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# Overview and Significance of Hurricanes on the Louisiana Coast, U.S.A.

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## ABSTRACT

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Hurricanes have played a critical role in the transgressive evolution of Louisiana's barrier islands and may account for up to 90% of shoreline retreat measured within the historic ($10^2$ years) time frame. Since 1901, some 55 tropical storms or hurricanes have made landfall along the Louisiana coast showing the highest incidence in September. Fewest landfalls have been recorded along the eastern region of Louisiana with the incidence being double that along the southcentral and southwest regions of the State. Approximately half the total number of tropical cyclone landfalls occurred in a thirty year period between 1931 and 1960, bounded by two of the 'quietist' decades of the past one hundred years; 1921–1930 with two direct landfalls, and 1961–1970 with two landfalls. Review of intensities of storms making landfall along the U.S. mainland through 1992 shows that 11 of the 50 strongest storms have impacted Louisiana. Given that the foredune elevation along the Louisiana coast seldom exceeds 2m above sea level, the significance of overwash processes and inlet breaching becomes readily apparent. Episodic landward translation of the beach of near 100 m is typical during stronger hurricanes. Post-storm recovery of the barrier islands has been thwarted by a reduction of sediment supplied to the littoral zone over time, subsidence, rapid relative sea-level rise and anthropogenic activity. Consequently, Louisiana's barrier islands are predisposed towards chronic erosion and land loss. Although hurricanes have proven destructive along the open coast, they have resulted in considerable deposition on portions of Louisiana's marshes. Examples include over 70 cm of mixed organic and inorganic debris accumulating after Hurricane Audrey (1957) and up to 16 cm of vertical accretion after Hurricane Andrew (1992). However, ongoing work suggests that substrate compression during storm passage may significantly reduce, or nullify, the effect of storm deposition on the marshes' long-term net elevation gain. Areas of floating marsh undergo considerable damage during severe hurricanes. Predictions of future wave and storm surge accompanying severe hurricanes (category 5) indicate that significant waves heights between 1 and 2 m can be anticipated as far inland as New Orleans. A gradual landward shift of larger waves is predicted with time due to the disappearance of barrier islands and coastal retreat. Wave heights up to 4 m are predicted in Lake Ponchartrain, located immediately north of New Orleans, for a category 5 hurricane making landfall along the Isles Dernieres. On considering that modeled surge levels increase from around 4 m to 7 m along the lake's northern shore, a hurricane of this magnitude will likely cause severe destruction and evacuation problems for the City of New Orleans and surrounding metropolitan areas.

**ADDITIONAL INDEX WORDS:** *Hurricanes, Hurricane Andrew, Louisiana, storm surge, overwash, beach erosion, numerical modeling.*

## INTRODUCTION

Historically, hurricanes have played a significant role in the morphology of barrier islands around the Louisiana coast (Figure 1), accounting for perhaps as much as 90% of shoreline retreat (KAHN, 1980). Several workers have studied hurricane impacts on the Louisiana coast, as well as the dynamics and timing of post-hurricane coastal recovery. A summary of this research, and a brief historical overview of hurricanes which have significantly impacted Louisiana, are presented in this paper. A review of the impacts of the most recent hurricane (Andrew) to have significantly impacted the barrier islands and marshes of Louisiana is also provided in addition to numerically-derived wave climate predictions along the coast and inland to New Orleans for a severe hurricane scenario.

## A BRIEF HISTORY OF HURRICANE IMPACTS IN LOUISIANA

Hurricanes strike the Louisiana coast approximately once every three years (NEUMANN *et al.,* 1993), normally between May and November. As shown in Table 1, among the earliest records of hurricanes impacting the Louisiana coast date back to September 1722 when a hurricane impacted New Orleans. Since that time, some thirty five hurricanes have had

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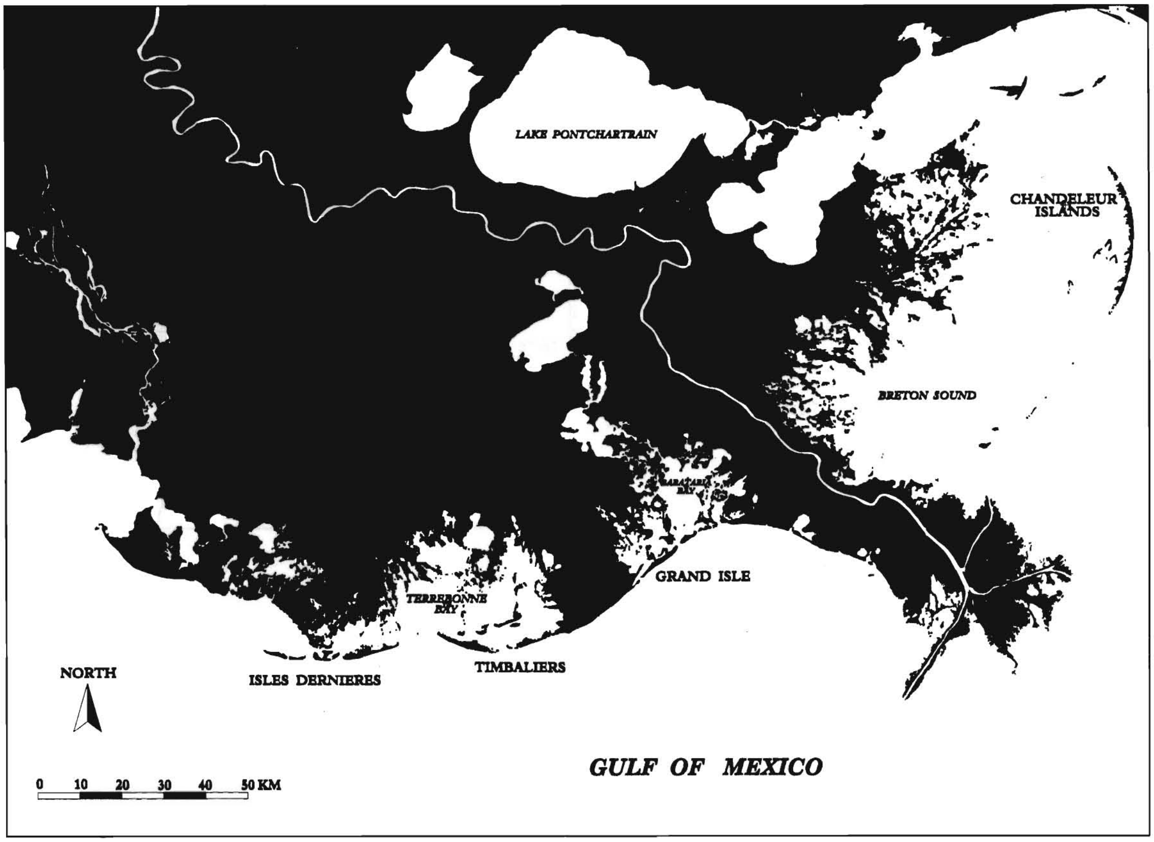

Figure 1. Map showing the distribution of barrier islands along the Louisiana coast.

significant morphological impacts along the Louisiana coast (Table 1). It should be noted that the latter value represents the number of hurricanes that have significantly impacted the morphology of the coast and is not a representation of the total number of systems to have made landfall within the state. The tracks of hurricanes, tropical storms and tropical depressions making landfall along or very near the Louisiana coast are presented in Figure 2 at decadal intervals beginning in 1901 (GRYMES, *in preparation*). These data are further summarized in Figure 3 by sub-dividing the Louisiana coastal zone into four landfall regions, with each region extending approximately 160 km. Figure 3 presents the number and seasonal distribution of hurricane and tropical storm landfalls along the coastal zone for the period 1901–1996 (GRYMES, *in preparation*).

Figures 2 and 3 demonstrate that Louisiana has been regularly affected by tropical weather throughout the Twentieth Century. These data indicate at least 55 landfalls by storms of tropical-storm or hurricane strength since 1901—a long-term average of at least one tropical storm or hurricane every other year. Landfall frequencies along the Louisiana coast through the past 100 years show a peak in activity during September, a pattern which reflects storm activity for the Gulf of Mexico and the Atlantic basin as a whole. Records over the past century indicate that 60% of all tropical cyclones making landfall in Louisiana have done so in August or September, with that number rising to 80% when considering hurricanes alone. Furthermore, while the total numbers of landfalling hurricanes and tropical storms since 1901 are similar (25 and 30, respectively), landfalls during these two months are dominated by hurricanes.

From a regional perspective, the eastern region of the Louisiana coastal zone, extending along an essentially south-to-north line east of the Mississippi River outlet, has experienced the fewest landfalls. This is not surprising, as a landfall in this region requires a storm to be moving along an east-to-west path. However, an historical review of tropical systems in the Gulf of Mexico indicates that the majority of these storms display a strong south-to-north component in their tracks at this latitude, with many of these storm tracks already showing a northeasterly motion, reflecting storm responses to mid-latitudinal atmospheric circulation features. It is also noteworthy that through the 1900s, the eastern region has experienced landfalls only during August and September, suggesting a limited 'active hurricane season' in terms of realized landfall threat for this portion of the Louisiana coast.

By comparison, landfall activity along the three south-facing regions of the coastal zone has been double that recorded in the eastern region through the 1900s. Data also show that

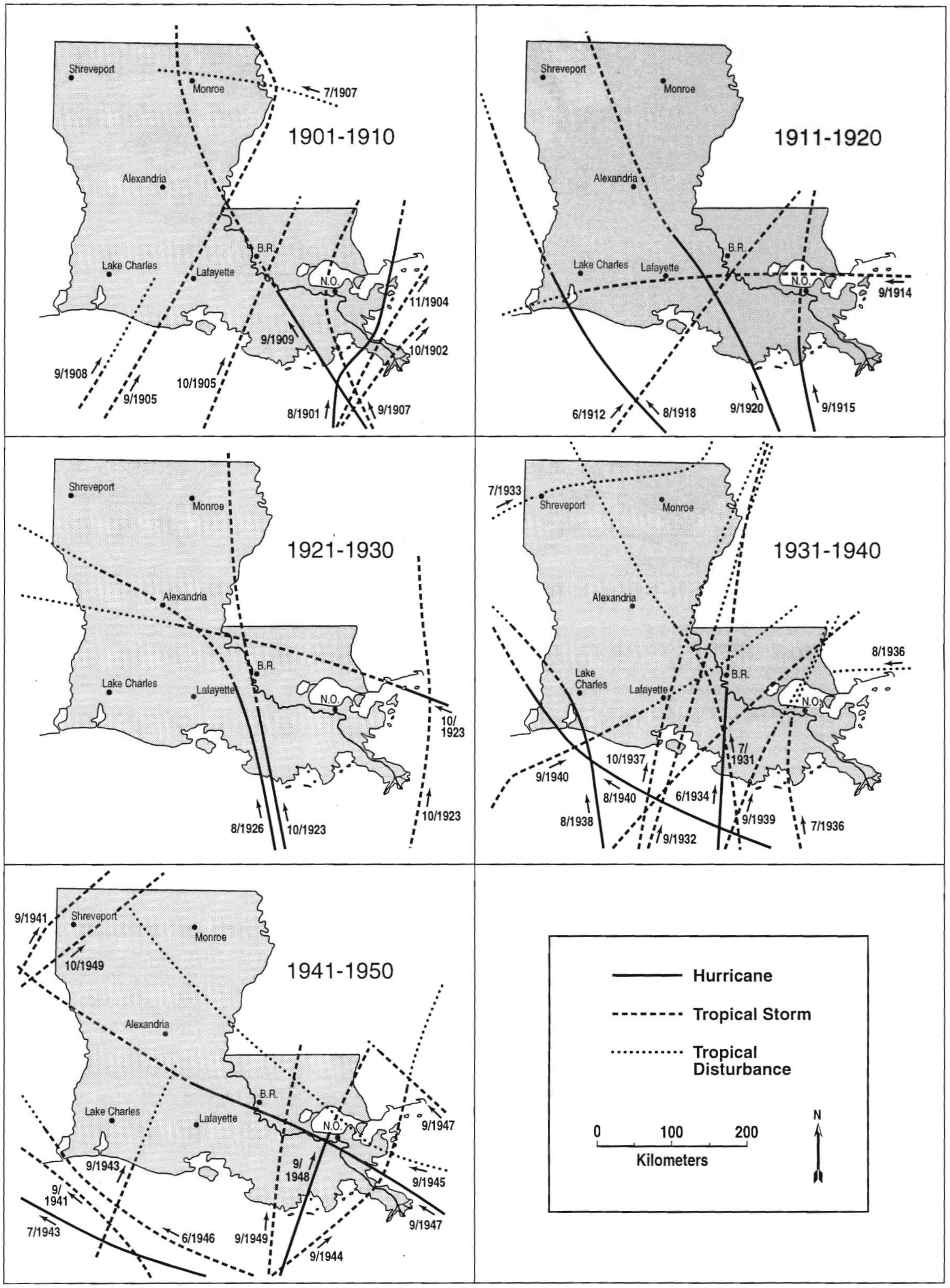

Figure 2. Tracks of hurricanes, tropical storms and tropical disturbances to have made landfall along or very near to the Louisiana coast from 1901–1996.

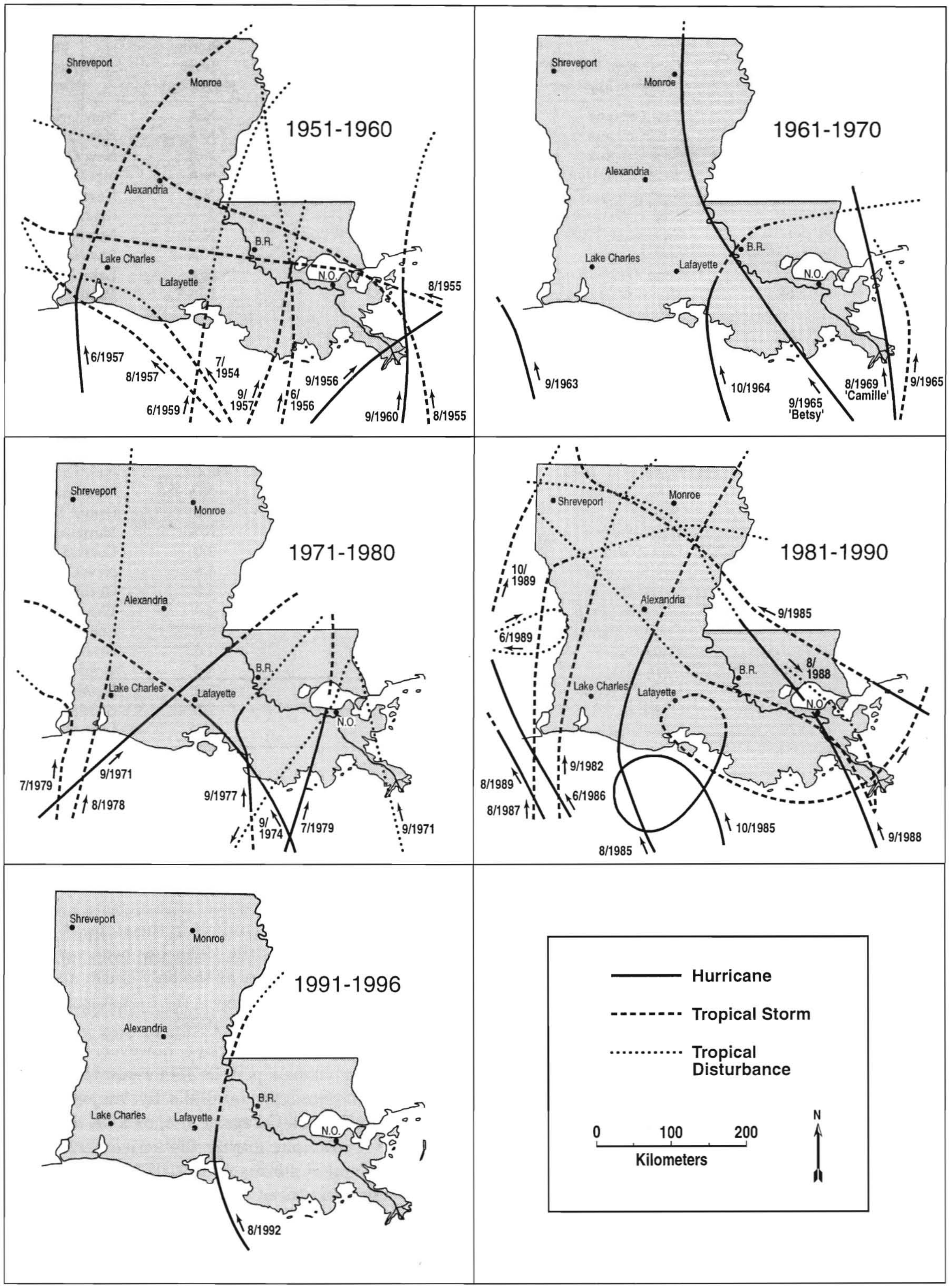

Figure 2. Continued.

Table 1. *Noteworthy hurricanes in Louisiana since 1711. (Data obtained from: U.S. Army Corps of Engineers, 1972; Neumann et al., 1993).*

| Name & Category | Date | Location of Landfall/ Nearest Approach | Location of Maximum Storm Surge | Maximum Storm Surge Height (m) | Section of Louisiana Coast Most Affected |
|---|---|---|---|---|---|
| N/A | 09/1722 | New Orleans | N/A | N/A | New Orleans |
| N/A | 09/11/1723 | New Orleans | N/A | N/A | New Orleans |
| N/A | 08/12/1779 | New Orleans | N/A | N/A | New Orleans |
| N/A | 08/24/1780 | Mississippi Delta | N/A | N/A | Mississippi Delta |
| N/A | 08/19/1812 | New Orleans | N/A | N/A | New Orleans |
| Barbados to LA | 08/1831 | East of New Orleans | Grand Isle | 2 | Grand Isle |
| Racer's | 09/1837 | Galveston, TX | N/A | N/A | New Orleans |
| Last Island | 08/10/1856 | Last Island | N/A | N/A | Last Island |
| N/A | 10/02/1860 | Lake Ponchartrain | N/A | N/A | Lake Ponchartrain |
| N/A | 09/1877 | Mouth of Mississippi River | N/A | N/A | Mouth of Mississippi River |
| N/A | 10/1886 | LA/TX Border | Cheniere Caminada | 1 | Cameron Parish |
| N/A | 10/1887 | New Orleans | N/A | N/A | New Orleans |
| N/A | 09/1893 | Barataria Bay | Deer Island, MS | 2.9 | Cheniere Caminada |
| N/A (4) | 09/08/1900 | Galveston, TX | Galveston | 6.0 | New Orleans |
| N/A (2) | 08/1901 | Port Eads | Mobile, AL | 2.5 | Port Eads |
| N/A (4) | 09/1909 | 80 km W. of New Orleans | Timbalier Islands | 5.0 | Sea Breeze |
| N/A (4) | 09/29/1915 | Mississippi Delta | Mississippi Delta | 4.0 | New Orleans |
| N/A (3) | 08/06/1918 | Lake Charles | N/A | N/A | Western Louisiana |
| N/A (3) | 09/25/1926 | Houma | Terrebonne Parish | 4.5 | Grand Isle |
| N/A (3) | 06/16/1934 | W. of Morgan City | N/A | N/A | Morgan City |
| N/A (2) | 08/07/1940 | Port Arthur | Frenier Isle | 2.0 | Coastal Louisiana |
| N/A (3) | 09/19/1947 | Bay St. Louis | Bay St. Louis | 4.8 | New Orleans |
| Flossy: 2 | 09/23/1956 | Grand Isle | Ostrica Lock | 4.0 | Grand Isle |
| Audrey: 4 | 06/27/1957 | Calcasieu Pass | Calcasieu Pass | 4.0 | Western Louisiana |
| Carla: 4 | 09/07/1961 | Central Texas | Port Lavaca, TX | 6.0 | Coastal Louisiana |
| Hilda: 3 | 10/03/1964 | Franklin | Grand Isle | 1.5 | Grand Isle |
| Betsy: 3 | 09/08/1965 | Grand Isle | Grand Isle | 3.0 | Grand Isle |
| Camille: 5 | 08/17/1969 | LA/MS Border | Pass Christian | 7.0 | Mississippi Delta |
| Edith: 2 | 09/16/1971 | Cameron | Vermillion Bay | 2.5 | Southern Louisiana |
| Carmen: 3 | 09/1974 | Lake Charles | N/A | N/A | Lake Charles |
| Frederic: 3 | 09/12/1979 | Dauphin Island, AL | Perdido Key | 3.2 | Southern Chandeleurs |
| Danny: 1 | 08/15/1985 | Lake Charles | Intracoastal City | 2.4 | W. Delta Barriers |
| Elena: 3 | 09/02/1985 | Biloxi, MS | Dauphin I., AL | 2.65 | Chandeleurs |
| Juan: 1 | 10/29/1985 | Morgan City | Cheniere Au Tigre | 2.19 | W. Delta Barriers |
| Gilbert: 5 | 09/16/1988 | Mexico | N/A | N/A | W. Delta Barriers |
| Andrew: 3 | 08/26/1992 | S. of Lafayette | E. Cote Blanche Bay | 1.71 | Isles Dernieres |

the 'active hurricane season' along this portion of the coast is substantially longer, extending from May through October. Given that the Atlantic basin hurricane season officially runs from June 1 through November 30, the lack of November landfalls in Louisiana is noted. However, hurricane activity at this time of year is normally centered far to the east of Louisiana, with storms tending to display northeasterly movement soon after development. Over the last 110 years, only three storms have been observed in the Gulf of Mexico east of 90°W after November 1 (NCDC, 1993), and none of these threatened the Louisiana coast.

It is apparent from the decadal series of storm tracks (Figure 2) that Louisiana has experienced runs of years when storm activity was above normal as well as periods of reduced landfall frequencies. Most notable is the 30-year period extending from 1931 through 1960, accounting for almost half of the tropical cyclone landfalls of this century. Yet this three-decade run of increased activity was bounded by two of the 'quietest' decades of the past one hundred years: 1921–1930 with only two direct landfalls in Louisiana and 1961–70 with three storms making landfall in the state. It is also noteworthy that the decade of the 1990s has been very quiet thus far, with Hurricane Andrew as the only storm making landfall in Louisiana. (In fact, Andrew is the first storm to directly strike the Louisiana coast since 1988).

From an impact perspective, however, there is little if any relationship between periods of increased landfall frequencies and the potential for landfalls by 'major' hurricanes (i.e., storms ranking as Category 3, 4, or 5 on the Saffir-Simpson scale). For example, during the active period of 1931–1960, only two 'major' storms struck the Louisiana coast. On the other hand, all three storms to strike the Louisiana coast during the decade of the 1960s—Hilda (1964), Betsy (1965) and Camille (1969)—were 'major' systems. And while the 1990s remain unusually quiet, with Andrew as the state's only landfall thus far, that Category 3 storm produced several hundred million dollars in damage.

Review of the intensities of storms making landfall along the U.S. mainland through 1992 shows that 11 of the 50 strongest storms have impacted Louisiana. These include

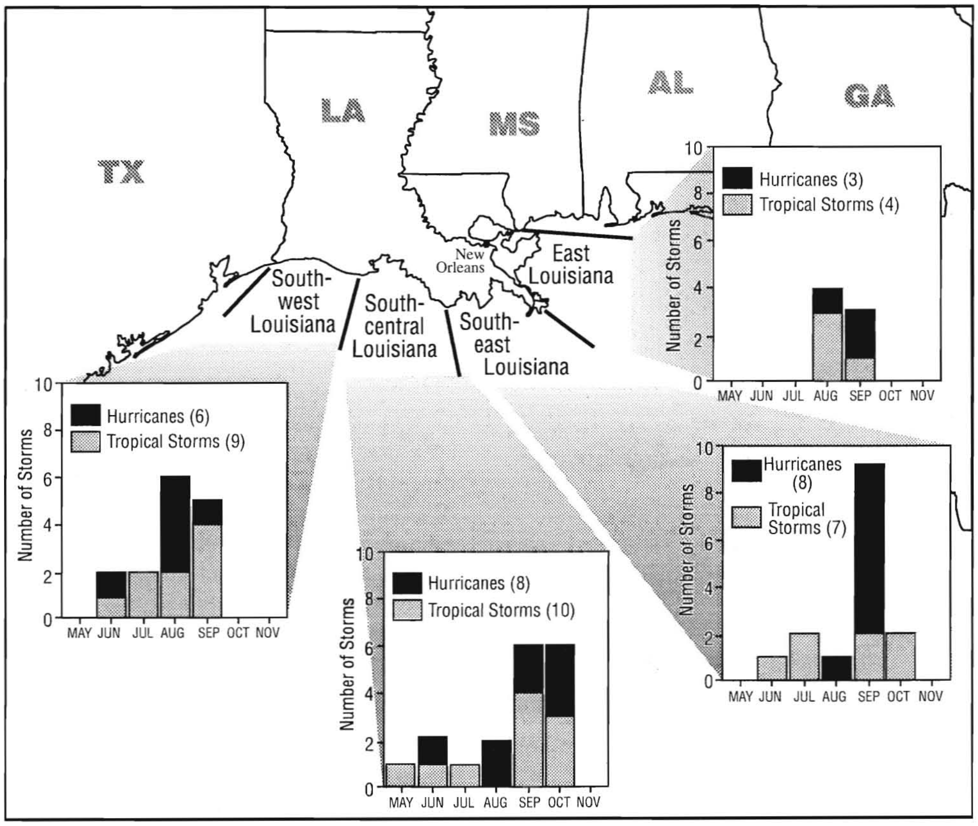

Figure 3. Number and seasonal distribution of hurricane and tropical storm landfalls for each of four sectors along the Louisiana coast. Note each sector is approximately 160 km long.

Camille, a Category 5 storm and at least four other storms of Category 4 strength. While storm tracks and landfall data for these intense systems indicate that none of the four regions of the Louisiana coastal zone has been spared, the south-central and southeastern regions have suffered the majority of the landfalls, with seven of these eleven intense systems entering the state in these two regions.

## GEOMORPHOLOGICAL IMPACTS OF PAST HURRICANES ON LOUISIANA'S OPEN COAST

Review of the literature indicates that washover processes associated with storm events play a critical role in the transgressive evolution of Louisiana's barrier islands (MORGAN *et al.,* 1958; WRIGHT *et al.,* 1970; BOYD and PENLAND, 1981; KAHN and ROBERTS, 1982; JEFFERY, 1984; DEBUSSCHERE *et al.,* 1991; STONE *et al.,* 1993; 1995). On Louisiana's beaches and barrier islands, hurricanes are perhaps the dominant morphodynamic agents, causing erosion, reduction in elevation, fragmentation, and migration (NUMMEDAL *et al.,* 1980; KAHN and ROBERTS, 1982). Hurricane Audrey (1957) was responsible for between 15 to 90 m retreat of the dune crest along the chenier plain (MORGAN *et al.,* 1958). Extensive overwash and breaching occurred along the Chandeleur Islands during Hurricane Camille (1969) which virtually destroyed Gosier Island, and flattened the profiles of Breton Island and the Chandeleurs (WRIGHT *et al.,* 1970). These barriers again underwent significant change during Frederic (1979) with shoreline retreat of up to 30 m occurring along the Chandeleurs (KAHN and ROBERTS, 1982). Similarly, the formation of washover channels and widespread breaching occurred on the Isles Dernieres during Hurricanes Juan (1985), Danny (1985), and Gilbert (1988) (PENLAND *et al.,* 1989). Post-storm recovery along these islands was particularly apparent along wider, higher elevated sections of the barriers (DEBUSSCHERE *et al.,* 1991). Rates of recovery after Juan and Danny were generally slower along the western flank of the barrier chain in response to an increasing distance downdrift from sediment bypassing Cat Island Pass (DEBUSSCHERE *et al.,* 1991). Recovery time was significantly less after Hurricane Gilbert and dramatic changes to the subaerial portions of the barriers were noticeable one year after landfall (DEBUSSCHERE *et al.,* 1991). The recovery of barrier islands following these storms has been found to be chiefly dependent upon the degree of damage incurred, and the availability of sediment within the system. Owing largely to factors such as subsidence, sea level rise, and inadequate sediment supply, Louisiana's barrier coast is predisposed towards land loss in the long term. As such, only incomplete recovery of barrier is-

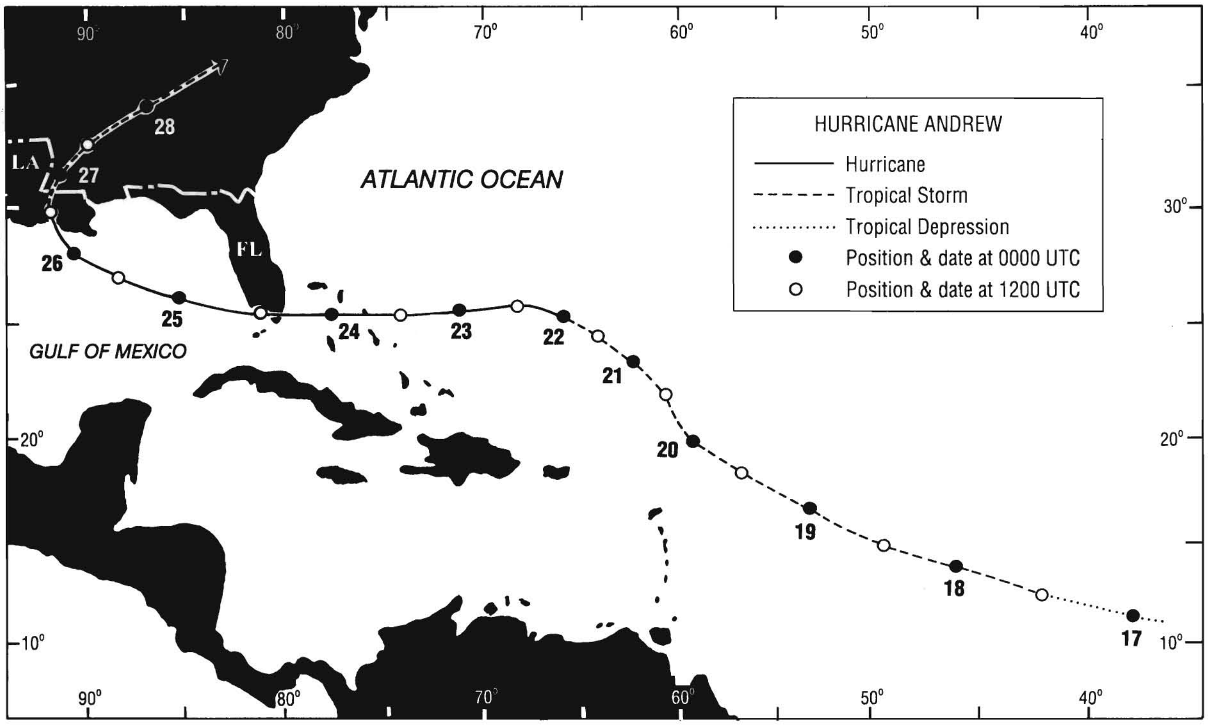

Figure 4. Map showing 12-hour positions of Hurricane Andrew for the period 0000 UTC 17 August through 0000 UTC 28 August, 1992. (From Grymes and Stone, 1995).

lands has been observed following major hurricanes such as Frederic (KAHN, 1986) and Andrew (DINGLER and REISS, 1995; STONE *et al.,* 1993; 1995).

## HURRICANE ANDREW

### General Overview

Perhaps one of the most devastating storms to strike the Louisiana coast was Hurricane Andrew in 1992. This particular storm provided a unique opportunity to quantify the biophysical impacts of catastrophic events on the barrier islands and wetlands of Louisiana because a considerable pre-landfall data set existed and numerous instruments and field experiments survived the impacts associated with Hurricane Andrew.

### Movement Across the Atlantic Towards the Gulf of Mexico

On 17 August, 1992, an easterly wave that had moved off the west coast of Africa was upgraded to a tropical storm, becoming a hurricane on 22 August (Figure 4). The system, Hurricane Andrew, made landfall along Florida on 24 August at 0905 UTC with estimated winds in excess of 65 $ms^{-1}$. Much variation in wind speed was observed prior to landfall in Florida as the cyclone moved across Great Bahama Bank to the east. Here, estimated maximum wind speeds fell to 50 $ms^{-1}$ and, only minimal change to the position and orientation of submarine platform sandbodies was observed after seismic lines had been resurveyed in the area (BOSS and NEUMANN, 1995). The rapid forward speed and intensity of Hurricane Andrew significantly impacted the morphology of Florida's southeast and southwest coast beaches. TEDESCO *et al.* (1995), discuss the importance of beach orientation relative to the storm track as a controlling agent for the severity of overwash. Beaches in southern Key Biscayne experienced most of the overwash because of their perpendicular orientation to the storm track. On the west coast of Florida, broad storm ramps occurred composed of sand and gravel lobes around the Highland Beach area of the Everglades National Park (TEDESCO *et al.,* 1995). While post-storm beach recovery had occurred by June 1993 on the east coast at Cape Florida, only 20–40% of the Highland Beach barrier sediments had

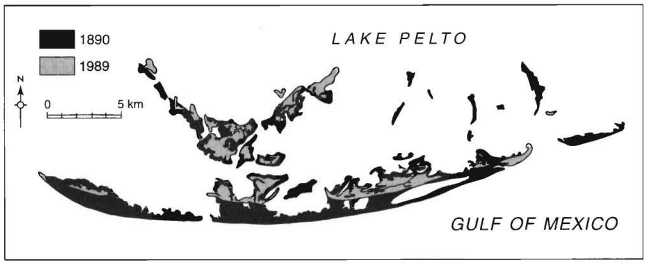

Figure 5. Aerial changes to the Isles Dernieres over the period 1890–1989 (From Williams et al., 1992).

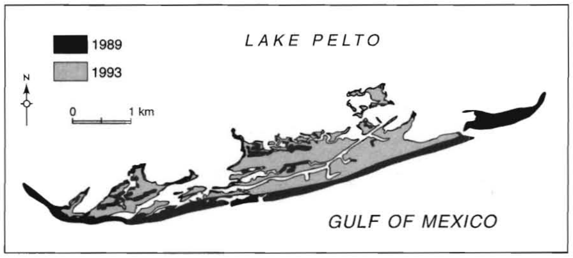

Figure 6. Aerial changes along Trinity Island largely due to Hurricane Andrew.

been redeposited by that time. Along the southwest Florida coast, RISI *et al.*, (1995) identified 4 types of deposits: A fine sand to mud layer deposited across the supratidal and wetland mangrove by onshore surge; carbonate and organic-rich muds comprising ebb surge deltas deposited on channel and creek flanks during and following the Hurricane; carbonate and organic-rich mud wedges comprising deltas formed during the flood and ebb surge along the coast and interior bays; and sand and shell deposits in the mangrove swamps formed during onshore surge.

A significant amount of information documenting the impacts of Andrew on shoreline habitats and forests was obtained by several researchers. For example, DAWES *et al.*, (1995) report that while seagrass communities at Lostman's River (Everglades National Park) underwent minor damage, the mangal and associated communities will likely require decades to recover. Severe damage and mortality of trees was most apparent in mangrove forests where between 59 and 85% of trees were killed (ARMENTANO *et al.*, 1995). However, observations at these sites made by the researchers in early 1994 indicate that vigorous seedling recruitment and resprouting had occurred. HORVITZ *et al.*, (1995) state that while hurricane disturbance is a normal part of the ecology of southern Florida, Hurricane Andrew's impacts may well be quite distinct from its predecessors because these forests contained vegetation far more abundant in exotics than before.

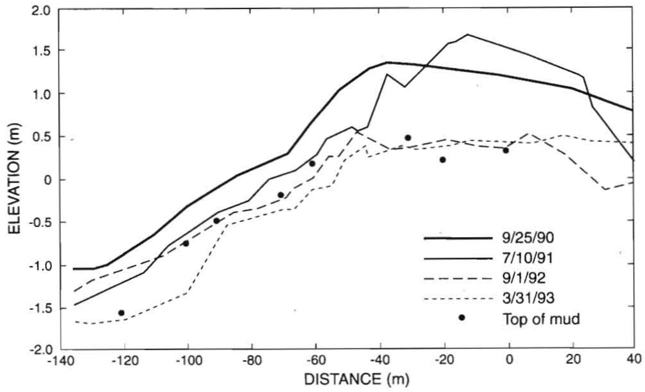

Figure 8. Time series of profile change along Trinity Island for the period 9/25/90–3/31/93. Dots indicate the location of the mud core of the island exposed during Hurricane Andrew.

## Movement Towards and Landfall Along the Louisiana Coast

On entering the Gulf of Mexico, Hurricane Andrew reintensified to Category 4 status with sustained winds in excess of 60 $ms^{-1}$ (Figure 4). The cyclone began turning to the west-northwest, directed by a high-pressure ridge to the northeast. Wave data obtained from two deepwater buoys operated by the National Data Buoy Center showed that waves began responding to the cyclone at least 12 hours in advance of the system. Significant deepwater wave heights and periods increased from around 1.0 m and 6.0 s, to 6.0 m and 17 s respectively at one of the buoys (GRYMES and STONE, 1995). Both buoys were located south of the storm track and likely underestimated wave conditions in the front right quadrant of the system. Hindcast estimates indicate that the significant wave height approached 14 m, although may have exceeded 20 m, on portions of the Louisiana shelf (STONE *et al.*, 1995). Long period waves traveled north towards the northeast Gulf coast at a celerity of approximately 9 $ms^{-1}$ (GRYMES and STONE, 1995). Along the Florida Panhandle at Perdido

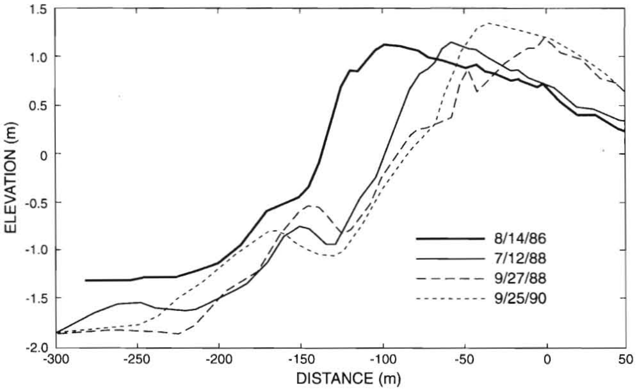

Figure 7. Time series of profile change along Trinity Island for the period 8/14/86–9/25/90.

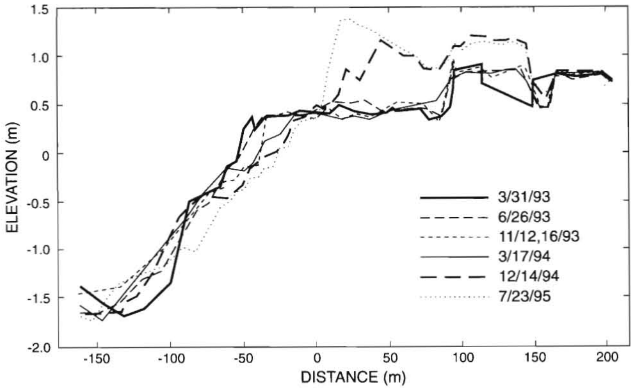

Figure 9. Time series of profile change along Trinity Island over the period 3/31/93–7/23/95.

Figure 10. Oblique aerial photograph shot shortly after landfall of Hurricane Andrew showing extensive overwash and breaching along the Isles Dernieres (Timbalier Island).

Key, significant wave heights and periods of 2.7 m and 12 s were recorded by a wave gauge in 7 m water depths during peak intensity. Directional wave spectra and wave kinematics were obtained utilizing the measured pressure and horizontal velocity by wave gages deployed at four sites along the Texas-Louisiana shelf (DIMARCO *et al.,* 1995). Hurricane waves with significant wave periods of 16 s were recorded approximately 20 km south of Terrebonne Bay, Louisiana, 14.5 hours prior to their arrival off South Padre Island, Texas. At the Louisiana site, the peak significant wave height exceeded 9 m in water depths of 20 to 21 m, approximately 30 km east of the storm center (DIMARCO *et al.,* 1995). The spectra were distinctly bimodal during the 8 hour period when the eye was located closest to the Louisiana gauge, with energy in the 0.15 to 0.22 Hz band accounting for 37% of the total energy. As the long waves propagated across the Louisiana shelf, wave attenuation was calculated to have occurred in water depths of up to 200 m (STONE *et al.* 1995). The low gradient inner shelf slope adjacent the Isles Dernieres played a critical role in dissipating wave energy, with calculated rates of 5 jl $m^{-3}$ occurring in depths of 25 to 30 m. Maximum near-bottom orbital velocities reached 20 cm $s^{-1}$ in depths of

Figure 11. Oblique aerial photograph shot shortly after landfall of Hurricane Andrew showing extensive breaching and overwash along Trinity Island.

around 150 m, and increased to 200 cm s$^{-1}$ in 30 m of water. Depth-limited breaker wave heights ranged from 0.5 m off Point AuFer Island to >3 m along the Caminada Moreau Headland, Louisiana (STONE *et al.,* 1995).

## Morphological Impacts Along the Southcentral Louisiana Coast

Severe overwash and breaching was apparent along over 100 km of the Louisiana barrier island coastline as Hurricane Andrew passed within 50 km of the Isles Dernieres, the western-most island chain. The rapid deterioration of the Isles Dernieres has been amply demonstrated in the literature (see MCBRIDE and BYRNES, this volume). However, although hurricane impacts are recognized as being highly significant in the transgressive evolution of this barrier chain, the magnitude of change due to the cumulative effects of storms has not been quantified for the historic time series. Aerial changes to the Isles Dernieres and adjacent mainland (Figure 5) suggests over 1 km of beach-face retreat and 78 percent landloss over the period 1890 through 1989 (WILLIAMS *et al.,* 1992). The degree of aerial change is shown in Figure 6 for Trinity Island due to Hurricane Andrew.

Trinity Island is the only barrier island in Louisiana where a detailed time history of beach profile change is available through a monitoring project conducted by the U.S. Geological Survey between 1986 and 1991. During the five years after the project began winter storms and Hurricane Gilbert (9/1988) resulted in approximately 90 m of beach face retreat (Figures 7 and 8) The retreat occured primarily when storm waves reworked the coarser-grained sediment offshore exposing the mud core of the island to erosion. In general, the beach slope maintained a consistent slope until the upper slope readjusted to waves generated by Hurricane Gilbert resulting in a 40 m landward translation of the berm. The effects of Andrew on the beach face are shown in Figure 8 where pre and post-Andrew profiles show landward translation of the beach face of 20 m resulting in exposure of the mud core. Over the five year survey period, the combined effects of storms removed 81 m$^3$/m of sediment resulting in landward (northward) relocation of the berm by 90 m. Andrew removed all of the sand from the beach face of Trinity Island, a net loss of 92 m$^3$/m. Approximately 85m$^3$/m of the sediment eroded was sand and the remainder, mud from the island's core. Most of the sediment was transported northward across the barrier and deposited as overwash fans in addition to infilling the small bayous Figures 9, 10 and 11. Beach face retreat of approximately 25 m was evident for up to two years following landfall of Hurricane Andrew and it

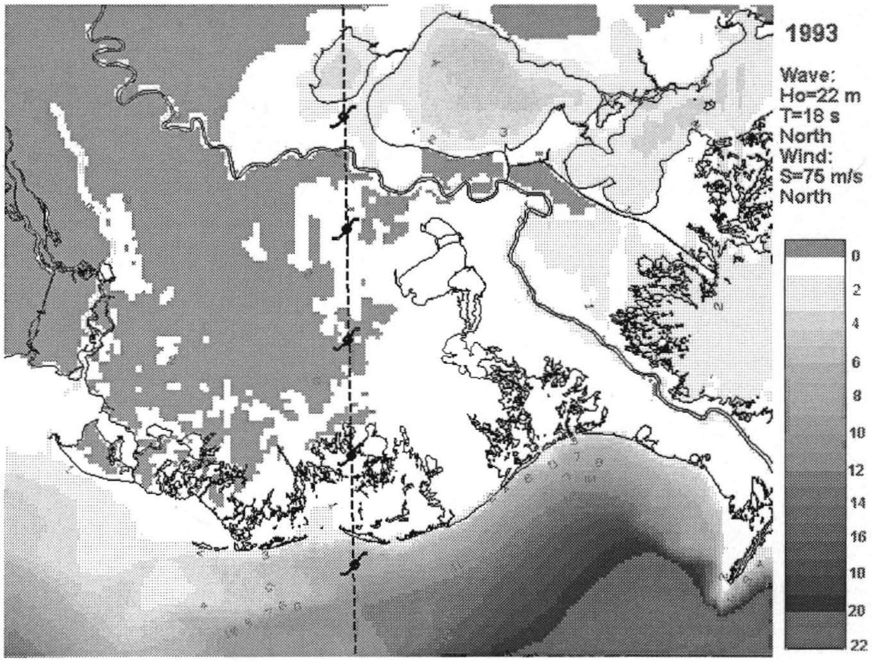

Figure 12. Numerically modeled significant wave height (m) distribution along the Louisiana coast and inland for a simulated category 5 hurricane making landfall over Timbalier Island for present day (1993) shoreline and bathymetric conditions.

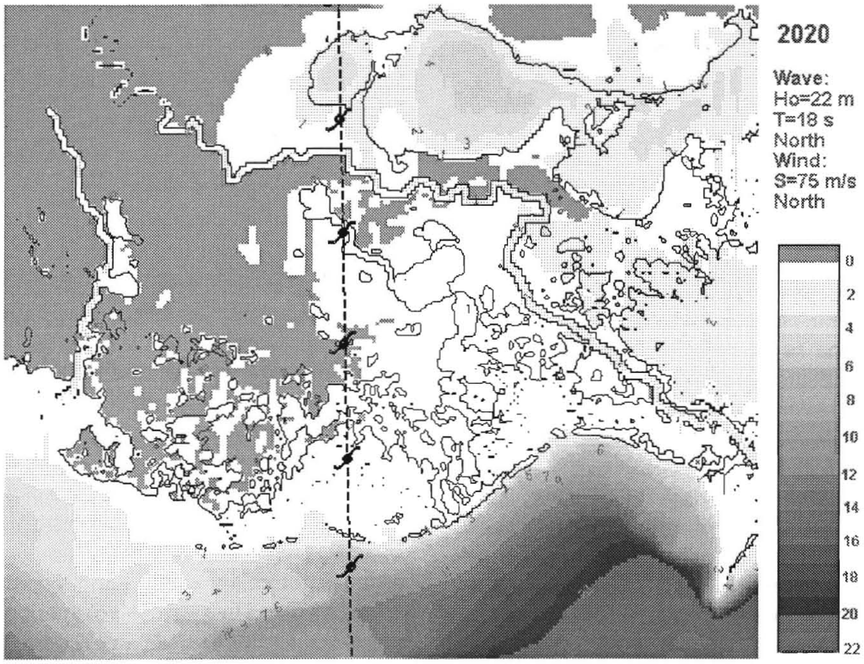

Figure 13. Numerically modeled significant wave height (m) distribution along the Louisiana coast and inland for a simulated category 5 hurricane making landfall over Timbalier Island for future (2020) shoreline and bathymetric conditions.

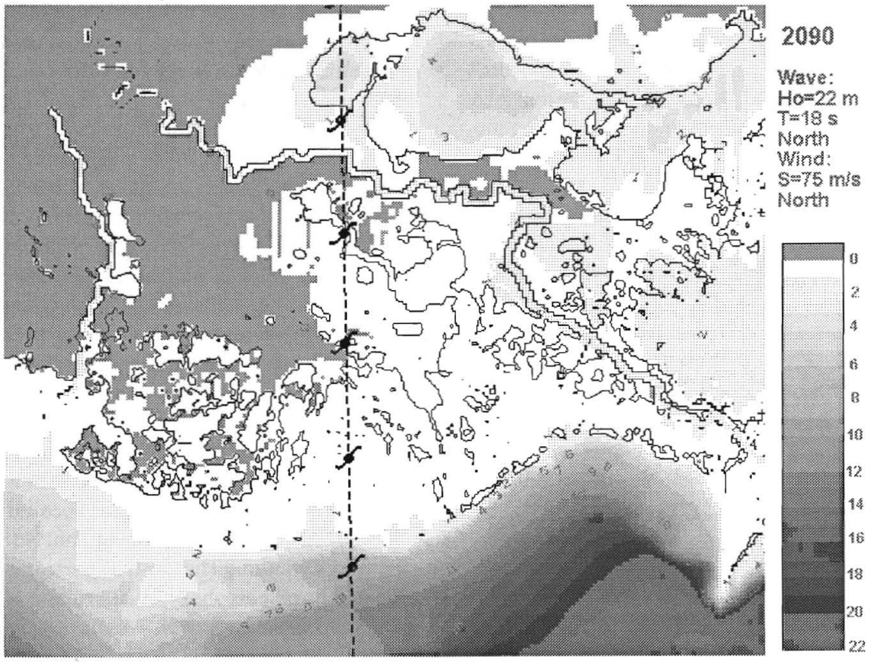

Figure 14. Numerically modeled significant wave height (m) distribution along the Louisiana coast and inland for a simulated category 5 hurricane making landfall over Timbalier Island for future (2090) shoreline and bathymetric conditions

was not until 1995 when enough sediment became available in the system for berm rebuilding (Figure 9).

## Water Levels and Impacts on Louisiana's Marshes

On Louisiana's coastal wetlands, hurricanes act as both destructive agents, and as important sources of sediment which help to counterbalance ongoing wetland loss. Deposition of up to 0.7 m of mixed organic and inorganic debris was noted on natural levees and behind obstructions following Hurricanes Audrey (1957) (MORGAN *et al.,* 1958) and Camille (1969) (WRIGHT *et al.,* 1970); however, certain hurricanes (*e.g.* Camille, 1969) have caused extensive damage to vegetation in the Mississipi Delta due to winds, waves, and the return flow of floodwaters (WRIGHT *et al.,* 1970). Hurricane Andrew caused widespread sediment deposition within the wetlands and comparatively little destruction of vegetation. CAHOON *et al.* (1995a) calculated vertical marsh accretion in the Terrebonne, Barataria, and Ponchartrain Basins of between 2 to 6 cm greater than that which occurred in either the previous, or the following, year. In a follow-up study, however, CAHOON *et al.* (1995b) note that factors such as substrate compression during storm passage may significantly reduce, or nullify, the effect of storm deposition on the marshes' long-term net elevation gain. GUNTENSPERGEN *et al.* (1995) measured storm deposits of an average depth of 16 cm in coastal marshes near Atchafalaya Bay; however, severe vegetative damage in areas of wrack accumulation and scour was also observed. While both CAHOON *et al.* (1995a) and GUNTENSPERGEN *et al.* (1995) stressed the importance of hurricanes as a sediment source for coastal wetlands, the latter further noted that hurricane impacts on marshes vary widely acccording to storm intensity, the marsh's position relative to the storm track, the antecedent condition, and geomorphology of the marsh.

HALFORD (1995) provides evidence indicating two contrasting effects of the storm surge on Louisiana's marshes: First, a period of rapid water level increase or decrease—depending on location relative to the storm track—occurred over a short time approximating 3 to 6 hours. According to HALFORD (1995), most of the coarse-grained sediment was probably deposited on the marsh surface during this phase along with much of the physical destruction to the system; second, relaxation of the water surface occurred after the storm moved inland over an approximate 24 hour period, during which time fine-grained sediment was distributed across the marsh surface. Sediment deposition and marsh surface change was measured up to 130 km from the storm track.

Areas largely composed of floating marsh were dramatically altered by surge and winds accompanying Hurricane Andrew. DINGLER *et al.,* (1995) note that in a few hours, vegetated brackish marsh was severely torn and large areas converted to open water. Their work also sheds new light on utilizing the drag coefficient over open water and a marsh surface. Based on wind data collected from vertically stacked sensors located in a brackish marsh, DINGLER *et al.,* (1995) conclude that the open-ocean formulations of the coefficient tend to overestimate the drag for wetland application when velocities are less than 20 m $s^{-1}$ and underestimate it for higher velocities.

Storm surge intruded a 20 km stretch of marsh in Terrebonne Bay over a period of at least 6 hours (JACKSON *et al.*

1995). A residual salt wedge, attributable to the storm, was detected at an intermediate marsh site 55 days after Hurricane Andrew had made landfall in Louisiana. Chemical analyses of pore water indicated an increase in alkalinity, ammonia, phosphate and manganese, implying an increase in organic matter decomposition (JACKSON *et al.* 1995). The authors suggest that this residual salinity of pore water may enhance wetland loss through long-term impacts on macrophyte production. The initial recovery of wetland plant communities was also determined near Atchafalaya Bay (GUNTENSPERGEN *et al.* 1995), where thick post-storm accumulations of sediment approximated 16 cm. In addition, lateral compression of the marsh enhanced vertical relief 5 to 10 times greater than normal. With the exception of thick wrack accumulation and areas of scour, the recovery of plant cover was rapid, although shifts in species dominance were apparent.

## WAVE CLIMATE PREDICTIONS

Ongoing work being carried out at Louisiana State University centers on wave prediction during deep water fiarweather, storm and severe hurricane conditions for predicted future barrier island, fringing marsh and bathymetric changes. Parts of this study are presented in this volume (see papers by MCBRIDE and BYRNES; SUHAYDA; this volume). Based on historic shoreline and bathymetric change trends, future predictions are made for 30 and 100 year scenarios. A component of this work involves numerically modeling storm surge and wave height distribution accompanying the hurricane of record for the Louisiana coast. The hurricane selected had a central pressure of 751.8 mm, a forward speed of 3.86 m/s, a radius to maximum winds of 40.8 km and a track that was due north over the Timbaliers with New Orleans occurring in the the front right quadrant of the system. Deep water wave statistics including a significant wave height of 22 m, and period of 18 s and sustained wind speed of 75 m/s were used as boundary conditions. A finite-difference model (STWAVE) for near-coast time-independent spectral wave energy propagation simulations was used (see CIALONE *et al.*, 1992 for a more detailed description). Surge levels were calculated using the Federal Emergency Management Agency (FEMA) model and is described in more detail in SUHAYDA (this volume). The wave model is based on a simplified spectral balance equation

$$\frac{\partial}{\partial x}(CC_g E(f, \theta) + \frac{\partial}{\partial y}(CC_g E(f, \theta) + \sum_{i=1}^{N} S_i = 0 \qquad (1)$$

where $E(f,\theta)$=spectral energy density, f=frequency of spectral component,$\theta$=propagation direction of the spectral component, $S_i$=source terms (shoaling, refraction, wind forcing, wave-wave nonlinear interactions, bottom interaction, *etc.*). STWAVE simulation requires a wave energy spectrum specified for the input boundary of the computational grid. It transforms the spectrum across the grid, including refraction and shoaling effects. The spectrum is modified to include the effects of bottom diffraction and the convergence/divergence of energy influenced by the local bathymetry. Wind-wave generation, nonlinear energy transfer, wave field and wave-bottom dissipation and wave breaking are considered. The model is computationally efficient because of its assumption that only wave energy directed into the computational grid is significant, *i.e.,* wave energy not directed into the grid is neglected.

The output from the hurricane simulations are shown in Figures 12, 13 and 14 for modern day (1993), 2020 and 2090. For the modern day scenario, the coastline is predominantly overtopped by waves approximating 2 m in height. Landward in the bays, waves typically attain heights of around 1 m increasing to 2 m southeast of New Orleans. Although not preseneted here, storm surge levels are as high as 3 m south of New Orleans. A gradual landward shift of larger waves is noticeable with time due to the dissappearance of barrier islands and coastal retreat, particularly for the 2090 scenario. This does not significantly influence wave heights landward of the coast where waves are generally limited to 1 m. For each of the three scenarios wave heights up to 4 m are predicted in Lake Ponchartrain located immediately north of New Orleans. On considering that surge levels increase from around 4 m along the central portions of the lake to 7 m along its northern periphery, a hurricane of this nature will cause severe destruction and evacuation problems for the City of New Orleans.

## CONCLUSIONS

Hurricanes play a significant role in the transgressive evolution of Louisiana's barrier islands. The magnitude of change due to the cumulative effects of storms has not, however, been adequately quantified for the historic time series and separated from the impacts associated with compactional subsidence, eustatic sea-level rise, reduction in sediment supplied to the littoral zone and anthropogenic activity. Some estimates suggest that storms may account for up to 90% of long-term ($10^2$ years) shoreline erosion. Given that foredune elevations rarely exceed 2 m above sea level, the severity of the impacts associated with weak storms, or stronger systems marginal to the Louisiana coast, are often severe. Post-storm recovery is not attained for stronger hurricanes, consequently the barriers experience fragmentation continue to experience in-place breakup, landward translation and conversion from sub-aerial to shoal features. Wave climate modeling for two future scenarios indicate substantial increases in wave energy in the bays and landward as far as New Orleans due to a marked reduction in the ability of the barrier islands to absorb wave energy and protect inland water bodies during severe storms.

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## LITERATURE CITED

ARMENTANO, T.V.; DOREN, R.F.; PLATT, W.J., and MULLINS, T., 1995. Effects of Hurricane Andrew on Coastal and Interior Forests of Southern Florida: Overview and Synthesis. *Journal of Coastal Research* Special Issue No. 21, 111–144.

BOYD, R. and PENLAND, S., 1981. Washover of Deltaic Barriers on the Louisiana Coast. *Transactions Gulf Coast Association Geological Society,* 31, 243–248.

CIALONE, M.A.; MARK, D.J.; CHOU, L.W.; LEENKNECHT, D.E.; DAVIS, J.E.; LILLYCROP, L.S., and JENSEN, R.E., 1992. *Coastal Modeling System (CMS) User's Manual. Instruction Report CERC-91-1,* WES, Corps of Engineers, Vicksburg, Mississippi.

BOSS, S.K. and NEUMANN, A.C., 1995. Hurricane Andrew on Northern Great Bahama Bank: Insights into Storm Behavior on Shallow Seas. *Journal of Coastal Research,* Special Issue No. 21, 24–48.

CAHOON, D.R.; REED, D.J.; DAY, J.W., JR.; STEYER, G.D.; BOUMAN, R.M.; LYNCH, J.C.; MCNALLY, D., and LATIF, N., 1995. The Influence of Hurricane Andrew on Sediment Distribution in Louisiana Coastal Marshe G.D.ls. *Journal of Coastal Research,* Special Issue No. 21, 280–294.

CAHOON, D.R.; REED, D.J., and DAY, J.W., JR., 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology,* 128, 1–9.

DAWES, C.J.; BELL, S.S.; DAVIS, R.A.; MCCOY, E.D.; MUSHINSKY, H.R., and SIMON, J.L., 1995. Initial Effects of Hurricane Andrew on the Shoreline Habitats of Southwestern Florida. *Journal of Coastal Research,* Special Issue No. 21, 103–110.

DEBUSSCHERE, K.; PENLAND, S.; WESTPHAL, K.A.; MCBRIDE, R.A., and REIMER, P.D., 1991. Morphodynamics of the Isles Dernieres Barrier Shoreline, Louisiana: 198401989. *Proc. Coastal Sediments'91* (Amer. Soc. Civil Eng.), 1, 1137–1151.

DIMARCO, S.F.; KELLY, F.J.; ZHANG, J., and GUINASSO, N., 1995. Directional Wave Spectra on the Louisiana-Texas Shelf During Hurricane Andrew. *Journal of Coastal Research,* Special Issue No. 21, 217–233.

DINGLER, J.R. and T. REISS, 1995a. Beach Erosion on Trinity Island, Louisiana Caused by Hurricane Andrew. *Journal of Coastal Research,* Special Issue No. 21, 254–264

DINGLER, J.R.; HSU, S.A., and FOOTE, A.L., 1995. Wind Shear Stress Measurements in a Coastal Marsh During Hurricane Andrew. *Journal of Coastal Research,* Special Issue No. 21, 295–305.

GRYMES, J.M. III and STONE, G.W., 1995. A Review of the Key Meteorological and Hydrological Aspects of Hurricane Andrew. *Journal of Coastal Research,* Special Issue No. 21, 6–23.

GRYMES, J.M. III (in preparation). A Review of Louisiana Tropical Weather. LOSC Publication Series. Louisiana Office of State Climatology/Southern Regional Climate Center. LSU Geography & Anthropology. Baton Rouge, Louisiana, USA.

GUNTENSPERGEN, G.R.; CAHOON, D.R., GRACE, J.; STEYER, G.D.; FOURNET, S.; TOWNSEND, M.A.; and FOOTE, A.L.; 1995. Disturbance and Recovery of the Louisiana Coastal Marsh Landscape from the Impacts of Hurricane Andrew. *Journal of Coastal Research,* Special Issue No. 21, 324–339

HALFORD, K., 1995. Estimating the Dynamic Water-Level Surfaces Associated with Hurricane Andrew Crossing the Louisiana coast. *Journal of Coastal Research,* Special Issue No. 21, 265–279.

HORVITZ, C.C.; MCMANN, S., and FREEDMAN, A., 1995. Exotic and Hurricane Damage in three Hardwood Hammocks in Dade County Parks, Florida. *Journal of Coastal Research,* Special Issue No. 21, 145–158.

JACKSON, L.L.; FOOTE, A.L., and BALISTRIERI, L.S., 1995. Hydrological, Geomorphological, and Chemical Effects of Hurricane Andrew on Coastal Marshes of Louisiana. *Journal of Coastal Research,* Special Issue No. 21, 306–323.

KAHN, J.H. 1980. The Role of Hurricanes in the Long Term Degradation of a Barrier Island Chain: Chandeleur Islands, Louisiana. M.S. Thesis, Louisiana State University, Department of Marine Science.

KAHN, J.H. 1986. Geomorphic Recovery of the Chandaleur Islands, Louisiana, After a Major Hurricane. *Journal of Coastal Research* 2(3), 337–344.

KAHN, J.H. and ROBERTS, H.H., 1982. Variations in Storm Response Along a Microtidal Transgressive Barrier Island Arc. *Sedimentary Geology,* 33, 129–144.

MORGAN, J.P.; NICHOLS, L.G., and WRIGHT, M., 1958. Morphological Effects of of Hurricane Audrey on the Louisiana Coast. *Coastal Studies Institute, Louisiana State University, Technical Report 10 (A).*

NATIONAL CLIMATIC DATA CENTER (1993). Tropical Cyclones of the North Atlantic Ocean, 1871–1992. Fourth Revision. Historical Climatology Series 6-2. U.S. Department of Commerce/National Oceanographic and Atmospheric Administration/NCDC. Asheville, North Carolina.

NEUMANN, C.J.; JARVINEN, B.J.; MCADIE C.J., and ELMS, J.D., 1993. *Tropical Cyclones of the North Atlantic Ocean, 1871–1992.* National Climatic Data Center, Asheville, North Carolina.

NUMMEDAL, D.S.; PENLAND, S.; GERDES, R.; SCHRAMM, W.; KAHN, J., and ROBERTS, H., 1980. Geologic response to huricane impacts on low-profile Gulf Coast Barriers. *Transactions-Gulf Coast Association of Geological Societies,* XXX, 183–190.

PENLAND, S.; DEBUSSCHERE, K.; WESTPHAL, K.A.; SUTER, J.R.; MCBRIDE, R.A., and REIMER, P.D., 1989. The 1985 Hurricane Impacts on the Isles Dernieres, Louisiana: A Temporal and Spatial Analysis of the Coastal Geomorphic Changes. *Transactions-Gulf Coast Association of Geological Societies,* XXXIX, 455–470.

PENLAND, S.; SUTER, J.R.; SALLENGER, A.H., JR.; WILLIAMS, S.J.; MCBRIDE, R.A.; WESTPHAL, K.E.; REIMER, P.D., and JAFFE, B.E., 1989. Morphodynamic Signature of the 1985 Hurricane Impacts on the Northern Gulf of Mexico. *Proceedings of the Sixth Symposium on Coastal and Ocean Management* (ASCE, July 11–14, 1989, Charleston, South Carolina), pp. 4220–4233.

RISI, J.A.; WANLESS, H.R.; TEDESCO, L.P., and GELSANLITER, S., 1995. Catastrophic Sedimentation from Hurricane Andrew Along the Southwest Florida Coast. *Journal of Coastal Research,* Special Issue No. 21, 83–102.

STONE, G.W.; GRYMES, J.M. III; ROBBINS, K; UNDERWOOD, S.G.; STEYER, G., and MULLER, R.A., 1993. A Chronological Overview of Climatological and Hydrological Aspects Associated with Hurricane Andrew and its Morphological Effects Along the Louisiana Coast, USA. *Shore and Beach,* 61(2), 2–13.

STONE, G.W; XU, J.P., and ZHANG, X. 1995. Estimation of the Wave Field During Hurricane Andrew and Morphological Change Along the Louisiana Coast. *Journal of Coastal Research,* Special Issue No. 21, 234–253.

TEDESCO, L.P.; WANLESS, H.R.; SESUA, L.A.; RISI, J.A., and GELSANLITER, S., 1995. Impact of Hurricane Andrew on South Florida's Sandy Coastlines. *Journal of Coastal Research,* Special Issue No. 21, 59–82.

U.S. ARMY CORPS OF ENGINEERS. 1972. *History of Hurricane Occurrences Along Coastal Louisiana.* New Orleans, Louisiana.

WILLIAMS, S.J.; PENLAND, S., and SALLENGER, A.H., (eds.), 1992. Atlas of Shoreline Change in Louisiana from 1853–1989. *U.S. Geological Survey, Miscellaneous Investigation Series I-2150-A,* 103 pp.

WRIGHT, L.D.; F.J. SWAYE, and J.M. COLEMAN. 1970. Effects of Hurricane Camille on the Landscape ot the Breton-Chandaleur Island Chain and the Eastern Portion of the Lower Mississippi Delta. *L.S.U. Coastal Studies Bulletin* (Feb. 1970), pp. 13–32.