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Hurricane Impacts on Coastal Wetlands: A Half-Century Record of Storm-Generated Features from Southern Louisiana

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ABSTRACT

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Temporally and spatially repeated patterns of wetland erosion, deformation, and deposition are observed on remotely sensed images and in the field after hurricanes cross the coast of Louisiana. The diagnostic morphological wetland features are products of the coupling of high-velocity wind and storm-surge water and their interaction with the underlying, variably resistant, wetland vegetation and soils. Erosional signatures include construction of orthogonal-elongate ponds and amorphous ponds, pond expansion, plucked marsh, marsh denudation, and shoreline erosion. Post-storm gravity reflux of floodwater draining from the wetlands forms dendritic incisions around the pond margins and locally integrates drainage pathways forming braided channels. Depositional signatures include emplacement of broad zones of organic wrack on topographic highs and inorganic deposits of variable thicknesses and lateral extents in the form of shore-parallel sandy washover terraces and interior-marsh mud blankets. Deformational signatures primarily involve laterally compressed marsh and displaced marsh mats and balls. Prolonged water impoundment and marsh salinization also are common impacts associated with wetland flooding by extreme storms. Many of the wetland features become legacies that record prior storm impacts and locally influence subsequent storm-induced morphological changes. Wetland losses caused by hurricane impacts depend directly on impact duration, which is controlled by the diameter of hurricane-force winds, forward speed of the storm, and wetland distance over which the storm passes. Distinguishing between wetland losses caused by storm impacts and losses associated with long-term delta-plain processes is critical for accurate modeling and prediction of future conversion of land to open water.

ADDITIONAL INDEX WORDS: *Wind stress, storm surge, landscape evolution, impact duration.*

INTRODUCTION

Hurricanes are one of the most common natural drivers of coastal disturbance and widespread morphological change. The most common studies of hurricane impacts on subaerial ecological systems inland from the shoreline pertain to the complex patterns of damage sustained by coastal forests. Research pertaining to hurricane wind-throw damage in forests is so advanced that models have been developed to explain the interactions among wind speed, topography, and trees (Doyle, Krauss, and Wells, 2009; Ramsey *et al.*, 2001). Research pertaining to the impacts of hurricanes on coastal wetlands, however, is in the rudimentary stages of development, and prior investigations typically have focused on storm-induced sedimentation (Reed, Commagere, and Hester, 2009; Turner *et al.*, 2006; Turner *et al.*, 2007), elevation change (Cahoon, 2006), or enhanced wetland productivity (Conner *et al.*, 1989).

Hurricanes frequently impact coastal Louisiana wetlands (Figures 1 and 2; Muller and Stone, 2001) because the upper atmospheric steering patterns and Coriolis effect cause the rotating storm centers to turn northward in the northern Gulf of Mexico. There are many accounts of storm impacts in coastal Louisiana, but most are brief descriptions of local changes without quantitative data about the regional magnitudes (areal extents) and durations of the impacts, and some of them focus on maximum changes for one event, such as beach erosion and washover deposition (Morgan, Nichols, and Wright, 1958; Ritchie and Penland, 1988; Stone *et al.*, 2003). Recent remote-sensing assessments of storm impacts indicate that extreme storms (Category 3 and greater) cause the most observable wetland loss (Barras, 2006, 2007a, 2009; Barras *et al.*, 2010).

None of the prior studies has presented a detailed comprehensive synthesis and quantitative analysis of hurricane morphological impacts in coastal wetlands. Consequently, a generic classification of hurricane impacts, regardless of storm intensity and marsh type, is lacking. Identification of storm-generated features also provides a basis for quantifying wetland losses that are attributable to specific events and for distinguishing those losses from losses caused by other coastal processes that result in the conversion of wetlands to open water.

The present study examines the historical record of hurricane impacts in coastal Louisiana and identifies the repeated

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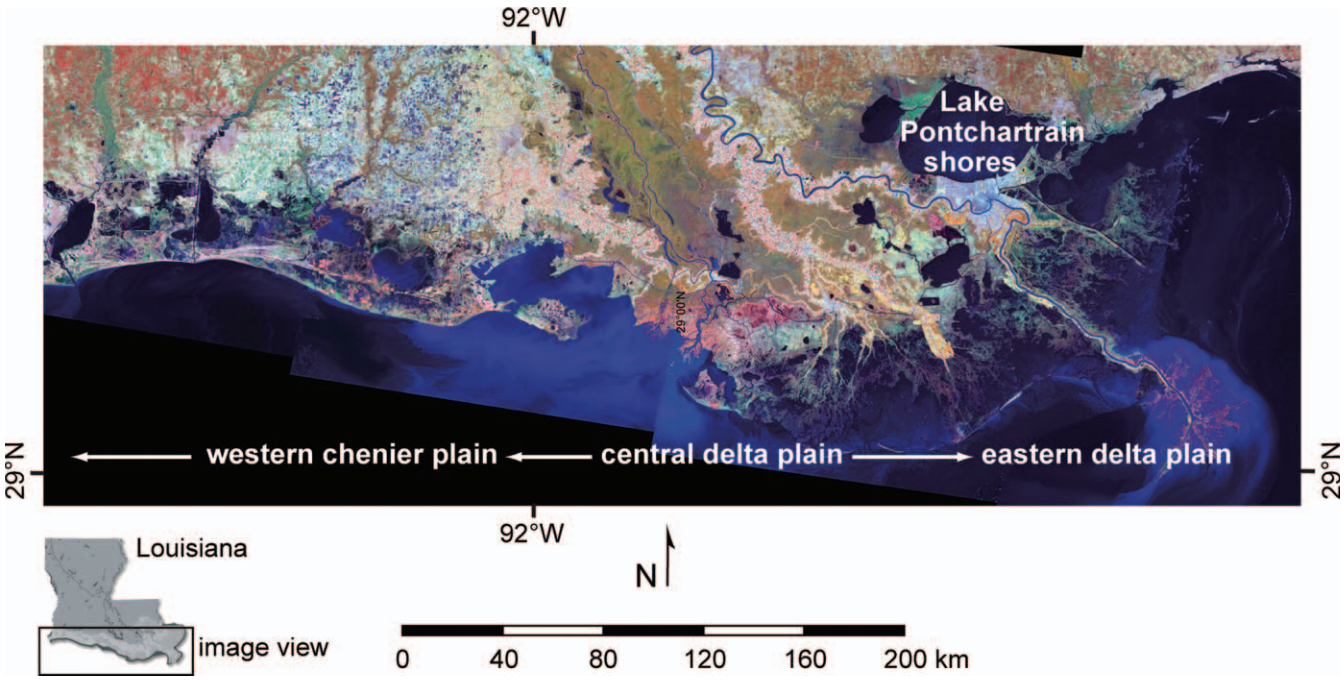

Figure 1. Fall 2006 Landsat Thematic Mapper satellite image of the coastal wetlands of southern Louisiana showing the major geographic subdivisions used to discuss hurricane impacts.

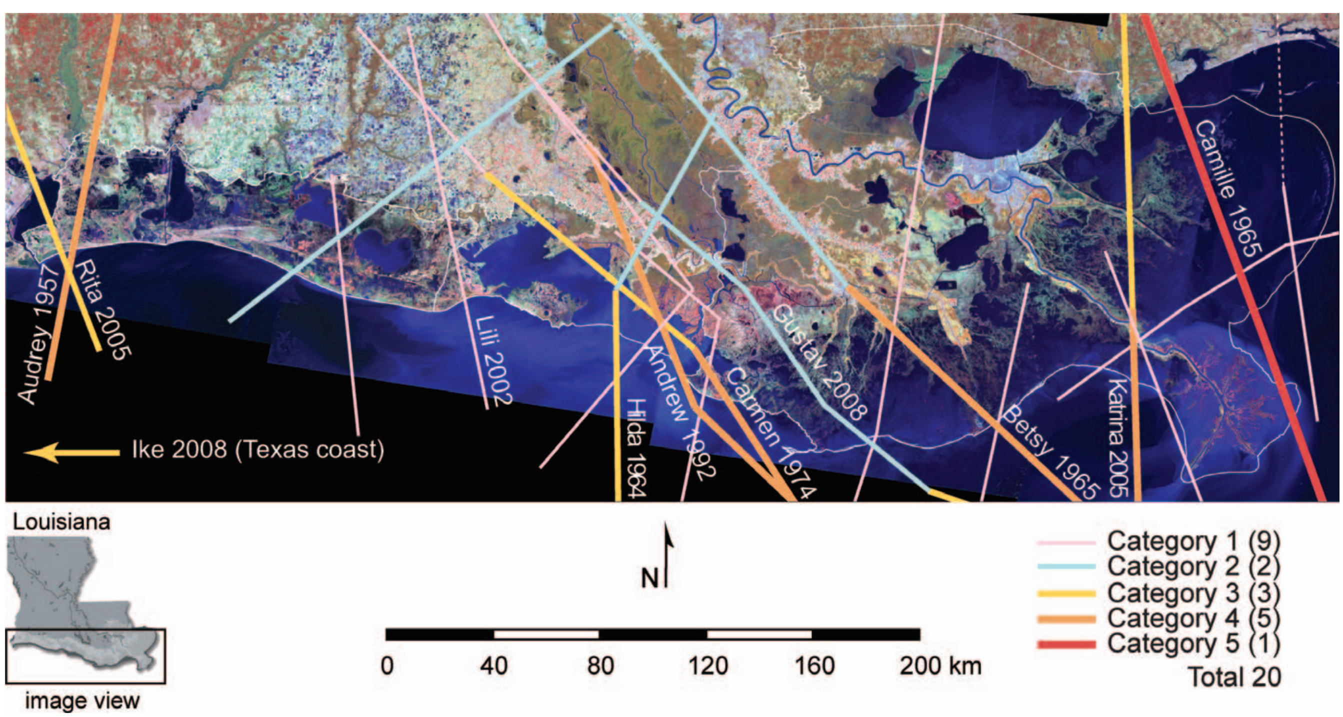

Figure 2. Tracks of hurricanes that modified the southern Louisiana coastal wetlands between 1957 and 2008. Source is the National Oceanic and Atmospheric Administration (2010).

Table 1. *Summary of wetland features formed by hurricane impacts, order of magnitude sizes, preferential occurrence, and reported recovery periods. Abbreviations of marsh type based on soil salinity are: F = fresh, I = intermediate, B = brackish, and S = saline. IR = incomplete recovery.*

Impact Feature	Sizes	Marsh Types	Recovery Period
Elongate ponds	m^2-km^2	F, I, B	IR
Amorphous ponds	m^2-km^2	F, I, B, S	IR
Expanded ponds	m^2-km^2	F, I, B, S	IR
Braided channels	km^2	F, I	IR
Plucked marsh	m^2	I, B, S	IR
Denuded marsh	m^2-km^2	I, B, S	few y to IR
Redistributed marsh	10s–100s m	F, I	few y to IR
Shoreline erosion	10s–100s m	F, I, B, S	IR
Marsh compression	1 m–10s m	F, I	few y
Displaced mats	1 m–10s m	F, I, B	few y
Wrack zones	10s–100s m	F, I, B, S	few y
Interior-marsh deposits	km^2	F, I, B, S	0 to few y
Shoreline deposits	10s–100s m	B, S	1 to few y
Impoundments	km^2	F, I, B	few y to IR
Marsh salinization	km^2	F, I, B	1 to few y

patterns of wetland erosion, deformation, and deposition. The study also provides magnitudes and durations of impacts so that event impacts can be differentiated from the long-term wetland losses associated with subsidence, the eustatic rise in sea level, and other nonstorm delta-plain processes. We focus primarily on those hurricane wetland impacts that can be recognized and measured on remotely sensed images or observed in the field. We selected the marshes of coastal Louisiana because they are some of the most studied wetlands in the world, and there is a 60-year record of high-quality aerial photographs and a 30-year record of satellite images that can be used to document the storm-impact features and track their preservation.

METHODS

The temporal and spatial analyses of hurricane impacts in wetlands of coastal Louisiana involved (1) comparing georectified high-resolution aerial photographs and satellite images that bracket a hurricane event, (2) mapping and classifying the morphological land–water changes, (3) analyzing the patterns of change, and (4) relating the patterns of change to the storm forces and local field conditions.

We plotted the paths of hurricanes that impacted the Louisiana coast between 1957 and 2008 (Figure 2) and compiled data for relevant storm parameters, including the duration of marsh inundation, wind directions and wind speeds, and timing of highest wind speeds at a location relative to estimated water depths above the marsh surface. To better understand the hydrodynamic processes that generate the storm-impact features, it was necessary to estimate the maximum overland flow depth at a site, which is the maximum storm-surge height minus the land elevation. The surge heights for each storm were obtained from tide-gauge records and field measurements as reported in the published literature, and wetland elevations were obtained from the Louisiana Department of Natural Resources (2010). References to wetland types (saline, brackish, intermediate, fresh; Table 1) follow the salinity-gradient zonations of Sasser *et al.* (2008), and the hurricane intensity categories (Table 2) follow the Saffir-Simpson scale (National Hurricane Center, 2011).

Storm-impact features in coastal Louisiana wetlands (Table 1) were identified on black and white, true color, and color-infrared aerial photographs and on Landsat Thematic Mapper (TM) satellite images. Ages ranged from 1938 to 2008 for the aerial photographs and 1983 to 2008 for the satellite images. Pixel resolution ranged from 1 to 6 m for the digitized aerial photographs, and 28.5 to 30 m for the TM images. To quantify wetland impacts for Hurricanes Katrina, Rita, Gustav, and Ike (Table 2), land and water areas were classified regionally on pre- and poststorm TM images using a spatial template that was common to all of the georeferenced images. Classified land and water areas within the template were extracted as raster files in a Geographic Information System using image-analysis software, and the differences in land and water areas (km^2) before and after each hurricane were tabulated as net gains and losses.

Most of the hurricane parameters (Table 2), except impact duration and beach erosion, were obtained from storm reports prepared and archived by the National Hurricane Center. Wetland-impact duration depends on the extent of wetlands (Sasser *et al.*, 2008) and the path, forward speed, and size of the storm, expressed as the radius of hurricane-force winds in the leading (NE) and trailing (SE) quadrants. Impact durations (hrs) were calculated by taking the wetland distance (km) over which the storm passed, adding the diameter of hurricane-force

Table 2. *Landfall parameters of significant hurricanes that impacted Louisiana coastal wetlands since 1957. Attendant increased water areas are from Barras (2007a) and Barras* et al. *(2010). NM = not measured.*

Hurricane Name	Year	Saffir-Simpson Scale	Max. Wind Speed (kph)	Max. Flow Depth (m)	Forward Speed (kph)	Hur. Wind Diameter (km)	Impact Duration (h)	Beach Erosion (m)	Increased Water Area (km^2)
Audrey	1957	4	160	3.0	24	384	16	60–90	NM
Hilda	1964	2	215	2.5	10	192	24	NM	NM
Andrew	1992	3	195	2.3	15	224	21	60–100	NM
Lili	2002	1	148	1.5	24	384	17	60–70	NM
Katrina	2005	3	200	5.3	24	384	23	50–†	230
Rita	2005	3	200	4.0	19	272	16	40–80	295
Gustav	2008	2	170	3.4	24	220	11	45–160	124
Ike	2008	2	140	4.2	20	390	21*	10–45	199

† Many segments of the Chandeleur Islands were destroyed.
* Estimated for Louisiana wetlands although landfall was in Texas.

winds (km), and dividing by the forward speed of the storm (kph) reported in the public advisory issued just before landfall. Gulf shoreline beach erosion and washover deposition in Louisiana wetlands caused by Hurricanes Katrina, Rita, Gustav, and Ike were measured by comparing pre- and poststorm Google Earth images. Increased water area (Table 2) includes both erosion and flooding of marshes and removal of aquatic vegetation from preexisting water bodies.

FACTORS INFLUENCING WETLAND IMPACTS

Wind and Water Characteristics

Water-level fluctuations and inundation histories in Louisiana coastal wetlands during a hurricane depend on the storm's prelandfall intensity, forward motion, changes in wind direction, and configuration of the shoreline relative to the storm path. The most common inundation history is a rapid rise and gradual fall in water level; however, a rapid rise and rapid fall or gradual rise and rapid fall also have been observed (Godeau and Conner, 1968; McGee, Tollett, and Goree, 2007). Regional histories of storm-surge flooding have been hindcast by hydrodynamic numerical models such as the Advanced Multi-Dimensional Circulation Model (ADCIRC) for Hurricane Katrina (ADCIRC Development Group, 2006; Ebersole *et al.*, 2010) or the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model for Katrina (National Oceanic and Atmospheric Administration, 2005). Model results show that for northward-tracking storms, water levels are set up on the eastern side of the track and simultaneously set down on the western side when winds are from the NE and E. The models also show that water levels across the wetlands drop rapidly as the storm moves farther inland and the winds are from the W and SW.

The maximum wetland destruction during a hurricane depends partly on the water depths at the time of maximum wind stress and partly on the efficiency of coupling between the wind and water. At some wetland sites, the maximum storm surge does not coincide with the maximum wind speeds. For example, during Hurricane Andrew, the maximum storm surge arrived several hours after the maximum winds were recorded in the central delta region (Dingler, Hsu, and Foote, 1995). There may be an optimum combination of high-wind speeds and shallow-flow depths that produce the observed storm-impact features.

It is uncertain how variable-wind speeds within a hurricane interact with variable-flow depths across the marsh to form storm-impact features. Paths of wind damage to buildings (Fujita, 1992; Wakimoto and Black, 1994), patterns of blown down trees (Wakimoto and Black, 1994), and morphological features in sandy coastal environments attributed to hurricane winds (Morton and Sallenger, 2003) provide clear ground evidence of coherent structures within the near-surface wind fields of hurricanes with horizontal spacing of tens to hundreds of m. High-resolution Doppler radar images show organized alternating bands of intense and weaker flow within the hurricane boundary layer that are attributed to streaks and roll vortices (Ellis and Businger, 2010; Lorsolo *et al.*, 2008; Wurman and Winslow, 1998). High-speed wind is transported toward the surface on the downdraft sides of the rolls, whereas air slowed by friction and turbulent drag of the ground is transported away from the ground on the updraft sides of the rolls. The roll vortices enhance the vertical transfer of energy and momentum between the wind and shallow storm-surge water and produce the alternating bands of higher and lower wind speed observed in the hurricane near-surface wind field (Ellis and Businger, 2010). For the coastal wetlands of Louisiana, the shapes, orientations, and patterns of hurricane-constructed elongate ponds, braided channels, plucked marsh features, denuded marshes, and compressed or displaced marsh mats (see following sections for definitions and discussion) indicate that high-velocity wind-driven currents play an important role in morphologically altering the marsh surface. As illustrated in Figures 3–9, the erosional and deformational storm-impact features documented in coastal Louisiana wetlands are products of scouring, plucking, and shearing. The depositional features (Figures 10 and 11) are

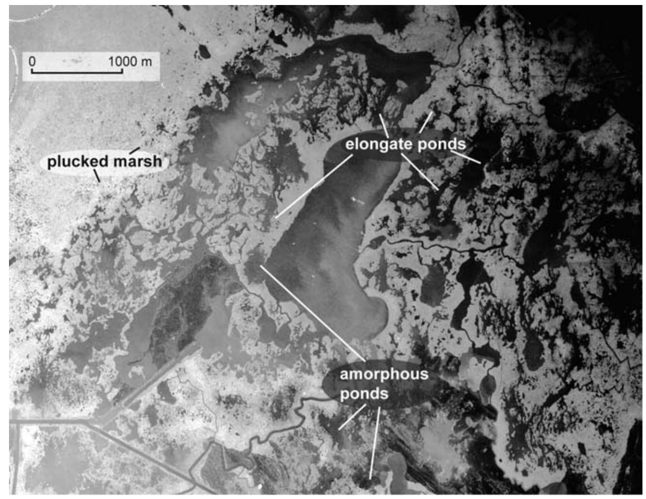

Figure 3. Orthogonal-elongate ponds and amorphous ponds both with marginal incised-drainage patterns and plucked-marsh features formed by Hurricane Hilda (1964) in the central delta region. Aerial photograph taken by Tobin, Inc., on January 24, 1965, approximately 4 months after the storm.

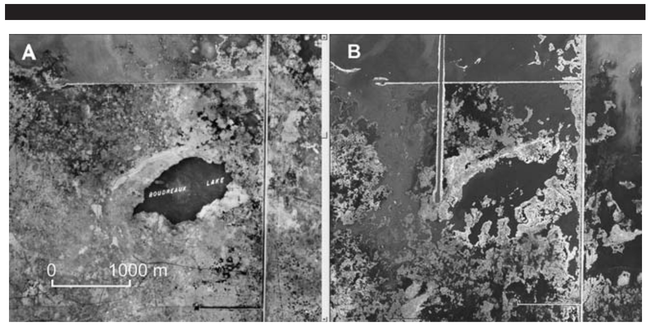

Figure 4. Boudreaux Lake in the western chenier-plain region (A) before and (B) after Hurricane Audrey (1957), illustrating an expanded pond with marginal incised drainage.

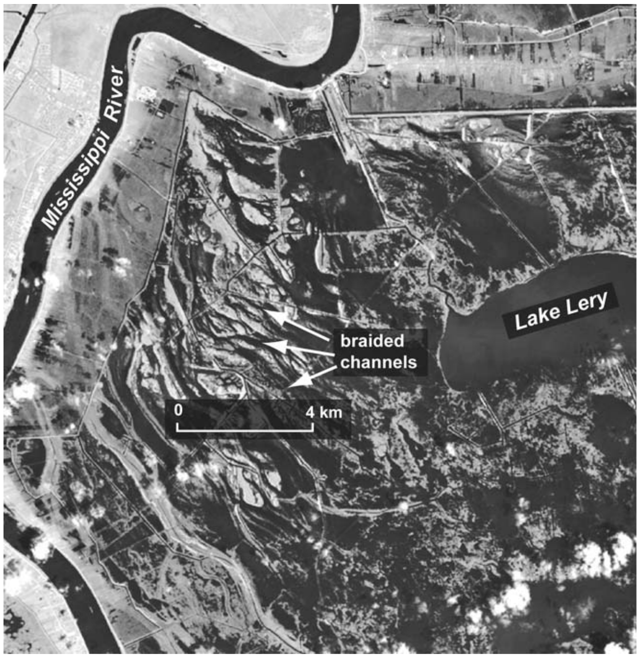

Figure 5. Braided channels formed by the storm surge of Hurricane Katrina (2005) in the eastern delta region.

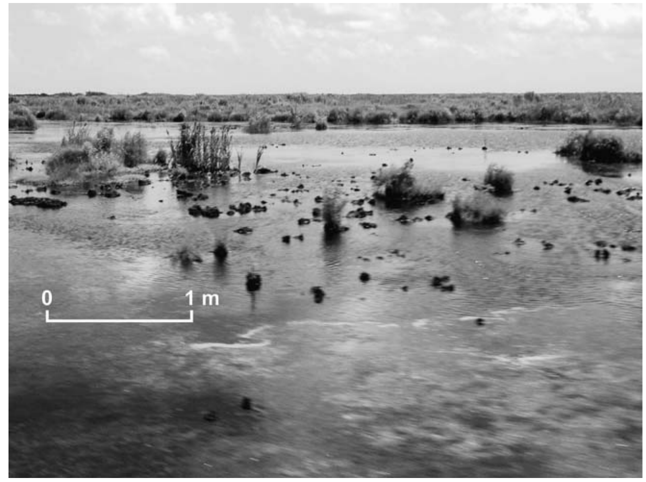

Figure 7. Remnants of marsh vegetation stripped to the sediment surface by Hurricane Rita (2005) in the western chenier-plain region.

products of sediment transport and local flow-boundary conditions.

Wetland and Water Elevations

Topographic features can influence wetland storm-water levels that would not be predictable just by monitoring the storm path and wind directions. Maximum surge heights commonly coincide with physiographic features having abrupt increases in elevation that act as barriers to wind-driven flow or that funnel the surge (Ebersole *et al.*, 2010). Examples are along the ocean shore (change from water to beaches and dunes), along the shores of embayments or lakes (change from water to upland with washover ridge), and along channels and canals within the coastal plain (change from wetland to natural or artificial levees).

The topographic obstructions contribute to greater wetland modification because greater flow depths allow development of higher waves and attendant greater turbulence and energy dissipation at the marsh surface. As a storm travels inland, rapid changes in the direction of wind stress can force high-velocity currents to flow away from the topographic features (Ebersole *et al.*, 2010) as formerly confined water is driven offshore in the return flow. Under these conditions, the return flow is not relaxed gravity-driven drainage but is forced by the

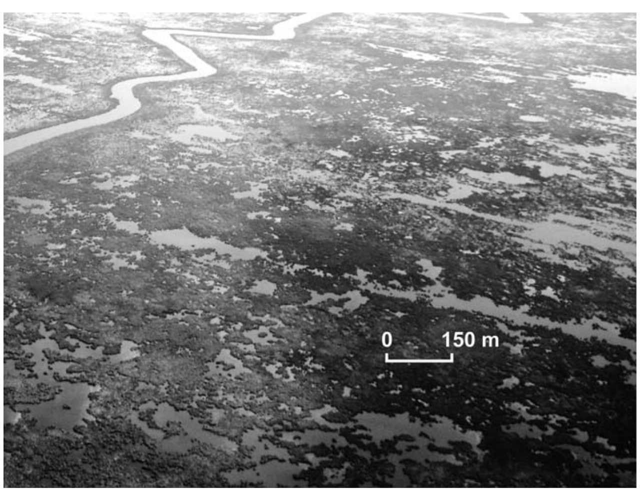

Figure 6. Closely spaced plucked-marsh features formed by Hurricane Katrina (2005) in the eastern delta region. Linear alignment of water bodies in the marsh coincide with former pipeline trenches.

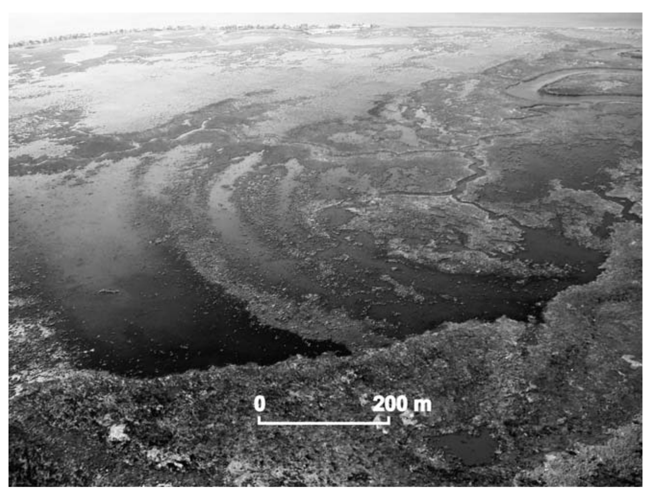

Figure 8. Brackish marsh deformed and relocated by Hurricane Katrina (2005) in the Lake Pontchartrain shores region.

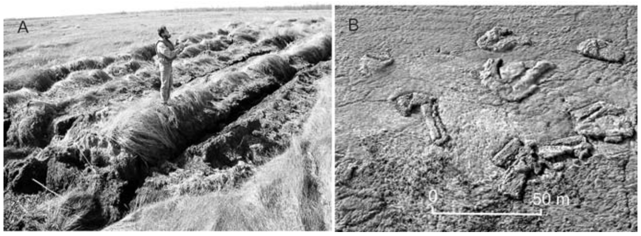

Figure 9. Wetland-deformation features produced by Hurricane Lili (2002) in the central delta region. (A) Highly compressed marsh mats with fold amplitudes of about 1 m. (B) Laterally displaced marsh mats and marsh balls.

wind. Consequently, the duration of marsh inundation and directions of receding floodwaters are variable owing to local topography and channel networks in the marsh.

Wetland Type

The composition of wetland plants and physical properties of the underlying substrates also influence the vulnerability of wetlands to storm impacts. Freshwater wetlands are the most susceptible to damage caused by saltwater flooding and impoundment (Conner *et al.*, 1989; Steyer *et al.*, 2010). Floating marshes are the most susceptible to deformation processes (Cahoon, 2006; Guntenspurgen *et al.*, 1995), whereas salt marshes rooted in mineral soils having high shear strengths are the most resilient wetlands to erosional storm impacts (Barras, 2006). Howes *et al.* (2010) reported that differences in wetland impacts by Hurricane Katrina could be explained by the composition and shear strength of soils. They documented that low-salinity marshes that incurred the most damage had shallow roots in soils that consisted of more organic material than mineral matter and exhibited a weak layer at the root base.

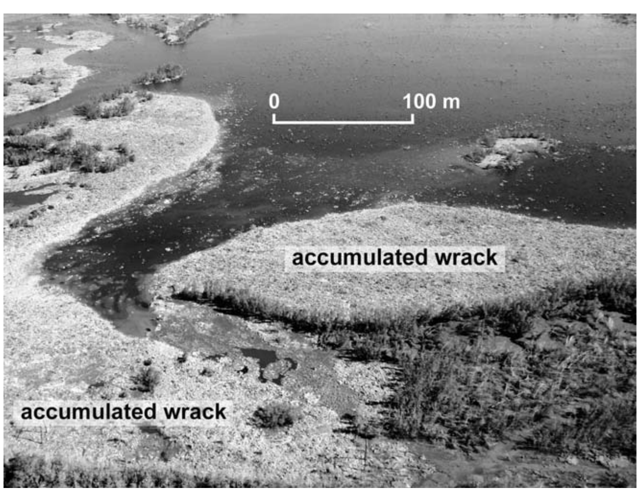

Figure 10. Extensive deposits of organic debris (wrack) concentrated and stranded by floodwaters of Hurricane Katrina (2005) in the eastern delta region.

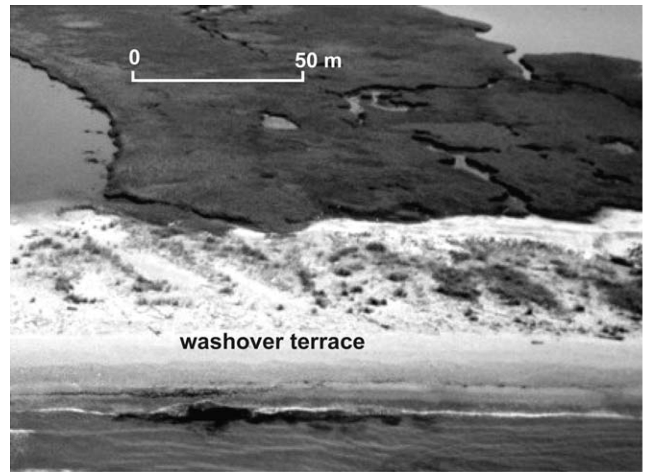

Figure 11. Washover terrace deposited on marsh vegetation of the central delta region by Hurricane Lili (2002).

The organic-to-mineral ratios of the soils seem to be more important than the salinity of the soil-pore water in determining storm-impact potential. For example, freshwater plants colonize the mineral-rich marsh soils of the Atchafalya and Wax Lake Deltas (Louisiana Department of Natural Resources, 2010). These subdelta marshes have been subjected to storm-surge flooding and high-wind velocities of Hurricanes Carmen, Andrew, Lili, and Rita, but none of those storms caused significant permanent impacts to the marsh surface even though storm-surge removal of floating and submerged aquatic vegetation within the subdeltas may have given the appearance of significant wetland loss. Minor long-term storm-induced pond formation has been observed in the organic fresh marshes located between the Wax Lake Outlet and the Atchafalya River (Barras, Bernier, and Morton, 2008); however, the number and size of storm-formed ponds increases immediately east and west of the Atchafalya River in the organic fresh and intermediate marshes where the formation and cumulative modification of surge-formed ponds can be traced over 70 years (J. A. Barras, unpublished data).

Man-Made Alterations

Human alterations of the marsh surface can affect hurricane impacts by disrupting and weakening the marsh soil, altering surface elevations, and providing preferred pathways for high-velocity flow. For example, the tracks of marsh vehicles used for geophysical surveys promoted pond formation by Hurricane Audrey (Harris and Chabreck, 1958). Other surface modifications, such as pipeline trenches (Figure 6) and dredged canals, locally increase surface roughness and reduce soil strength that enhances wetland erosion.

STORM-IMPACT FEATURES

Hurricanes commonly deposit sediments on the coastal platform and increase marsh elevations (Cahoon, 2006; Reed, Commagere, and Hester, 2009; Turner *et al.*, 2006), but they

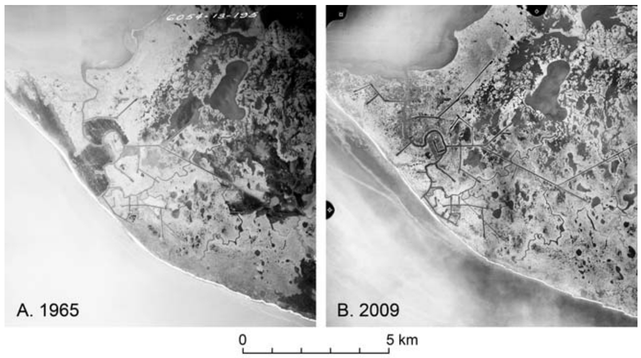

Figure 12. Preservation and expansion of storm-generated marsh morphological features at Point au Fer (A) 4 months after Hurricane Hilda (1964) and (B) in 2009. Preserved impacts include orthogonal-elongate ponds and amorphous ponds with marginal incisions, braided channels, and plucked marsh. Location shown in Figure 1.

can also erode the wetland landscape and locally lower elevations (Barras, 2007b; Barras *et al.*, 2010). The following destructive and constructive hurricane impacts identified in coastal Louisiana wetlands are presented in the order of highest- to lowest-impact severity and greatest to least preservation potential.

Erosional Signatures

The combined forces of hurricane winds and storm surge over the delta plain can strip off the aboveground marsh vegetation, undermine the plant roots, or completely remove the marsh mat (Barras, 2007b; Barras *et al.*, 2010). These erosional processes form the most prominent and lasting features produced by hurricanes in Louisiana wetlands.

Orthogonal-Elongate Ponds

Newly formed orthogonal-elongate ponds (Figure 3) are one of the most common storm-impact features that result in large-scale (km^2), nearly instantaneous wetland loss. They also have not been previously recognized. The ponds are referred to as elongate and orthogonal because they are relatively narrow compared to their overall length, and they are characterized by offsets approximately at right angles to the long-axis orientation. The long-axis orientations of the elongate ponds, which have predominant NW to NE components (Figure 3), seem to be influenced by both tidal-channel orientation and direction of wind-driven currents.

First-generation elongate ponds can be as small as a few m wide and a few tens of m long up to as large as 300 m wide and 4.0 km long with length-to-width ratios between five and 10. Elongate ponds form preferentially in marshes that (1) were already slightly lower than the surrounding landscape and (2) have relatively low mineral content, such as fresh, intermediate-brackish, and intermediate marshes (Barras, 2007b; Barras *et al.*, 2010). Some elongate ponds are legacy features that have retained their shape for more than 45 years after they formed (Figure 12).

Amorphous Ponds

Amorphous ponds have no preferred shapes or orientations (Figure 3), and they can form in all marsh types. In saline marshes, they are smaller than and not as prevalent as in brackish marshes (Barras, 2007b; Barras *et al.*, 2010). Amorphous ponds are constructed by marsh scour to depths below the water table, and they have maximum cross-pond dimensions between 15 m and 1.5 km. Irregular margins around the pond perimeter and dendritic incisions can give the ponds a starburst appearance, which is more common in intermediate to fresh marshes. Amorphous ponds are associated with, but are not as common as, elongate ponds because the high-velocity wind-driven currents that result in marsh removal tend to follow linear paths. Once formed, the amorphous ponds can retain their shape for more than 63 years (1947 hurricane and Figure 12), can be enlarged by subsequent erosion, or can merge with other storm-generated erosional features to form larger open-water bodies.

Pond Expansion

A common storm impact is expansion of preexisting wetland ponds by enlargement in width (Figure 4) and increases in depth (Harris and Chabreck, 1958). Enlargement includes erosion of a pond perimeter, removal of wetlands within a pond, and coalescing of adjacent ponds. Both perimeter and interior pond expansion can involve erosion of the pond banks (Figure 4) or compression of mats of floating vegetation (Figure 8). Enlargement is not uniform around a pond, and erosion typically occurs on a side that is impacted most by the direction of the wind-blown currents and waves if fetch is sufficient. For a given storm, pond expansion in salt and brackish marshes typically is less than expansion in intermediate to fresh marshes.

Pond expansion usually is reported as increased water area (Barras, 2003, 2007a, 2009; Barras *et al.*, 2010) because linear distances around the perimeter are variable but can be as much as 200 m for large, interior water bodies. Pond expansion is normally a permanent loss of wetlands that remains as a legacy of individual or cumulative storm impacts on the delta-plain surface.

Marginal Incised Drainage

Marginal incised-drainage patterns (Figures 3 and 4) are common secondary storm impacts associated with orthogonal-elongate ponds, amorphous ponds, and pond expansion. The dendritic drainage patterns form in response to headward channel erosion across an elevated scarp at the pond edge during floodwater recession. The resulting hydraulic head across the abrupt surface gradient and gravity-driven flow produce the energy for the pond-margin excavation as the water attempts to minimize the difference in elevation between the lower pond and higher marsh surface. Widths and depths of the incised-drainage channels decrease in an upstream direction toward their termination; channel lengths vary from about 5 to 350 m. Unless the drainage channels are obliterated by pond expansion, they can persist in their original state for decades.

Braided Channels

Braided channels represent the interconnection of closely spaced elongate channel segments with multiple "downstream" intersections (Figure 5). The braided pattern commonly occurs where runoff from storm-surge flooding was augmented by local topography, such as along levees, which can amplify surge heights and increase velocities of return flow. The largest storm-constructed braided channels observed in coastal Louisiana, which were 0.5 to 1 km wide and as much as 5 km long, formed when storm surge driven onto the artificially high levee of the Mississippi River by Hurricane Katrina flowed seaward toward upper Breton Sound (Figure 5). Braided channels tend to form in intermediate and intermediate to fresh marshes (Barras, 2007b; Barras *et al.*, 2010).

There may be a morphological continuum between large, closely spaced elongate ponds and braided channels where high-velocity return flow is confined. Because braided channels are large erosional features, both in size and depth of scour, they are permanent alterations to the landscape that can last decades.

Plucked Marsh

Plucked-marsh surfaces consist of numerous small, closely spaced, circular or irregular scours that are distributed over a wide area, resulting in a pockmarked appearance (Figures 3 and 6). These features are common in saline, brackish, and intermediate marshes where mineral matter represents a high percentage of the substrate (Barras, 2007b; Barras *et al.*, 2010). Selective marsh removal can be above or below the local water level. Most of the individual scours within a field of plucked-marsh features are not aligned; however, some plucked features that are spaced along linear pathways may be precursors of orthogonal-elongate ponds or artifacts of prior marsh disturbance, such as pipeline trenches (Figure 6) or marsh-vehicle tracks. Plucked-marsh scours that are nearly equidimensional range in diameter from about 2 to 20 m. The areas of plucked marsh are susceptible to further damage from later hurricanes, so their preservation depends on subsequent storm histories. Some fields of plucked marsh have been preserved for more than five decades (Hurricane Audrey features and Figure 12).

Denuded Marsh

Denuded marshes represent conversion of densely vegetated wetlands to mud flats. This landscape evolution occurs as a result of stripping of aboveground vegetation leaving only plant stubble and roots (Figure 7). Wetland scour is restricted to depths above the water table; otherwise, greater scour depths would result in pond formation. Widths of denuded marshes can range from 2 m to 13 km. One of the largest impact areas was in upper Breton Sound where Hurricane Katrina denuded most of the brackish-intermediate marsh (Barras, 2007b). These features generally do not recover if the root mat has been removed and result in very shallow ponds where the stripped area remains below the permanent submergence level. A few cm of erosion can be the difference between permanent wetland loss or recovery. If the root mat is not entirely destroyed and the area remains above the elevation of permanent submergence, denuded marshes can partly or completely recover in one growing season (Chabreck andPalmisano, 1973; Chamberlain, 1959). Denuded wetland sites are more common in intermediate, brackish, and salt marshes than in fresh marshes (Barras, 2007b; Barras *et al.*, 2010).

Floating-Marsh Redistribution

Redistribution of floating marsh (flotant) involves the relocation of buoyant, usually freshwater, aquatic vegetation (Guntenspergen *et al.*, 1995) by wind-driven currents (Figure 8). The removal or lateral displacement of floating vegetation, such as water-lily mats, can be ephemeral or permanent. Consecutive storm impacts result in a cumulative reshaping of storm-formed ponds within flotant marsh (Barras, 2007a). Examination of TM satellite imagery showed that a flotant-marsh area in western Terrebonne basin removed in 1992 by Hurricane Andrew's surge was reshaped by Hurricanes Lili (2002) and Rita (2005) and had not recovered by 2006 (Barras, 2007a).

Shoreline Erosion

Shoreline erosion is measurable retreat of the shore along the perimeter of a water body that has substantial fetch to storm waves. Waves breaking at the shore erode the marsh soil and roots, and currents transport the eroded sediments to less energetic sites of deposition. In coastal Louisiana, storms erode shorelines along the Gulf of Mexico, embayments, or lakes within the delta plain. Shoreline erosion can occur in any marsh type; however, magnitudes of erosion along the Gulf shore in saline marshes generally exceed those along the bay shores or interior water bodies surrounded by brackish, intermediate, or fresh marshes. Maximum Gulf shoreline erosion reported for different hurricanes ranged from 10 to 160 m (Table 2; Morgan, Nichols, and Wright, 1958; Penland *et al.*, 1989; Stone *et al.*, 1997). Shoreline erosion, which is quantified by comparing pre- and poststorm imagery, is almost always permanent, and the wetland area seldom recovers naturally.

Deformation Signatures

Deformed marsh features result from lateral compression or displacement of the marsh mat. These signatures are restricted in areal extent, so they contribute the least to the storm-generated land-water changes and net long-term landscape evolution. Compaction of wetland sediments as a result of surficial loading by storm-surge waters (Cahoon, 2006) is a minor form of deformation, but it is not observed or quantified on remotely sensed images. Therefore, storm-related wetland compaction is not included in our discussion of morphological impacts.

In-Situ Marsh Compression

Hurricane impacts include *in-situ* folding of marsh mats that form steep ridges and troughs with short wavelengths and moderate relief (Guntenspergen *et al.*, 1995; Figure 9A). Crests of the ridges are higher than the surrounding marsh elevation. The multiple folds are parallel to subparallel with each other and with the adjacent open-water body. The compression features, which occur predominantly in fresh marshes of the upper delta plain (Barras, 2007b; Barras *et al.*, 2010), can form on the margins or within open-water bodies, and they are commonly associated with the floating-marsh redistribution impact. Fold wavelengths are 2 to 5 m, whereas trough-to-crest heights are 0.5 to 1.5 m (Barras, 2003; Guntenspurgen *et al.*, 1995). The fold wavelengths and heights are related to the velocity of the storm surge and shear strength of the marsh mat (Cahoon, 2006). Considering the areal extents of most storm impacts, the compressed marshes are spectacular but local anomalies that are ephemeral disruptions to the landscape; they are not easily identified using either aerial photography or satellite imagery. Cahoon (2006) reported that the marsh folded by Hurricane Andrew had returned to the surrounding marsh elevation 2 years after the storm. This lowering of the surface elevation probably was a result of gravity-driven processes and fold relaxation.

Lateral-Marsh Displacement

Laterally displaced marsh mats (Figure 9B) and marsh balls are the end products of deep scour and erosion of brackish and fresh marshes. The relocated marsh can be in the form of tabular strips or disaggregated clumps. The strips of root mat tend to be relocated as a concentrated deposit, whereas the marsh balls tend to be disseminated over a broad area (Barras, 2007b; Barras *et al.*, 2010). Marsh mats are minor impact features that are not commonly reported. During Hurricane Andrew, rectangular and irregular slabs of marsh root mat 15–20 m long and 5–10 m wide were laterally transported and stranded both upright and overturned on the undisturbed marsh surface (Guntenspurgen *et al.*, 1995). Hurricane Lili produced marsh mats of comparable size (Figure 9B). Considering the extent of most hurricane wetland impacts, displaced marsh mats and balls are small-scale ephemeral features that do not significantly alter the landscape.

Deposition Signatures

Baumann, Day, and Miller (1984), Rejmanek, Sasser, and Peterson (1988), Reed (1989), Reed, Commagere, and Hester (2009), and Turner *et al.* (2006, 2007) recognized that storms are agents of wetland aggradation that supply sediments to coastal marshes. Their studies and those of others have demonstrated that storm sedimentation varies in composition, concentration, and distribution within the marshes.

Wrack Zones

Wrack zones (Figure 10) consist of broad bands of accumulated unattached organic debris and trash that are produced by wetland storm-surge erosion and transport. The wrack deposits typically are emplaced along topographic highs, such as natural levees, marsh remnants, and spoil banks of dredged canals (Barras, 2007b). An estimated 17 km^2 of wrack was deposited in upper Breton Sound after Hurricanes Gustav and Ike in 2008 (Barras *et al.*, 2010). Hurricanes strip the marsh of dead detritus and concentrate the debris as wrack-zone deposits. Bayous and canals act as conduits and temporary repositories for the large volume of organic debris and clumps of vegetation stripped out of the adjacent marshes (Harris and Chabreck, 1958; Meeder, 1987). Wrack deposits, which can be as much as 100 m wide and 1 m deep (Chamberlain, 1959), are mostly ephemeral features that eventually blend with the surrounding landscape as a result of decomposition of the organic components or growth of vegetation from seeds transported in the deposits.

Interior-Marsh Deposits

Inorganic sediments deposited during a storm are either dispersed throughout the marsh vegetation or are concentrated as blankets thick enough to bury the vegetation (Guntenspurgen *et al.*, 1995). Normally, the dispersed deposits are transported as sediments suspended in the floodwaters; the thickest deposits usually accumulate near the source, such as along the shore of a large body of water. Both types of deposits cause aggradation of the marsh surface.

Storms disperse mud deposits in interior wetlands (Cahoon *et al.*, 1995; Turner *et al.*, 2006), but they are not visible on poststorm images. Therefore, field investigations are necessary to document dispersed deposits and to distinguish relatively thick mud-blanket deposition from the denuded marsh impact that results from complete removal of the aboveground vegetation. Although the depositional impacts are permanent, the visible effects are not because vegetation will either grow through the dispersed deposits or will be reestablished on top of the thicker sediment blankets.

Shoreline Deposits

Perhaps the most frequently reported hurricane morphological impacts are the widespread shoreline deposits that result from the inland transport of sand and shell by storm overwash (Figure 11). This process and associated deposits occur along the shores that are overtopped and inundated by waves and storm surge. The deposits form washover fans and terraces parallel to the wetland shores of the Gulf of Mexico or shores of large embayments. Typical widths of washover deposits are 5 to 20 m along the embayment shores, whereas ranges of 20 to 150 m have been reported along the Gulf shore for extreme storms (Faulkner *et al.*, 2007; Morgan, Nichols, and Wright, 1958; Nyman, Crozier, and Delaune, 1995; Ritchie and Penland, 1988).

Thick washover deposits ($>$50 cm) can raise the land elevation above the zone of frequent inundation. Consequently, an overwashed former wetland near the shoreline can be colonized by nonmarsh vegetation and converted to an upland habitat (Courtemanche, Hester, and Mendelssohn, 1999). Marsh areas that were buried by the Hurricane Andrew overwash and completely barren had recovered up to 40% plant cover 2 years after the storm. The areas that experienced heavy sand loading also exhibited greater species diversity and percentage cover during the recovery period compared to the lower marshes (Courtemanche, Hester, and Mendelssohn, 1999). Hurricane shoreline deposits are permanent additions to the landscape, but they are not preserved where the shores are eroding.

Shoreline deposits have slightly higher elevations than the surrounding marsh so they also have slightly greater preservation potential. For example, the shorelines of orthogonal ponds formed by Hurricane Betsy (1965) were all that remained of marsh removed by Hurricane Katrina (2005) (Barras, 2006). Shoreline remnants of former ponds are commonly the only vegetated areas remaining in some denuded marshes.

Surficial Wetland Alterations

Some physical and chemical wetland storm impacts do not involve erosion, deformation, or deposition. The impacts related to other processes typically involve prolonged retention of storm-surge water on the wetland surface and adverse physiochemical plant reactions to water logging and salinization.

Levee Breaks and Water Impoundments

Many water-control impoundments have been constructed in the marshes of coastal Louisiana to expand the rangeland for cattle grazing and to increase the habitat area available for waterfowl and other wildlife. The marsh-management weirs, levee impoundments, and lined banks of dredged access canals can impede poststorm drainage of the marsh (Meeder, 1987; Morgan, Nichols, and Wright, 1958) and water can be retained for as much as 6 months (Shiflet, 1963). Impounded marshes in the chenier plain region remained flooded for over 9 months after Hurricane Rita (Barras, 2007b).

Water logging is a result of prolonged poststorm flooding, low elevation, and poor surface drainage. Some water impoundment is associated with overtopping of artificial levees and entrapment within the water-control area. Conner *et al.* (1989) concluded that impounded marshes experienced more severe and permanent damage attributable to the ponding of saline floodwaters compared to natural, free-draining marshes. The impoundment levees can fail as a result of excessive hydrostatic pressure associated with higher water levels surrounding the impoundments during storm-surge flooding. Longevity of the storm-flooded impoundments depends on the severity of the impact and subsequent measures to restore favorable wetland conditions. Some storm-flooded impoundments take several years before prestorm conditions are reestablished (Ensminger and Nichols, 1957; Shiflet, 1963). Penland *et al.* (2000) identified areas of permanent wetland loss in the Mississippi delta plain that they attributed to water logging and failed impoundments that may have been caused by hurricane impacts.

Marsh Salinization

Widespread physiological stress and dieback of marsh vegetation can occur suddenly during storms as a result of saltwater flooding and intolerance of marsh plants to a rapid increase in plant surface and soil salinity. Marsh salinization, also referred to as salt burning (Guntenspurgen *et al.*, 1995), is greatest in fresh and intermediate marshes where the salinity difference is greatest and the plants are less tolerant to high concentrations of salt in the soil-pore water. Inundation of fresh marshes by storm-driven seawater tends to damage or kill the aboveground vegetation that remains in place. Saltwater burning of wetland vegetation typically is an ephemeral impact that may last only one or two growing seasons (Guntenspurgen *et al.*, 1995) or persist for more than 2 years after storm impact (Steyer *et al.*, 2010).

HURRICANE ATTRIBUTES AND WETLAND IMPACTS

Hurricane wetland impacts in coastal Louisiana occur within a swath that roughly parallels the storm path and corridor of strongest winds. Although the wetland impacts are spatially restricted for any given hurricane, they can cover a broad area depending on the path of the storm and its physical attributes. The high frequency of hurricanes traversing the northern Gulf of Mexico and their random spatial distribution through time ensure that all regions of the Louisiana coastal wetlands have been impacted repeatedly by historical storms (Figure 2). The following accounts summarize the significant wetland impacts of mostly Category 3 and greater hurricanes since 1957, which is the period for which coastal wide high-resolution poststorm imagery is available. To facilitate discussion, the area of investigation was subdivided into four geographic regions: (1) Lake Pontchartrain shores, (2) eastern delta plain, (3) central delta plain, and (4) western chenier plain (Figure 1).

Hurricane Audrey (1957)

Hurricane Audrey was a strong Category 4 storm that accelerated just before it was onshore, impacting wetlands of the western and central regions of coastal Louisiana (Figure 2). Storm waters associated with Audrey penetrated inland as much as 40 km and flow depths exceeded 3 m near the shore (Landreneau and Shamburger, 2007). The period of maximum coastal flooding near landfall, which lasted about 10 hours, occurred after the initial period of high-wind stress and before passage of the storm center (Ross and Blum, 1957). As the storm crossed the coast, winds shifted from the E to the SE and then to the SW, or directly onshore. The flooded wetlands experienced maximum wind gusts of at least 160 kph that extended as much as 70 km east of the storm center; wind speeds exceeding 120 kph lasted approximately 8 hrs (Landreneau and Shamburger, 2007). Total impact duration was about 16 hours (Table 2).

Audrey scoured multiple orthogonal-elongate ponds and increased the depths and sizes of ponds (Harris and Chabreck, 1958). Marshes stripped of vegetation were revegetated during the next growing season, 1 year after the storm (Chamberlain, 1959). Clumps of *Spartina patens* mat were excavated from a brackish marsh and transported inland as much as 8 km to a fresh marsh in the chenier plain (Chamberlain, 1959), and beaches along the Gulf shore of the chenier plain retreated 60 to 90 m (Morgan, Nichols, and Wright, 1958).

In the western chenier plain, wrack accumulations approximately 100 m wide and 1 m deep were deposited against tall marsh plants; interior marshes received 8 to 10 cm of mud; and two arc-shaped wedges of mud about 1 m thick, 300 m wide, and 3.5 km long were deposited along the shore (Chamberlain, 1959). Lateral encroachment of salt-marsh vegetation had covered approximately 50% of the mud deposits 14 months after the storm (Chamberlain, 1959). Sources of the fine-grained sediments were nearshore mudflats supplied by the Atchafalaya River. Sandy washover deposits extended inland 30 to 150 m along the Gulf shore (Morgan, Nichols, and Wright, 1958) and 10 to 15 m into wetlands along the shore of East Cote Blanche Bay.

Saline waters flooded an impounded fresh marsh at Grand Chenier, killing the vegetation and promoting a complete change in vegetative cover (Ensminger and Nichols, 1957; Shiflet, 1963). More salt-tolerant plant assemblages and lowered productivity lasted 4 years before plant composition and soil salinities returned to prestorm conditions.

Hurricane Hilda (1964)

Information regarding the physical attributes of Hurricane Hilda and the magnitudes and durations of coastal flooding in the Mississippi Delta is limited. Although Hilda weakened to a Category 2 storm just before it crossed the central delta-plain region (Figure 2), it remained a damaging storm with respect to coastal wetlands. Maximum wind speeds and flow depths across the marsh near landfall were about 215 kph and 2.5 m, respectively (Dunn and Staff, 1965).

Many of the erosional and depositional impacts that were formed during the 24-h-impact period were present 4 months after Hurricane Hilda (Figure 3). The storm-impact features included multiple orthogonal-elongate ponds and amorphous ponds with marginal incised drainage, braided channels, plucked marsh, and sandy washover terraces. Most of the erosional morphological features formed by Hurricane Hilda were still present more than 45 years after the storm (Figure 12).

Hurricane Andrew (1992)

Hurricane Andrew was a Category 5 storm that inflicted severe damage on the SE coast of Florida before crossing the Gulf of Mexico and making a second landfall in Louisiana (Figure 2) as a strong Category 3 storm. At landfall, Andrew had maximum sustained wind speeds of about 195 kph (Rappaport, 1994), and wind speeds of approximately 180 kph extended about 100 km away from the eye, encompassing much of the central delta region. Maximum flow depths of 1.7 m and 2.3 m were recorded in marshes of the central delta region, and flow depths of more than 1 m were recorded 175 km east of the storm center (Grymes and Stone, 1995; Guntenspurgen *et al.*, 1995). In contrast, west of the storm path water levels were depressed as much as 1 m, owing to the strong offshore-directed wind and low astronomical tide. Near the storm path, water levels initially were below normal, but they increased as the storm moved onshore so that the peak surge coincided with the high astronomical tide (Grymes and Stone, 1995).

During its 21-h-impact period (Table 2), Hurricane Andrew formed elongate ponds, excavated floating marshes, removed the upper surface of marshes, and compressed marshes in the central delta region (Barras, 2007b; Cahoon, 2006; Guntenspurgen *et al.*, 1995). Although the continental shelf dissipated much of the wave energy of Andrew, wetland erosion, overwash, and breaching were extensive along the Gulf shore (Stone, Xu, and Zhang, 1995). Beach erosion generally ranged from 60 to 100 m. The storm also dislocated large intact sections of marsh about 30 km east of the storm path (Guntenspurgen *et al.*, 1995).

Hurricane Andrew deposited thick accumulations of wrack in the marshes, which slowed plant recovery near Atchafalaya Bay (Guntenspurgen *et al.*, 1995) and extensive blankets of sand and mud (Courtemanche, Hester, and Mendelssohn, 1999; Guntenspurgen *et al.*, 1995; Nyman, Crozier, and Delaune, 1995). Deposit thicknesses ranged from 3 to 9 cm and averaged 3.9 cm in *Spartina alterniflora* marshes, but 6.6 cm in *Juncus roemelanus* stands owing to their greater stem density. Cahoon *et al.* (1995) measured as much as 6 cm of silt deposited at several sites in the delta plain. At some marsh locations near Atchafalaya Bay, the mud blanket was so thick (10–16 cm) that it buried the prestorm vegetation and constructed a bare mud surface (Guntenspurgen *et al.*, 1995). Hurricane Andrew washover deposits were as much as 100 cm thick (Courtemanche, Hester, and Mendelssohn, 1999) and extended inland from the shore as much as 50 m (Nyman, Crozier, and Delaune, 1995). Marsh salinization occurred in intermediate and fresh marshes around Atchafalaya Bay; however, signs of recovery were reported 6 months after the storm. Post-Andrew recovery of the marshes occurred within a year for all of the impact categories except for the areas stripped of vegetation or where thick accumulations of wrack were deposited (Guntenspurgen *et al.*, 1995). Monitoring of marsh elevation by Cahoon (2006) showed that the compressed marshes returned to their prestorm elevation 2 years after the storm.

Tropical Storm Isidore and Hurricane Lili (2002)

In 2002, both Tropical Storm Isidore and Hurricane Lili crossed the central delta region (Figure 2). Although neither storm was a Category 3 event at landfall, they demonstrated that even low-intensity storms are capable of modifying the landscape and leaving imprints that influence future storm impacts and marsh evolution.

Hurricane Isidore was a Category 4 storm that weakened after multiple Caribbean landfalls and was downgraded to a tropical storm before it crossed the coast (Figure 2). At landfall, Isidore recorded sustained winds of 100 kph and associated interior flow depths of approximately 2.0 m (Avila, 2002). Seven days later while some areas of the delta plain were still flooded from Isidore, Hurricane Lili, a Category 1 storm, crossed the central region with an estimated maximum wind speed of 148 kph. Flow depths associated with Lili near landfall and east of the storm center were about 1.5 m (Lawrence, 2003). The wetland impacts of Lili lasted about 17 hours (Table 2).

A systematic analysis of wetland impacts from Tropical Storm Isidore was not conducted, but examination of poststorm images showed that onshore-directed wind-driven currents from Breton Sound caused extensive deformation of marshes (Barras, 2007b). The morphological wetland impacts of Hurricane Lili were concentrated in the right-front quadrant of the hurricane where it crossed the coast (Figure 2). Lili formed orthogonal-elongate ponds, expanded preexisting ponds, and plucked marsh (Barras, 2007b). Depths of the newly formed ponds ranged from 0.5 to 1.3 m (Barras, 2003). Lili also caused extensive fresh-marsh deformation including *in-situ* compression of the marsh surface and lateral displacement of large marsh mats as much as 1 m thick (Barras, 2003; Cahoon, 2006). Lili eroded the beach as much as 70 m and deposited washover fans about 50 m wide along the barrier islands of the central delta region (Stone *et al.*, 2003). In the same general area, Hurricane Lili modified and reactivated some of the morphological features constructed by Hurricane Andrew and formed new orthogonal ponds adjacent to similar ponds formed by Hurricane Audrey 45 years earlier.

Hurricane Katrina (2005)

Hurricane Katrina was one of the most memorable storms to strike the Louisiana coast because it caused such widespread destruction and deep flooding. Katrina was an intense former Category 5 storm that lost strength and weakened to a strong Category 3 storm just before landfall (Figure 2). As with other extreme hurricanes, many of the maximum wind speeds and water levels were not recorded because the instruments failed. Katrina had a large radius of maximum winds that extended the storm impacts over the entire eastern delta region, and wind speeds comparable to those at initial landfall (200 kph) were estimated along Katrina's path as it crossed the coast near the Mississippi–Louisiana border (Knabb, Rhome, and Brown, 2006b). Large water-level gradients were recorded across the impacted area as a result of Katrina's path relative to open water and land elevations. Some of the highest flow depths (3.7 to 5.3 m) in the eastern delta region occurred between upper Breton Sound and the Mississippi River, where the storm surge was blocked by the high artificial levees. Even west of the storm center, flow depths were abnormally high, such as 3.7 m at Grand Isle and 2.4 m at Fourchon (Knabb, Rhome, and Brown, 2006b). Because Katrina was so large and traversed a broad extent of wetlands, its impacts lasted about 21 hours (Table 2).

Hurricane Katrina produced all of the erosional, deformational, and depositional storm-impact features within the eastern delta region and Lake Ponchartrain shores. Katrina formed elongate ponds and amorphous ponds, expanded ponds, constructed braided channels (Figure 5), denuded marshes, plucked marshes (Figure 6), excavated flotant, eroded shorelines, deformed floating marshes (Figure 8), and formed marsh balls (Barras, 2007b). Katrina also deposited mud (Turner *et al.*, 2006), organic detritus (Reed, Commagere, and Hester, 2009), and bands of wrack (Figure 10) in the interior marshes of the eastern delta region. The Chandeleur Islands were breached in many places and beach erosion generally exceeded 50 m. Some segments of the barrier-island chain were destroyed (Barras, 2007b). The cumulative impacts of Katrina increased the water area in coastal Louisiana by 230 km^2 (Barras, 2007a).

Hurricane Rita (2005)

Hurricane Rita was the second extreme storm of the 2005 season to impact coastal wetlands in Louisiana. Making landfall approximately 1 month after Hurricane Katrina, Rita crossed the coast in the western chenier plain (Figure 2). Rita was a Category 5 storm that weakened to Category 3 before landfall. Maximum sustained winds near the storm center at landfall were about 200 kph, and wind speeds of 55 kph extended more than 200 km east of the storm's center (Knabb, Brown, and Rhome, 2006a). Rita produced a high storm surge that flooded the chenier-plain wetlands as much as 25 km inland (Knabb, Brown, and Rhome, 2006a). Flow depths across the chenier plain were up to 4 m, although most of the marshes experienced flow depths of 1 to 2 m (McGee, Tollett, and Goree, 2007).

The impacts of Rita on coastal wetlands lasted about 16 hours (Table 2). Morphological wetland changes in the central delta plain and chenier plain included expanded ponds, braided channels, excavated flotant, denuded marshes, deformed marshes, and deposited marsh balls (Barras, 2007b). Rita deposited a washover terrace 10 to 12 m wide and parallel to the Gulf shoreline (Guidroz, Stone, and Dartez, 2006). Average thickness of the washover deposit was 25 cm (Faulkner *et al.*, 2007) where maximum flow depth was about 4.0 m. Inorganic-sediment deposition associated with Hurricane Rita extended inland from the shore 6 to 8 km in the chenier plain, and the sand-to-clay ratio decreased in a landward direction (Steyer, 2008). Rita also deposited bands of organic wrack in the central delta and western chenier-plain regions (Barras, 2007b) and reactivated some of the deformed marshes that were initially deformed by Hurricane Lili. All together Rita impacts increased the water area in the chenier plain by 295 km^2 (Barras, 2007a).

Neyland (2007) compared a fresh marsh in the chenier plain 3 months before and 9 months after Hurricane Rita and discovered that the marsh had been killed by saline water. After investigating the combined impacts of Hurricanes Katrina and Rita on marshes in Louisiana, Steyer *et al.* (2010) reported a complex poststorm landscape response depending on the type of marsh and the type of impact. In the eastern delta-plain region, where marsh impacts primarily involved physical removal, there was a substantial recovery of vegetation cover, but a shift in plant communities as different species colonized the disturbed fresh and intermediate marshes. In the chenier-plain region, where impacts involved both physical disturbance and prolonged saltwater flooding, marsh pore-water salinities remained high, there was low vegetation recovery, and vegetation changes were toward more salt-tolerant species. Two growing seasons after the storms there were substantial overall increases in vegetation cover in brackish and fresh marshes although recovery to prehurricane conditions was incomplete (Steyer *et al.*, 2010).

Hurricane Gustav (2008)

Hurricane Gustav briefly reached Category 4 strength, but the storm weakened as it crossed Cuba and entered the Gulf of Mexico. Gustav was a fast moving Category 2 hurricane with maximum winds of 170 kph (Brown *et al.*, 2010) when it made landfall in the central delta region (Figure 1). Maximum flow depths across the delta-plain marshes, which ranged from 1.0 to 3.4 m, corresponded to the lowest barometric pressure

(McGee *et al.*, 2008). The low angle of Gustav's track relative to the Louisiana coastline caused hurricane-force winds to extend completely across the central and eastern delta regions.

The most significant wetland changes caused during the 11-h-impact period of Gustav (Table 2) were the reactivation of some scour ponds formed by Katrina and removal of ephemeral aquatic vegetation in the fresh-intermediate transition areas that had partly recovered from Katrina. In addition, Gustav eroded elongate ponds, expanded preexisting ponds, and deposited wrack along topographically high features (Barras *et al.*, 2010). Gustav impacts along the barrier islands of the eastern and central delta regions included barrier breaching, beach erosion as much as 160 m, and deposition of washover terraces as much as 150 m wide. Gustav's wetland impact features in the eastern delta region were smaller than those formed by Katrina, and they likely would have been larger if Hurricane Katrina had not heavily impacted that same area in 2005 (Barras, 2009).

Hurricane Ike (2008)

Hurricane Ike was another former Category 4 event that weakened after passing over Cuba and entering the Gulf of Mexico. Although Ike made landfall on the upper Texas coast as a strong Category 2 hurricane, its impacts extended into the western chenier plain of Louisiana because its unusually large field of hurricane-force winds extended up to 195 km from the storm center. Maximum surface winds recorded in Louisiana were 140 kph (Brown *et al.*, 2010). Considering its intensity category, Ike also generated an exceptionally high-storm surge. Flow depths across the chenier-plain wetlands decreased eastward from 4.2 m near the Texas–Louisiana border to 1.5 m near Vermillion Bay (East, Turco, and Mason, 2008).

Hurricane Ike formed new marsh ponds, enlarged preexisting ponds, denuded marshes, removed aquatic vegetation from floating marshes, and accumulated extensive deposits of wrack (Barras *et al.*, 2010). Ike caused beach erosion of 10 to 45 m along the chenier plain, whereas washover deposition extended 150–230 m into the adjacent wetlands. Some areas of the chenier plain flooded by Hurricane Ike had been flooded about 2 weeks earlier by Hurricane Gustav. During the 21-h-impact period of Ike (Table 2), water area in the chenier plain increased about 199 km^2 (Barras *et al.*, 2010).

DISCUSSION AND CONCLUSIONS

Most of the morphological wetland impacts (Table 1) are formed by each extreme storm. The most substantive morphological impacts in terms of areal extent and persistence are the newly formed ponds and expanded ponds that account for hundreds of km^2 of open water that do not recover. Unlike the erosional wetland impacts of extreme storms that persist indefinitely, the deformational and depositional impacts are eventually obscured by poststorm colonization of marsh plants. Our systematic analyses of multiple events demonstrate that many of the storm-generated geomorphic changes remain as legacies and some historical storm impacts still can be identified nearly a half-century later (Figure 12). The largest erosional features (elongate and amorphous ponds) have

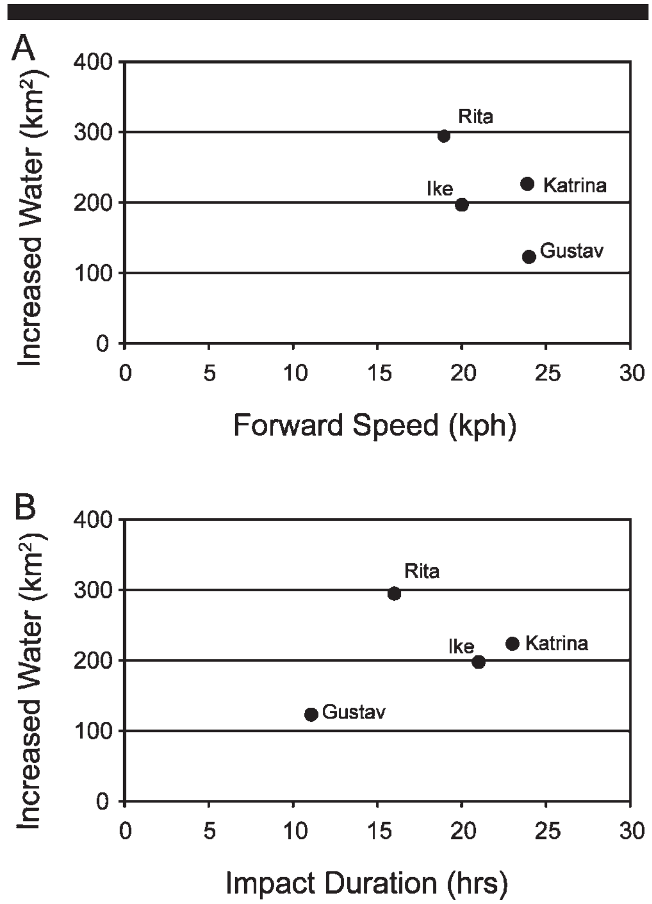

Figure 13. Plots of increased water area (wetland loss) caused by hurricane impacts in coastal Louisiana versus foward speed (A) and impact duration (B) of Hurricanes Katrina, Rita, Gustav, and Ike. Data are presented in Table 2.

diagnostic characteristics that are preserved in the landscape and can be used to identify previous storm impacts. Multiple generations of storm-impact features are preserved at many wetland locations, and the ancestral storm impacts influence subsequent wetland changes by creating permanent open water. An example is at Point au Fer (Figure 12) where impacts of Hurricane Hilda (1964) were later modified and amplified by Hurricane Andrew (1992), and again by Hurricane Lili (2002).

Particularly damaging to the wetlands are the back-to-back impacts produced by dual same-season storms, such as Tropical Storm Isidore and Hurricane Lili (2002). The combined impacts of Hurricanes Katrina and Rita (2005) increased water area in coastal Louisiana wetlands by more than 525 km^2, while Hurricanes Gustav and Ike (2008) increased water area nearly 325 km^2 (Barras *et al.*, 2010). Between 1956 and 2008, the increase in water area primarily occurred within a few hours because of storm impacts.

Although only four hurricane impacts have been analyzed quantitatively (Katrina, Rita, Gustav, Ike), the data (Table 2) indicate that there are direct correlations between increased water area (wetland loss) and (1) impact duration (Figure 13),

(2) maximum flow depth, (3) maximum wind speed, and (4) hurricane-wind diameter. In contrast, there is an inverse correlation between increased water area and forward speed of a storm (Figure 13). In general, a slow moving, relatively small hurricane that encounters a broad swath of wetlands along its path in the delta region like Hurricane Hilda (Table 2) is likely to cause similar wetland losses as a fast moving, relatively large storm that crosses a narrow band of wetlands in the western chenier-plain region, such as Hurricane Audrey. The calculations indicate that wetland-impact durations (Table 2) depend more on forward speed and storm size than on the distance of wetlands over which the storm passes.

Hurricanes in the northern Gulf of Mexico typically weaken prior to landfall but the high wind speeds, deep-water waves, and storm surges generated at their peak intensities amplify coastal flooding and accentuate the wetland impacts that are produced after landfall. Also, the peak wind speed and maximum storm surge may not occur simultaneously at a particular location in the marsh. However, wind-shear stresses must exceed shear stresses generated by winter storms in order to generate the destructive morphological changes.

Storm-related erosion is the predominant natural process by which wetlands deteriorate as they become progressively more exposed to ocean waves and storm surges during the destructive phase of long-term delta-lobe evolution. Storm erosional impacts are enhanced by a relative rise in sea level that shifts the zone of storm-induced wetland loss progressively farther inland. Some erosional features are manifestations of rapid water-level fluctuations associated with drawdown and surge under the influence of changing hurricane wind directions during approach and after landfall when the wetland surface is flooded. Formation of the erosional features likely involves wind stress, microstructure of the hurricane wind field (Ellis and Businger, 2010; Lorsolo *et al.*, 2008), and coupling of high-speed winds with shallow water across the wetland surface.

Comparing the shapes and sizes of erosional wetland-loss areas formed by short-term (hours to days) hurricane impacts (Table 1) with wetland-loss areas attributed to long-term (decadal) subsidence and erosion (Barras, Bernier, and Morton, 2008; Morton *et al.,* 2005) provides a basis for distinguishing between the different temporal and spatial scales of land-water change. In general, erosional storm-impact features have distinct shapes and spatial distributions, depending on storm-landfall location. They occur in both stable and degraded wetlands and are generally smaller than the broad areas of marsh converted to open water by subsidence and erosion. Furthermore, long-term marsh degradation typically results in either large open-water areas or fragmented marsh where the areas of water exceed the areas of broken marsh that are remnants because of their elevations above the surrounding water. However, cumulative storm-impact features can eventually resemble areas of long-term degrading wetlands when the wetlands are in advanced stages of deterioration.

The duration of erosional-wetland features generated by a single storm (Figure 12), the cumulative wetland impacts of successive storms (Barras, 2007a, 2009; Barras *et al.*, 2010), and the accelerated wetland losses observed after recent storms (Barras, 2006, 2009) together indicate that the Mississippi River delta plain and adjacent chenier plain are in a period of episodic degradation. The oldest topographic maps and aerial photographs indicate that before the early 20th century, the delta and chenier-plain wetlands were mostly continuous masses of vegetative cover with rounded ponds and meandering channels of different scales. United States Geological Survey topographic maps in the 1930s show that: (1) storm-generated ponds eroded in delta-plain marshes were restricted to the lowest marshes within about 25 km of the shore, and (2) marshes of the chenier plain exhibited fewer storm-generated features than marshes in the delta plain. Unlike the delta plain, the chenier plain is characterized by thin (<1 m) mixed organic- and mineral-marsh soils, sandy beach ridges with higher elevations (3 m) within the marsh, and a thin (<6 m) section of Holocene sediments overlying stiff Pleistocene muds (Gould and McFarlan, 1959). All three of these factors likely contributed to the earlier lower density of storm-impact features in the chenier plain by increasing the shear strengths of the marsh soils, reducing the fetch of open water during a storm surge, and reducing the natural long-term rates of wetland subsidence. Since the 1930s, the zone of high-density storm-impact features has migrated inland in both the delta plain and the chenier plain as a result of rapid land-surface subsidence, the cumulative marsh impacts of several extreme storms, and the absence of natural marsh-rebuilding processes.

Comparing wetland storm impacts of coastal Louisiana with those reported elsewhere shows some important similarities and differences in wetland responses to storm inundation. For example, the Louisiana marshes are more susceptible to a broad range of erosional and deformational storm impacts. The greater susceptibility of Louisiana marshes to wave and wind-driven currents is partly due to thick organic-rich soils that cover much of the area that have low shear strengths (Howes *et al.*, 2010). The marshes also have low elevations (Louisiana Department of Natural Resources, 2010) because of the low tidal range (<0.5 m). Beach erosion and deposition of overwash sediments along marsh shorelines, deposition of fine-grained sediments in marsh interiors, and deposition of wrack over the marsh surface are globally ubiquitous storm impacts that have been reported elsewhere, including the eastern Gulf of Mexico (Horton, Rossi, and Hawkes, 2009), the Atlantic coast of the United States (Donnelly *et al.*, 2001), Ireland (Wheeler, Orford, and Dardis, 1999), and China (Yang *et al.*, 2003). However, eroded elongate ponds, plucked marshes, or displaced mats, which are common hurricane impacts in the Mississippi delta, have not been reported for coastal settings where the marsh soils contain a high percentage of minerals and the marshes are elevated because the tidal ranges are typically greater than 1 m. Furthermore, the high-wind velocities and coherent structures (streaks and rolls) that are present in surface winds of hurricanes (Ellis and Businger, 2010; Lorsolo *et al.*, 2008), which are likely responsible for the wetland features in coastal Louisiana, may not be present in the extratropical storms that impact marshes in the northeastern United States or western Europe.

Before the early 20th century, land-building processes of the Mississippi fluvial-deltaic system provided sufficient sediment supply and nutrients for partial or complete self-healing of the coastal wetlands after extreme-storm impacts, a capability that no longer exists. Future natural wetland losses in southern Louisiana will likely result from storm impacts in the context of losses associated with long-term coastal-plain submergence and saltwater intrusion. The cumulative wetland losses will likely lead to greater wetland vulnerability and probably periods of storm-induced accelerated wetland losses. The episodic wetland losses will depend on extreme-storm frequency, landfall intensity, and landfall location; therefore, the rates and locations of storm-generated wetland losses will be difficult to predict. Rapid prelandfall deployment of instruments in forecasted wetland-impact areas will provide improved measurements of the timing and magnitude of hurricane processes, which will lead to improved prediction in the future.

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