A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi. Part II: Synoptic Description and Analysis of Hurricanes Katrina and Rita

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ABSTRACT

Hurricanes Katrina and Rita were powerful storms that impacted southern Louisiana and Mississippi during the 2005 hurricane season. In Part I, the authors describe and validate a high-resolution coupled riverine flow, tide, wind, wave, and storm surge model for this region. Herein, the model is used to examine the evolution of these hurricanes in more detail. Synoptic histories show how storm tracks, winds, and waves interacted with the topography, the protruding Mississippi River delta, east–west shorelines, manmade structures, and low-lying marshes to develop and propagate storm surge. Perturbations of the model, in which the waves are not included, show the proportional importance of the wave radiation stress gradient induced setup.

1. Introduction

Hurricanes Katrina and Rita were powerful storms that impacted the central Gulf of Mexico. Katrina's winds reached category 5 strength in the Gulf of Mexico, but weakened to category 3 strength as the storm approached the continental shelf. Its southerly track placed it within 50 km of New Orleans and the infrastructure of southeastern Louisiana, and its storm surge of 8.8 m along the coastline of Mississippi was the largest ever recorded in the United States. In contrast, Rita's southeasterly track exposed large portions of southwestern Louisiana to hurricane-strength winds and southeastern Louisiana to tropical storm–strength winds. Rita caused extensive inundation in the region. Its maximum storm surge reached 4.7 m along the coastline of Cameron Parish in southwestern Louisiana, but it also generated a surge of up to 3 m along portions of the New Orleans hurricane protection system, more than 300 km from the center of the storm.

The observed data for both storms is unprecedented in its coverage, detail, and accuracy. Wind measurements were collected from a diverse set of observing platforms including airborne stepped frequency microwave radiometer (SFMR), GPS dropwindsondes, airborne and land-based Doppler radar, portable land-based mesonets, and instrumented platforms and buoys. National Oceanic and Atmospheric Administration (NOAA) and Louisiana State University Coastal Studies Institute stations recorded wave heights and periods (more information available online at http://www.ndbc.noaa.gov). The Federal Emergency Management Agency

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(FEMA) and the U.S. Army Corps of Engineers (USACE) surveyed high water marks throughout the region (URS 2006; Ebersole et al. 2007), and the U.S. Geological Survey (USGS), NOAA, and the USACE recorded hydrographs at locations at the coast and far inland (McGee et al. 2006).

Although Rita was a somewhat smaller and weaker storm compared to Katrina, especially on the continental shelf as it approached landfall, the differences in storm characteristics do not fully explain the significant differences in the resulting storm surges, which were influenced by the geography of their landfall locations. In southeastern Louisiana and Mississippi, where Katrina made landfall, the geography includes a shallow continental shelf, which extends 100–120 km south of the Mississippi–Alabama coastline but only 10–15 km south of the so-called ''bird's foot'' of the Mississippi River delta; the Chandeleur and Mississippi Sound Islands, which act as barriers; low-lying marshes near the delta, which can slow the propagation of storm surge; steep topography interspersed with low-lying bays and marshes along the Louisiana–Mississippi–Alabama coastline; natural river banks and levee protection systems that stop and build storm surge elevations; and the geographic ''pocket'' formed where the toe of Louisiana meets the Mississippi coast, which holds surge generated by winds blowing from the east and south. In southwestern Louisiana, where Rita made landfall, a different set of features exists: an east–west coastline without major protrusions that would stop flow or force wave breaking; a shallow, broad continental shelf, which extends 100–150 km into the Gulf of Mexico; an interconnected series of inland lakes and bays; and extensive low-lying marshes and topography, which extend 60–100 km inland with mild slopes less than 0.001. These geographic features, combined with the unique characteristics of these strong storms, produced waves and surge that varied significantly throughout the region.

In a companion paper, the authors present a hurricane modeling system of southern Louisiana and Mississippi that simulates coupled riverine flow, tides, winds, wind waves, and storm surge (Bunya et al. 2010, hereinafter Part I). This system applies the NOAA Hurricane Research Division Wind Analysis System (H*WIND) and the Interactive Objective Kinematic Analysis (IOKA) kinematic wind analyses (Powell et al. 1998; Cox et al. 1995), the ocean Wave Model (WAM; Komen et al. 1994; Gunther 2005), the Steady-State Irregular Wave (STWAVE) nearshore wave model (Smith and Smith 2001; Thompson et al. 2004), and the Advanced Circulation (ADCIRC) model (Luettich and Westerink 2004; Westerink et al. 2008). Riverine flows, tides, winds, wind waves, and storm surges are validated independently. The resulting system is comprehensive, provides detail at a wide range of scales, and can be used to simulate hurricane storm surge and waves with a high level of confidence. However, although the observed data are useful to validate this system, they do not fully describe the evolution of the hurricanes or the interaction of the forcing mechanisms and their effects on winds, waves, surge, and currents.

In this paper, the coupled modeling system is used to examine the synoptic histories of Katrina and Rita. The components of wind (from the IOKA–H*WIND analysis) and storm surge (from ADCIRC) are presented at selected times during each storm, and maximum values of significant wave heights, wave radiation stress gradients, and wave-induced setup are examined. These histories allow an analysis of the evolution of storm surge, the mechanisms that drove the surge, and where that surge propagated.

2. Hurricane Katrina

Hurricane Katrina was a relatively fast-moving storm characterized by its low pressure, its intensity, and especially its large size. Katrina approached the Mississippi shelf as a category 5 storm on the Saffir–Simpson scale before degrading when it reached the continental shelf, as summarized in Fig. 1 and Table 1 (Knabb et al. 2005). The strongest 1-min sustained wind speed estimated by the National Hurricane Center reached 77 m s^{-1} with 902 hPa as the lowest atmospheric pressure. It made landfall as a strong category 3 storm at about 1110 UTC 29 August 2005 along the southern reach of the Mississippi River in Plaquemines Parish. The storm then tracked north, passing over Lake Borgne, and making a second Gulf landfall as a category 3 hurricane at 1445 UTC 29 August 2005 near the Louisiana–Mississippi state line. NOAA recorded significant wave heights up to 16.9 m, the largest ever measured at their buoys (Ebersole et al. 2007). Note that the geographic landmarks discussed in this paper are presented in Figs. 2–5 in Part I.

a. Synoptic history

At 0700 UTC 29 August 2005, shown in Figs. 2–3, Katrina is downgraded to a category 4 storm with the eye approximately 130 km south and 4 h from the initial landfall. The easterly winds range from 20 to 40 m s^{-1} (10 min averaged) and are blowing water into Breton and Chandeleur Sounds as well as Lake Borgne. Note the effect of the directional roughness wind boundary layer adjustment (Part I). In the bird's foot of the Mississippi River delta and near Lake Pontchartrain, the winds are reduced in areas where the winds are blowing

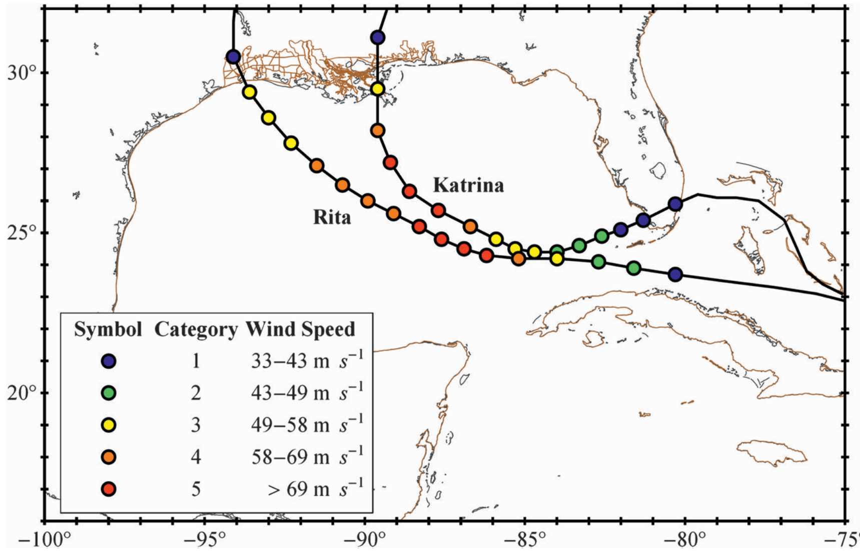

FIG. 1. Storm tracks for Hurricanes Katrina and Rita.

overland; however, nearshore regions experience the full marine winds when they are directed onshore. Regions with extensive tree canopies, where the winds are not applied, are also shown in Fig. 2. The hurricane pushes storm surge of 1.5–2.5 m from the deeper Gulf of Mexico onto the Mississippi–Alabama shelf, which begins near the delta and extends east–northeast. Water is stopped by the Mississippi River banks and levees and by the St. Bernard/Chalmette protection levees, where surge is building up to 2–3.5 m. Water levels are raised on the southwest end of Lake Pontchartrain, while water levels are suppressed in the eastern part of the lake. The water level rise in Lake Borgne and the drawdown of water in eastern Lake Pontchartrain cause a strong surface water gradient across the Chef Menteur Pass and the Rigolets Strait, which connect these two lakes. This gradient creates a current that drives water into Lake Pontchartrain and this current is reinforced by the easterly winds. The currents in the Rigolets and Chef Menteur channels are already 1–2 m s^{-1}. This process initiates the critical rise of the mean water level within Lake Pontchartrain. Finally, the predominantly easterly and northerly winds to the west of the Mississippi River force a drawdown of water away from the west-facing levees and into northern Barataria, Timbalier, and Terrebonne Bays.

At 1100 UTC 29 August 2005, shown in Figs. 4–5, Katrina is near its initial landfall. The eye is west of the southern Plaquemines Parish levees, and the highest wind speeds are east from the bird's foot of the Mississippi River delta. Note the asymmetry in the wind field, which features 45 m s^{-1} southerly winds to the east and 30–40 m s^{-1} easterly winds north of the eye. The surge has been pushed onto the Mississippi–Alabama shelf to at least 2.5 m and builds to 5.8 m against the river banks and levees of lower Plaquemines Parish. The surge in this region has started to propagate up the Mississippi River and also extends broadly into Breton Sound. The currents over the Chandeleur Islands are 2–2.5 m s^{-1} as surge is pushed over these islands from the southeast. Farther north, surge continues to build to 4 m against the St. Bernard/Chalmette protection levee due to the easterly and local northeasterly winds. A depression exists on the east side of Lake Borgne, as surge from the east is slow to replace the lake waters that have been blown to the west. A water surface slope is induced by local winds inside Lake Pontchartrain, creating a positive wind setup on the southwest (downwind) side of the lake and setdown on the northeast (upwind) side. The difference in water level between Lakes Pontchartrain and Borgne has increased to 2.5 m, and in response, the currents in Chef Menteur Pass and the Rigolets Strait are increasing to 1.5–3 m s^{-1}. In the bird's foot of the Mississippi River delta, the surge levels are about 2.5–3.5 m, and, as later analysis will show, about 0.7–0.8 m of the surge there is due to wave breaking. Northerly winds build surge to a level of about 2.5 m on the north side of Grand Isle.

At 1400 UTC 29 August 2005, shown in Figs. 6–7, Katrina is now centered over Lake Borgne. Across the Mississippi–Alabama shelf, winds are now southerly and southeasterly. Winds are blowing away from the east-facing levees near lower Plaquemines Parish and the bird's foot of the Mississippi River delta, English Turn, St. Bernard/Chalmette, and New Orleans east. In Lake Pontchartrain, shifting winds are now northerly and northwesterly. Winds are pushing storm surge against

TABLE 1. Summary of positions, central pressure, radius to maximum winds, maximum wind speed, and Saffir–Simpson category for Hurricane Katrina (Knabb et al. 2005).

UTC time and date	Lon	Lat	Pressure (hPa)	Max wind speed (m s^{-1})	Category on Saffir–Simpson
1800 UTC 23 Aug 2005	−75.1	23.1	1008	13.8	
0000 UTC 24 Aug 2005	−75.7	23.4	1007	13.8	
0600 UTC 24 Aug 2005	−76.2	23.8	1007	13.8	
1200 UTC 24 Aug 2005	−76.5	24.5	1006	16.1	
1800 UTC 24 Aug 2005	−76.9	25.4	1003	18.4	
0000 UTC 25 Aug 2005	−77.7	26.0	1000	20.7	
0600 UTC 25 Aug 2005	−78.4	26.1	997	22.9	
1200 UTC 25 Aug 2005	−79.0	26.1	994	25.3	
1800 UTC 25 Aug 2005	−79.6	26.2	988	27.6	
0000 UTC 26 Aug 2005	−80.3	25.9	983	32.1	1
0600 UTC 26 Aug 2005	−81.3	25.4	987	29.8	1
1200 UTC 26 Aug 2005	−82.0	25.1	979	34.5	1
1800 UTC 26 Aug 2005	−82.6	24.9	968	39.0	2
0000 UTC 27 Aug 2005	−83.3	24.6	959	41.3	2
0600 UTC 27 Aug 2005	−84.0	24.4	950	43.7	2
1200 UTC 27 Aug 2005	−84.7	24.4	942	45.9	3
1800 UTC 27 Aug 2005	−85.3	24.5	948	45.9	3
0000 UTC 28 Aug 2005	−85.9	24.8	941	45.9	3
0600 UTC 28 Aug 2005	−86.7	25.2	930	57.4	4
1200 UTC 28 Aug 2005	−87.7	25.7	909	66.6	5
1800 UTC 28 Aug 2005	−88.6	26.3	902	68.9	5
0000 UTC 29 Aug 2005	−89.2	27.2	905	64.3	5
0600 UTC 29 Aug 2005	−89.6	28.2	913	57.4	4
1200 UTC 29 Aug 2005	−89.6	29.5	923	50.5	3
1800 UTC 29 Aug 2005	−89.6	31.1	948	36.8	1
0000 UTC 30 Aug 2005	−89.1	32.6	961	22.9	
0600 UTC 30 Aug 2005	−88.6	34.1	978	18.4	
1200 UTC 30 Aug 2005	−88.0	35.6	985	13.8	
1800 UTC 30 Aug 2005	−87.0	37.0	990	13.8	
0000 UTC 31 Aug 2005	−85.3	38.6	994	13.8	
0600 UTC 31 Aug 2005	−82.9	40.1	996	11.5	

the west-facing levees along the Mississippi River near Venice. On the east side of the river, surge builds broadly to more than 4 m on the shelf and intensifies along the Mississippi coast. The surge that built against the lower Mississippi River levees propagates northeastward toward Chandeleur Sound, while surge levels decrease along lower Plaquemines on the east side of the river. The peak surge propagating in the Mississippi River is 4 m and has reached metropolitan New Orleans. Although water levels have increased overall, the surge along the St. Bernard–Chalmette protection levee is decreasing. Water accumulates from the east and overtops the CSX railroad between Lakes Borgne and Pontchartrain, where the difference in water level is still increasing and causes high volumes of water to flow into Lake Pontchartrain. Water blows from the north of Lake Pontchartrain and builds to nearly 3 m along the southern shores, while a drawdown develops along the north shore. The highest surge along the south shore migrates from west to east as the winds shift. The currents over the Chandeleur Islands have decreased to 1.5–2 m s^{-1}, but the currents over the Mississippi Sound Islands have increased to 2–2.5 m s^{-1} as the water moves northward.

At 1600 UTC 29 August 2005, as shown in Figs. 8–9, Katrina is now located about 40 km and an hour north of its second landfall. The wind speeds have decreased, but wind field asymmetry has increased and the structure has broadened as the hurricane makes landfall. Wind speeds are 30–35 m s^{-1} over much of the continental shelf and are 25–30 m s^{-1} over Lake Pontchartrain. The surge from southern Plaquemines Parish has combined with the local surge forced by the southerly winds to increase water levels on the shelf along the Mississippi-Alabama coast to about 6 m. The surge spreads inland through the low-lying bays but is stopped by the relatively steep topography and builds to 8.8 m. Water blows eastward across Lake Pontchartrain while it flows from Lake Borgne due to the sustained 1.8–2.3-m water level differential between the two lakes. The currents in the Rigolets Strait range from 1.8 to 2.7 m s^{-1}. Water has started flowing from Chandeleur Sound back into the Gulf of Mexico.

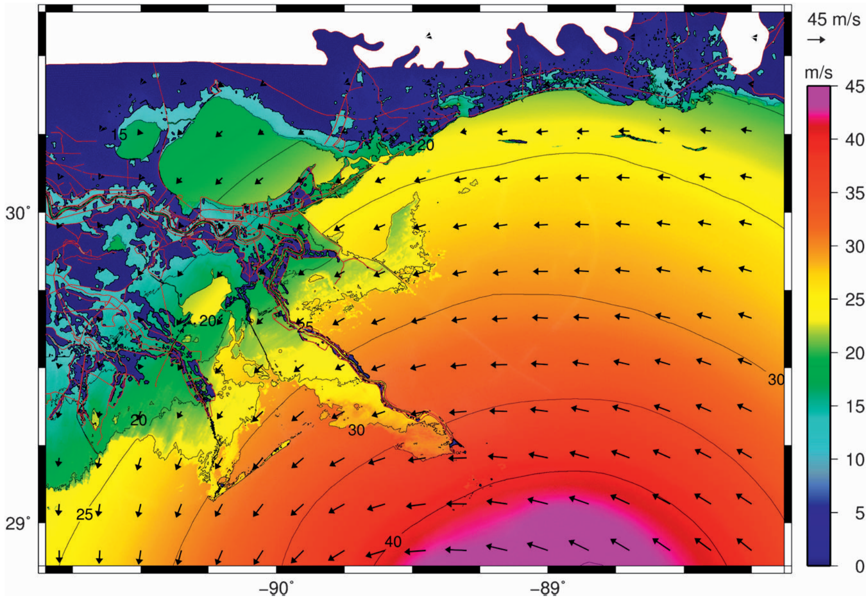

FIG. 2. Hurricane Katrina wind contours and vectors (m s^{-1}) at 0700 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

At 1900 UTC 29 August 2005, shown in Figs. 10–11, the winds are predominantly southwesterly and have decreased, but they still range from 20 to 30 m s^{-1} over much of the continental shelf. The surge from the Mississippi coast relaxes and spreads back into Mississippi, the Chandeleur and Breton Sounds, and Lake Pontchartrain. Although winds are blowing westerly across Lake Pontchartrain and causing a drawdown in the west and increased surge in the east, the currents through Rigolets Strait are still easterly, due to the sustained water level differential between the two lakes. The currents in Chandeleur Sound and Mississippi Sound have turned toward the Gulf, with currents of 2–2.5 m s^{-1} over the barrier islands. The islands combined with the

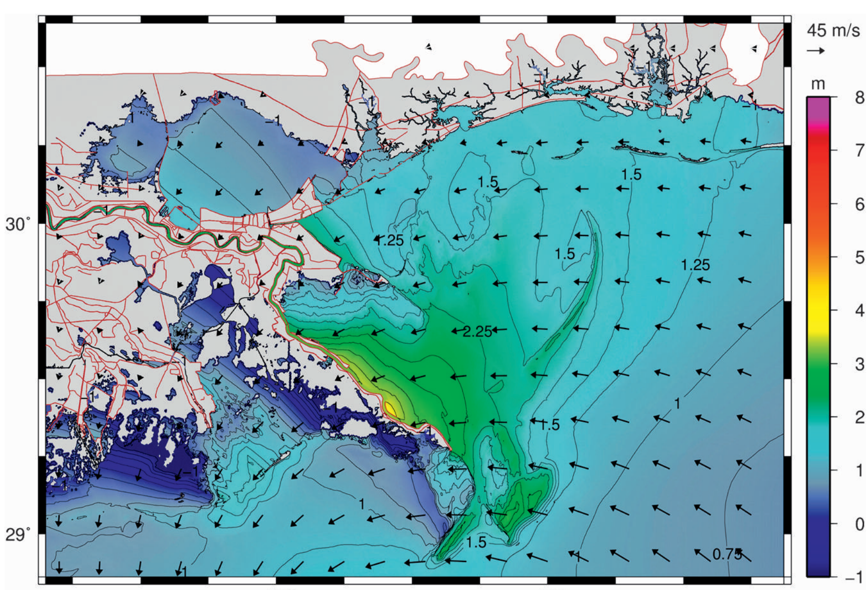

FIG. 3. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 0700 UTC 29 Aug 2005 in southeastern Louisiana.

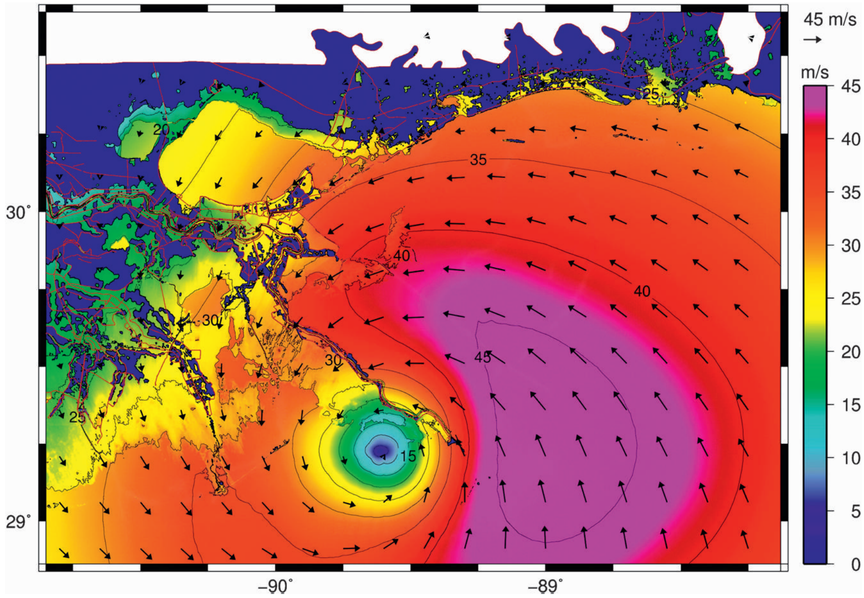

FIG. 4. Hurricane Katrina wind contours and vectors (m s^{-1}) at 1100 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

increased roughness of the marshes and shallow depths on the protected side of the islands slow the high waters from flowing back to the open Gulf and lead to significant water level differentials between the Gulf- and Sound-side of the islands.

At 2300 UTC 29 August 2005, shown in Figs. 12–13, the wind speeds in southeastern Louisiana have decreased to 15 m s^{-1} or less, and the recession process continues. The surge in Lake Pontchartrain is at 2 m without a significant differential and has relaxed due to the slower wind speeds. Water still flows slowly from Lake Borgne into Lake Pontchartrain because of the surface water gradients between these lakes (although the gradient is decreasing). Note the slow withdrawal

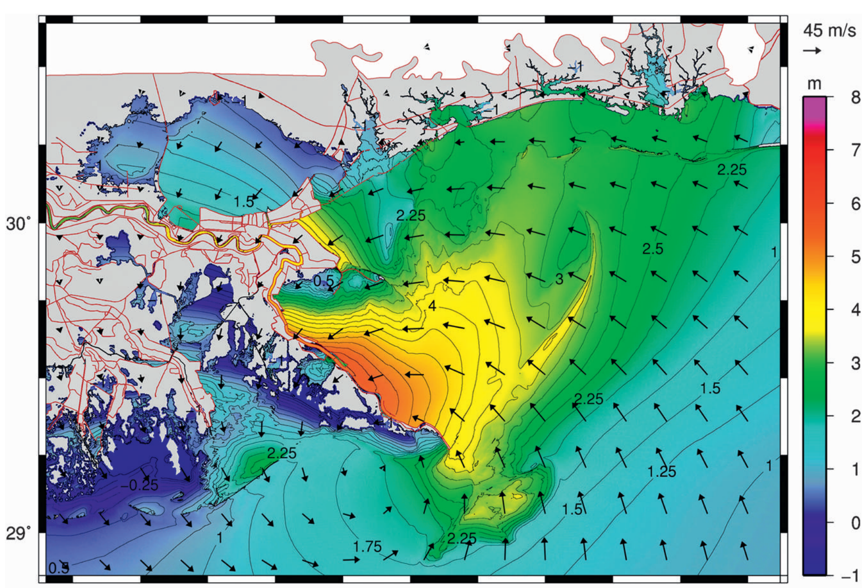

FIG. 5. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1100 UTC 29 Aug 2005 in southeastern Louisiana.

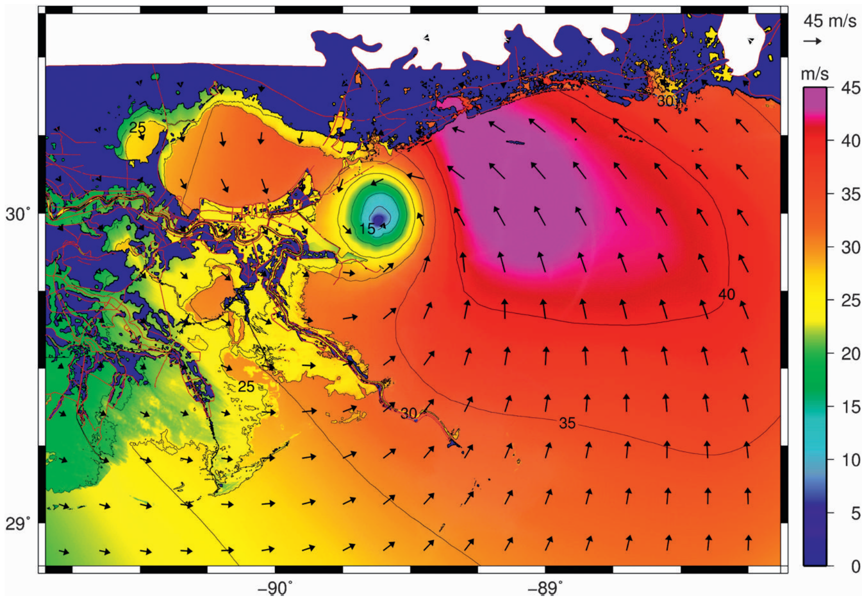

FIG. 6. Hurricane Katrina wind contours and vectors (m s^{-1}) at 1400 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

from the marshes and bays, where localized surge levels still range from 2 to 4 m or greater. The recession is resisted by the barrier islands and marshes.

b. Contours of wave-related maxima

Figure 14 shows the maximum significant wave heights for Katrina. Wave heights up to 17 m are seen near the bird's foot of the Mississippi River delta coinciding with the passage of the most intense winds to the east of the storm track as well as refraction on the steep sided delta. Strong gradients in wave height are produced by wave breaking along the edge of the delta. Wave heights are reduced more gradually in the areas northeast and west of the delta, where wave breaking occurs on the shallow

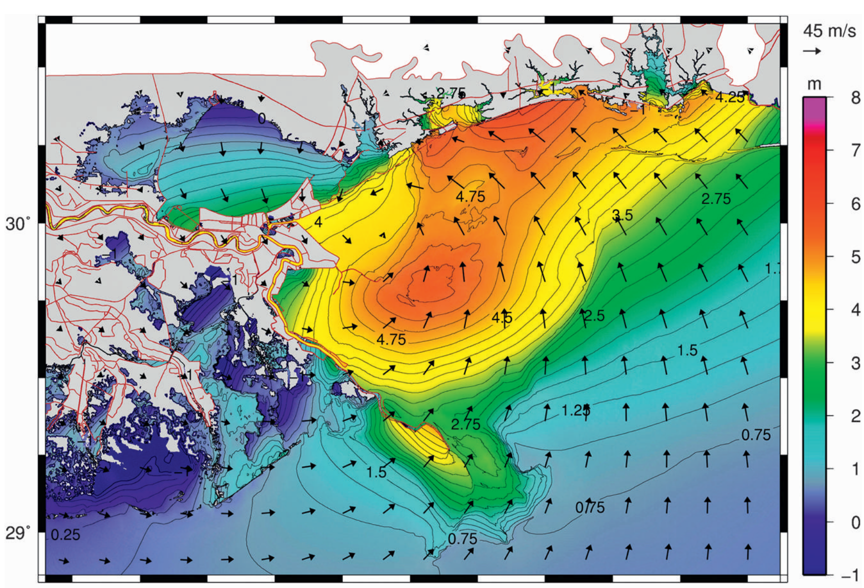

FIG. 7. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1400 UTC 29 Aug 2005 in southeastern Louisiana.

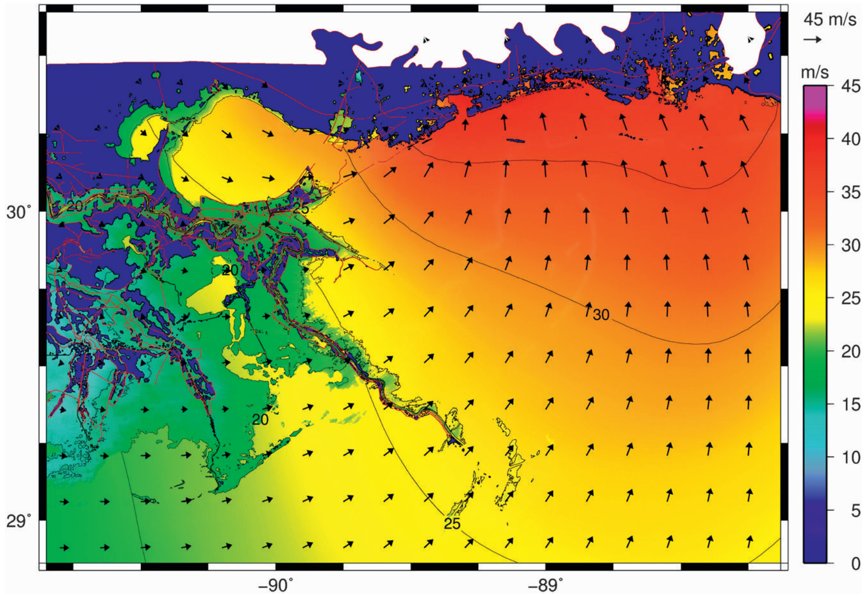

FIG. 8. Hurricane Katrina wind contours and vectors (m s^{-1}) at 1600 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

shelf. The barrier islands further reduce the nearshore wave height as waves break either on the seaward side or over the top of submerged islands. Wave energy also propagates through the gaps between the islands into the sounds. The Biloxi and Caenarvon Marshes east of the delta (shown within the white shoreline in Fig. 14) also show reduced wave height because of their shallow depths and vegetation. Wave heights along the interior shorelines are typically less than 1–3 m.

Figure 15 shows the maximum storm event wave radiation stress gradients for Katrina. Wave radiation stress gradients are the forces applied to the water column as waves transform and are contributors to coastal circulation and surge levels. Forces are greatest where

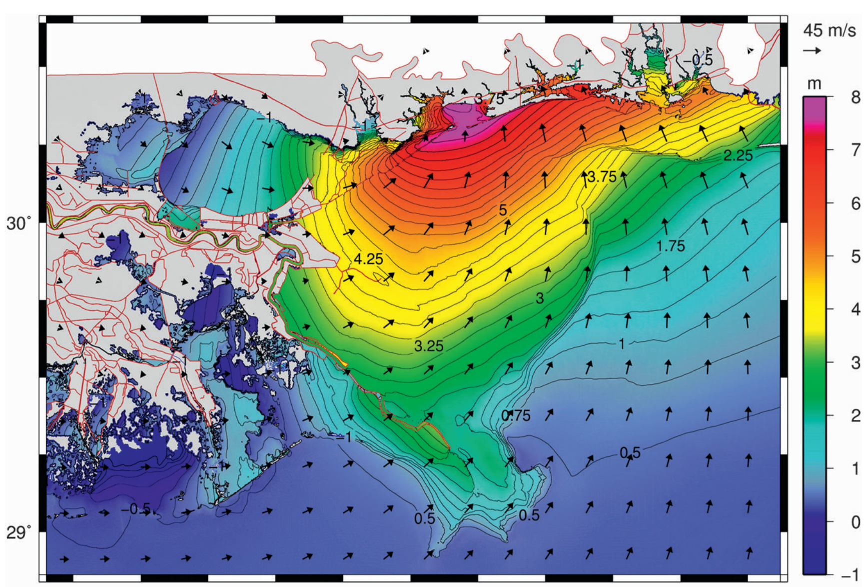

FIG. 9. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1600 UTC 29 Aug 2005 in southeastern Louisiana.

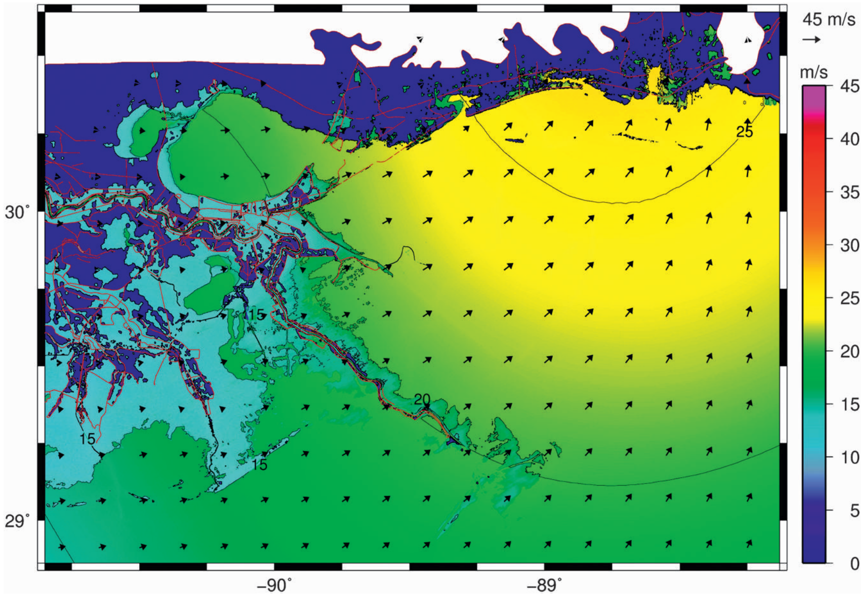

FIG. 10. Hurricane Katrina wind contours and vectors (m s^{-1}) at 1900 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

spatial changes in significant wave heights are greatest. The edges of the nearshore STWAVE domains are visible in Fig. 15, both along the southwest part of the figure and near Lake Pontchartrain. The regions with the largest radiation stress gradients occur at the bird's foot of the Mississippi River delta and over the barrier islands.

Figure 16 shows the effect of waves on the maximum computed water levels for Katrina. The figure shows the differences between the maximum water levels for the fully coupled simulation and a simulation that did not include wave effects. The wave radiation stress gradients increase the water levels throughout much of the domain. The largest differences are located in the regions

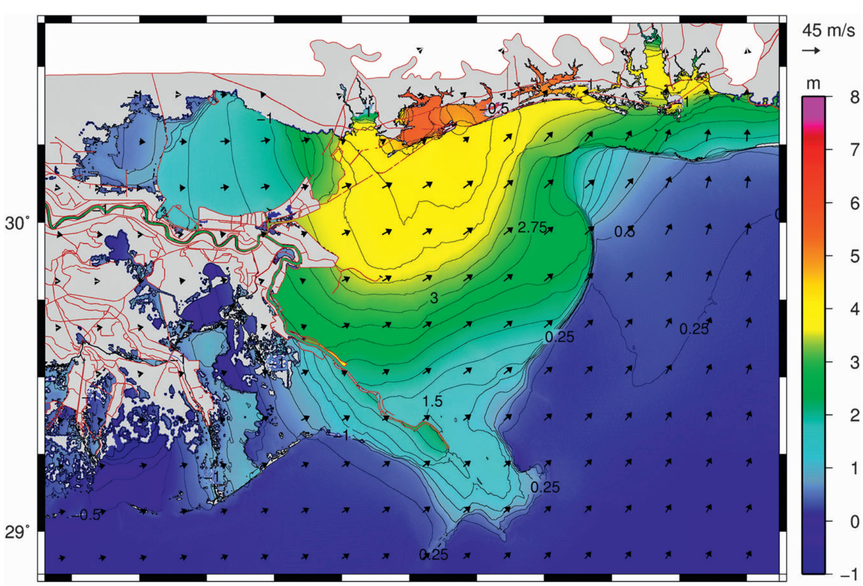

FIG. 11. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1900 UTC 29 Aug 2005 in southeastern Louisiana.

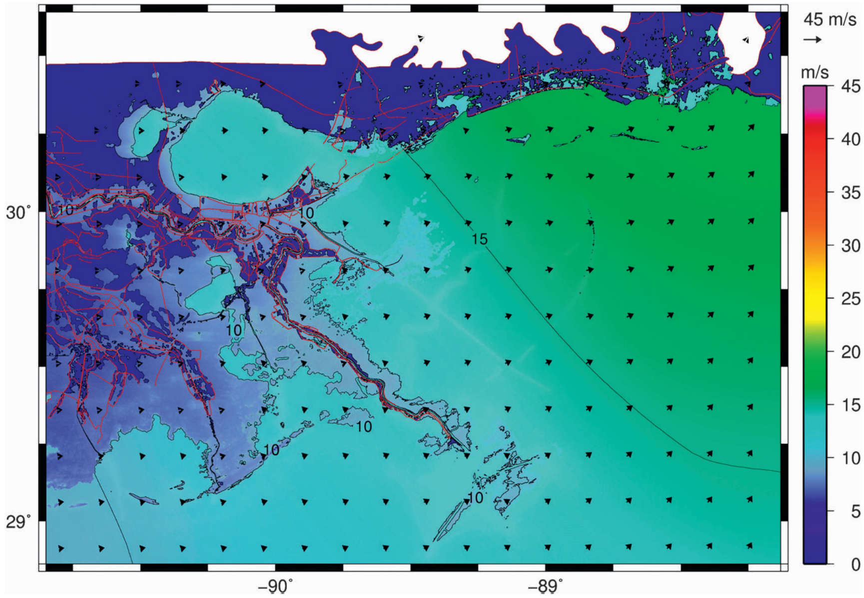

FIG. 12. Hurricane Katrina wind contours and vectors (m s^{-1}) at 2300 UTC 29 Aug 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

where rapid wave transformation occurs through depth-limited wave breaking, such as the bird's foot of the Mississippi River delta, Grand Isle, and other barrier islands. Waves are focused on the delta by refraction, and wave radiation stress gradients increase the water levels by about 0.7–0.8 m, which is about 25%–35% of the maximum water levels in that region. The continental shelf does not extend much farther than the delta itself, and thus the surge heights are limited, and the relative contribution of wave-breaking induced setup is significant (Resio and Westerink 2008). The water levels are increased over large areas by at least 0.2–0.4 m inshore of the dominant wave breaking zones induced by the barrier islands, and localized maxima of about 0.5 m

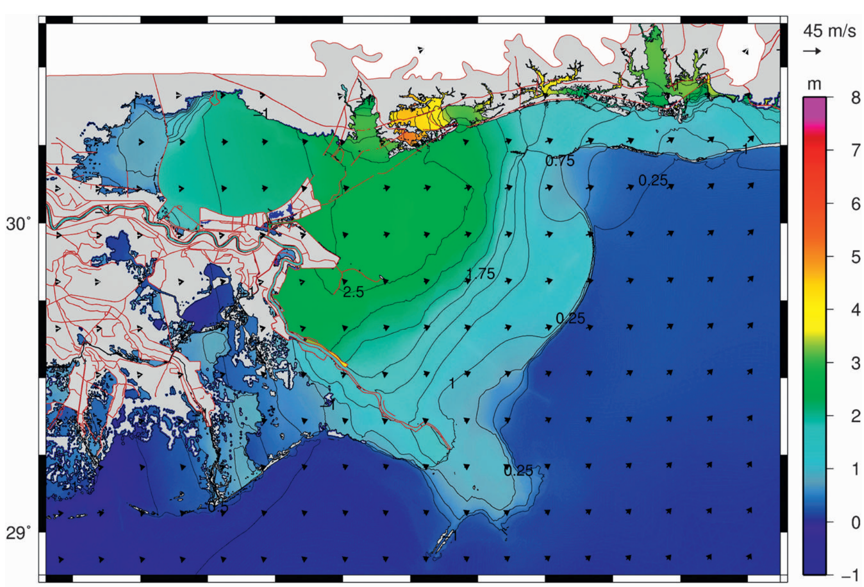

FIG. 13. Hurricane Katrina elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 2300 UTC 29 Aug 2005 in southeastern Louisiana.

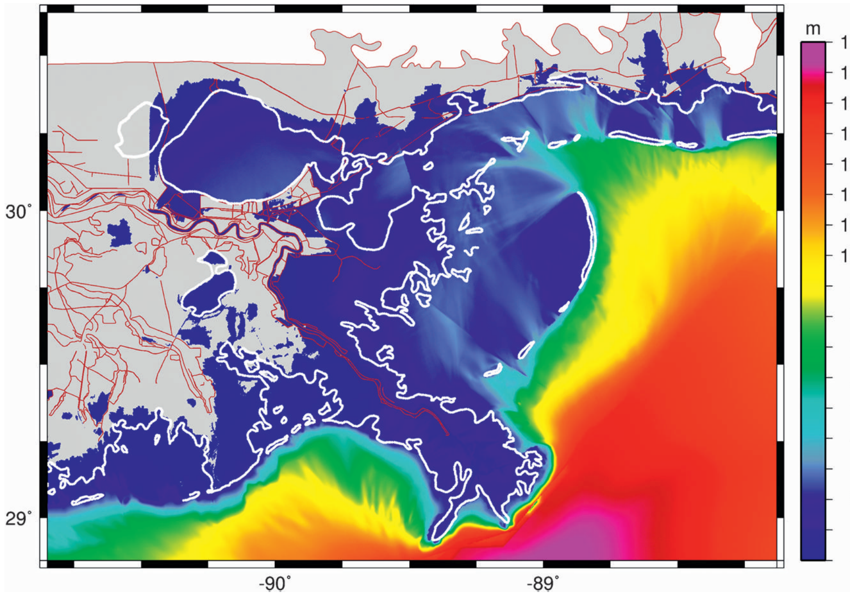

FIG. 14. Maximum significant wave heights (m) for Hurricane Katrina in southeastern Louisiana.

occur in Plaquemines Parish and the region near English Turn. Wave effects contribute about 5%–10% to overall surge levels, which is consistent with the broad continental shelf in this region. In Lake Pontchartrain, wave growth occurs from north to south, and radiation stresses act to push water to the north of the lake. Wave breaking on the south shore causes a focused increase of water levels on the south shore, which is not resolved sufficiently in the modeling system.

3. Hurricane Rita

Hurricane Rita made landfall at the western edge of Louisiana, and did not directly threaten the New Orleans area. However, Rita was also an intense storm. Its minimum central pressure of 897 hPa was the fourth-lowest ever recorded in the Atlantic basin (Knabb et al. 2006). As summarized in Fig. 1 and Table 2, Rita became a category 5 storm by 1800 UTC 21 September 2005, and it

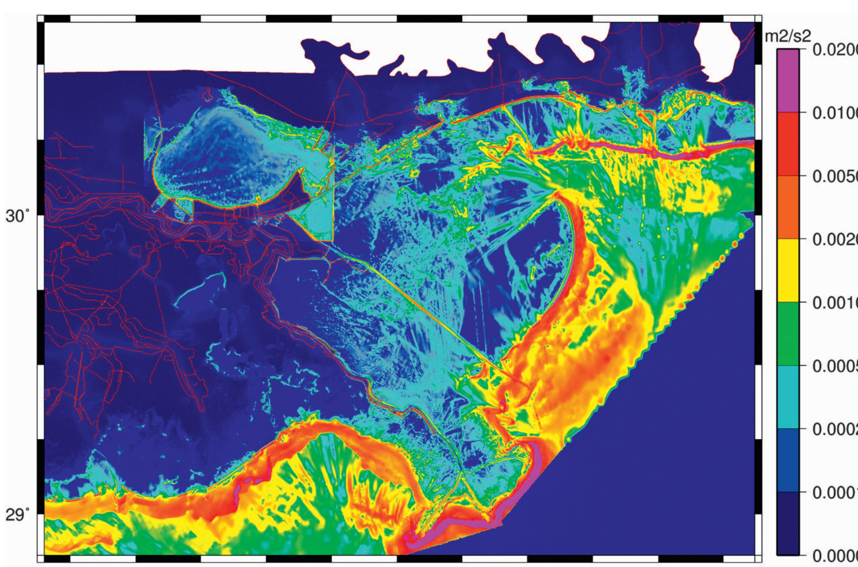

FIG. 15. Maximum wave radiation stress gradient contours ($m^2\ s^{-2}$) for Hurricane Katrina in southeastern Louisiana.

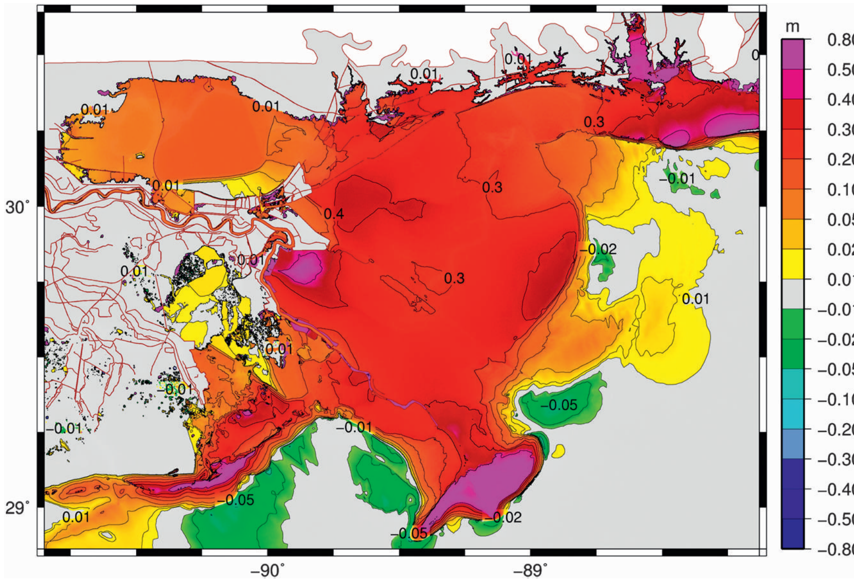

FIG. 16. Effect of waves on the maximum water levels (m) during Hurricane Katrina.

retained its strength for the next 18 h as it moved toward the west by northwest across the Gulf of Mexico. The storm weakened on 23 September 2005 as it turned more to the northwest. Rita made landfall as a category 3 storm at 0740 UTC 24 September 2005 near Sabine Pass and the border between Texas and Louisiana. Note that the geographic landmarks discussed in this paper are shown in Figs. 2–5 in Part I.

a. *Synoptic history in southwest Louisiana*

At 1200 UTC 23 September 2005, Rita was located about 350 km and 20 h away from landfall, and had already weakened to a category 4 storm (Knabb et al. 2006). In Fig. 17, coastal winds over the shelf are predominantly northeasterly and range up to about 20 m s^{-1}. Note the effect of the directional land masking dominated by the low-lying marshes and the absence of extensive canopied regions. The wind speeds range from about 15 m s^{-1} over the inland lakes to 5–10 m s^{-1} over the surrounding topography to 0 m s^{-1} in the heavily canopied Atchafalaya River basin.

These winds forced water out of many of the coastal water bodies, including Sabine, Calcasieu, Grand, and White Lakes, and Vermilion Bay in Fig. 18. The four lakes and Vermilion Bay are connected to the Gulf of Mexico through a combination of natural waterways and shipping channels. However, there is additional hydraulic connectivity between the lakes themselves. Some is due to the low-lying, marshy character of the surrounding land and the man-made shipping channels, most notably the Gulf Intracoastal Waterway (GIWW), which is depicted in Fig. 18 as a thin line that runs along the north sides of these four lakes and Vermilion Bay. At this early stage of the hurricane, the area to the south of Grand Lake was inundated. The drawdown in northern Vermilion Bay leads to flooding of Marsh Island.

At 0300 UTC 24 September 2005, Rita was located about 95 km and 5 h away from landfall, and had deteriorated to a strong category 3 storm. In Fig. 19, the largest wind speeds occur to the northeast of the eye and have magnitudes of about 44 m s^{-1}. The wind speeds in the coastal and inland water bodies are 30 m s^{-1} or higher, and the directional land masking reduces the wind speeds overland to 20–25 m s^{-1}. The hurricane winds do not blow away from the coastline, except for the region to the west of Sabine Lake, where significant drawdown exists. The winds are easterly and southeasterly, and they range from 30 to 35 m s^{-1} along the coastline from Vermilion Bay to Calcasieu Lake.

Because of these winds, the surface water elevation gradients have also intensified in Fig. 20. The four lakes experience cross-lake water level differences of at least 2 m and extensive flooding of their western shores. The region around Grand Lake is flooded. Most of the water to the west is held by a local highway, but some of it is pushing through the GIWW to the region east of Calcasieu Lake. The water that began in Calcasieu Lake has pushed to the south and west, and it is now building against the north facing side of a local highway. The water in Sabine Lake has also pushed to the south. Large portions of southwestern Louisiana are inundated. About 1–2 m of surge has built on the broad continental shelf, pushed by the southerly winds. The surge builds to 2.5 m on the protruding Tiger and Trinity shoals south of Marsh Island.

TABLE 2. Summary of positions, central pressure, radius to maximum winds, maximum wind speed, and Saffir–Simpson category for Hurricane Rita (Knabb et al. 2006).

UTC time and date	Lon	Lat	Pressure (hPa)	Wind speed (m s^{-1})	Category on Saffir–Simpson
0000 UTC 18 Sep 2005	−69.9	21.3	1009	11.5	
0600 UTC 18 Sep 2005	−70.7	21.6	1009	11.5	
1200 UTC 18 Sep 2005	−71.5	21.9	1007	13.8	
1800 UTC 18 Sep 2005	−72.3	22.2	1005	16.1	
0000 UTC 19 Sep 2005	−73.0	22.4	1002	20.7	
0600 UTC 19 Sep 2005	−73.8	22.6	999	22.9	
1200 UTC 19 Sep 2005	−74.7	22.8	997	25.2	
1800 UTC 19 Sep 2005	−75.9	23.1	994	27.6	
0000 UTC 20 Sep 2005	−77.2	23.3	992	27.6	
0600 UTC 20 Sep 2005	−78.8	23.5	990	27.6	
1200 UTC 20 Sep 2005	−80.3	23.7	985	32.1	1
1800 UTC 20 Sep 2005	−81.6	23.9	975	39.0	2
0000 UTC 21 Sep 2005	−82.7	24.1	967	43.7	2
0600 UTC 21 Sep 2005	−84.0	24.2	955	50.5	3
1200 UTC 21 Sep 2005	−85.2	24.2	941	55.1	4
1800 UTC 21 Sep 2005	−86.2	24.3	920	66.6	5
0000 UTC 22 Sep 2005	−86.9	24.5	897	68.9	5
0600 UTC 22 Sep 2005	−87.6	24.8	897	71.2	5
1200 UTC 22 Sep 2005	−88.3	25.2	908	64.3	5
1800 UTC 22 Sep 2005	−89.1	25.6	914	57.4	4
0000 UTC 23 Sep 2005	−89.9	26.0	915	54.8	4
0600 UTC 23 Sep 2005	−90.7	26.5	924	52.9	4
1200 UTC 23 Sep 2005	−91.5	27.1	927	52.9	4
1800 UTC 23 Sep 2005	−92.3	27.8	930	50.5	3
0000 UTC 24 Sep 2005	−93.0	28.6	931	48.2	3
0600 UTC 24 Sep 2005	−93.6	29.4	935	45.9	3
1200 UTC 24 Sep 2005	−94.1	30.5	949	29.8	1
1800 UTC 24 Sep 2005	−94.1	31.6	974	20.8	
0000 UTC 25 Sep 2005	−94.0	32.7	982	16.1	
0600 UTC 25 Sep 2005	−93.6	33.7	989	13.8	
1200 UTC 25 Sep 2005	−92.5	34.7	995	11.5	
1800 UTC 25 Sep 2005	−91.4	35.8	1000	11.5	
0000 UTC 26 Sep 2005	−90.1	37.0	1003	9.2	
0600 UTC 26 Sep 2005	−88.0	39.5	1006	9.2	

At 0600 UTC 24 September 2005, Rita was located about 35 km and 2 h away from landfall. In Fig. 21, the region of maximum winds of about 44 m s^{-1} is positioned just south of Calcasieu Lake. Over the inland lakes, the winds range from 25 to 35 m s^{-1}. Even at this stage of the hurricane, the winds at the coast are directed alongshore and range from 30 to 40 m s^{-1} along the coastline itself, although strong southerly winds are blowing across a broad swath of the shelf.

Figure 22 shows the storm surge, which extends along the coast from Calcasieu Lake to Vermillion Bay. The region of southerly winds has moved closer to shore, and it has pushed 2–3 m of surge against the shore. This surge propagates inland but is slowed by the topography and marshes. To the east of the eye, the connectivity of Vermilion Bay allows the southeasterly winds to push water into the marshes to its west. To the west of the eye, northerly winds are causing significant drawdown in Sabine Lake and the Gulf outside Sabine Pass. Strong winds over all of the inland water bodies have created strong east–west water level gradients.

At 0800 UTC 24 September 2005, Rita has just made landfall near Sabine Pass, and the winds have begun to decrease (Fig. 23). The maximum wind speed of 38 m s^{-1} occurs to the south of Calcasieu Lake. The wind speeds farther east, in the region north of Vermilion Bay, are about 25 m s^{-1}. However, the winds have shifted and are now southerly along the coastline. The maximum surge occurs at the coastline to the south of Calcasieu Lake, and these winds blow that surge inland. Figure 24 shows a broad swath of surge that is driven by the southerly winds and has built along the coast from Sabine Pass to Marsh Island. However, it faces resistance from the coastal highway and the increased friction of the marshes. In Vermilion Bay, where the surge can enter more freely around and over Marsh

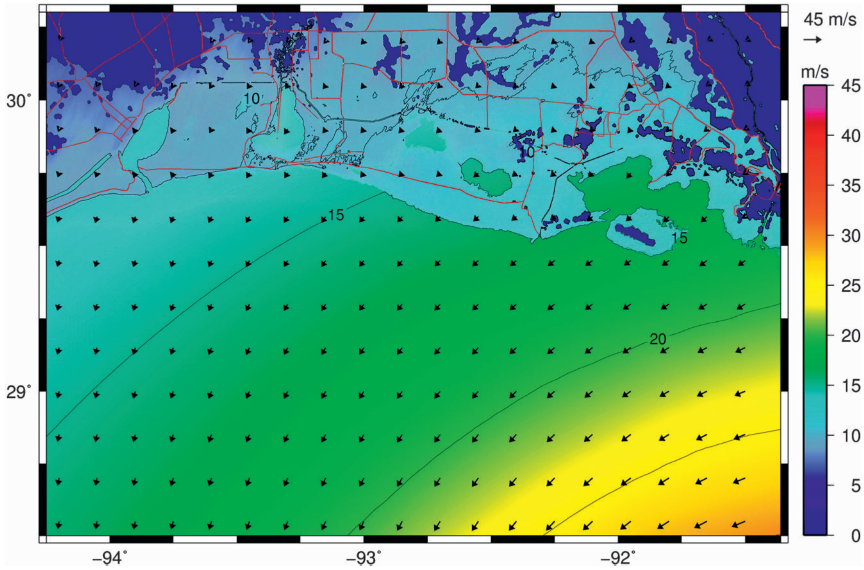

FIG. 17. Hurricane Rita wind contours and vectors (m s^{-1}) at 1200 UTC 23 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

Island, the surge has reached 2–2.5 m and is building against the northwest shore. East–west water level gradients are still prevalent in most of the lakes.

At 1100 UTC 24 September 2005, Rita was located about 45 km inland. Figure 25 shows the winds are decreasing over Calcasieu Lake itself, where the maximum wind speed is now about 29 m s^{-1}. The directional land masking has less of an effect at this stage of the hurricane, when the marshes are inundated with significant surge. A large region of the system continues to experience southerly winds of 25 m s^{-1} or greater, and thus the storm surge continues to be pushed against the coastline south of Calcasieu Lake.

Figure 26 shows Calcasieu Lake has filled with surge, and its natural shoreline is indistinguishable from its inundated surroundings. The surge propagating through Calcasieu Lake causes a local depression in coastal surge levels and leads to high water at the north side of the

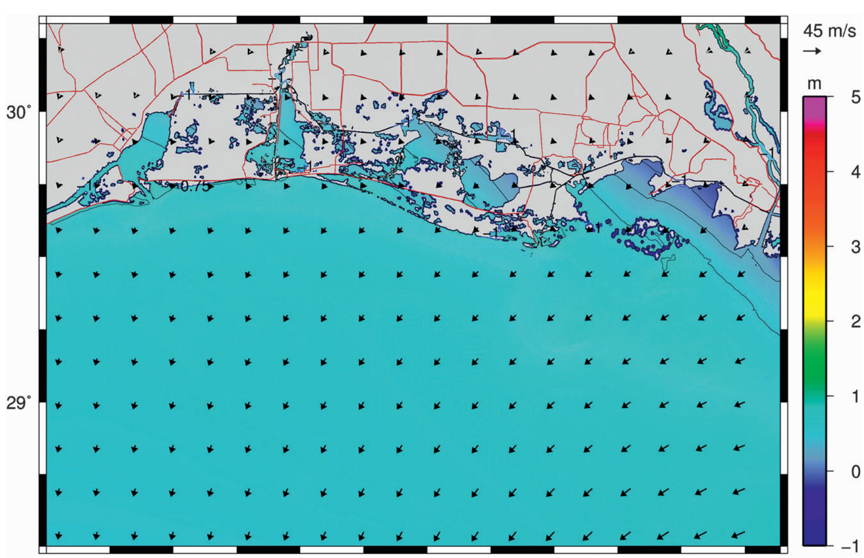

FIG. 18. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1200 UTC 23 Sep 2005 in southwestern Louisiana.

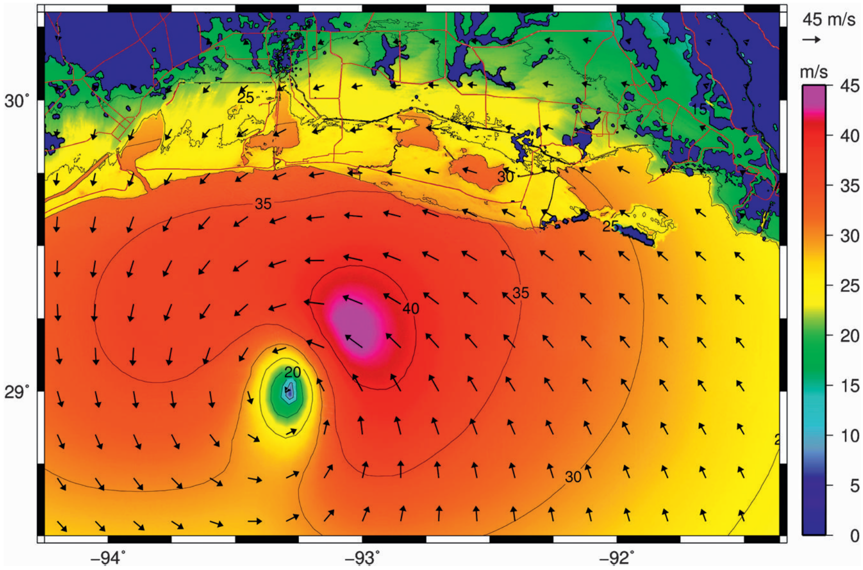

FIG. 19. Hurricane Rita wind contours and vectors (m s^{-1}) at 0300 UTC 24 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

lake. The overland surge has not reached this far north in adjacent regions, but surge is moving up this system of interconnected channels and lakes. Surge is able to propagate faster and more efficiently through Calcasieu Lake, and thus its water levels in the south are relatively lower than those in the surrounding marshes, which are slowing the surge as it propagates northward. Sabine Lake is filling with surge moving from the Gulf through Sabine Pass, but overland surge from the east is also flowing into the lake. A gradient is visible on the south side of Grand Lake, where about 2 m of surge is flowing into the lake. Vermilion Bay and vicinity has filled with water levels reaching 3 m.

Finally, at 2100 UTC 24 September 2005, Rita was located about 225 km north of Sabine Pass. The maximum wind speeds of about 17 m s^{-1} now occur over Sabine and Calcasieu Lakes, as indicated in Fig. 27. Over the marshes, the wind speeds range from 13 m s^{-1}

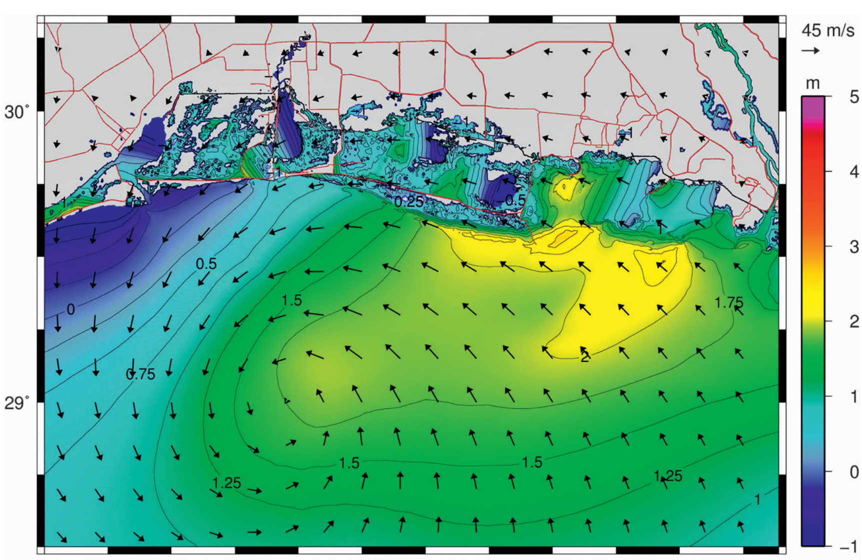

FIG. 20. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 0300 UTC 24 Sep 2005 in southwestern Louisiana.

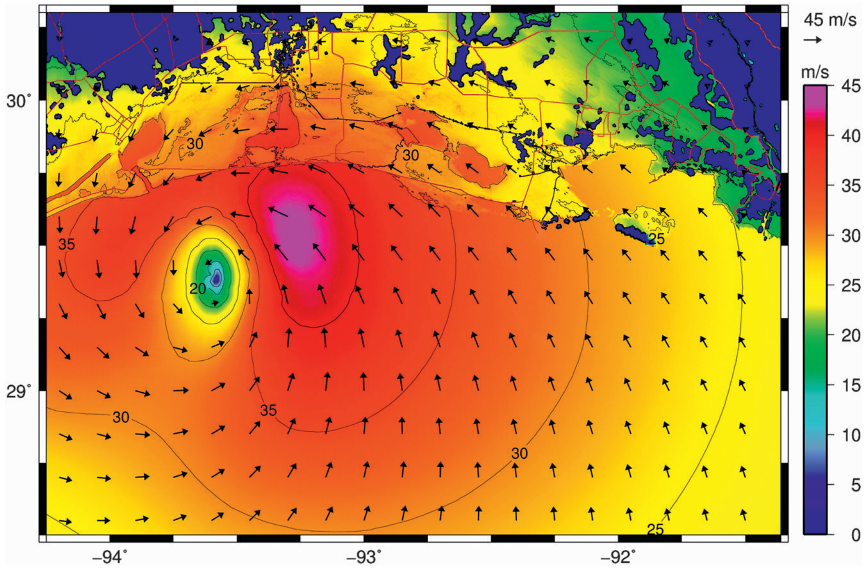

FIG. 21. Hurricane Rita wind contours and vectors (m s^{-1}) at 0600 UTC 24 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

in the west to 10 m s^{-1} in the east. Figure 28 shows the surge has propagated inland, water is held in the marshes, and water has receded rapidly from the shelf. The southwesterly winds are trying to push surge up the upper Calcasieu Shipping Channel toward Lake Charles, Louisiana, but the water elevations continue to decrease as water recedes back through Calcasieu Lake and into the Gulf. The high friction of the marshes now restrains the recession process, which continues for days after the storm (Part I).

b. Synoptic history in southeast Louisiana

Figure 29 shows the winds across southeastern Louisiana at 1200 UTC 23 September 2005, when the eye of Rita is about 320 km from New Orleans. The tropical storm–strength winds are easterly and already strong in

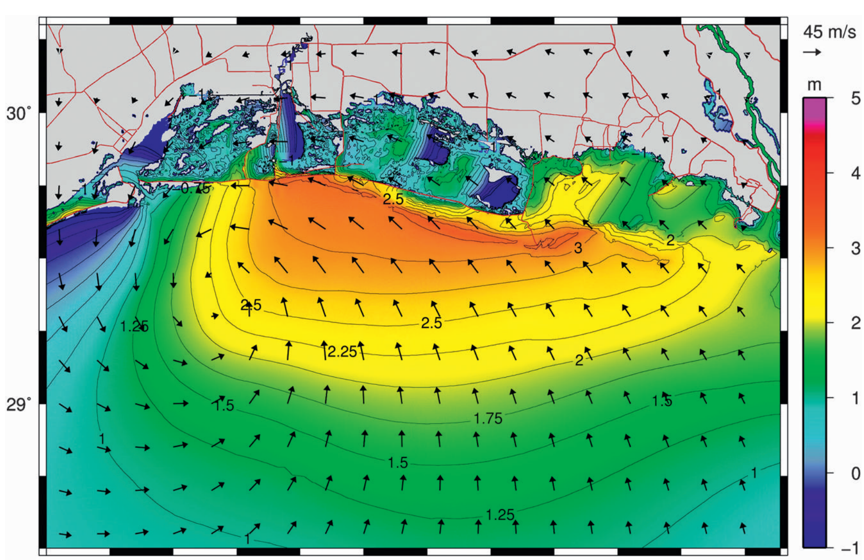

FIG. 22. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 0600 UTC 24 Sep 2005 in southwestern Louisiana.

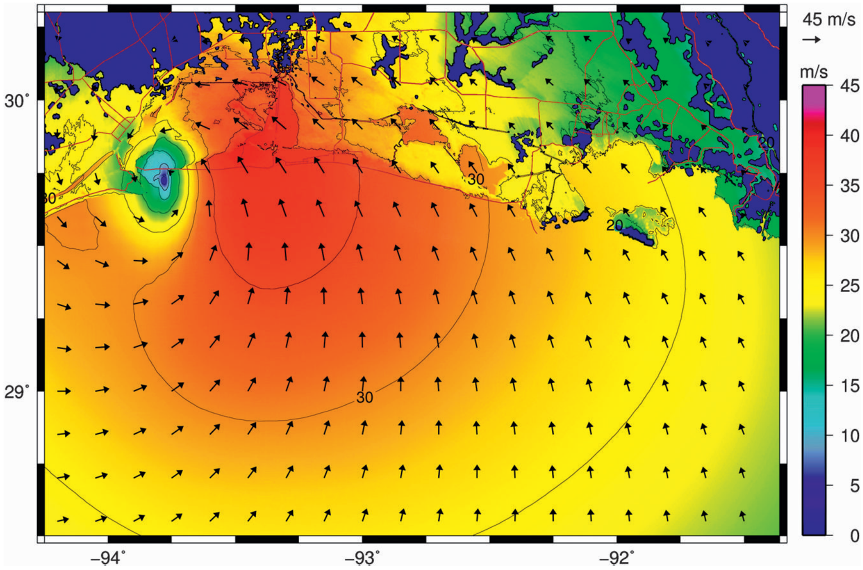

FIG. 23. Hurricane Rita wind contours and vectors (m s^{-1}) at 0800 UTC 24 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

this region, with 15–20 m s^{-1} winds extending over the Chandeleur and Mississippi Sound Islands and the shallow continental shelf. In Fig. 30, significant surge is occurring in this region. The easterly winds push water against the western edge of Lake Pontchartrain, against the east side of metropolitan New Orleans, and against the levees along the lower Mississippi River. A depression exists in the eastern part of Lake Pontchartrain, where water is slow to flow in from Lake Borgne. The gradient in water levels between these two lakes, combined with the easterly winds, drives currents of 1.5–2 m s^{-1} through the passes into Lake Pontchartrain. The surge has reached 2 m in parts of Plaquemines Parish.

Figures 31–32 advance forward in time to 0300 UTC 24 September 2005. Rita is centered about 300 km southwest of New Orleans. In southeastern Louisiana, the winds have shifted to blow southeasterly at 15 m s^{-1},

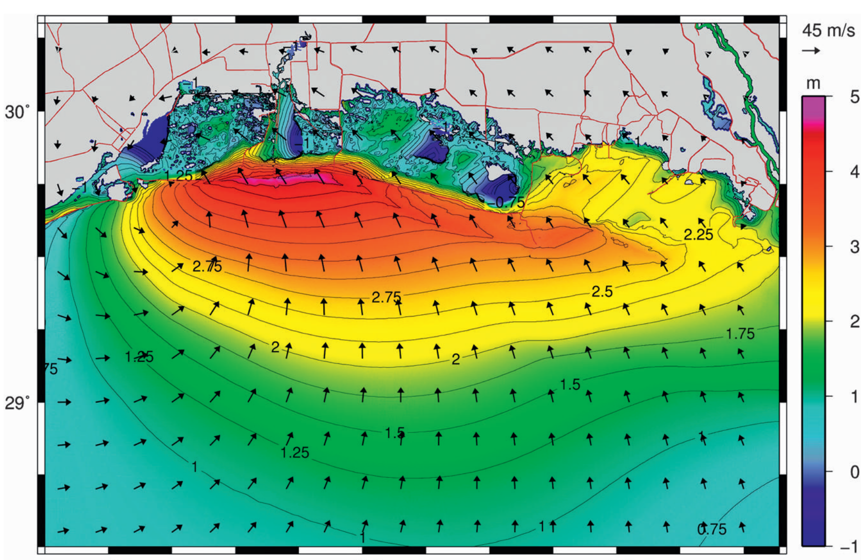

FIG. 24. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 0800 UTC 24 Sep 2005 in southwestern Louisiana.

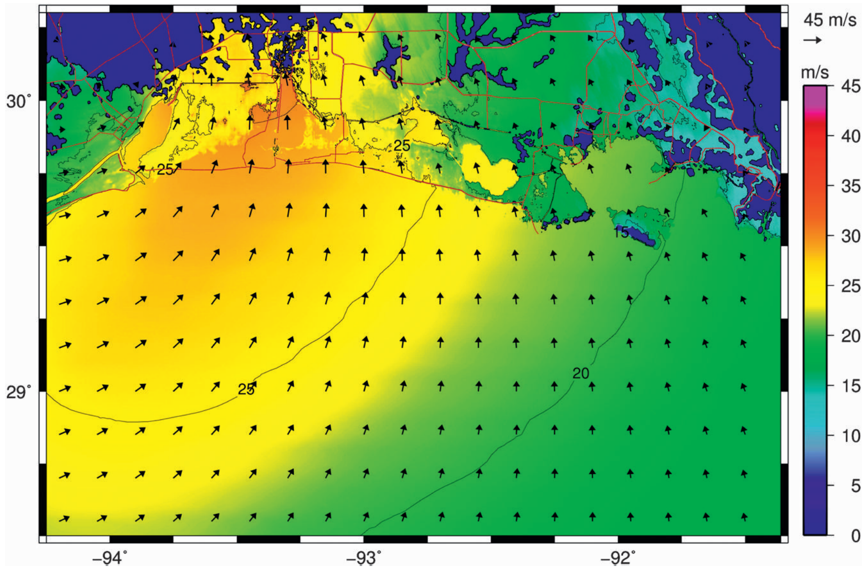

FIG. 25. Hurricane Rita wind contours and vectors (m s^{-1}) at 1100 UTC 24 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

pushing surge along the Mississippi River levees and toward New Orleans. Lake Pontchartrain has filled with 2 m of water, and 3 m of storm surge is built against the levees near English Turn. The winds and surge that have developed in the region remain steady for the next 8 h. In fact, a steady-state balance between the water surface gradient and the wind stress controls this region during this part of the storm.

Moving forward to 1100 UTC 24 September 2005, Rita was centered about 375 km from New Orleans. In Fig. 33, the winds are very similar to the conditions of 8 h earlier, but have begun to decrease slowly, allowing the storm surge to decrease slowly as well, as shown in Fig. 34. The surge elevation has decreased to less than 2.75 at English Turn to the southeast of New Orleans. Significant surge is driven into and held inside Lake

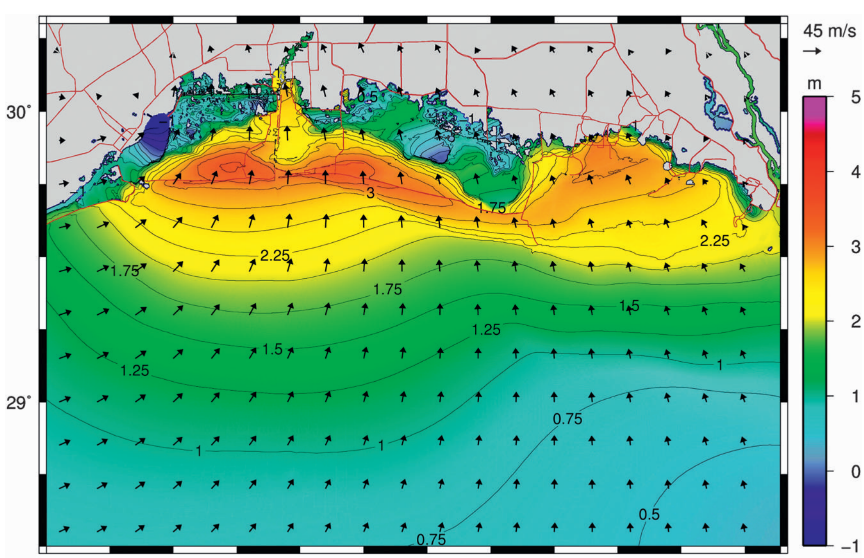

FIG. 26. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1100 UTC 24 Sep 2005 in southwestern Louisiana.

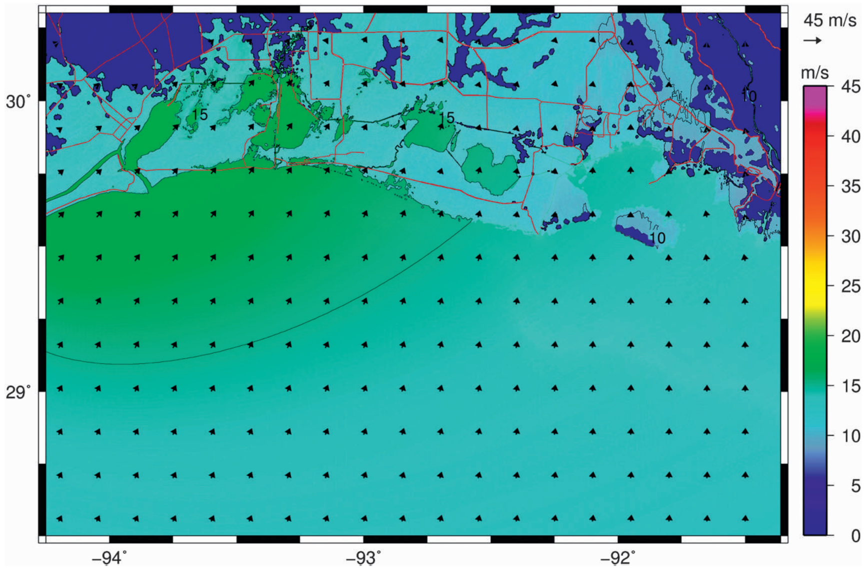

FIG. 27. Hurricane Rita wind contours and vectors (m s^{-1}) at 2100 UTC 24 Sep 2005 in southwestern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

Pontchartrain. The surge is smaller outside of the barrier islands, where the water levels are less than 0.75 m.

Finally, at 2100 UTC 24 September 2005, Rita was located more than 400 km from New Orleans, and the wind speeds have decreased in southeastern Louisiana (Fig. 35). In open water, the wind speed is 10 m s^{-1} or less throughout most of the region. The flood waters are slowly receding in a process that is dominated by the friction in the marshes and passes (Fig. 36), which are holding water on all sides of New Orleans. Lake Pontchartrain also holds its water efficiently.

c. *Contours of wave-related maxima*

Figure 37 shows the maximum significant wave heights in southwestern Louisiana. The wave heights are 10–12 m along the outer shelf and reduced to 3–5 m near the shore by breaking. Although the coastal marshes were inundated, wave height reduced dramatically due to depth-limited

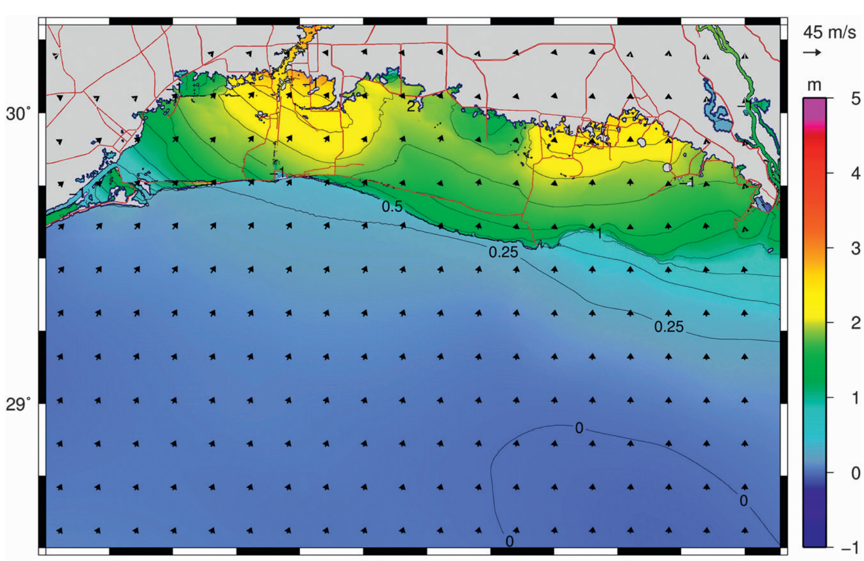

FIG. 28. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 2100 UTC 24 Sep 2005 in southwestern Louisiana.

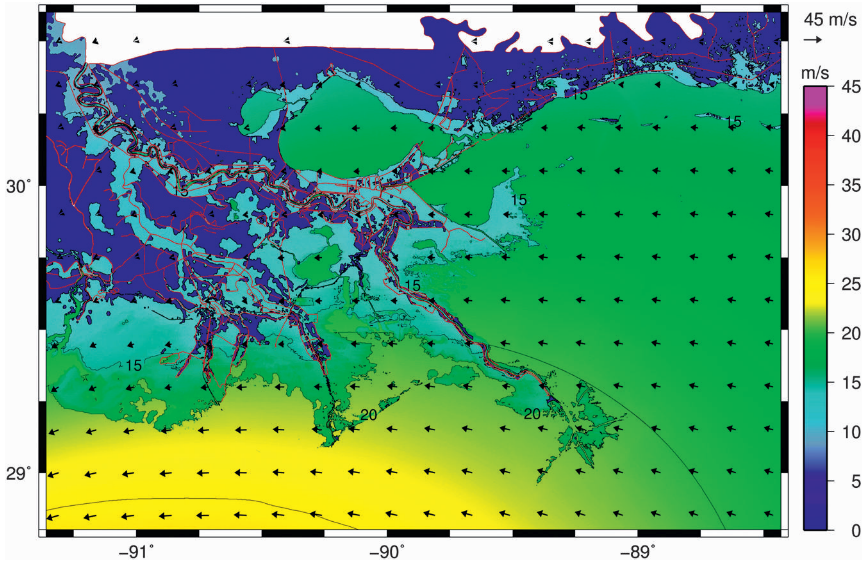

FIG. 29. Hurricane Rita wind contours and vectors (m s^{-1}) at 1200 UTC 23 Sep 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

breaking and friction. Figure 38 shows the maximum wave radiation stress gradients in southwestern Louisiana. The edge of the nearshore STWAVE domain is visible in the southern part of the figure, where the interpolation between the three models has caused large gradients at some nodes. However, the behavior becomes better near the shore, where the models contain high resolution to capture the wave breaking zones. The maximum wave radiation stress gradients occur along the shoreline and to the south of the Tiger and Trinity Shoals. Wave radiation stresses also appear in lakes that are farther inland, suggesting local wave generation and breaking along their shores.

Figure 39 shows the maximum significant wave heights in southeastern Louisiana. The wave height trends were similar to those produced for Katrina (transformation and dissipation on the shelf, and further sheltering and breaking induced by the barrier islands), but the larger

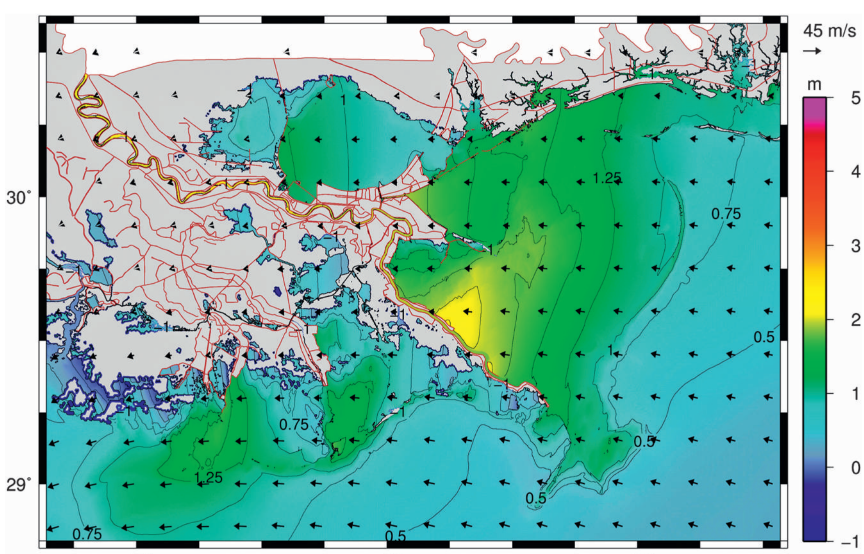

FIG. 30. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1200 UTC 23 Sep 2005 in southeastern Louisiana.

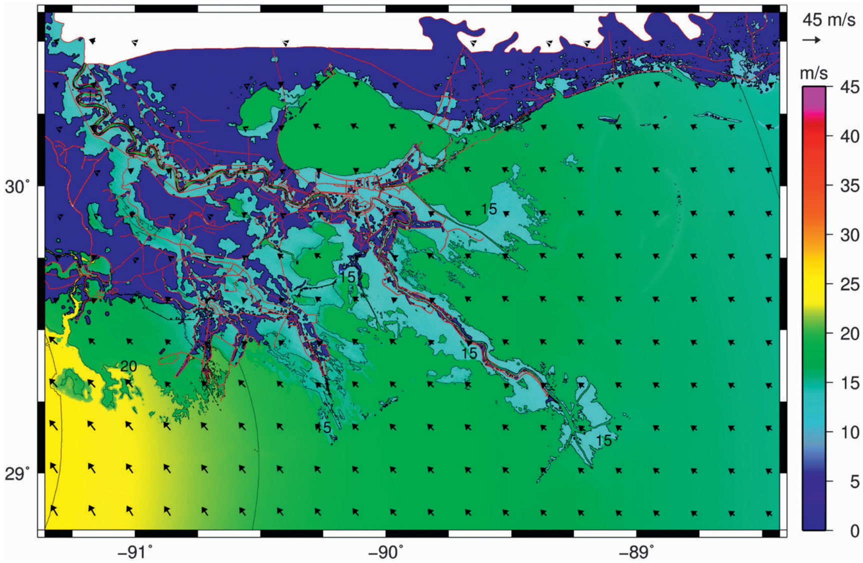

FIG. 31. Hurricane Rita wind contours and vectors (m s^{-1}) at 0300 UTC 24 Sep 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

wave heights in this region are west of the delta due to the storm track. Higher water levels and onshore winds in Barataria and Terrebonne Bays (west of the delta) produced larger wave heights in these inshore areas in Rita compared to Katrina, although the wave heights on the shelf west of the delta were lower for Rita (7–8 m) than Katrina (11–13 m).

Figure 40 shows the maximum wave radiation stress gradients in the same region. Significant wave breaking occurs along the shoreline near Grand Isle in the southwestern part of the figure, throughout the bird's foot of the Mississippi River delta, and along barrier islands at the periphery of the Chandeleur and Mississippi Sounds. Behind these features, though, the wave radiation stress gradients are not significant.

Figures 41–42 show the effect of waves as the difference between the maximum water levels from two simulations: the fully coupled simulation and a simulation

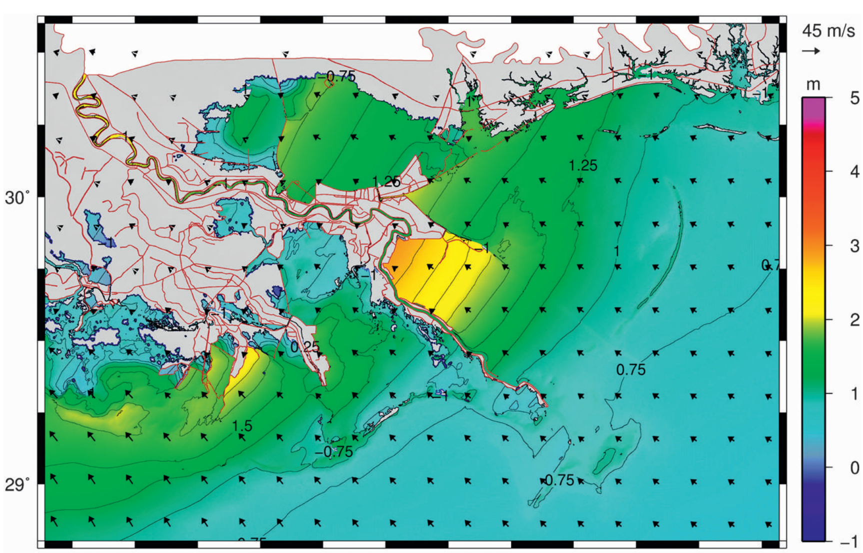

FIG. 32. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 0300 UTC 24 Sep 2005 in southeastern Louisiana.

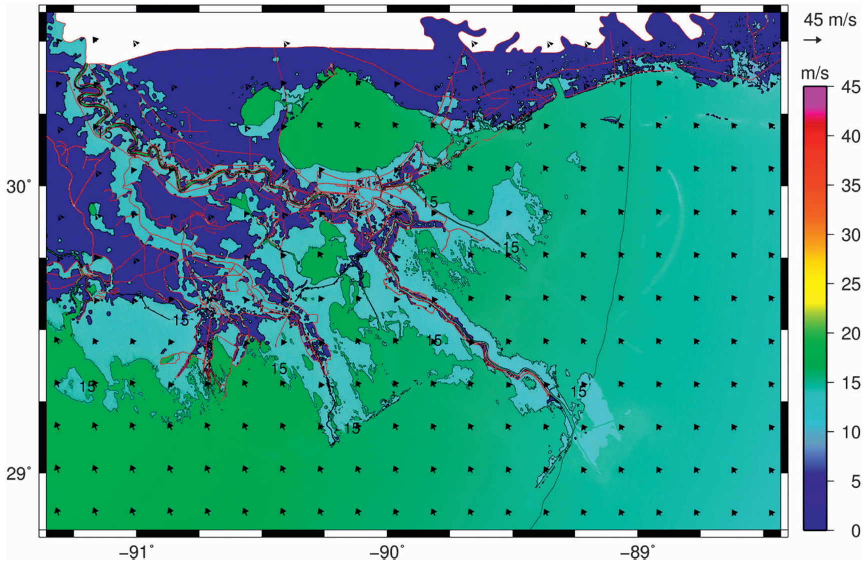

FIG. 33. Hurricane Rita wind contours and vectors (m s^{-1}) at 1100 UTC 24 Sep 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

that did not include waves. As the waves break at the shoreline, they generate significant radiation stress gradients that push additional water inland. The maximum water levels are larger throughout much of the floodplain of southwestern Louisiana, by as much as 0.1–0.3 m or about 5%–15% of the local surge. These modest increases in surge due to wave breaking are consistent with the broad continental shelf and expansive wetlands in southwestern Louisiana. The wave-induced setup would be larger and more concentrated if the shelf was narrower or if the nearshore had a steeper slope. In southeastern Louisiana, the waves break at the barrier islands in the east and along the coastline in the south, and they increase the water levels by 0.05–0.2 m. Note the localized maxima of 0.4 m in Terrebonne Bay, Grand Isle, and the bird's foot of the Mississippi River delta. These contributions represent about 40% of the total surge in these regions.

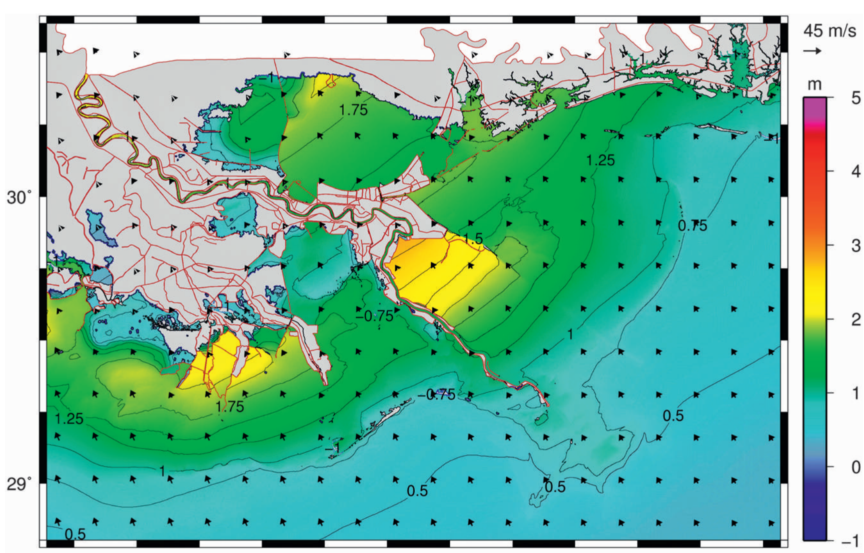

FIG. 34. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 1100 UTC 24 Sep 2005 in southeastern Louisiana.

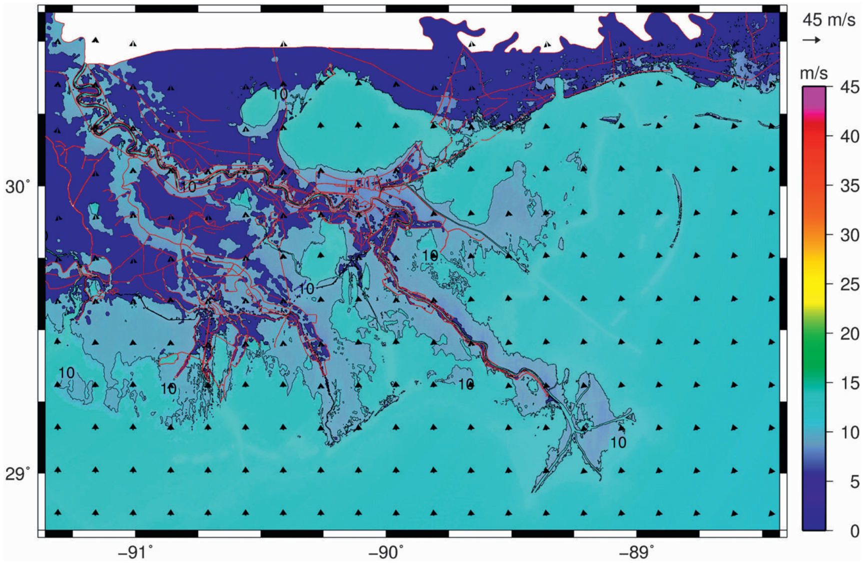

FIG. 35. Hurricane Rita wind contours and vectors (m s^{-1}) at 2100 UTC 24 Sep 2005 in southeastern Louisiana. Winds are shown with a 10-min-averaging period and at 10-m elevation.

4. Conclusions

The comprehensive synoptic histories of Hurricanes Katrina and Rita show that hurricane storm surge is a complex process that depends on the unique characteristics of the hurricanes and the geographical features of the regions they impact. The system's response to Katrina was markedly different east and west of the Mississippi River, highly localized, varied over even a few kilometers, and changed dramatically as the storm moved along its southerly track. In the early part of the storm, its asymmetry created strong easterly and southerly winds, which pushed 1.5–2.5 m of surge onto the broad, shallow shelf and into southeastern Louisiana. The shallower the water, the more effective the wind stress is at creating surge and piling it against obstructions. Currents were significant over the barrier islands and around the bird's foot of the Mississippi River delta. Surge collected against

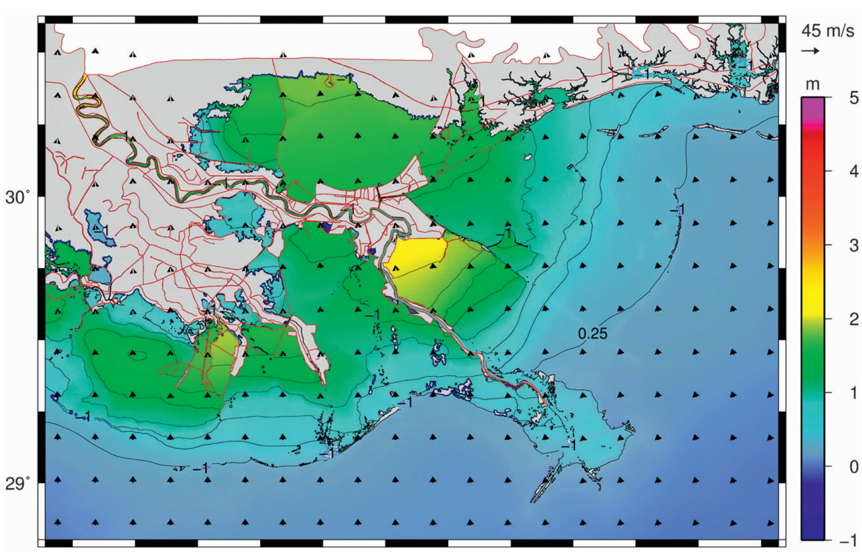

FIG. 36. Hurricane Rita elevation contours (m) relative to NAVD 88 (2004.65) and wind vectors (m s^{-1}) at 2100 UTC 24 Sep 2005 in southeastern Louisiana.

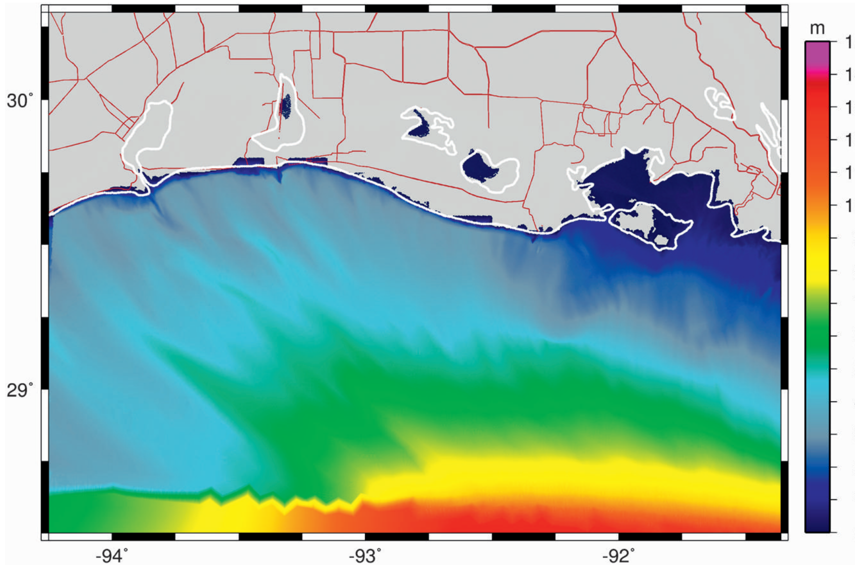

FIG. 37. Maximum significant wave heights (m) for Hurricane Rita in southwestern Louisiana.

the east-facing banks and levees of the lower Mississippi River and delta. Instead of flowing past the river and into the marshes and bays to the southwest, this surge propagated partially up the river, eventually flowing past New Orleans and Baton Rouge. Another component propagated across Breton Sound toward Mississippi. The marshes did not play a significant role in this part of the storm, because the water levels became too large to be dominated by bottom friction. At least 2–3 m of storm surge formed behind the barrier islands and remained on the shelf throughout the storm. The exception was the Caernarvon Marsh southeast of English Turn, which controlled how fast water was able to propagate across the marsh and build against the Mississippi River levees at English Turn before the winds shifted. These shifting winds also limited the storm surge near the Chalmette extension levee. Water was forced into Lakes Borgne and Pontchartrain, and these lakes experienced significant gradients as surge was pushed toward their western and southern shores. In addition, water from Lake Borgne

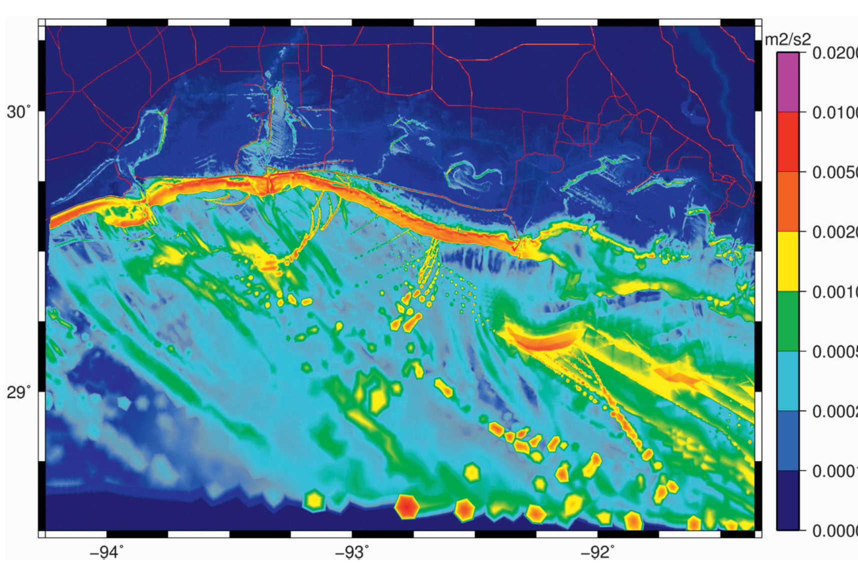

FIG. 38. Maximum wave radiation stress gradient contours (m^2 s^{-2}) for Hurricane Rita in southwestern Louisiana.

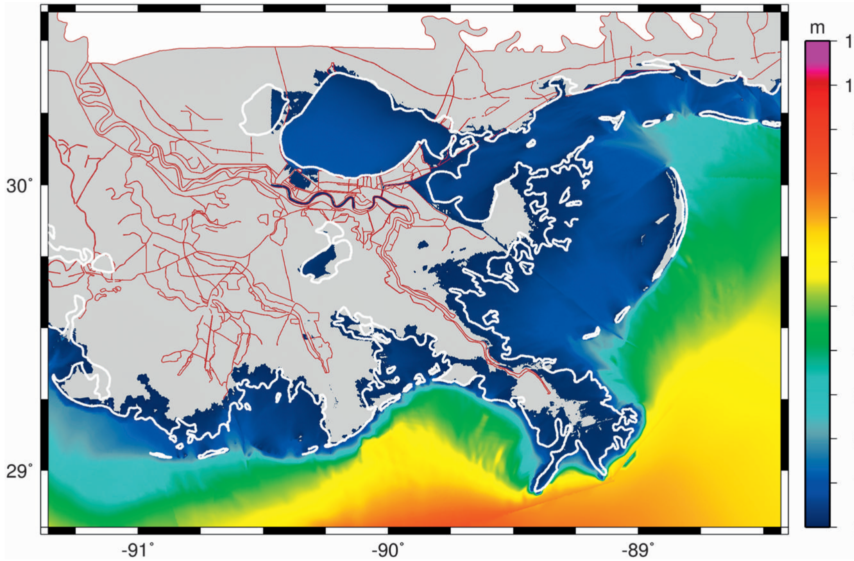

FIG. 39. Maximum significant wave heights (m) for Hurricane Rita in southeastern Louisiana.

was not flowing into Lake Pontchartrain fast enough to replace the water being blown to the west and south, creating a strong interlake gradient.

As the storm made landfall in Mississippi, its winds shifted to blow southerly and westerly. Surge was pushed northward, where it built against the steep topography along the coastline of Mississippi and Alabama. This surge flooded the bays and coastline and pushed additional water into Lakes Borgne and Pontchartrain. The surge was held in the lakes and bays because of limited hydraulic connectivity through the straits to the connecting water bodies, the locally steep topography, and the limited extent of the floodplain. The surge was held on the continental shelf because of the marshes and barrier islands, which greatly slowed the flood recession process. The wave-induced setup was significant throughout the region, but especially in the bird's foot of the Mississippi River delta, where it was 25%–35% of the overall water level. The delta's proximity to the edge of the continental shelf exposed it to large waves but little surge.

Rita caused extensive overland flooding in southwestern Louisiana. In the early part of the storm, its winds

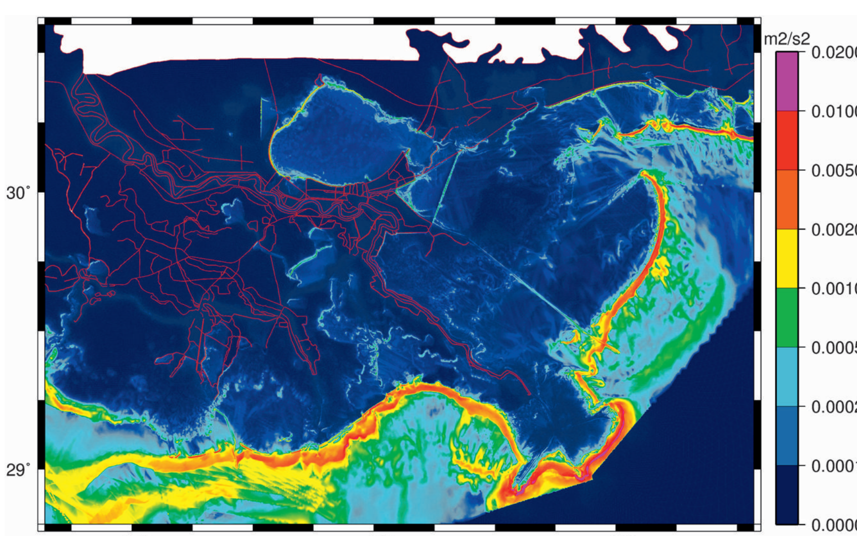

FIG. 40. Maximum wave radiation stress gradient contours ($m^2\ s^{-2}$) for Hurricane Rita in southeastern Louisiana.

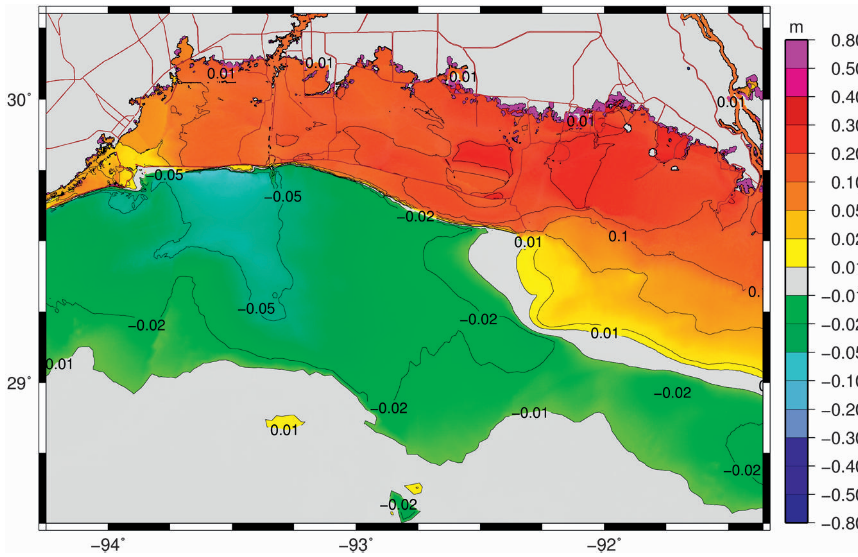

FIG. 41. Effect of waves on the maximum water levels (m) during Hurricane Rita in southwestern Louisiana.

were easterly throughout much of the region, and they pushed water from lakes and bays onto the surrounding marshes, building within the low-lying land and against embankments and structures. However, storm surge did not form at the coastline, because the easterly winds were not directed toward shore, and the region does not contain natural protrusions that would collect surge, in contrast to the region impacted by Katrina. Instead, the winds pushed water along and even away from the shore. Significant drawdown was experienced along the coast of southwest Louisiana, but especially near Sabine Pass, west of the eventual landfall location.

The southerly winds prior to landfall built surge to 1–2 m on the continental shelf. When these southerly winds reached the coastline, the surge built to levels exceeding 4 m over a large area. The surge at the coast is dominated by the wind and relative hydraulic efficiencies of the ocean and land. The winds held the water at the coast and enabled its release into the low-lying marshes. This surge propagated quickly through Calcasieu Lake, but it also flowed over the marshes and low-lying topography. In the days after the storm, the recession process was relatively slow and dominated by the friction of the marshes. The observed inland surge attenuation rates are consistent

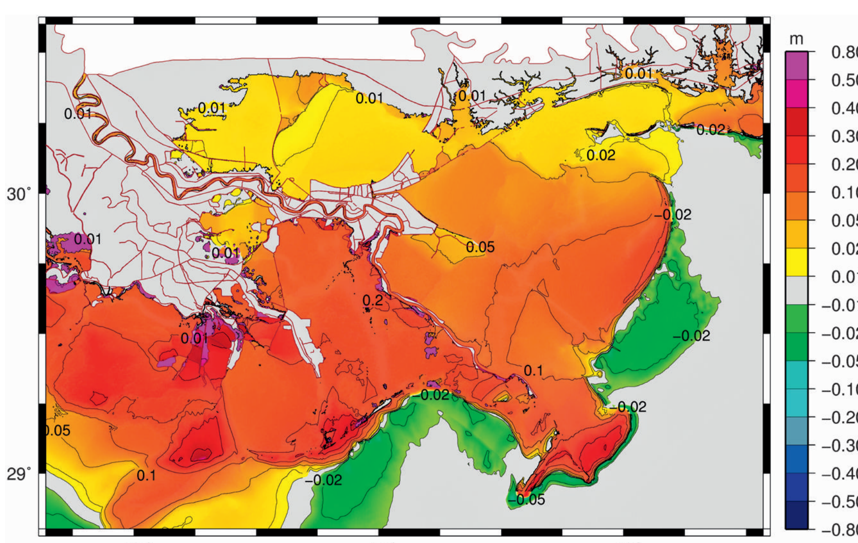

FIG. 42. Effect of waves on the maximum water levels (m) during Hurricane Rita in southeastern Louisiana.

with those observed in previous storms in southwestern Louisiana (Resio and Westerink 2008). Wave radiation stress gradients were strong along the coastline. The wave-induced setup was significant; water levels were increased by about 0.1–0.3m throughout the region. This setup was proportionately less than for Katrina, but it is consistent with the broad continental shelf of southwest Louisiana.

Like Katrina, Rita created significant surge in complex southeastern Louisiana. Its eye was never closer than about 300km to New Orleans, but its southeasterly track produced winds of tropical storm strength that were southeasterly and a relatively constant 15–20 m s^{-1}. A steady state was created in which the winds pushed significant surge against the banks and levees of the Mississippi River and the marshes and structures between Lakes Pontchartrain and Borgne, resulting in surge of about 2 m in Lake Pontchartrain and about 3 m at the levees near English Turn. Once the surge had collected against these levees, it was held there by the near-steady winds. Marsh friction did not play a role in the eventual surge level because a steady-state balance between water surface gradients and wind stress was reached.

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