Surge Generation Mechanisms in the Lower Mississippi River and Discharge Dependency

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Abstract: The Lower Mississippi River protrudes into the Gulf of Mexico, and manmade levees line only the west bank for 55 km of the Lower Plaquemines section. Historically, sustained easterly winds from hurricanes have directed surge across Breton Sound, into the Mississippi River and against its west bank levee, allowing for surge to build and then propagate efficiently upriver and thus increase water levels past New Orleans. This case study applies a new and extensively validated basin- to channel-scale, high-resolution, unstructured-mesh ADvanced CIRCulation model to simulate a suite of historical and hypothetical storms under low to high river discharges. The results show that during hurricanes, (1) total water levels in the lower river south of Pointe à La Hache are only weakly dependent on river flow, and easterly wind-driven storm surge is generated on top of existing ambient strongly flow-dependent river stages, so the surge that propagates upriver reduces with increasing river flow; (2) natural levees and adjacent wetlands on the east and west banks in the Lower Plaquemines capture storm surge in the river, although not as effectively as the manmade levees on the west bank; and (3) the lowering of manmade levees along this Lower Plaquemines river section to their natural state, to allow storm surge to partially pass across the Mississippi River, will decrease storm surge upriver by 1 to 2 m between Pointe à La Hache and New Orleans, independent of river flow. **DOI:** 10.1061/(ASCE)WW.1943-5460.0000185. *© 2013 American Society of Civil Engineers.*

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Introduction

Southeastern Louisiana is extremely susceptible to major hurricane events because of the increased probability of landfall along the north central Gulf coast, and also because of the protrusion of the delta and river system onto the shelf (Stone et al. 1997; Resio and Westerink 2008). The construction of the extensive regional levee system in Southeastern Louisiana has been driven by a number of factors, including high river stage events, hurricane events, the perception that a contained river will self-scour, and the growth of communities. Historically, the design of Southeastern Louisiana's hurricane flood risk reduction system has hinged on raising and adding levees in response to river or hurricane events that impacted the region (Humphreys and Abbot 1867; Tompkins 1901; Pabis 1998; Rogers 2008). As shown in Fig. 1, manmade levees and polders border both the east and west banks, whereas for 55 km between Pointe à La Hache and Venice, manmade levees border only a narrow strip of sparsely populated land on the west bank; the east bank across from this protected area retains its natural levee. Recent detailed studies of historical hurricanes indicate that the manmade levees on the Mississippi River's west bank in Lower Plaquemines help capture storm surge and allow the surge to propagate upriver past New Orleans, impacting hurricane inundation risk along the riverine communities on both the west and east banks (Bunya et al. 2010; Dietrich et al. 2011; Martyr et al. 2013). It is clear that raising levees can increase surge elevations within the river because attenuation due to lateral spreading onto the floodplain is blocked. However, the regional impact of raising levees has generally been

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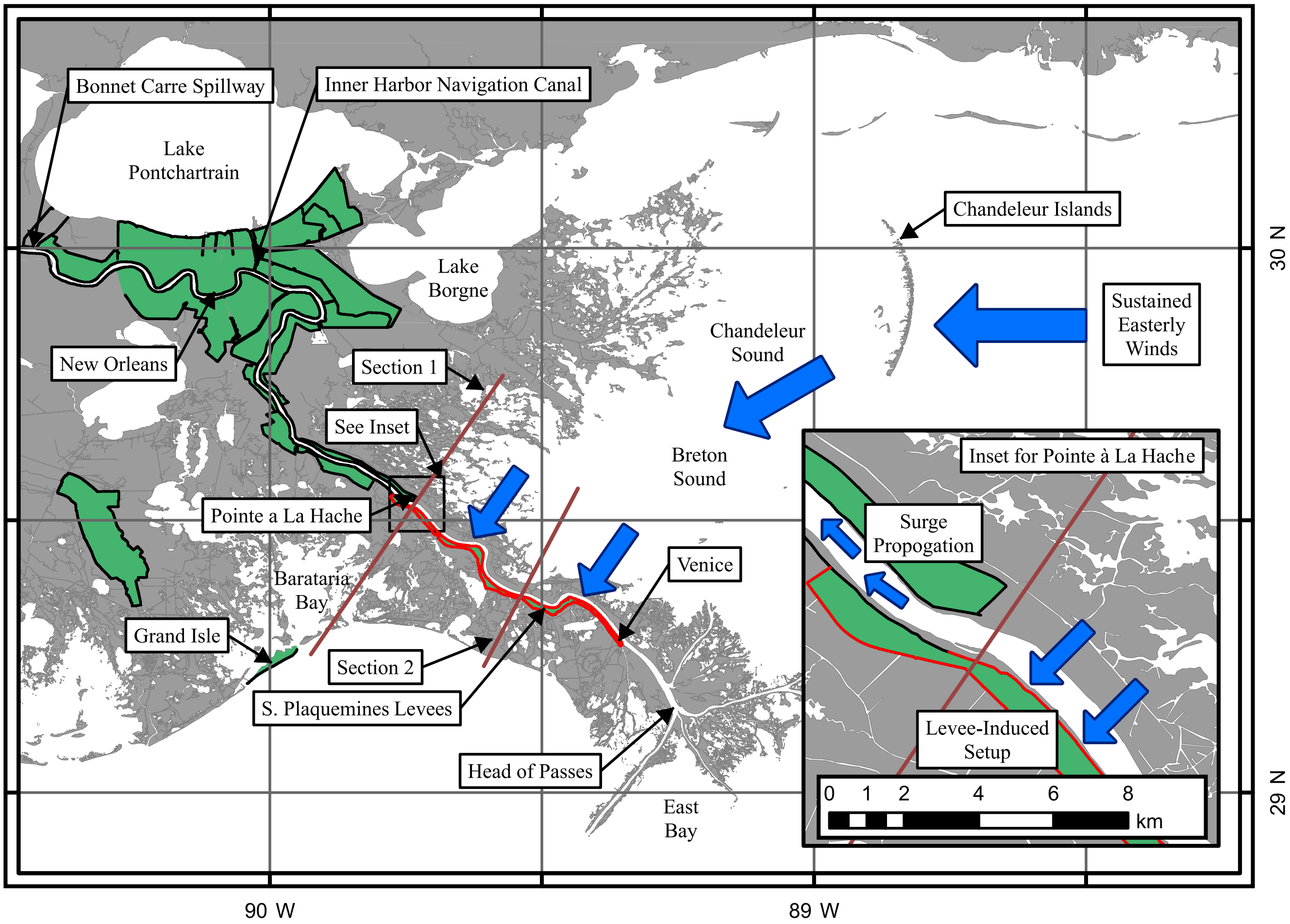

Fig. 1. (Color) Map of Southeastern Louisiana; green areas are polder areas protected by levee systems; black lines indicate levees; red lines indicate the levees on the west bank of the Mississippi River that confine a narrow strip of Lower Plaquemines between Pointe à La Hache, Louisiana, and Venice, Louisiana; blue vectors indicate typical water currents driven by easterly winds during hurricanes

unclear, as has the influence of river discharge on storm surge generation and propagation, and so it is these questions that this case study seeks to address.

As illustrated in Fig. 1, as a hurricane approaches Southeastern Louisiana, the counterclockwise rotation of the wind field directs surge across the barrier islands and Chandeleur and Breton Sounds and into the coastal marshes and wetlands (Resio and Westerink 2008; Ebersole et al. 2010). The hurricane's sustained easterly winds force water to rise in these shallow areas and then to spill over the natural east bank of Lower Plaquemines and into the Mississippi River. Once storm surge has entered the river, it builds against the west bank levee and, because of the river's deep channel, the surge efficiently propagates upriver (Martyr et al. 2013). de Jong et al. (2007) and Van de Waart et al. (2009, 2010) recognized that levees along the southern portion of the Mississippi River system were artificially blocking storm surge and they proposed several alternatives to allow storm surge to pass across the west bank, including full and partial removal of the Plaquemines levees. This case study uses a newly validated model (Martyr et al. 2013), which, compared with previous studies such as de Jong et al. (2007) and Van de Waart et al. (2010), features a much higher resolved mesh, additional river flow-dependent physics, and different levee scenarios. The influence of discharge on the generation and propagation of storm surge in the river is explored, as well as the mechanisms and degree by which storm surge is captured in the Mississippi River, by comparing the sensitivity of storm surge with the existence or nonexistence of the 55-km section of manmade Lower Plaquemines Levees. To this end, a suite of storms, both historical and hypothetical, were simulated to compare surge levels in the Lower Mississippi River, its banks, and adjoining wetlands under multiple discharge conditions in addition to the two levee scenarios.

Methods

This analysis employed the ADvanced CIRCulation (ADCIRC)-2DDI, a continuous-Galerkin finite-element model that solves depth-integrated barotropic shallow water equations on an unstructured mesh (Luettich and Westerink 2004; Dawson et al. 2006; Westerink et al. 2008, Tanaka et al. 2011). The ADCIRC model has been very successful in simulating the complex response characteristics of the Northern Gulf of Mexico to hurricane and tidal forcing (Bunya et al. 2010; Dietrich et al. 2012, 2011; Martyr et al. 2013). Validation studies for recent hurricanes include Katrina (2005) and Rita (2005) using the SL15 mesh (Bunya et al. 2010; Dietrich et al. 2010), Gustav (2008) using the SL16 mesh (Dietrich et al. 2011), and Ike (2008) using the TX2008r33 mesh (Kennedy et al. 2011). These models utilize unstructured meshes to resolve the basin, shelf, floodplain, and channel scales and incorporate spatial frictional variability into the physical dissipation terms for circulation (Bunya et al. 2010). The SL15 mesh (Bunya et al. 2010) was used by the

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COE and FEMA in the design and analysis of the Flood Risk Reduction System for Southeastern Louisiana and to establish the flood risk in the region (COE 2009; FEMA 2009).

The next-generation SL16 mesh, with a higher level of resolution and depiction of the river and delta, and containing roughly twice the number of finite elements of the SL15 mesh, was used as the base mesh for this study. The SL16 SWAN + ADCIRC model hindcasts for Hurricanes Katrina, Rita, Gustav, and Ike match 85% of measured high water marks to better than 50 cm with an average absolute error of 15 cm and a standard deviation of 18 cm (Dietrich et al. 2012). In addition to the increased resolution of the river, its delta, and surrounding wetlands, this study also makes use of the improvements by Martyr et al. (2013) that feature (1) parameterization of frictional resistance that is flow-regime dependent, and (2) implementation of a temporally varying riverine flow-driven radiation boundary condition. The addition of the higher resolution and time-varying flow physics improved performance significantly in the Mississippi River when compared with previous models (Bunya et al. 2010; Dietrich et al. 2011). The SL16 SWAN + ADCIRC model using flow-dependent friction and flow-dependent river radiation boundary conditions matches the flow-stage relationships along the river to within 14 cm, flow distributions within the deltaic system with a correlation coefficient $R^2 = 0.93$, and hydrographs during Gustav (2008) within the river with a scatter index = 0.14 and mean normalized bias = 0.2 (Martyr et al. 2013). The SL16 model has improved significantly as compared with earlier models because of its feature resolution, as well as its flow-dependent physics.

To simulate the existing flood protection system and to fully understand the influence of the river levees, the SL16-Raised Levees mesh (9,946,399 elements, 5,035,501 nodes) was modified from the SL16 mesh by raising all levees along the river to 50 m to ensure that no overtopping would occur. For the case without the 55-km section of manmade levees along the west bank of the Lower Plaquemines, the SL16-Lowered Levees mesh (9,946,878 elements, 5,034,023 nodes) was generated from the SL16-Raised Levees mesh by removing the west bank levee system south of Pointe à La Hache and replacing this levee with a 1.82-m NAVD88 (2004.65) maximum natural levee that is fully integrated into the mesh. The 1.82-m height is the maximum natural levee height on the east bank.

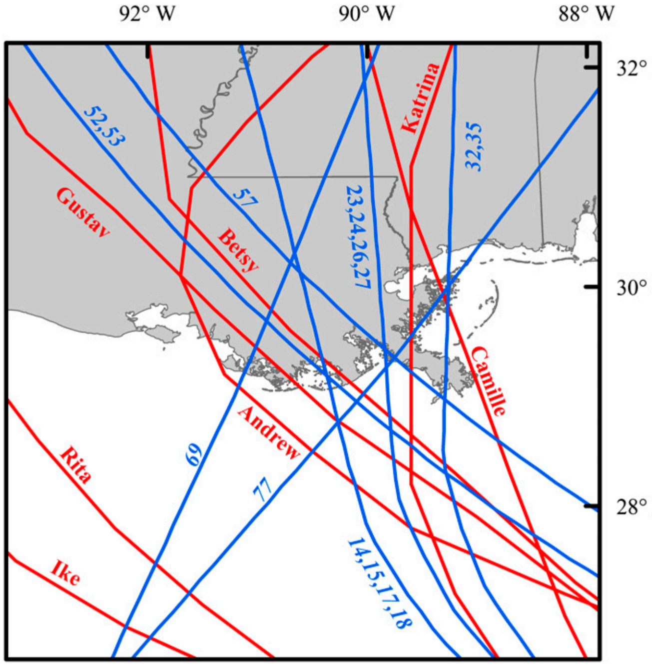

Fig. 2. (Color) Map of storm tracks: historical storms (red) and synthetic storms (blue)

Seven historical and 15 hypothetical storms were simulated without tides and waves for a storm-dependent duration ranging from 10 to 27 days (which includes 6 days to ramp and settle the system prior to wind forcing) and using a 1-s model time step. As shown in Fig. 2, the storms were selected to cover a wide range of probable combinations of central pressure, radius to maximum winds, and track. The seven historical storms, Betsy (1965), Camille (1969), Andrew (1992), Katrina (2005), Rita (2005), Gustav (2008), and Ike (2008), were major storms that impacted Southern Louisiana and have been well documented. The historical storm wind fields used in this study applied objectively analyzed measurements from available anemometers, airborne and land-based Doppler radar, airborne stepped-frequency microwave radiometers, buoys, ships, aircraft, coastal stations, and satellite measurements. The reconstructions applied a combination of inner core assimilation using the National Oceanic and Atmospheric Administration's Hurricane Research Division Wind Analysis System (H*WIND) when available (Powell et al. 1996, 1998), which were then blended with Gulf-scale winds using an interactive objective kinematic analysis system (Cox et al. 1995; Cardone et al. 2007). The resulting winds for Hurricanes Katrina (2005), Rita (2005), Gustav (2008), and Ike (2008) were applied in validation hindcasts for both wave and surge fields (Bunya et al. 2010; Dietrich et al. 2010, 2011, 2012; Kennedy et al. 2011). The 15 synthetic storms were selected from the 152 storms that were developed for Southeastern Louisiana as part of the Interagency Performance Evaluation Team's methodologies and the Joint COE-FEMA study's selection of a 100-year storm set using the Joint Probability Method with Optimal Sampling (Resio 2007; Ebersole et al. 2007; Link et al. 2008; COE 2009; FEMA 2009).

The SL16 mesh incorporates the Mississippi and Atchafalaya River flows in its river radiation boundary conditions. Three steady discharges (5,664 m^3/s, 14,158 m^3/s, and 22,654 m^3/s) were selected to cover a likely range of discharge conditions during hurricane season, which occurs between June and November. Using historical gauge data from Tarbert Landing during hurricane season (http://www.mvn.usace.army.mil/eng/edhd/wcontrol/miss.asp), flow rates of 5,664 m^3/s and 22,654 m^3/s were estimated to be the 2-year, 7-day low and the 2.5-year high using a Log-Pearson III frequency analysis. In comparison, the discharges at Tarbert Landing averaged over the 7 days prior to landfall of Katrina, Rita, Gustav, and Ike were 4,842, 5,437, 8,807; and 12,318 m^3/s, respectively. The SL16 models apply a 70% and a 30% appropriation of discharge into the Mississippi and Atchafalaya Rivers, respectively, which is the ratio maintained by the COE at Old River Control Structure.

River Base Flow and Storm Surge Response

The combination of two meshes, three steady river discharges, and 22 storms amounted to a total of 132 simulations being performed. Katrina and synthetic storms 77, 32, and 35 had tracks that passed directly over the Mississippi River south of Pointe à La Hache; Katrina and storm 77 passed between Pointe à La Hache and Empire, whereas storms 32 and 35 passed just south of Venice. These storms are significant because the radius of maximum winds for the storm set ranged from 15 to 40 km, so these storms would have focused the highest winds perpendicular to the 55-km section of Lower Plaquemines west bank levees. Because of Katrina's impact in Southeastern Louisiana and the surge generated in the Mississippi River, it is an ideal case to examine the

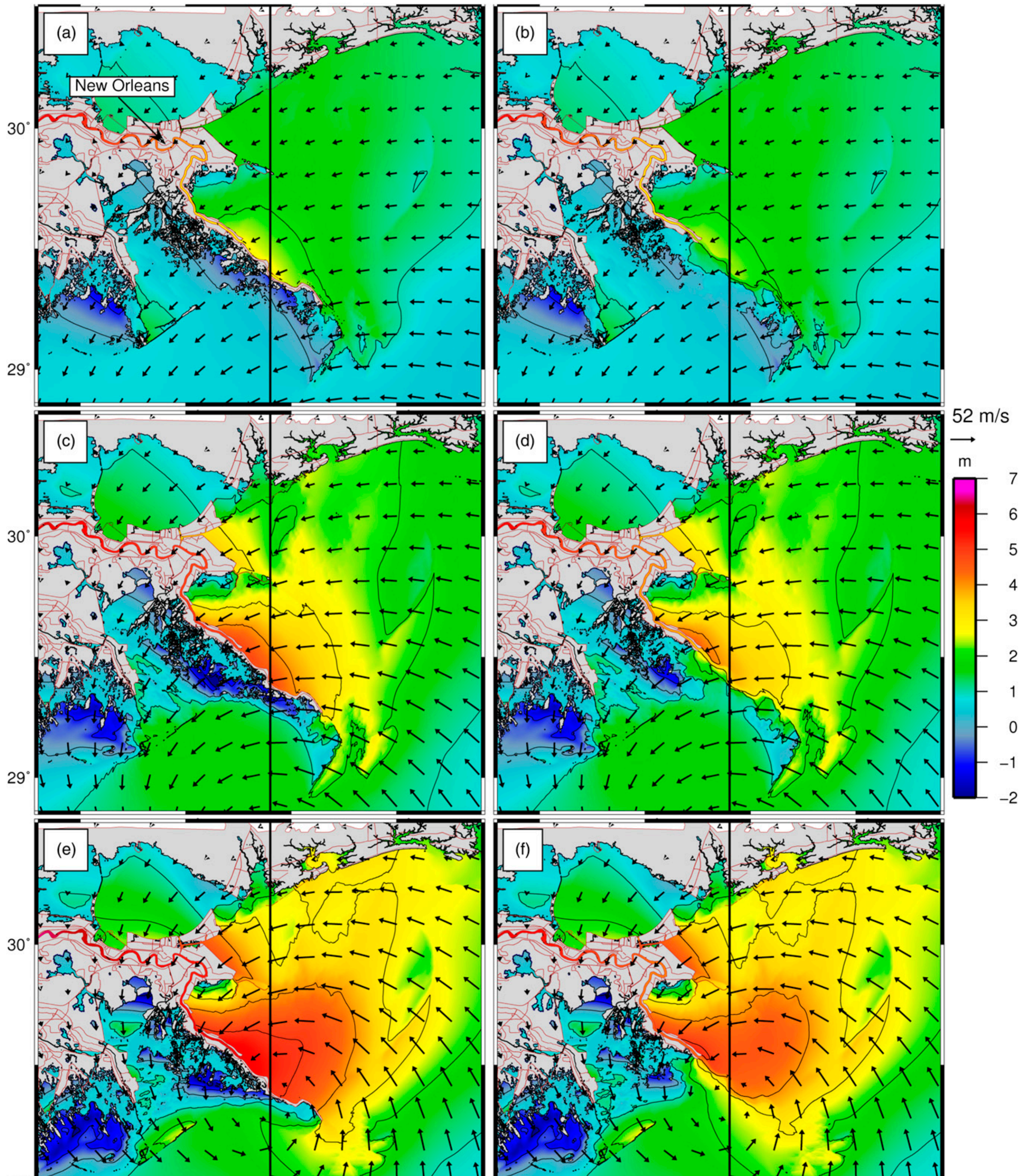

Fig. 3. (Color) Contours of ADCIRC water level (m relative to NAVD88 2004.65) and wind vectors (m/s) in Southeastern Louisiana during Hurricane Katrina under high flow river conditions; the center vertical black line represents the south-north track of Hurricane Katrina; (a, c, and e) SL16-Raised Levees model; (b, d, and f) SL16-Lowered Levees model; the plots correspond to the following times on August 29, 2005: (a and b) 0430 UTC, (c and d) 0930 UTC, (e and f) 1200 UTC

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genesis of surge within and around the river, as well as the differences between the two levee alternatives being studied.

Hurricane Katrina under High River Flow Conditions

Fig. 3 shows a sequence of wind and surge fields during the 7.5 hours leading to Katrina's landfall for the two levee scenarios being studied under high river flow conditions. Katrina passed directly over Lower Plaquemines in a south-north direction. When the eye of a hurricane is offshore in the Gulf, the storm produces shore-parallel winds along the Gulf's north continental shelf, which are easterly winds in the case of Southeastern Louisiana. The Mississippi River juts from the northwest to the southeast and protrudes to the edge of the continental shelf. This protrusion traps the surge generated by these easterly winds. As Katrina moved northward to the coast, its winds increased in intensity and the angle from the eye became more pronounced. The winds rotated in the northwest quadrant to align orthogonally to the lower arm of the Mississippi River, while maintaining easterly sustained winds ahead of Katrina's track, even more effectively generating surge over the sounds and wetlands adjacent to the river.

Figs. 3(a and b) show, prior to landfall, that storm surge is driven by the easterly winds and builds against the Lower Plaquemines levees in both the SL16-Raised Levees configuration and in the SL16-Lowered Levees configuration. The sustained easterly winds drive storm surge east of the river over the barrier islands and into Breton Sound, submerging the barrier islands and raising water levels in the marshes and wetlands. There is also a bulge along the east bank in both scenarios, where the wind-driven storm surge meets the raised natural levees of the east bank, the frictional resistance of the wetlands to the east of the river, and the lateral overbank discharge from the river.

In Figs. 3(c and d), Katrina is less than 2 hours from landfall, and significant differences between the two scenarios can be seen in the water surface elevation along the east bank because of the bank-perpendicular winds. The raised levees scenario in Fig. 3(c) features a bulge in the water surface from Venice to 25 km upriver of Pointe à La Hache, whereas the lowered levees scenario features a bulge roughly 1 m less in maximum elevation from Pointe à La Hache to 25 km upriver. This difference is also highlighted in the Mississippi River primarily south of New Orleans. At this point, storm surge south of Pointe à La Hache in the raised levees scenario [Fig. 3(c)] is entirely trapped against the west bank levees, whereas in the lowered levees scenario [Fig. 3(d)], storm surge passes partially across the now natural west bank of the river and into the adjacent marshes and then to the Gulf. It is important to note that the west river bank and adjacent wetlands in the lowered levee scenario still partially trap the surge in the river through frictional resistance generated by the cross-bank flows. Once the storm surge enters the Mississippi River, it efficiently propagates upriver because of the river's width and depth.

In Figs. 3(e and f), Katrina has made landfall and is on the east bank of the Mississippi River. At this time, storm surge levels have reached their maxima in the Mississippi River for both scenarios. Northwest of the eye, the maximum radius of winds is perpendicular to the east bank just upriver of Pointe à La Hache. North of the eye and ahead of the track, winds are still easterly and are pushing surge into the Breton sound. To the west of the track, the winds are northerly and are pushing water out of Barataria Bay and into the Gulf. In the raised levees scenario [Fig. 3(e)], the storm surge is trapped by the west bank levees, thus raising water levels on the east side and up the river. In the lowered levees scenario [Fig. 3(f)], the storm surge is still partially passing across the west bank and over the marshes and then being blown into the Gulf (thereby not increasing water levels in populated areas to the north of Barataria Bay). In comparing panels in Fig. 3, it is clear that the lowered levees scenario reduces water surface elevations on the east bank and within the river and does not increase water surface elevations west of the river aside from the inundation of the currently protected polder and adjacent marshes.

Maximum of the Maximum

To address the effects of river flow and the wide range of diverse characteristics of storms, Maximum of the Maximum (MOM), which are a composite of maximum storm surge water levels, were computed for the seven historical storms and the combined seven historical and 15 synthetic storms for the low and high river discharges and the two levee alternatives. Fig. 4 shows the differences between the two levee alternatives, with warm and cold colors defining areas where the lowered levees scenario would raise and lower water levels, respectively. In Fig. 4, the lowered levees scenario shows a consistent trend of reducing water levels on the east side and within the river, and increasing water levels on the west side in Barataria Bay; however, the differences away from the river are within unpopulated wetlands and are on the order of less than 30 cm. In comparing the top and bottom subfigures, which represent the cumulative and historical MOMs, respectively, the impact of lowering the levees is somewhat larger for the larger storm set, although both sets still indicate a 1- to 2-m decrease in flood levels for the lowered levees scenario along the lower east bank and within the river. This is reflective of stronger and better aligned storms 32 and 35, which make landfall just south of Venice and feature their maximum radii of winds perpendicular along the 55-km river stretch of the west bank levees. In comparing the left and right subfigures, which represent the high- and low-flow MOMs, respectively, there is relatively little difference between the two river flow conditions, with the exception of a small increase in water elevations to the west of the river, reflecting prestorm river discharge flowing into Barataria Bay in the lowered levee scenario. The most striking detail in these plots is the difference in water surface elevation for the river, which has its maximum difference of about 1.5 to 2 m at Pointe à La Hache and gradually declines upriver.

River Profiles

Maximum water surface elevations for river flow only and for the seven historical storms were extracted along the thalweg of the Mississippi River for the raised levees and the lowered levees scenarios. Profiles along the river for base flow, maximum total water levels, and differences in water level between the raised levees and lowered levees scenarios are plotted in Fig. 5(a) for low flow on the river and in Fig. 5(b) for high flow on the river for the five most impactful storms. Fig. 5 shows that the river-only base flow elevations for the raised and lowered levees scenarios are identical for low river flow conditions. Furthermore, the lowered levees case lowers the entire river's level as compared with the raised levees scenario under high river flow conditions. Under high river flow conditions, this 20-cm decrease can be attributed to the additional lateral outflow that occurs on the west bank for the lowered levees scenario, whereas under low river flow conditions, discharge is retained within the banks.

For both low and high flow conditions (Fig. 5), the water surface elevation for the lowered levees scenario is lower than for the raised levees scenario. For each hurricane, this difference is plotted at the bottom of Figs. 5(a and b). The difference plots for the low and high flow conditions are typically similar in both shape and magnitude. There are some exceptions; for example, for the relatively low surge within the river during Hurricane Ike, there is no effect in lowering

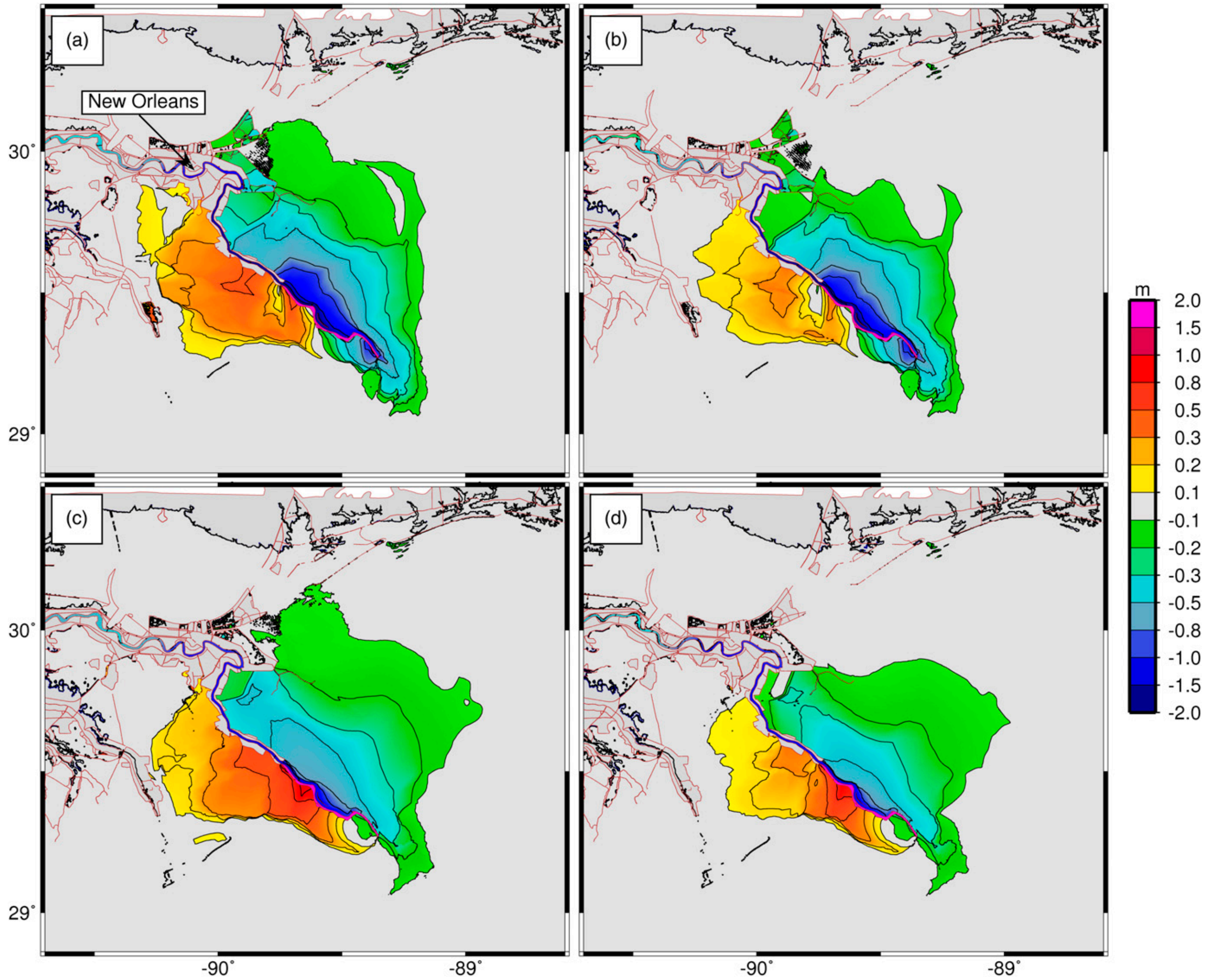

Fig. 4. (Color) Differences in MOM between SL16-Raised Levees scenario and SL16-Lowered Levees scenario: (a) all storms (high flow); (b) all storms (low flow); (c) historical storms (high flow); (d) historical storms (low flow)

surge by lowering the levees for the low flow case, whereas the lowered levees scenario lowers the elevation of the river for high flow almost identically to the lowering in river stage only for high flow. Thus, the low surge for Ike simply propagates on top of a lower river. For each hurricane, the greatest shift in the difference between the raised levees and lowered levees configurations occurs along the 55-km river section of lowered levee, with the greatest differences near Pointe à La Hache. South of the Bonnet Carré Spillway, Katrina has the largest water surface elevations of any of the historical storms. For Katrina, the difference between the lowered levees and raised levees scenarios is 1 to 1.5 m between Pointe à La Hache and the Bonnet Carré Spillway. By lowering the levees in South Plaquemines, the water surface elevation in the Mississippi River during Hurricane Katrina at New Orleans would be approximately 1 m lower. Past New Orleans, the difference between the two scenarios gradually disappears as the storm surge attenuates as it propagates upriver.

Fig. 6 shows the MOM river profiles for the seven historical and the combined historical and statistical sets for the raised levees and lowered levees scenarios. As in Fig. 5, the lowered levees scenario has lower water surface elevations than the raised levees scenario, and the difference plots are similar for both flow conditions. Fig. 6 indicates that the cumulative storm set features higher water surface elevations and greater differences in magnitude than the historical storm set. Hypothetical storms 32 and 35 made landfall further south along the Mississippi River than did Katrina and were also larger in terms of intensity and size, so these storms in particular amplified the effect of the 55-km river section of west bank levees. The lowering of these levees would reduce the MOM in the Mississippi River by 2.17 m (2.18 m) at Pointe à La Hache and by 0.90 m (1.14 m) at the Inner Harbor Navigation Canal entrance for low (high) flow conditions. Although the differences between the lowered levees and the raised levees scenarios do not appear to be dependent on discharge, the water surface elevation is strongly dependent on discharge upriver of Pointe à La Hache.

Storm Surge Generation in the River

To explore the influence of west bank levee capture mechanisms and discharge on storm surge generation, base flow, and maximum total river water levels for three discharges during simulations of Katrina were plotted along the profile of the Mississippi River for the SL16-Raised Levees scenario [Fig. 7(a)] and the SL16-Lowered Levees scenario [Fig. 7(b)]. Also shown at the bottom of each figure

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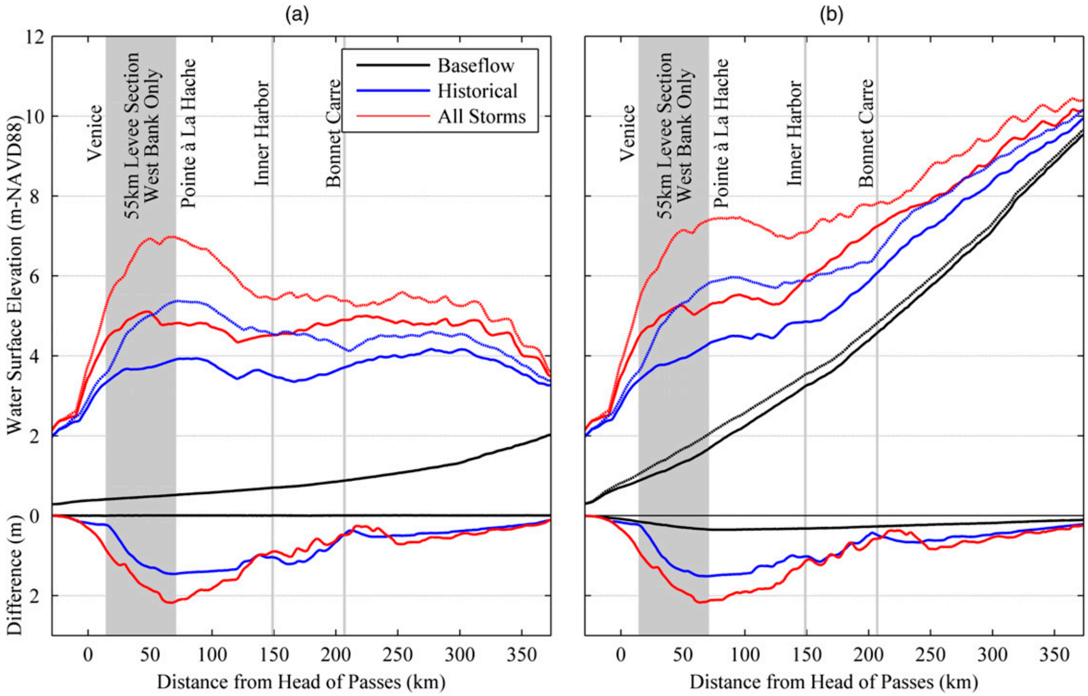

Fig. 5. (Color) Historical storm surge up the Mississippi River: (a) low flow; (b) high flow; dashed lines represent SL16-Raised Levees scenario; solid lines represent SL16-Lowered Levees scenario

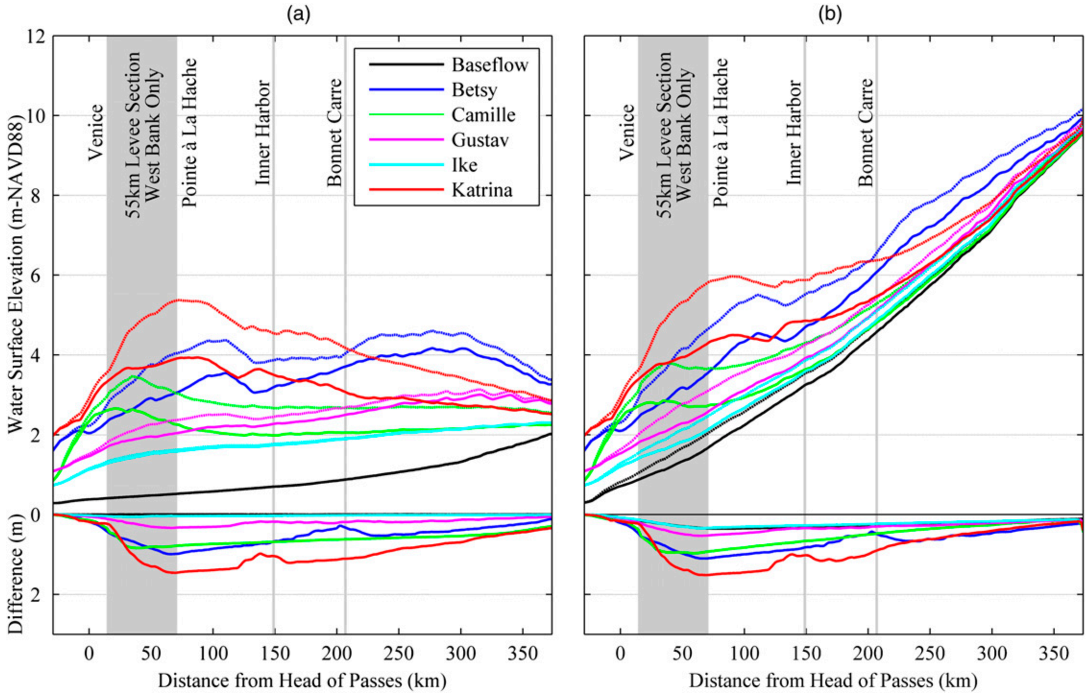

Fig. 6. (Color) MOM storm surge up the Mississippi River: (a) low flow; (b) high flow; dashed lines represent SL16-Raised Levees scenario; solid lines represent SL16-Lowered Levees scenario

are the maximum surges, defined as the difference between the maximum total water levels that occur during the storm and the corresponding river base flow water levels. For each of the three discharge cases and levee scenarios, the total storm water levels along the 55-km levee section are nearly identical, diverging slightly approaching Pointe à La Hache. In sharp contrast, river base flow water levels are quite different along the 55-km levee section, differing by almost 2 m at Pointe à La Hache for the low and high river flows. Surge, coming from the east of the river, spills on top of the ambient river base flow; therefore, the total generated surge for

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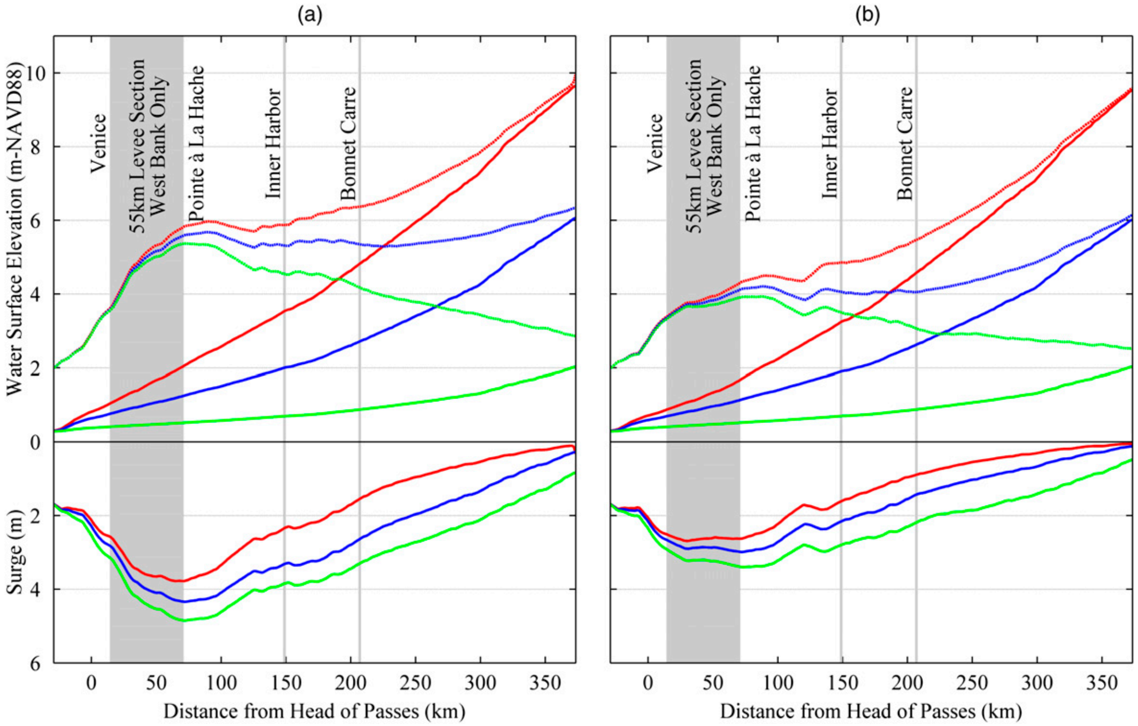

Fig. 7. (Color) Maximum Hurricane Katrina storm surge up the Mississippi River: (a) SL16-Raised Levees scenario; (b) SL16-Lowered Levees scenario; red lines represent high flow (22,654 m^3/s); blue lines represent medium flow (14,158 m^3/s); green lines represent low flow (5,664 m^3/s); dashed lines indicate the SL16-Raised Levees scenario and solid lines indicate the base flow water levels

the higher flow rates is substantially lower than for the lower flow rates, as is illustrated in the bottom panels of Fig. 7. This is consistent for both levee scenarios, but both total water levels and surges are noticeably greater for the case with raised levees. Finally, it is noted that all the bottom panel surge curves in Fig. 7 are essentially parallel upriver from Pointe à La Hache until 300 km upriver from Head of Passes. This suggests that frictional dissipation of the surges is not or only weakly flow dependent. There does appear to be a flow effect on dissipation nearing Baton Rouge, where the river becomes much shallower.

Supplementing the thalweg river profiles, Fig. 8 shows base flow and maximum Katrina water levels for low and high river flows and the two levee scenarios at two cross-river sections (facing downriver), as designated in Fig. 1. Although low river base flows are contained within the banks of the river, higher river base flows with their higher ambient water levels spill over the natural east bank levees and into the adjacent wetlands. The lowered levees case also allows for lateral outflow on the west bank in addition to the east bank, decreasing the ambient river water level. The river base flow differential between the low and high flows at both sections is substantial. The maximum storm total water levels for the raised levees scenarios are fairly level across the left/east overbank until they reach the right/east bank natural levee. At both cross-river stations, the water levels in the river and left/east bank are weakly dependent on discharge, with a greater difference occurring at the upriver section, whereas the water levels on the right/west side of the bank are identical and not dependent on flow rate because the raised levee blocks all exchanges. With regard to the storm water levels for the lowered levees scenario, they are again weakly dependent on river flow. There is a considerable dip into the river across the left/east bank and an additional dip on the other side across the right/west bank, more noticeably for Section 1 than for Section 2. Here, the overbank friction from the adjacent wetlands and natural levees are the mechanisms by which storm surge is captured in the river; despite the lowering of levees, bank- and wetland-induced friction hampers the process of a cross-river storm surge current, capturing the surge in the river, limiting the decrease of water levels within the river, and minimizing the regional effects of the lowered levee scenario.

These figures illustrate the following key points: (1) ambient river flow–only stages are strongly dependent on river discharge along the critical 55-km Plaquemines Parish levees; (2) total storm water levels in the lower river are only weakly dependent on river discharge along this section and are, in fact, controlled by regional processes, specifically water being pushed in by wind from the east; (3) storm surge amplitude decreases with increasing flows because of the associated higher prestorm river base flow water levels in the lower river and decreasing room for spillage from storm surge overbank penetration from the east; (4) this dependency on discharge applies to both the raised and the lowered levee scenarios; (5) the gradient of the surge upriver is nearly parallel for each flow rate, which shows that attenuation rates are not dependent on these discharge ranges until the surge has passed well upriver of New Orleans; (6) the amplitude of storm surge is increased by having manmade levees on the west bank and; (7) both high levees and much lower natural levees with adjacent wetlands are mechanisms by which storm surge is captured in the river, with the manmade west bank levee system being considerably more effective.

Conclusions on System Response

The lower section of the Mississippi River, south of Pointe à La Hache, juts into the Gulf of Mexico nearly to the edge of the continental shelf. Historically, this area has been very susceptible to major hurricane landfalls. As a hurricane moves through the Gulf, its

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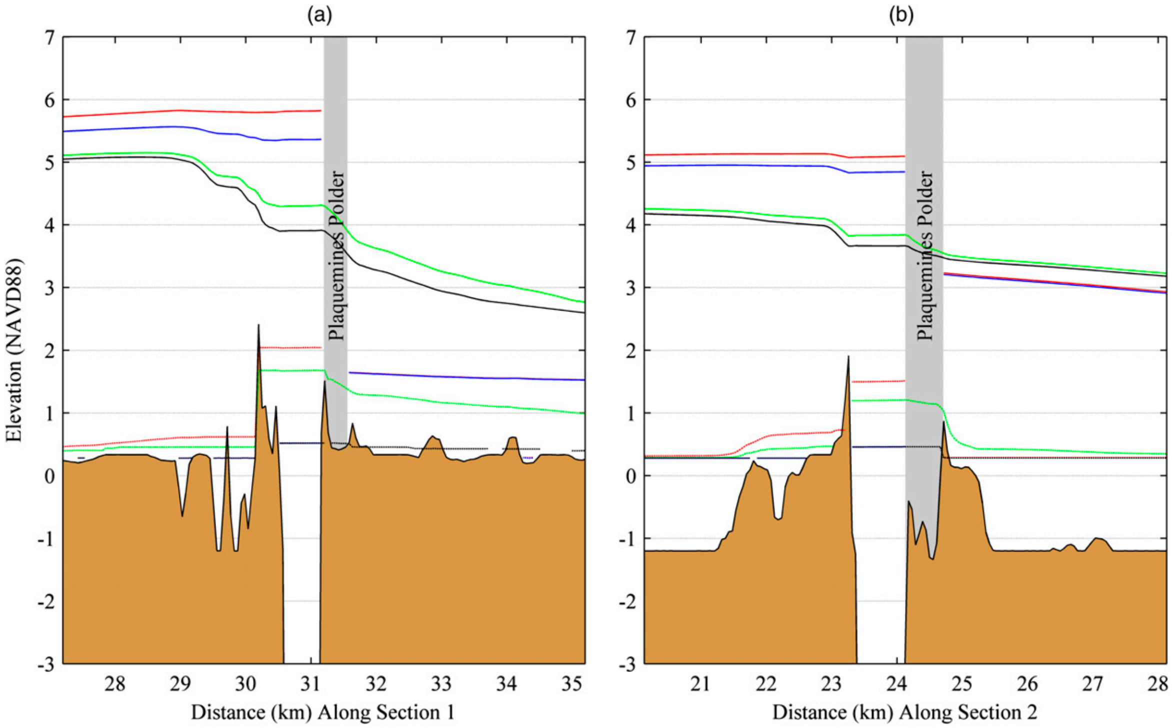

Fig. 8. (Color) Maximum Hurricane Katrina water levels along the Mississippi River: (a) Section 1; (b) Section 2; for SL16-Raised Levees scenario, red lines represent high flow (22,654 m^3/s) and blue lines represent low flow (5,664 m^3/s); for SL16-Lowered Levees scenario, green lines represent high flow and black lines represent low flow; solid lines indicate the maximum total water level and dashed lines indicate the base flow water levels

counterclockwise rotation sends winds ahead of its path in an east-west direction, parallel to the large-scale coastline of the northern Gulf. These sustained easterly winds develop a shore-parallel current that becomes blocked by the arm of the Lower Plaquemines Section and the bird's foot of the Mississippi River. As the center of the hurricane approaches landfall, the intensity of the easterly winds increases, driving surge into the shallow marshes and wetlands, where it builds until it overtops the natural east bank levees of the Mississippi River. Once storm surge enters the Mississippi River, it is trapped against the west bank levees, where it rises and propagates upriver until the storm passes and the winds change direction. It is noted that the riverine storm surge is a common feature of the regional surge, as is illustrated by the substantial surges generated within the river for Hurricanes Betsy (1965), Camille (1969), Katrina (2005), and Gustav (2008).

This study used a new high-fidelity model and a suite of historical and hypothetical storms to show that storm surge generation potential in the lower river is influenced by levees, discharge, storm track, and friction along the wetland overbanks. Spatial water levels for all storms showed that the effects of levee configuration and discharge are limited primarily to the river corridor itself. River profiles for each hurricane highlighted the influence that track plays on the severity of storm surge generated, by showing that storms, such as Katrina, with tracks passing directly over Lower Plaquemines, have the greatest potential for generation of storm surge, because of the alignments and intensity of winds and surge orthogonal to the river system. Although the west bank levees along Lower Plaquemines were found to influence the potential for surge in the river by completely blocking lateral flow, the adjacent wetlands and natural levees in the levee-removed scenario were also found to be a capture mechanism, by hampering strong cross-currents. Although both act as capturing mechanisms of surge in the river, the existence of manmade west bank levees leads to the capture of an additional 1 to 2 m of surge in the river.

Ambient water levels in the Mississippi River increase upriver with a strong dependency on river flow rate. The lowering of the west bank levees will allow higher flow rates to laterally flood the west banks of the Mississippi River (in addition to the naturally occurring flooding that occurs on the east bank) and decrease ambient water levels upstream for higher river flow events. For Hurricane Katrina, the total water levels in the lower Mississippi River south of Venice were found to be controlled by surrounding water levels that overtop the low-lying nonlevee lower section of the river and as such are not affected by flow rates. At the upriver end of the 55-km west bank levee section, total water levels tend to be slightly affected by flow rates, but not to the degree by which ambient river water levels differ. Because storm surge is generated on top of ambient water levels, which increase in the river with higher flow rates, and because total water levels are controlled by the overbank water levels, there is capacity for surge to build in the river. In addition, the surge gradient upriver is nearly parallel for each flow rate, which shows that although generation of surge amplitude is dependent on discharge, attenuation and dissipation rates are not. These relationships were found to occur for both levee scenarios.

Implications

Raised levees along the 55-km west bank section of Lower Plaquemines on the Mississippi River force an unnecessary escalation to base flood elevations upriver for more than 250 km, which is the approximate transition point where high discharges from watershed runoff begin to control base flood elevations. The current results suggest an alternative approach to developing the flood risk reduction system in Southeastern Louisiana; specifically, the lowering of levees along a 55-km stretch of the lower river on the

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west bank between Pointe à La Hache and Venice. Conceptually, this alternative suggests that by reducing the Lower Plaquemines levees to their natural state, storm surge would pass across the Mississippi River through the adjacent wetlands and back into the open Gulf, thus alleviating setup in the river. Simulations performed on a suite of historical and hypothetical storms using ADCIRC-2DDI have shown that this alternative can reduce flooding up the Mississippi River by 1 to 2 m between Pointe à La Hache and New Orleans and that any increased flooding is localized to the lower west bank of the Mississippi River, specifically the sparsely populated section of Lower Plaquemines and the unpopulated wetlands in and around Barataria Bay.

The lowering of levees along the 55-km river section of the Mississippi River's west bank of the Lower Plaquemines south of Point à La Hache includes lowering of levees along both sides of the polder, the riverbank and the Gulf, for a total of 110 km and the net reduction of protected area by approximately 42 km^2. It is noted that having localized ring levees around small portions of this proposed system, such as around towns such as Venice and Buras, will be local enough to not diminish the impact of the total water level reduction in the regional system while affording protection to the communities that are currently situated in Lower Plaquemines. The proposed selective levee elimination would reduce the risk of potential flooding along more than 500 km of levees upriver by as much as 2 m, which, comprehensively quantified within the context of riverine and storm surge joint probability, could reduce base flood elevations and save US$ billions in construction and maintenance of levees.

The alternative of lowering the west bank levees would permit the west bank to behave like the lower east bank, where processes like overbank and porous flow from both high river and storm events can naturally build wetlands to the west of the river; however, detailed design studies examining this alternative will have to consider the effect of sea level rise, subsidence, and the increasing efficiency of natural west bank and wetland resistance, as these evolve and build, in retaining the surge within the river.

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