, storm surge using ADCIRC (Blain et al., 1994, 1998; Westerink et al., 1994; Luettich and Westerink, 2004; Dawson et al., 2006; Westerink et al., 2008) and waves using WAM (Komen et al., 1994; Gunther, 2005) and STWAVE (Smith, 2000; Smith et al., 2001; Smith and Smith, 2001), to examine the regional-scale hydrodynamic conditions that developed during Katrina. Wave and surge models were coupled over a large regional area. Subsequent to the IPET work (IPET, 2007a), further advancements led to development of the even more detailed SL15 ADCIRC storm surge model application. Dietrich et al. (2009) describe the regional-scale characteristics of storm surge and waves during Hurricanes Katrina and Rita, based on results from the SL15 application.

A highly detailed representation of the complex bathymetry and topography that characterizes the southeastern Louisiana and Mississippi coasts is incorporated into the SL15 application, as shown in Fig. 3. Grid mesh resolution adopted in creating this

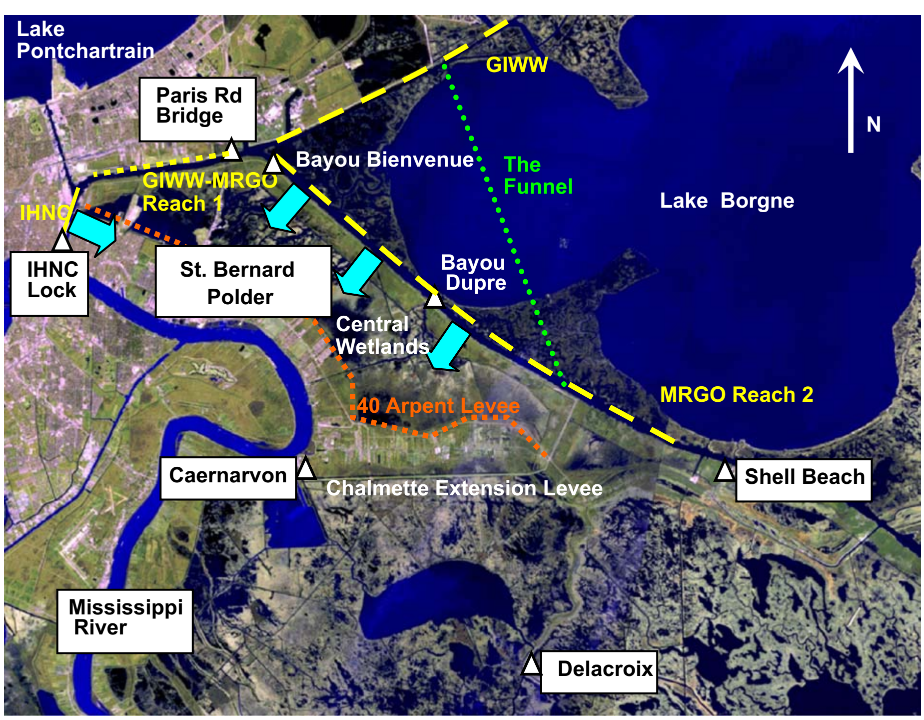

Fig. 2. Location map for the region of interest. Blue arrows indicate major flooding paths into the St. Bernard Polder during Hurricane Katrina.

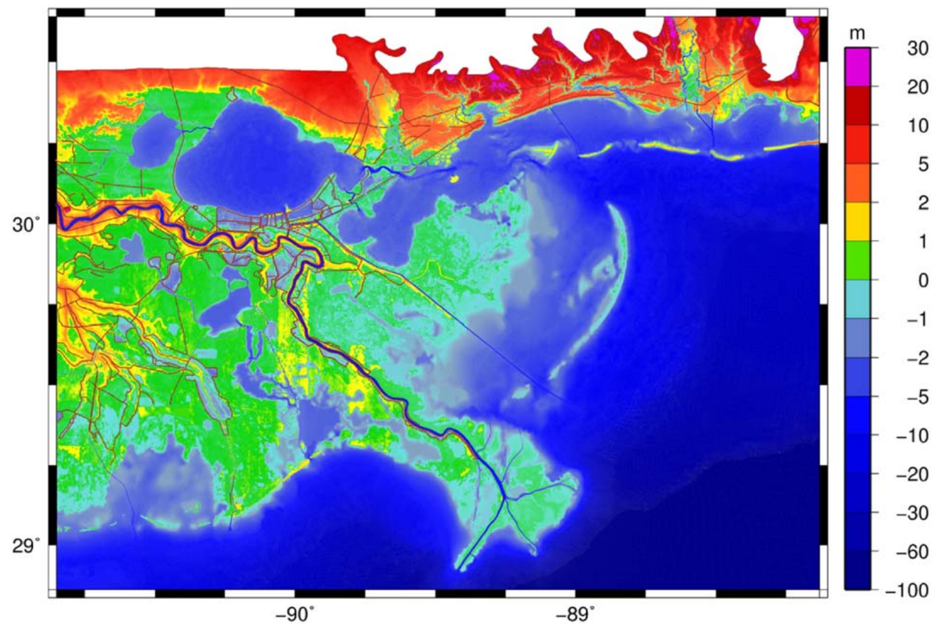

Fig. 3. Map showing elevation of topography and bathymetry incorporated into the SL15 storm surge model application.

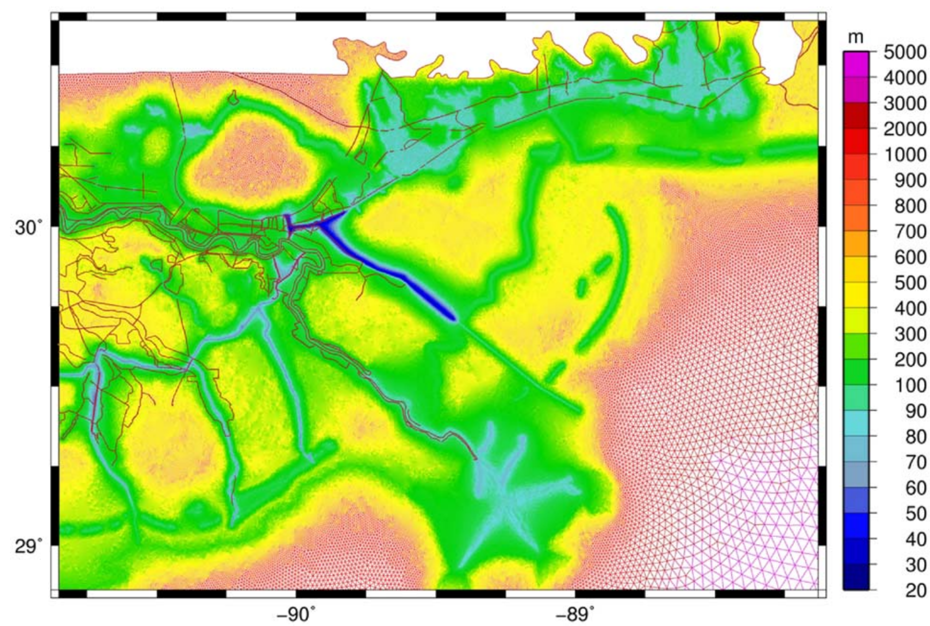

Fig. 4. Grid resolution incorporated into the SL15 storm surge model application.

representation is shown in Fig. 4 for the same region. The shallower nearshore regions and interior coastal areas that can be inundated, including wetlands, were generally resolved with grid node spacing of 100–500 m. Regions where wave breaking was expected to produce high gradients in wave heights, which influence radiation stresses and wave setup, at barrier islands for example, were resolved with node spacing on the order of 100–300 m. Channels were generally resolved using node spacing of less than 100 m, down to 30 m in some key channel segments. Levees, elevated roadways, and other important but relatively narrow features that can influence surge propagation were treated as sub-grid barriers. These features are shown as brown line segments in Fig. 4. The high degree of grid detail is necessary to accurately simulate the propagation of storm surge throughout this very complicated physical system.

Wind fields applied as surface boundary conditions to the surge model were developed through heavy assimilation of measured data acquired from many sources and a wide array of sensors. The techniques used to reconstruct the hurricane wind fields are described in a companion paper presented in this same journal issue and in IPET (2007a). Extensive validation of the wind fields was done and results are shown in (IPET (2007a).

3. Evolution of the storm surge through time

Figs. 5–9 present results from the SL15 model application. They illustrate how storm surge developed and evolved with time in the vicinity of the St. Bernard Polder during Hurricane Katrina. The top panels of each figure show colored contours of wind speed in

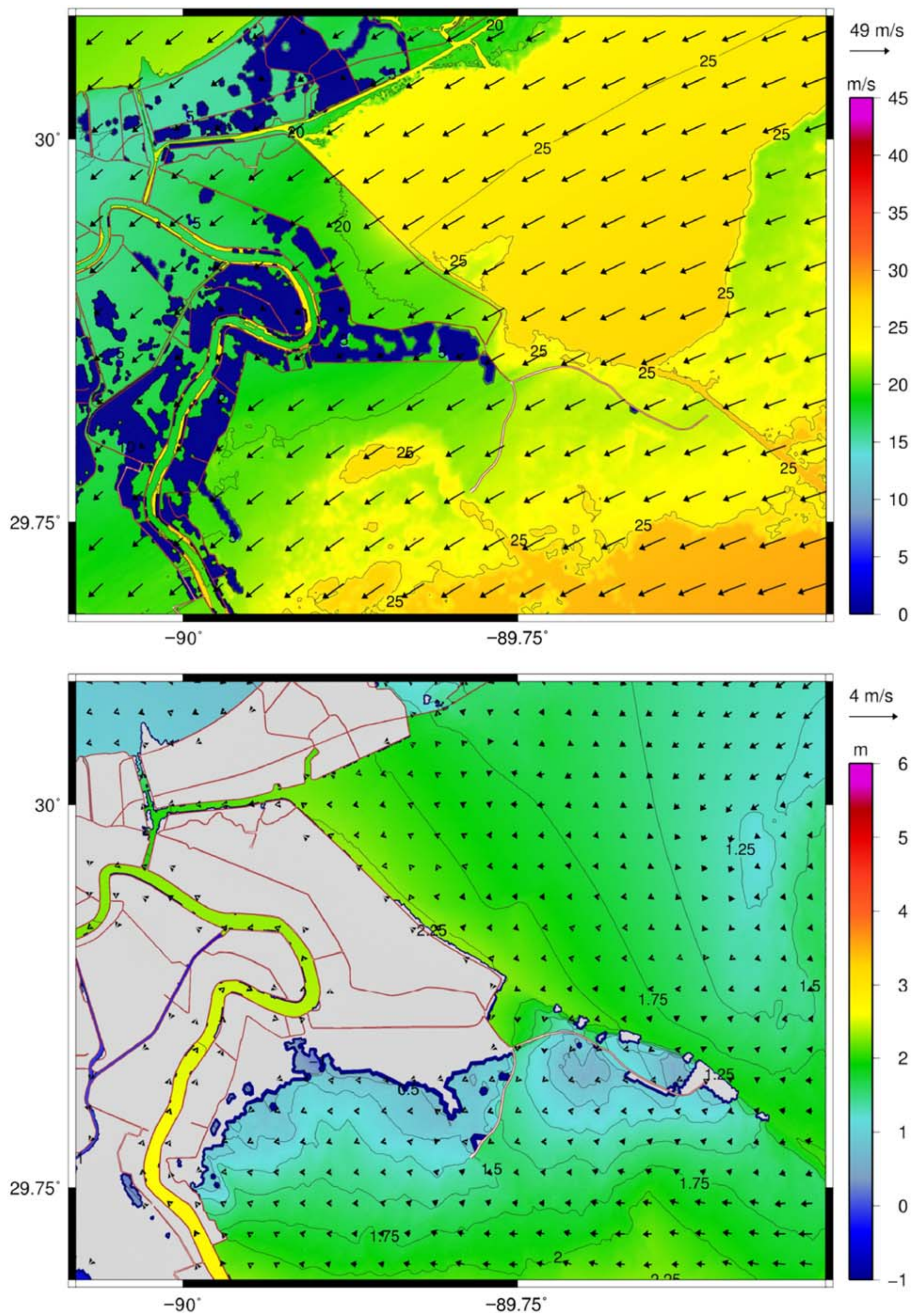

Fig. 5. Wind speed (m/s) and direction snap-shot (top) and storm surge elevation (m NAVD88 2004.65) and water velocity (m/s) snap-shot (bottom) from SL15 ADCIRC model at 0700 UTC (2:00 a.m. CDT) on August 29, 2005.

m/s; wind vectors also are shown (length of the vector is proportional to wind speed). The bottom panels show colored contours of water surface elevation, in meters NAVD88 2004.65; vectors show depth-averaged current velocities in m/s (length of the vector is proportional to current speed). The time of each snap-shot is listed in the caption. Both universal, UTC, and local daylight, CDT, times are reported. Specific surge elevations are referenced throughout this section. References to surge levels in the IHNC reflect actual observations made at the IHNC lock during the storm (IPET, 2007a). References to surge levels along the other polder boundaries reflect model calculations.

Wind is the primary force that generates storm surge and surface wind waves. For several days prior to landfall, winds peripheral to the storm blew consistently from the east–northeast, from the east, and from the east–southeast across the broad Mississippi–Alabama shelf and the shallow Mississippi Sound. These prevailing directions arose due to the counter-clockwise rotation of winds around the hurricane center as it tracked northward through the Gulf of Mexico. Wind speeds were approximately 2.5 m/s four days before the storm's first landfall at Buras LA; 10 m/s at a time 24 h before landfall; and 15 m/s at a time 12 h before landfall. Once the stronger core winds of the storm arrived, peak wind speeds rapidly grew to 45 m/s and then subsided just as quickly as the storm moved rapidly through the region.

Fig. 5 shows the storm surge at 2:00 a.m. CDT on 29 August, 2005, approximately four hours prior to the storm's first landfall south of the St. Bernard Polder along the Mississippi River.

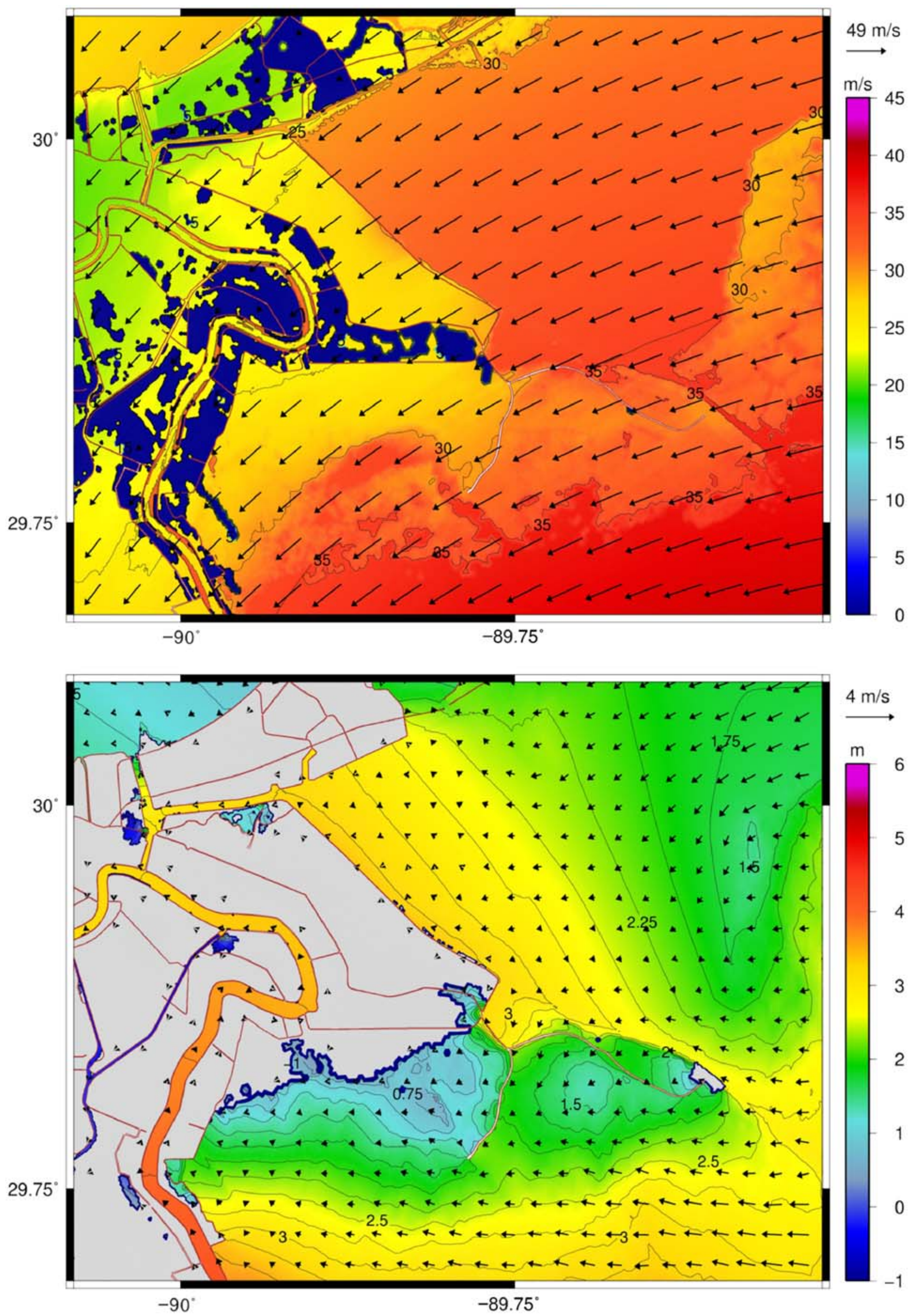

Fig. 6. Wind speed (m/s) and direction snap-shot (top) and storm surge elevation (m NAVD88 2004.65) and water velocity (m/s) snap-shot (bottom) from SL15 ADCIRC model at 1000 UTC (5:00 a.m. CDT) on August 29, 2005.

Maximum wind speeds in the Lake Borgne area exceeded 25 m/s, and winds blew from the northeast. Storm surge regionally built up to levels of 1.5–2.3 m in and around the polder. Computed storm surge was rather uniform along Reach 2 of the MRGO and was 2.3 m in magnitude. Current vectors show water being driven into the region from the east by the wind. This east-to-west movement of water was the predominant pattern prior to landfall. Storm surge that was built up in Lake Borgne propagated through the GIWW/MRGO Reach 1 channel into the IHNC navigation channel adjacent to the polder, and surge elevations reached approximately 2–2.3 m in both channels. Note that even though surge was 2.3 m along the MRGO Reach 2 levee, penetration of the storm surge had not yet reached the southern Chalmette Extension Levee. The gray-shaded region just south of the levee indicates wetland areas that had yet to be inundated. The slowness of the surge to propagate into area is related to the frictional resistance provided by the Caernarvon Marsh, and to local topographic features to the east, and to the northeasterly winds which are blowing away from the Chalmette Extension Levee. Despite the fact that, regionally, water is blown towards the Chalmette Extension Levee, locally it is being blown away from it.

Fig. 6 shows surge conditions three hours later, at 5:00 a.m. CDT on 29 August, approximately one hour prior to landfall. Stronger winds blew from the northeast, at angles that were nearly perpendicular to the northwest–southeast oriented levee section adjacent to the MRGO Reach 2. Winds increased as the storm's core approached. Current vectors indicate that an increasing amount of water was being pushed into the region by

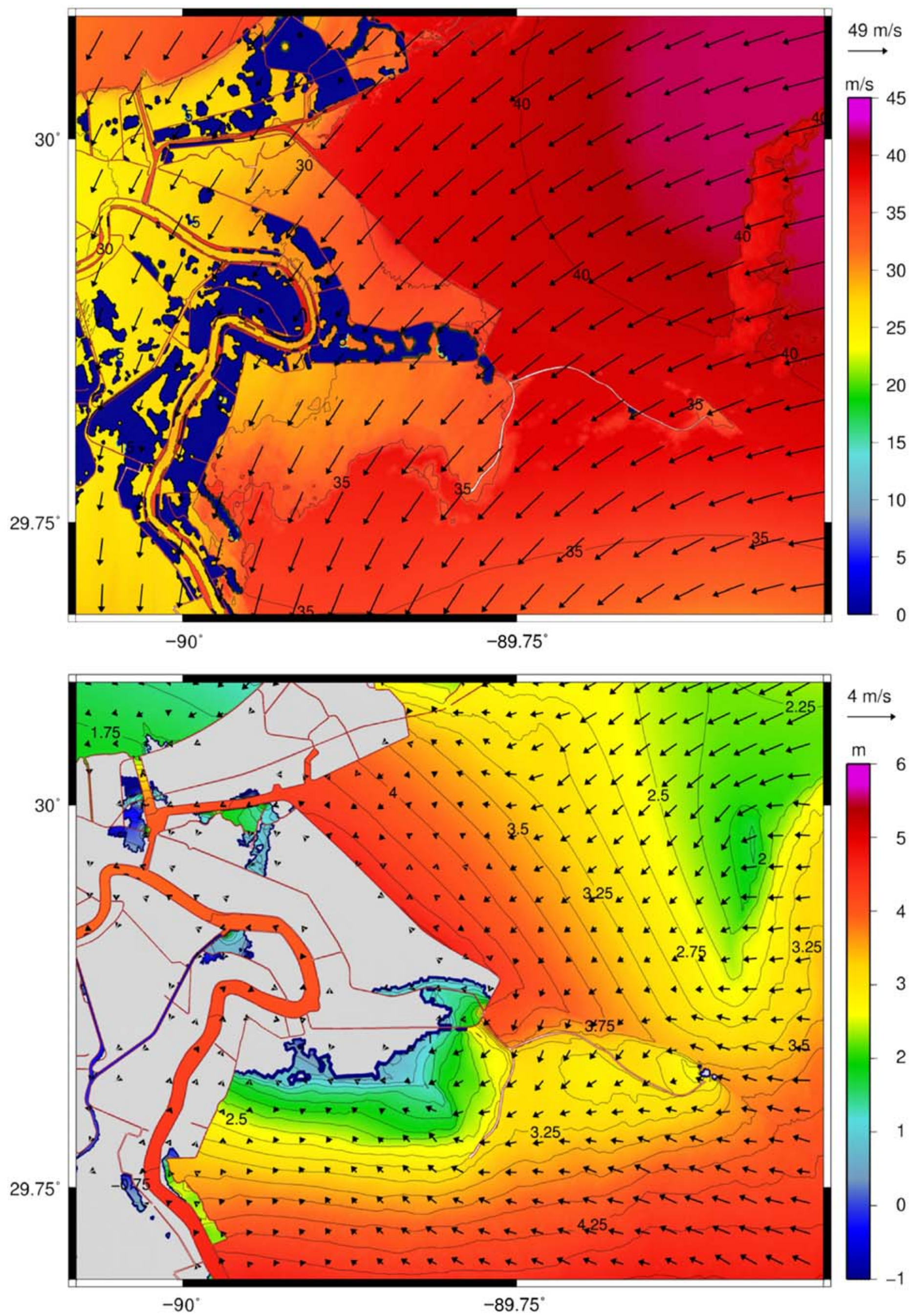

Fig. 7. Wind speed (m/s) and direction snap-shot (top) and storm surge elevation (m NAVD88 2004.65) and water velocity (m/s) snap-shot (bottom) from SL15 ADCIRC model at 1200 UTC (7:00 a.m. CDT) on August 29, 2005.

the wind from the east. Water depth also was increasing which contributed to an even greater influx of water into the region. Storm surge along the eastern side of the polder resulted from water being readily pushed across Lake Borgne and then stacked up against the MRGO Reach 2 Levee. At this location and point in time, the water momentum is dominated by a balance between the wind stress and the water surface slope. Surge contours were nearly perpendicular to the wind direction and parallel to the levee alignment. Computed storm surge along the levee adjacent to MRGO Reach 2 increased to an elevation approaching 3.5 m.

As the surge level rose in Lake Borgne, it also rose adjacent to levees along the MRGO/GIWW Reach 1 and the IHNC because of the connectivity created by the navigation channels. Water levels in Reach 1 and the IHNC were less than levels along the east-facing levee of the polder because the IHNC has an open connection to Lake Pontchartrain at its northern end. As seen in the figures, surge levels in Lake Pontchartrain were much lower than they were in Lake Borgne at this stage of the storm. Therefore, a water surface gradient was induced within the navigation canals that connect the two lakes. The gradient was small from Paris Road Bridge to the confluence of GIWW/MRGO Reach 1 and the IHNC; the gradient increased sharply between this confluence and Lake Pontchartrain. The gradient was much larger north of the confluence due to the fact that the IHNC is narrower and has severe flow constrictions in this portion of the channel. Thus, severe hydraulic entrance and exit energy losses at

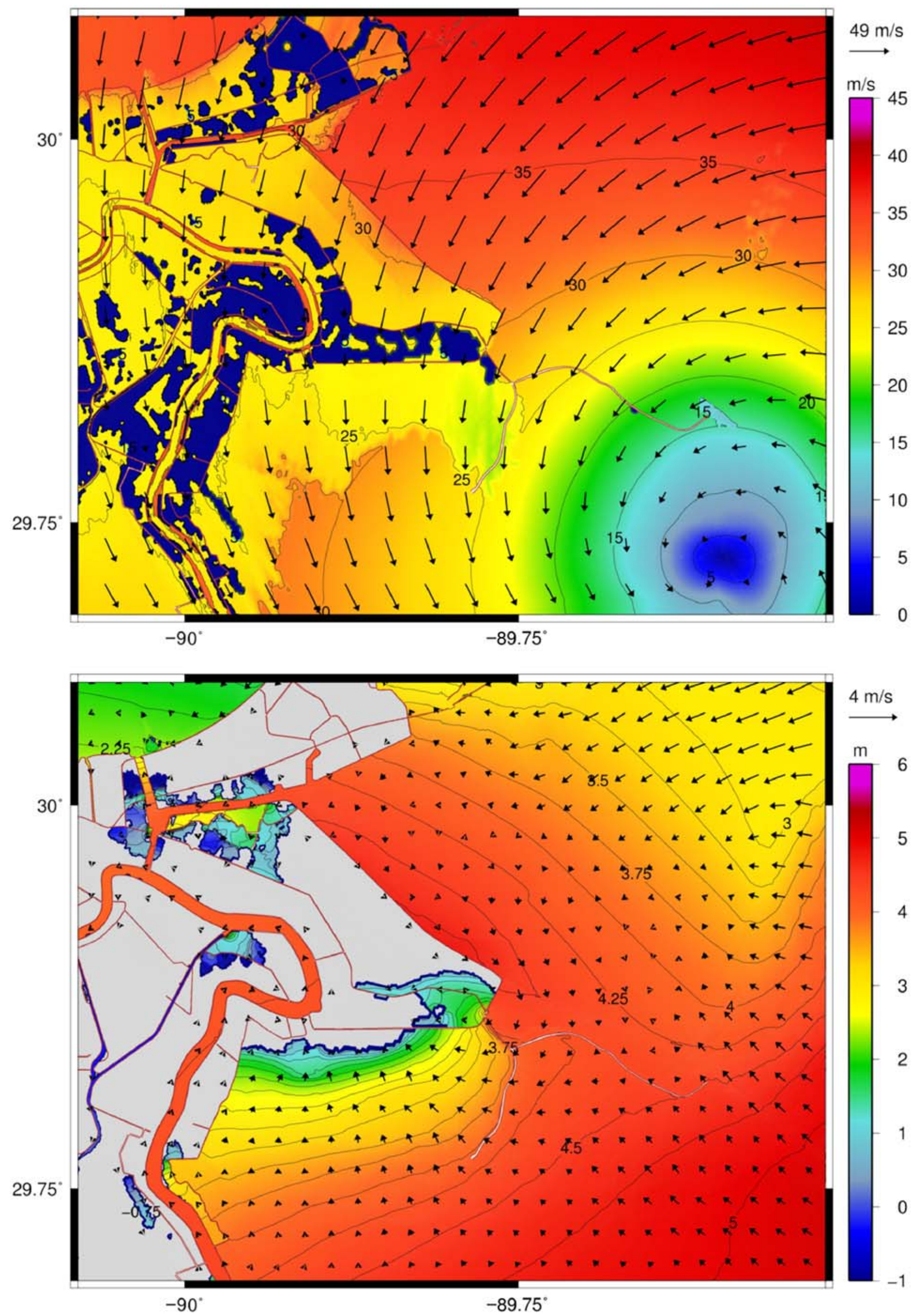

Fig. 8. Wind speed (m/s) and direction snap-shot (top) and storm surge elevation (m NAVD88 2004.65) and water velocity (m/s) snap-shot (bottom) from SL15 ADCIRC model at 1300 UTC (8:00 a.m. CDT) on August 29, 2005.

the constrictions, which are created as water flows passed them, and frictional losses at other perturbations and infrastructure all contributed to the high gradient in surge level within the northern half of the IHNC. The gradient in water level south of the confluence was much smaller. Water level at the IHNC lock is predominantly controlled by the levels at the GIWW/MRGO Reach 1 and IHNC confluence and was at an elevation of approximately 3.2 m.

Note that while the east-facing levees of St. Bernard Polder were being subjected to a 3.5 m storm surge, the wetlands immediately south of the Chalmette Extension Levee had not yet been inundated and there was no surge along most of this levee. Winds were locally blowing from the northeast, away from the Chalmette Extension Levee, and the progression of storm surge was in fact slowed as water was locally blown away from this area. However, surge penetration was progressing (compared to the previous figure, the gray-shaded area is decreasing in size). Water was being regionally forced toward this area from the east, flowing from areas of higher storm surge around the southeastern corner of the polder, and from the east and southeast in conjunction with the approaching core winds of the hurricane.

Fig. 7 shows surge conditions at 7:00 a.m. CDT, approximately 1 h following first landfall at Buras, LA. The storm center was still south–southeast of the polder, not yet visible in the top panel, but winds were rapidly increasing. The momentum balance described previously is clearly evident in Lake Borgne. Due to the increased

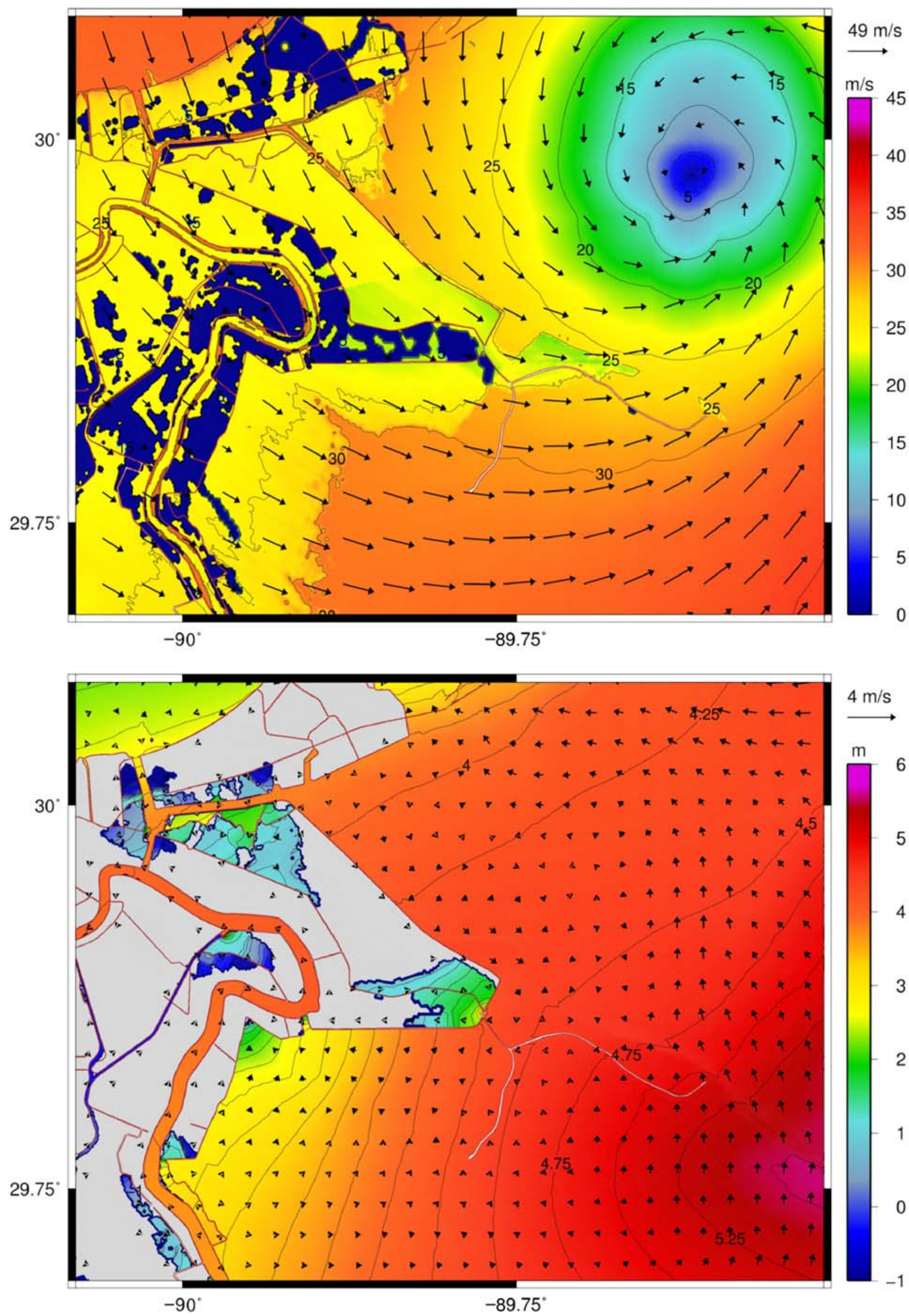

Fig. 9. Wind speed (m/s) and direction snap-shot (top) and storm surge elevation (m NAVD88 2004.65) and water velocity (m/s) snap-shot (bottom) from SL15 ADCIRC model at 1400 UTC (9:00 a.m. CDT) on August 29, 2005.

wind stress, the water surface slope, or gradient, was approaching its greatest amplitude, with the surface elevation contour lines being much closer together. Computed peak surge was approximately 4.8 m, and levels were fairly uniform along much of the levee. The time of this snap-shot was just prior to the time of maximum storm surge along the MRGO Reach 2 side of the polder. Note that the ADCIRC model does not treat the widespread and severe levee degradation that occurred during the storm along the MRGO Reach 2 levee; therefore the massive amount of water that entered the polder along this levee reach is not evident in the simulated result.

Surge levels were less, by about 0.3 m, near the north and south ends of the MRGO Reach 2 levee as water flowed to the north into the MRGO/GIWW Reach 1 channel and to the south around the southeast corner of the polder. The surge near Paris Road Bridge was about 4.3 m. At the IHNC lock, peak surge levels were less, approximately 3.7 m. Surge elevations at the IHNC lock were still controlled by elevations at the confluence of the GIWW/MRGO Reach 1 and the IHNC, but were now also being affected by the winds that were locally blowing from the north–northeast, nearly along the man channel axis. Surge levels in the IHNC were also influenced by the elevations of levees and floodwalls. The peak storm surge exceeded the crest elevations of most walls along the IHNC, so considerable water flowed over the walls and into the adjacent polders, which influenced water levels in the IHNC.

At this time the surge was building from the southeast at Shell Beach (3.5–4 m) and at Delacroix (approximately 4 m) as surge that built up earlier along the southern levees adjacent to the river in Plaquemines Parish propagated northward. Most of the Chalmette Extension Levee had yet to experience storm surge as winds were still locally blowing away from the levee. Along the Chalmette Extension Levee, surge was building from the east and southeast.

Fig. 8 shows conditions at 8:00 a.m. CDT. The center of the hurricane was southeast of the polder, and south of Lake Borgne, clearly visible in the top panel. Winds were shifting in direction as well as dropping in intensity with the approach of the storm's center. Storm surge along MRGO Reach 2 was already beginning to decrease in response to the shifting and decreasing winds. Winds in the IHNC were blowing from the north at this time, and at the IHNC lock the surge increased to a level of 4.2 m. Surge conditions within the IHNC are influenced by the water levels in both Lake Pontchartrain and Lake Borgne, and by local wind conditions. At this point in time, water levels along the south shoreline of Lake Pontchartrain were increasing in response to winds and waves from the north, wind was blowing along the axis of the IHNC producing potential for additional wind setup within the canal, and water levels were beginning to decrease in Lake Borgne but were still high. As the intensity of winds, which were blowing water away from the southern levee of the polder, decreased with arrival of the storm core the storm surge began to rapidly penetrate into the Chalmette Extension Levee area, driven by high surge levels to the east and south. A gradient in storm surge level existed along this levee from zero in the west to 3.5 m in the east, at this point in time. Surge continued to build at Shell Beach (4–4.5 m) and at Delacroix (4.5 m).

Fig. 9 shows the storm surge at 9:00 a.m. CDT. The center of the storm was over Lake Borgne to the east of the polder, about 45 min before making its second landfall along the Louisiana and Mississippi border. At this time winds in the IHNC were from the north–northwest, parallel to the northern portion of the IHNC, the surge reached its peak level along the south shore of Lake Pontchartrain at the entrance to the IHNC, and the surge reached its peak at the IHNC lock (4.4 m). Because winds blow counter-clockwise around the eye of the hurricane, winds in the region were shifting rapidly as the storm center moved through. Winds began to blow from the northwest pushing water away from the eastern MRGO Reach 2 levee and surge levels began to decrease more rapidly. Surge was approaching its maximum levels along the southern Chalmette Extension Levee, as regional surface water gradients pushed water into the area. A surge gradient along the levee was evident, from 3 m in the west to 4.2 m in the east.

As the storm continued to move north, surge surrounding the St. Bernard Polder continued to decrease along the entire periphery of the polder.

4. Water volume entering the "Funnel"

Levees along the GIWW and MRGO Reach 2 navigation channels form what has been called the "Funnel." A transect across what is considered to be the outer boundary of the Funnel is shown as the green dotted line in Fig. 2. Model results were examined to quantify the volumes of water entering and leaving through each of three discrete segments along this transect. The three segments are: the GIWW channel, MRGO Reach 2 channel, and a segment between the channels which crosses Lake Borgne and the wetlands that surround the lake. The volume of water moving both into and out of each segment was calculated for the period of time from 1200 UTC on August 28 through 1200 UTC on August 30, a time that encompassed the surge event. These calculations were made to assess the volume of water that entered the Funnel via the MRGO channel versus the volume entering through the other pathways.

The calculated total volume entering the Funnel through the MRGO Reach 2 channel was 32 million cu m. The total volume that entered through the GIWW channel was 6 million cu m. The total volume entering through the Lake Borgne and the inundated wetlands segment was 632 million cu m. The vast majority of water that moved into the Funnel, 94%, passed through Lake Borgne and over the inundated wetlands, not through the channels. Only 5% of the water volume entered through the MRGO channel, and only 1% entered through the GIWW channel.

Figs. 5–9 illustrate why 94% of the water volume moved into the Funnel via Lake Borgne and the inundated wetlands, and not via the MRGO Reach 2 channel. The dominant movement of water as evidenced by the water velocity vectors shown in these figures was toward the Funnel from the east, driven by the northeasterly winds. This influx raised surge levels regionally to elevations of 2.7–4.0 m; and where northeasterly winds stacked the water against the MRGO Reach 2 levee, surge levels were even higher. Velocity vectors showed that the MRGO Reach 2 channel was a small contributor to the water entering the Funnel compared to the regional movement of water into the Funnel through Lake Borgne and the inundated wetlands. The figures show the dominance in Lake Borgne of the momentum balance between surface wind shear stress and water surface gradient, and the east-to-west movement of water that establishes this water surface gradient. While the surge model does not simulate the wave overtopping, erosion and dynamic breaching of the levee and wall system (that is beyond the current capabilities of the model) the movement of water into the polder through the breaches is not expected to change the dominance of the east-to-west pathway through which water enters the region in response to wind from the northeast and east.

The storm surge snap-shots show that the Funnel had little influence on amplification of the storm surge during Katrina. In response to the predominant momentum balance between wind stress and water surface slope, maximum surge was generated along the MRGO Reach 2 levee, perpendicular to the primary and persistent northeasterly winds. Peak surge did not occur at the apex of the Funnel. Any funneling effect, acting to drive water into and concentrating surge in the Funnel's apex, would be greatest for predominant winds out of the southeast. Southeasterly winds would be associated with a hurricane that tracks south of the polder and toward the northwest; Katrina tracked toward the north as it approached landfall.

5. Measured high water marks—indicators of peak storm surge level

Fig. 10 shows high water marks that were acquired in the vicinity of the polder, and outside the levee perimeter, by a number of organizations: the US Army Corps of Engineers (the Corps), Federal Emergency Management Agency (FEMA), United State Geological Survey (USGS), and Louisiana State University (IPET, 2007a). All marks cite water surface elevations referenced to NAVD88 2004.65. Information about each mark was carefully reviewed by an IPET interagency expert team comprised of engineers and scientists from the Corps, National Oceanic and Atmospheric Administration, and the USGS. In the figure, marks having a white background were rated as good or excellent indicators of storm surge levels, i.e., those recovered from protected areas, inside a structure. Those marks having a shaded blue background were rated as fair/poor; but they are shown because they provide useful information in key areas along the levee system where excellent marks were not available. In each of

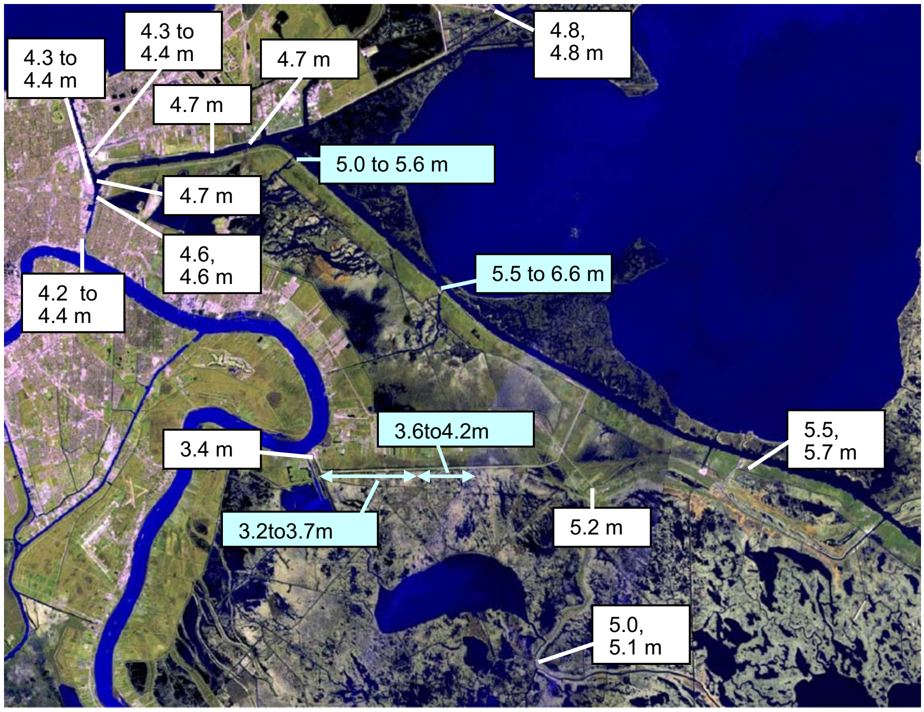

Fig. 10. Measured high water marks (meters, NAVD88 2004.65). White shaded values indicated good and excellent quality high water marks while blue shaded values indicate fair/poor high water marks (marks from IPET (2007a) have been converted to metric units).

these particular cases, the fair/poor marks were most likely strongly influenced by wave action.

Considering only the marks rated as excellent/good, the highest recorded peak storm surge level in the region was at Shell Beach (marks of 5.5 and 5.7 m). At a point just west of Shell Beach, the next highest excellent-rated mark was recorded, 5.2 m. At Delacroix, two good marks showed peak surge levels of 5.0 and 5.1 m. A trend is evident, with high water marks decreasing from east to west through this area. ADCIRC results are consistent with this trend (see Figs. 8 and 9).

High water marks recorded along the south side of the Chalmette Extension Levee showed considerable variability, but they also showed an identifiable trend for decreasing peak surge levels from east to west along the western half of this levee. These high water marks were reflected in debris (primarily vegetation) left by the water level and wave conditions that impinged upon the southern levee face. These debris lines are uncertain as an indicator of peak storm surge level since they likely included the effects of wave run-up on the levee face. At the far western end of the levee, an excellent mark of 3.4 m was recorded at Caernarvon. The trend in fair/poor marks nearby is consistent with this excellent mark. Together, they confirm the trend of decreasing peak water levels from east to west. A very large gradient in peak water level was evident, a change on the order of 1.8 m (3.4–5.2 m) over the entire length of this reach of levee. ADCIRC results are consistent with the observed gradient (see Fig. 9).

High water marks recorded at the Bayou Bienvenue and Dupre gate structures, adjacent to MRGO Reach 2, varied greatly. Accuracy of marks at both sites, as indicators of peak storm surge level, was highly uncertain. These fair/poor-rated marks reflected accumulation of debris (primarily vegetation) that was left either on rails or sills. The lower of the high water marks at both sites reflected marsh grass accumulation on a lower railing. The higher marks reflected vegetation accumulation on an upper railing or some other exposed part of a structure. Debris left on railing, and debris deposited on top of something such as a sill, might not be a good indicator of peak storm level. For example, debris on a sill might have been left during a time of falling surge. The marks might also reflect water surface fluctuations due to short-period wind wave action because of the completely open exposure of these sites. During the storm, high winds were blowing from the east and southeast creating significant wave energy at both sites (IPET, 2007a). Exposure to wave action probably contributed to the high degree of variability reflected in the marks. The peak surge computed along the MRGO Reach 2 levee (4.8 m) is consistent with both sets of high water marks, both of which likely also include the effects of waves.

Along the GIWW, two excellent-rated high water marks recorded along the Chef Menteur Pass indicated peak surge levels of 4.8 m. Peak surge near Paris Road Bridge was 4.7 m, based upon a high water mark acquired along the north bank of the channel. Just to the west of Paris Road Bridge, a second excellent mark in the vicinity recorded the same water level, 4.7 m, also along the north bank. At the confluence of the GIWW/MRGO Reach 1 with the IHNC, a single mark east of the Port of New Orleans (PONO) floodwall indicated a level of 4.7 m. High water marks suggested that peak surge levels were rather uniform throughout the GIWW/MRGO Reach 1. ADCIRC results in this channel are consistent with this observation (see Figs. 7 and 8).

In the IHNC, there were a number of high water marks measured west of the PONO floodwall (but east of the federal hurricane protection levee), all in the 4.3–4.4 m range. East of the PONO floodwall, adjacent to the IHNC, peak surge levels were approximately 4.6–4.7 m. The two marks that indicated 4.6 m peak surge levels (see Fig. 10 for approximate locations) were located just north of the Florida Avenue Bridge on the west side of the canal. At the IHNC lock, several high water marks ranged from 4.2 to 4.4 m.

In light of basic hydraulic principles, had there been no flow over the floodwalls or flow through breaches along the IHNC, south of the confluence of GIWW/MRGO Reach 1 and IHNC, and assuming no flow through the IHNC lock, the peak storm surge at

Table 1
Comparison between measured high water marks and computed maximum water surface elevations.

Location	Measured (m)	Computed (m)	Difference (m)	Difference (%)
Chef Menteur S	4.8	4.0	−0.8	−17
Chef Menteur N	4.8	3.9	−0.9	−19
				Avg −18
Paris Rd Br	4.7	4.4	−0.3	−6
W of Paris Rd Br	4.7	4.3	−0.4	−9
				Avg. −8
Shell Beach E	5.7	4.6	−1.1	−19
Shell Beach W	5.5	4.7	−0.8	−15
Reggio	5.2	4.5	−0.7	−13
				Avg. −16
Delacroix N	5.0	4.3	−0.7	−14
Delacroix S	5.1	4.3	−0.8	−16
				Avg. −15
Caernarvon	3.4	3.4	0	0
PONO–E-1	4.7	4.1	−0.6	−13
PONO–E-2	4.6	4.1	−0.5	−11
PONO–E-3	4.6	4.1	−0.5	−11
				Avg. −12
PONO–W-1	4.4	4.1	−0.3	−7
PONO–W-2	4.3	4.1	−0.2	−5
PONO–W-3	4.4	4.1	−0.3	−7
PONO–W-4	4.3	4.1	−0.2	−5
				Avg. −6
IHNC Lock-1	4.2	4.2	0	0
IHNC Lock-2	4.2	4.2	0	0
IHNC Lock-3	4.4[a]	4.2	−0.2	−5
				Use -5

[a] Observations made by IHNC Lock operator.

the lock would have been similar to that at the confluence, 4.7 m, with a small degree of variability when northerly winds further increased water levels over this relatively short stretch of channel. However, in light of the widespread overflow and the breaches, and the large areas available to receive the water, a considerable amount of water steadily flowed from the IHNC into adjacent populated polders at the peak of the storm. Therefore peak surge levels were reduced in the southern part of the IHNC and west of the PONO floodwall. A gradient in water level along the IHNC was created, increasing from the IHNC lock to the confluence of the IHNC with GIWW/MRGO Reach 1.

6. Surge model validation and accuracy

Bunya et al. (2009) describe validation of the coupled SL15 surge-wave models for Hurricanes Katrina and Rita, and they cite statistical comparisons and show a number of graphical comparisons depicting model accuracy throughout the Louisiana and Mississippi region. No model calibration was done via tuning of model input parameters. For Hurricane Katrina, two extensive sets of high water marks were assembled, one by the US Army Corps of Engineers (Corps) and another by the Federal Emergency Management Agency (FEMA). Both sets of marks were compared to maximum water surface elevations computed using the SL15 model. Each data set consisted of more than 100 high-quality marks. Overall, the average error in computed maximum water surface elevation was 0.02 and 0.19 m for the Corps and FEMA data sets, respectively. Standard deviation of differences between computed maximum water level and measured high water marks, were 0.47 and 0.44 m for the two data sets, respectively. This magnitude of model error is considered to be quite small for a storm surge simulation over a large regional area that produced peak surges up to 8 m.

Table 1 shows a comparison between the measured high water marks shown in Fig. 10 and computed maximum water surface elevations at the same locations. In general, for this entire local area, model computations of maximum water levels were less than or equal to elevations of the high water marks. Differences were greater in the vicinity of Lake Borgne, ranging from 14% to 19%, and they decreased in magnitude toward the west. For example, at Caernarvon, the difference between measured and computed water level was zero; and in MRGO Reach 1 and in the IHNC, differences ranged from zero to 13%. In light of the consistent under predictions in this area, estimates of actual water surface elevations during Hurricane Katrina were made by using the differences in Table 1 to make adjustments to computed water surface elevations through the use of simple scaling. Differences, as a percentage, at points near Lake Borgne were higher than differences computed on the whole for the entire Louisiana and Mississippi region. Larger differences between computed and observed maximum water levels at the more exposed locations around Lake Borgne might be due to accuracy of local wind conditions as the hurricane interacted with land, remnant effects of waves on high water marks, or to model limitations in simulating the effects of rapidly turning wind fields and the dynamics of interacting surge, waves and bottom during such rapidly changing and complex forcing conditions.

7. Sources of floodwater entering the polder

7.1. Western boundary (along the IHNC)

One important series of events lead to early indundation of the heavily populated areas of the St. Bernard Polder. Geotechnical failure during high water levels caused two breaches of the

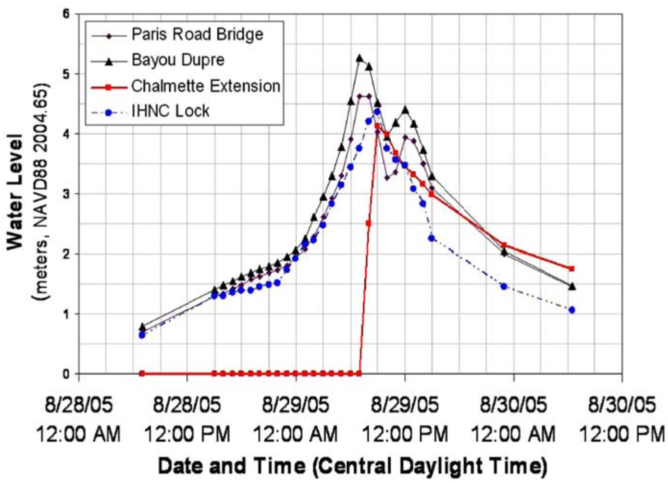

Fig. 11. Estimates of hydrographs along the periphery of the St. Bernard Polder.

floodwall system just to the north of the IHNC lock. Fig. 11 shows the hydrograph measured at the IHNC lock; a peak surge of 4.4 m was observed. Floodwalls at the two breach sites generally had crest elevations of approximately 3.7–3.8 m, lower in a few isolated spots. The smaller northern breach, approximately 75 m in length, was induced by a geotechnical failure (IPET, 2007b) while the surge elevation was only approximately 2.7 m. The hydrograph suggests that water flowed through this breach for 8–9 h, until the water level in the IHNC first peaked and then fell below the level inside the inundated polder (maximum water surface elevation inside the polder reached 3.3 m). Because the peak surge elevation reached 4.4 m, much of the floodwall would have been overtopped for 2–3 h. The larger southern breach, approximately 260 m in length, was induced by overflow of the floodwall, scour on the protected side, and subsequent rotational failure of the wall (IPET, 2007b). Water flowed through the south breach for 5–6 h. These events led to entry of flood water into the Lower 9th Ward, which is located at the western end of the St. Bernard Polder.

7.2. Northern boundary (along GIWW/MRGO Reach 1)

Fig. 11 shows the hydrograph for a location at Paris Road Bridge. The hydrograph was derived using results from the SL15 application, which were simply scaled upward using a ratio of the computed peak value and the measured value of 4.7 m (based on the two excellent high water marks). The hydrograph shows two peaks. The first peak was associated with the initial water level rise as the hurricane approached and winds forced water against the levees building the storm surge, then water levels fell as the eye of the storm passed just to the east and strong winds from the north and west began to blow water eastward out of the Lake Borgne region. The second peak was due to ebbing of the storm surge that built up on the shelf and along the coast of Mississippi. Once the storm made its second landfall and the eye moved into Mississippi, winds along the coast decreased quickly. As the surface wind stress eased, water which had been driven onto the shelf and accumulated along the eastern Louisiana and Mississippi coasts began to flow back toward the Gulf of Mexico. The size of gaps between barrier islands and regional water surface gradients restricted the rate at which the water returned to the Gulf; some flowed back out over the barrier islands. And some of the water flowed back toward Lake Borgne where water surface elevations had decreased to a relatively lower level in response to winds blowing from the west. This flow back into the Lake Borgne region produced the second peak.

Levee crest elevations along the south side of the GIWW/MRGO Reach 1 channel were generally 4.6–5.8 and 4.3–4.6 m in some isolated areas. Peak water levels were quite uniform along this entire stretch of levee (approximately 4.7 m), so overflow into the polder induced by the high initial surge peak was relatively small; and any overflow would have been of short duration. The second peak would not have induced much, if any, overflow into the polder. This levee reach remained intact during the storm.

7.3. Eastern boundary (along MRGO Reach 2)

A second series of events that led to a major influx of flood water, the greatest source, was the severe levee erosion and degradation, and subsequent widespread breaching that occurred at many locations between Bayou Bienvenue and Bayou Dupre, and just southeast of Bayou Dupre, along the eastern periphery of the polder. Fig. 11 shows an estimated hydrograph for Bayou Dupre. The hydrograph was derived using SL15 ADCIRC model results scaled upward to match an estimate of actual peak storm surge of 5.3 m along this reach of levee (IPET, 2007a).

A second peak in the hydrograph is also evident at this location, caused by the same process that was previously described. The crest elevations of levees and floodwalls along MRGO Reach 2 exhibited great variability, from approximately 5.5 m to as low as 3.5 m. Significant stretches of levee had crest elevations of 4.7–5.0 m. The peak surge of 5.3 m was high enough to create steady overflow conditions (and was exacerbated by wave-induced overtopping) over long stretches of levee, exceeding crest elevations of levees and walls by a meter or more in places. The combined action of steady overflow and wave-induced overtopping, which lasted for hours, severely eroded the levees along much of the this reach, degrading and lowering levee crests and leading to substantial breaching (IPET, 2007b). Widespread breaching lead to a massive influx of water into the polder, raising water levels inside to maximum elevations of approximately 3.3 m (IPET, 2007a). In light of the shallow water within the inundated interior of the polder and the high wind stresses, substantial internal water surface gradients would have been generated. Extremely high water remained within the polder for hours following passage of the storm, until water levels outside the polder dropped below interior levels and flood water began to recede and exit the polder through breaches along the IHNC and through levee breaches along the MRGO Reach 2. The occurrence of a second peak greatly increased the duration of time that water levels in Lake Borgne were high enough to continue to force water into the flooded polder.

7.4. Southern boundary (along the Chalmette Extension Levee)

Fig. 11 shows a representative hydrograph for a point approximately midway along the southern Chalmette Extension Levee. The hydrograph was derived using model results scaled upward to an estimated peak water level of 4.1 m. Note the very rapid rate of rise, the asymmetric shape and the lag in time of peak surge compared to other hydrographs. The surge snap-shots presented previously showed how surge penetration into this region was delayed, relative to the build-up along the MRGO Reach 2 levee. The delay was induced by the winds pushing water away from this levee until the storm center passed through, and by the frictional resistance of the marsh and presence of topographic features which slowed propagation of the surge wave into this region. The very rapid rate of rise occurred once the wind intensity decreased and the higher surge gradients finally pushed water into the area. Also recall the large gradient in peak storm surge along this levee as evidenced by the high water marks, which showed a difference of approximately 1.8 m from the western end to the eastern end. In light of crest elevations along this levee (4.0–5.8 m), and the shorter duration of high surge, little or no steady overflow was experienced along most of this levee. The Chalmette Extension Levee remained intact during the storm.

8. Conclusions

The SL15 ADCIRC model application provided accurate calculations of, and extremely valuable insights into, the development and propagation of hurricane-induced storm surge into the region.

The considerable variability in surge conditions (both peak surge and hydrograph shape) around the St. Bernard Polder was influenced by these factors: prevailing regional and local wind conditions and patterns that are dictated by hurricane track and by the evolving structure of surface wind fields; presence of channels which created hydraulic connectivity between water bodies; presence of wetlands and topographic features; and orientation and configuration of the levee system itself and its influence on water movement and surge propagation. In light of this inherent complexity, a different hurricane will undoubtedly produce a different set of responses along the periphery of the polder in terms of both peak surges and hydrograph shapes.

The greatest surge levels were experienced along the eastern boundary of the polder, where the momentum balance was dominated by the surface wind stress and the water surface slope. The MRGO Reach 2 channel was not found to be a major conduit for surge propagation into the Funnel; most water moved through Lake Borgne and over the inundated wetlands which surround the lake. Connectivity provided by navigation channels enabled surge generated in Lake Borgne to propagate through the GIWW/MRGO Reach 1 channel and into the IHNC. Peak surge along the Chalmette Extension Levee was less than along other polder boundaries, and high surge levels occurred for a much shorter duration, primarily because winds blew water away from this levee during much of the most intense phase of the storm. The northern and eastern boundaries of the polder experienced a second surge peak due to the recession of the storm surge from the shelf and coast of Mississippi.

The greatest volume of flood water entered the polder through its eastern boundary. This was due primarily to greater differences between peak surge levels and levee/floodwall crest elevations which produced considerable wave overtopping and overflow, which led to levee and wall breaching. The presence of the second storm surge peak extended the amount of time during which water was forced into the breached polder.

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