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Chapter A of
Sand Resources, Regional Geology, and Coastal Processes of the Chandeleur Islands Coastal System: an Evaluation of the Breton National Wildlife Refuge

Scientific Investigations Report 2009–5252

U.S. Department of the Interior
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Edited by Dawn Lavoie

In cooperation with the U.S. Fish and Wildlife Service

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Chapter A. Hurricane Impact and Recovery Shoreline Change Analysis and Historical Island Configuration: 1700s to 2005

By Sarah Fearnley,[1] Michael Miner,[1] Mark Kulp,[1] Carl Bohling,[1] Luis Martinez,[1] and Shea Penland[1]

Abstract

Changes of shoreline positions in the Chandeleur Islands in the Breton National Wildlife Refuge, La., have been occurring for thousands of years. In this chapter, results of analyzing the shoreline changes that have occurred since the early 1700s are presented as part of a larger collaboration among the U.S. Fish and Wildlife Service, the U.S. Geological Survey, and the University of New Orleans Pontchartrain Institute for Environmental Sciences. The goal of this task was to analyze shoreline change data for southeast Louisiana from before and after several major storms and to investigate the relation between hurricane impact intensity and frequency and the amount of linear shoreline erosion to the islands.

Several maps from between 1744 and 1848 were examined to determine the historical position of the islands before the extensive influence of humans. The geomorphic response of the shoreline during the past century was investigated by using maps from five time periods including 1855, 1922, 1989, 2004, and 2005. Hurricane impact and recovery, geomorphic change, and age of discovery maps displaying all the data used in the analysis are available in appendix A–1. Detailed statistical datasets for both the geomorphic shoreline change analysis and the hurricane shoreline change analysis are available in appendixes A–2 and A–3.

Results from historical (1855–2005) shoreline change analysis conducted along the Chandeleur Islands demonstrate that tropical cyclone frequency dominates the long-term evolution of this barrier island chain. Island area changed at a rate of -0.16 km^2/yr for the relatively quiescent time period until 1996, when an increase in tropical cyclone frequency accelerated the reduction in island area to a rate of -1.01 km^2/yr. Shoreline retreat rates were also affected by more frequent hurricanes, increasing from -11.4 m/yr between 1922 and 1996 to -41.9 m/yr between 1982 and 2005. The erosional impact caused by the passage of Hurricane Katrina in 2005 is unprecedented. Between 2004 and 2005, the shoreline of the northern Chandeleur Islands moved by -201.5 m/yr, compared with an average rate of erosion of -38.4 m/yr between 1922 and 2004. A linear regression analysis of shoreline change predicts that the barrier island chain will become devoid of backbarrier marsh as early as 2013 if the storm frequency observed during the past decade persists. If storm frequency decreases to pre-1996 recurrence intervals, the backbarrier marsh is predicted to remain until 2037. The backbarrier marsh is an important controlling factor in stabilizing the barrier chain and maintaining subaerial exposure. Southern portions of the barrier island chain where backbarrier marsh is now absent behave as ephemeral islands that are destroyed after storm impacts and reemerge during extended periods of calm weather, a coastal behavior that will eventually be characteristic of the entire island chain.

Introduction

The Chandeleur Islands are an 80-km-long arcuate-shaped barrier island chain located in southeast Louisiana on the north-central coast of the Gulf of Mexico (fig. 1). These islands are the longest barrier island chain in the gulf and are important because they (1) attenuate storm impacts for mainland Louisiana and Mississippi (Stone and Orford, 2004; Stone and others, 2005), (2) regulate estuarine salinity and circulation (Reyes and others, 2005) for an approximately 8,750-km^2 estuary that supports a $2.7 billion fisheries industry, and (3) provide unique habitat for threatened and endangered species including nesting sea turtles (*Caretta caretta*, *Chelonia mydas*), brown pelicans (*Pelecanus occidentalis*), piping plovers (*Charadrius melodus*), and least terns (*Sterna antillarum*) (Poirrier and Handley, 2007). The islands are reworked remnants of the relict St. Bernard Delta Complex of the Mississippi River that was active 3,800–1,800 years before present (BP) (Frazier, 1967; Tornqvistand others, 1996). They are separated from the Louisiana mainland wetlands by the approximately 40-km-wide Breton and Chandeleur Sounds. As a result of this geographic position, the islands are susceptible to the effects of almost any major storm

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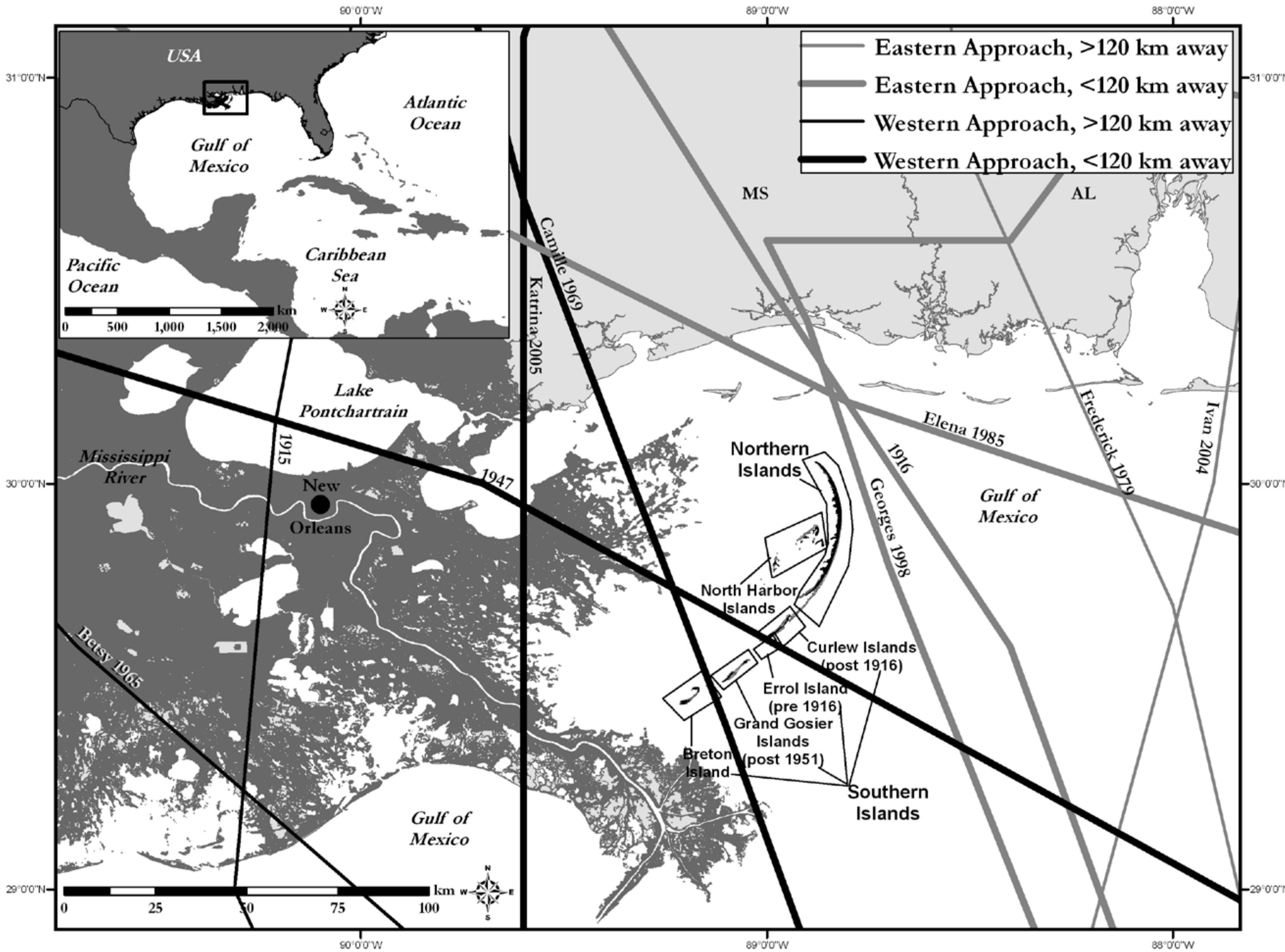

Figure 1. Map depicting the storm paths of 10 major storms impacting the Chandeleur Islands in southeastern Louisiana during the 20th century. The Chandeleur Islands are shown in black near the center of the figure, and the individual islands that make up the island arc are outlined in boxes and labeled. Storms passing directly over or just to the west of the islands are the most devastating, and storms passing to the east result in the least amount of shoreline erosion.

entering the northern Gulf of Mexico and have been impacted by about 42 hurricanes since the early 1900s.

It has been suggested that the long-term evolution of the Chandeleur Islands and their fate are governed by tropical cyclone impacts, which result in a long-term net land loss driven by insufficient poststorm recovery leading to the islands' conversion to an inner shelf shoal through transgressive submergence (Kahn and Roberts, 1982; Penland and others, 1983, 1988; Kahn, 1986; Suter and others, 1988). McBride and others (1992) suggested that the Chandeleur Islands would remain supratidal until the year 2360 on the basis of projected shoreline change and linear regression analysis of island area changes between 1855 and 1989. These predictions did not account, however, for the increase in northern Gulf of Mexico storm frequency and intensity that ensued in the decade following their analysis.

Recent increased storm frequency associated with the impacts of Hurricanes Georges, Ivan, and Katrina during the past approximately 10 years is unprecedented for the Chandeleur Islands during the historical record (1855–2005). These multiple, closely spaced (temporally) storm impacts culminated with those of Hurricane Katrina (Aug. 2005) completely inundating the islands, removing more than 90 percent of the sand, exposing backbarrier marsh along the gulf shoreline to wave attack (Miner and others, this volume), and reducing total island area by about 50 percent. These hurricane impacts have raised new questions regarding the longevity and sustainability of the Chandeleur Islands and their ability to recover from future storms. This study uses spatial analysis techniques to relate historical shoreline position and island area changes for several time periods (dating back to 1855) to hurricane impact frequency and storm intensity. The overall goal is to forecast the timeframe of island conversion to an inner shelf shoal.

History of the Chandeleurs

The Chandeleur Islands, located in both St. Bernard and Plaquemines Parishes in southeast Louisiana, are the largest barrier island arc in the northern Gulf of Mexico. The islands are remnants of the relict St. Bernard Delta Complex of the Mississippi River and trend north to south unlike the rest of the east-west trending barrier island chains in the northern Gulf of Mexico (Penland and others, 1988). As a result of the barrier chain's remote geographic position and lateral extent, it has been impacted by numerous storms throughout the past century.

Four historical maps of the Chandeleur Islands were used in this analysis to help develop a better understanding of the geomorphic configuration and position of the islands and Biloxi Marshes behind the islands for a time period extending back more than a century before the earliest U.S. Coast Survey maps of the islands were produced. Two maps produced by French geographer J.N. Bellin in 1744 (fig. 2) and 1764 (fig. 3) show similar representations of the location and extent of the islands (app. A–1). The 1778 map produced by British geographer G. Gauld (fig. 4) and the 1845 map produced by an unknown author (fig. 5) show the islands having a similar shape to those on the Bellin maps; however, the location and extent of the Biloxi Marshes to the west of the islands differ on all four maps. Thus, they should be viewed with caution because the various mapmakers' interpretations are not consistent, the dates of the actual surveys are not well documented, and navigation was primitive. Detailed prints of all four historical maps are in the Pontchartrain Institute for Environmental Sciences library at the University of New Orleans.

The barrier island and marshes depicted in the 1778 map by Gauld (fig. 4) are the best representation of the configuration prior to the influence of humans on delta processes. Shorelines that are more resilient to subsidence and erosion than marsh and barrier island shorelines are, such as the Mississippi and Alabama shorelines and the shorelines of Lakes Pontchartrain and Borne (Louisiana Geological Survey, 2008), appear in a similar configuration in Gauld's map to more recent maps, such as the much used 1932 topographic map of Louisiana by the U.S. Geological Survey. In the 1778 map by Gauld, the Chandeleur Islands are shown as two robust barriers separated by a large tidal inlet. The northern islands in 1778 included what became Errol Island until 1916 and Curlew Island until 1951, when Grand Gosier and Curlew became separate islands (figs. 1 and 4). The southern island in 1778 is Breton Island in a position seaward of the northern island. Also apparent is the extension of relict distributary channels along the shoreline of the Biloxi Marshes extending seaward towards the islands.

Hurricane History

The Chandeleur Islands have been impacted by 9 major storms during the 20th and 21st centuries; however, more than 40 hurricanes of varying strengths have impacted southeast Louisiana during the same time period (table 1; Williams and others, 1992; Yamazaki and Penland, 2001; Stewart, 2004; Knabb and others, 2005). Ten storms were selected for this investigation (see fig. 1). Storms were identified as significant on the basis of proximity to the Chandeleur Islands (passed within 150 km) and intensity (winds more than 119 km/h). A 1947 hurricane, estimated to be Category 1 or 2 on the Saffir-Simpson Hurricane Scale, was included in the analysis when other Category 1 and 2 storms were excluded because the 1947 hurricane passed directly over the southern Chandeleur Islands (fig. 1).

Hurricanes Frederic (1979), Elena (1985), Georges (1998), and the 1916 hurricane all passed within 120 km of the islands to the east (fig. 1). During the passage of these storms the eastern eye wall of the storm, where storm surge and windspeeds are the greatest, was seaward (east) of the islands. The 1915 hurricane, the 1947 hurricane, and Hurricanes Camille (1969) and Katrina (2005) passed landward (west) of

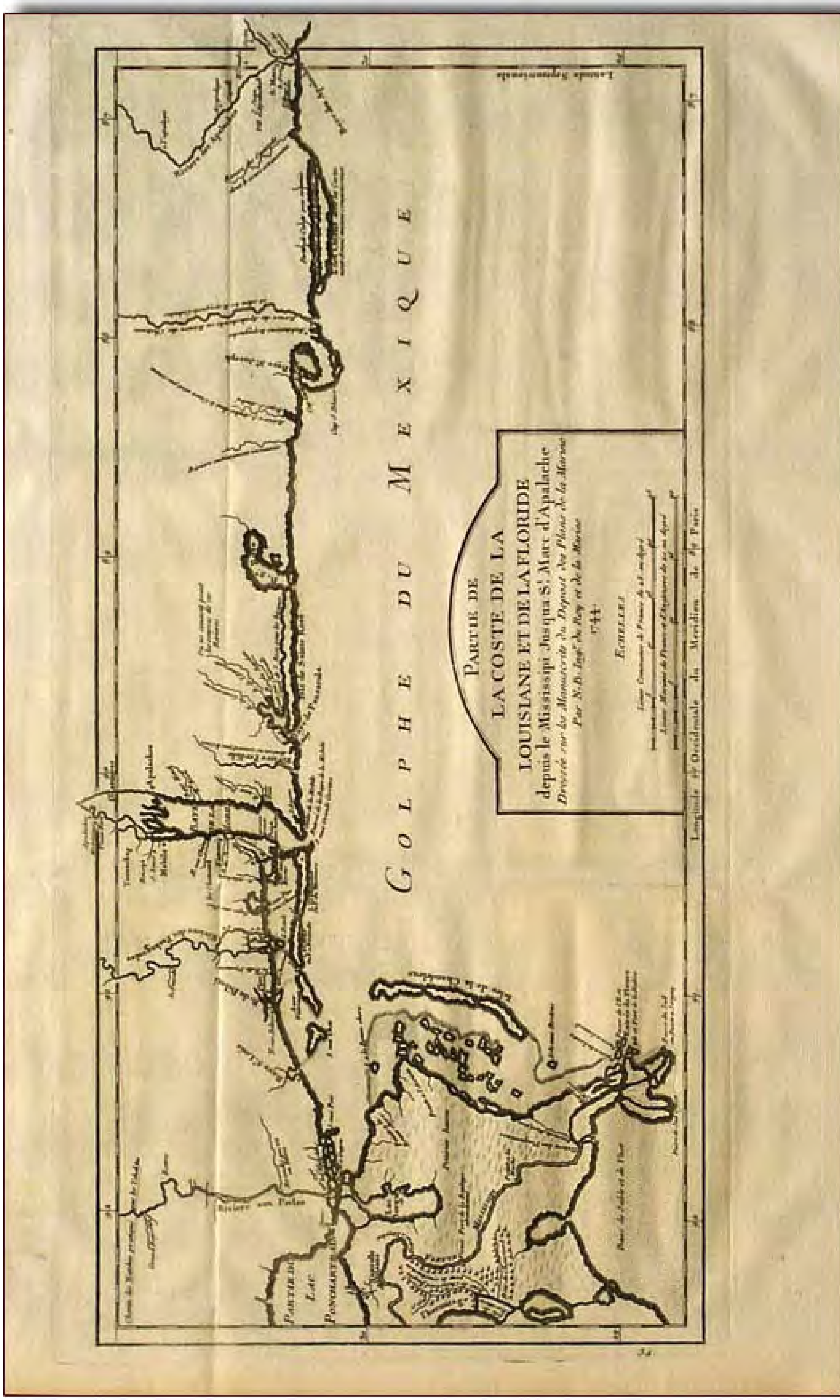

Figure 2. Historical map of the northern Gulf of Mexico by Bellin, 1744, showing the position of the Chandeleur Islands (on file at the University of New Orleans Pontchartrain Institute for Environmental Sciences library).

Figure 3. Historical map of southeastern Louisiana by Bellin, 1764, showing the position of the Chandeleur Islands (on file at the University of New Orleans Pontchartrain Institute for Environmental Sciences library).

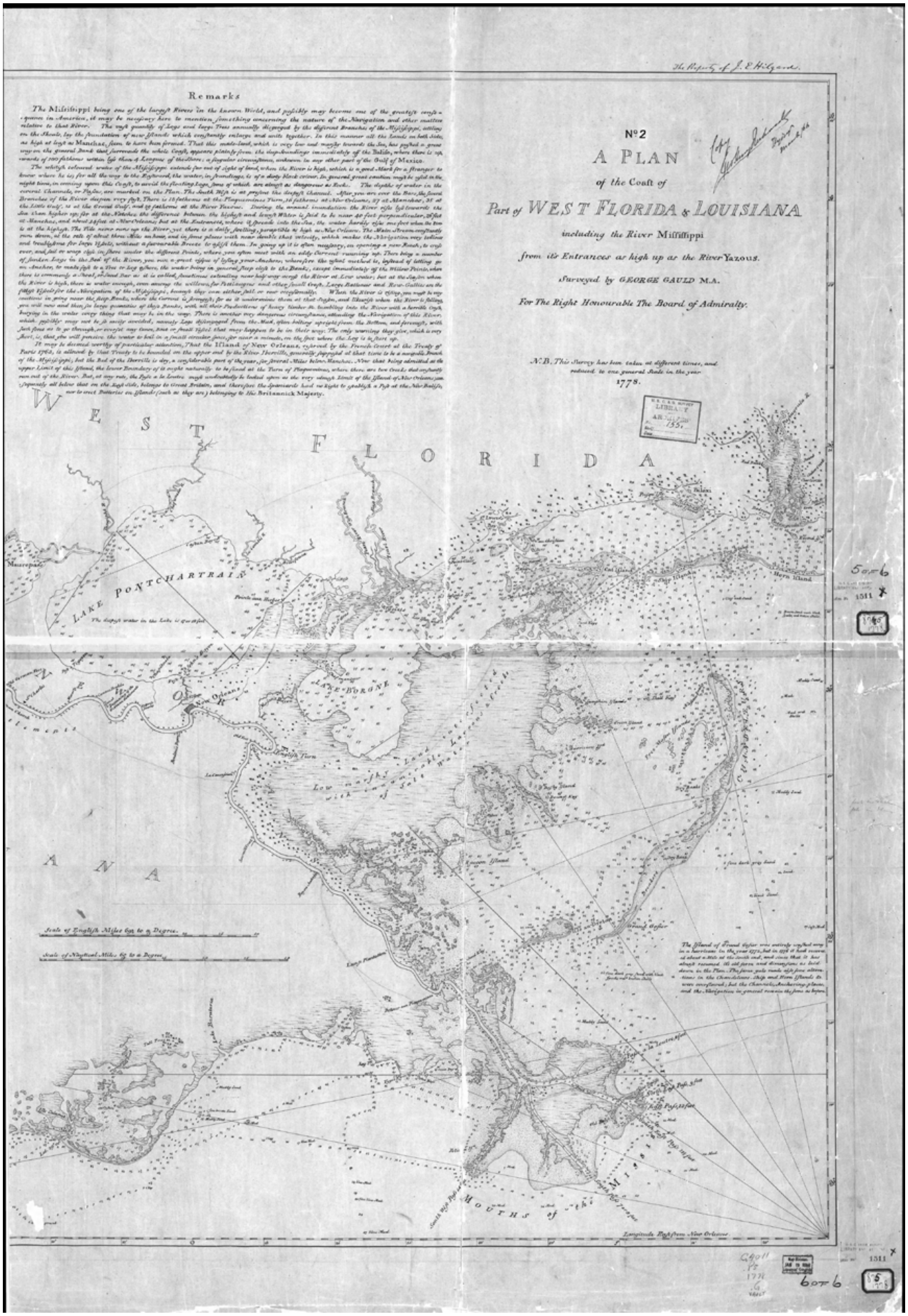

Figure 4. Portion of a larger historical map of the State of Louisiana by Gauld, 1778, showing the Chandeleur Islands and southeastern Louisiana (on file at the University of New Orleans Pontchartrain Institute for Environmental Sciences library).

Figure 5. Historical map of the State of Louisiana showing the position of the Chandeleur Islands in 1845 (by an unknown author; on file at the University of New Orleans Pontchartrain Institute for Environmental Sciences library).

Table 1. A list and descriptions of the major hurricanes to impact the Chandeleur Islands, La., in the 20th century and the dates of the prestorm and poststorm imagery used for this analysis.

Year	Date of landfall	Name	Description	Prestorm imagery date	Poststorm imagery date
1915	Sept. 29	No. 6	4-m storm surge was reported in New Orleans, La. Storm surge at Grand Isle, La., was estimated at 3 m; nearly the entire island was under water.*	1855	1922
1916	July 5	No. 2	Made landfall near Gulfport, Miss., with >190 km/h winds, crossing the Chandeleur Islands, La., as a strong Category 3 storm.&	1855	1922
1947	Sept. 19	No. 4	>2.5 m of water flooded New Orleans from this hurricane that tracked directly over the city, generating a surge that easily overtopped the region's protective levees.*	1922	1951
1965	Sept. 9	Betsy	Passed into Louisiana on September 9 with winds >250 km/h after passing over southern Florida. Grand Isle was inundated with a nearly 3 m surge height. The entire island was covered, and the rest of the inundated area in Louisiana exceeded 12,000 km^2.*	1951	1965
1969	Aug. 17	Camille	One of the most violent storms ever to hit the U.S. mainland. Crossed the southern Chandeleurs as a Category 5 storm. A 6-m storm surge was recorded near New Orleans.*	1969	1969
1979	Sept. 12	Frederic	Made landfall in southern Alabama, crossing within 16 km east of the Chandeleur Islands.*	1978	1982
1998	Sept. 28	Georges	Made final U.S. landfall near Biloxi, Miss., with maximum sustained surface winds of 167 km/h and a minimum central pressure of 96,400,000 MPa. Maximum storm surge in Louisiana was >2.5 m at Point a la Hache. The storm severely eroded the Chandeleur Islands.**	1996	1998
2004	Sept. 16	Ivan	Made landfall just west of Gulf Shores, Ala., with winds of >190 km/h and an eye wall diameter of 60–80 km. The storm passed approximately 160 km to the east of the Chandeleur Islands.+	2004	2005
2005	Aug. 29	Katrina	Made landfall on the southern tip of Florida as a Category 1 storm before restrengthening in the Gulf of Mexico and passing into southern Louisiana as a Category 3 storm. Katrina made landfall by crossing the Mississippi River at Buras, La., and then continued north making a third landfall along the Louisiana-Mississippi border; however, hurricane-force winds extended for 320 km from the center of the massive 225-km-wide eye. The surge, which peaked along the Mississippi Gulf Coast at over 8 m, also flooded 80% of the city of New Orleans when several levees were breached.++	2004	2005

* From Williams and others (1992).

** From Yamazaki and Penland (2001).

+ From Stewart (2004).

++ From Knabb and others (2005).

& From National Hurricane Center (2008).

or directly over the islands (fig. 1). During storms that passed to the west, the islands were directly impacted by the eastern eye wall, and more erosion of the shoreline likely took place than during the passage of storms to the east of the islands.

Methods

Shoreline Change Analysis

Linear shoreline change measurements were made from early ground survey data and remotely sensed imagery. The vector shoreline data originated from a variety of sources including georeferenced U.S. Coast and Geodetic Survey (USCGS) topographic surveys (T-sheets) and USCGS hydrographic smooth sheets (H-sheets), black and white and color infrared aerial photography, and satellite imagery. The geometry of the 1855 shoreline is a compilation of an 1869 T-sheet for the southern islands and an 1855 T-sheet for the northern islands. Sources used to determine shoreline position in each of the analysis years are presented in table 2.

ESRI ArcGIS software, version 9.2 (Environmental Systems Research Institute, Inc., Redlands, Calif.), was used to complete all shoreline measurements by using the following steps: (1) obtain shoreline, (2) establish baseline and transects, and (3) calculate shoreline change for each time period relative to the offshore baseline (fig. 6). A more comprehensive documentation of methods, uncertainty analysis, and measurement accuracy can be found in McBride and others (1992), Morton and others (2004), and Martinez and others (2009).

Island Area Calculation

Island area was determined for the Chandeleur Islands for all years in which polygon shoreline data were available. The polygons represent the entire island boundary from the gulf shoreline to the backbarrier rather than a single line depicting the mean high water mark along the gulf shoreline of the islands.

Island area was plotted against time, and a trend line was fitted to the data, yielding a slope value. Where the trend line intersects with the x-axis (time), the y value (area) will be zero, yielding a date of estimated island conversion to an inner shelf shoal. Trend lines were determined for the entire dataset and also for two intervals within the dataset, one representing a period of lower storm frequency and the other representing a second period of higher storm frequency.

Table 2. Sources of imagery used in the determination of shoreline position of the Chandeleur Islands, La., for each of the analysis years.

[T-sheet refers to topographic sheets; B&W refers to black and white; CIR refers to color infrared]

Year	Original imagery type	Imagery source
1855	T-sheet	U.S. Coast and Geodetic Survey
1922	T-sheet	U.S. Coast and Geodetic Survey
1951	B&W aerial photography	University of New Orleans Pontchartrain Institute for Environmental Sciences
10-13-1965	B&W aerial photography	National Oceanic and Atmospheric Administration
04-1969	B&W aerial photography	Louisiana State University School of the Coast and Environment
10-1969	B&W aerial photography	Louisiana State University School of the Coast and Environment
1978	B&W aerial photography	Louisiana State University School of the Coast and Environment
1982	CIR aerial photography	National Oceanic and Atmospheric Administration
1996	CIR aerial photography	University of New Orleans Pontchartrain Institute for Environmental Sciences
1998	CIR aerial photography	University of New Orleans Pontchartrain Institute for Environmental Sciences
2002	QUICKBIRD satellite imagery	University of New Orleans Pontchartrain Institute for Environmental Sciences
2004	QUICKBIRD satellite imagery	University of New Orleans Pontchartrain Institute for Environmental Sciences
2005	QUICKBIRD satellite imagery	University of New Orleans Pontchartrain Institute for Environmental Sciences

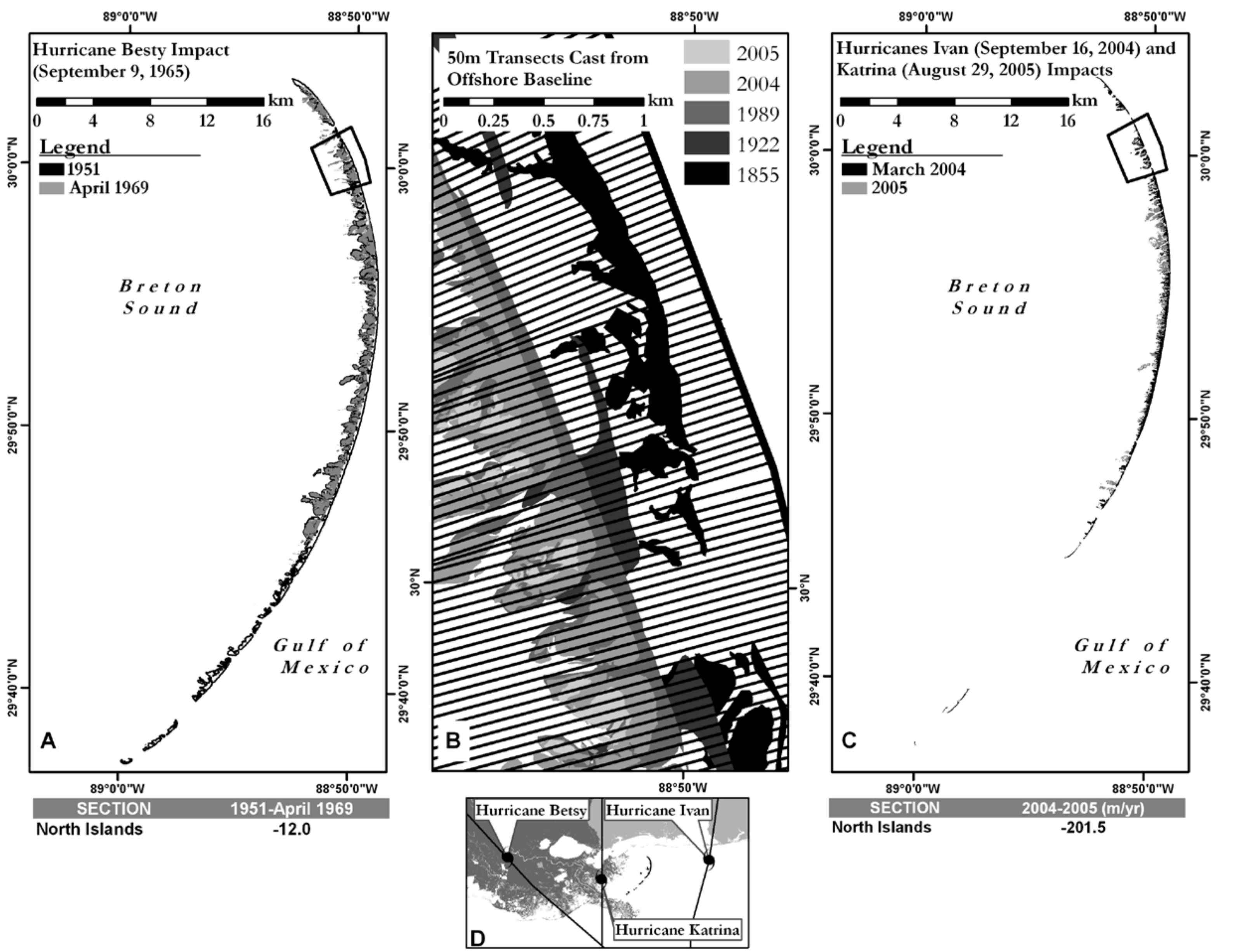

Figure 6. Linear shoreline change map of the northern Chandeleur Islands, La., for the time periods 1951–69 and 2004–5 (*A*–*D*), during which Hurricanes Betsy (1965) and Katrina (2005) impacted the islands (*D*). *A*, Linear shoreline change for the time period 1951–69. *B*, A depiction of transects established from the offshore baseline and extending landward perpendicular to the position of the shoreline. *C*, Linear shoreline change for the time period 2004–5.

Uncertainty Analysis and Accuracy of Measurements

Morton and others (2004) attributed error to three categories in this type of shoreline change analysis: (1) measurement errors that affect the accuracy of each shoreline position, (2) sampling errors that do not account for the along-strike variability of shoreline position, and (3) statistical errors associated with compiling and comparing shoreline positions. The largest errors exist because of scales and inaccuracies in the original surveys. T-sheets typically contain the largest measurement and sampling errors on the order of ±10 m; however, the influence of this error is reduced by long time periods between analysis years (McBride and others, 1992). Measurement and sampling errors for more shorelines produced from more recent satellite imagery decreased to ±1 m. These measurements take into account both Global Positioning System (GPS) positioning errors and errors resulting from the resolution of the imagery (Martinez and others, 2009). Error associated with statistical averaging of transect measurements was accounted for by using the standard deviation of the data.

Results

Northern Chandeleur Islands

Storm Impact and Poststorm Recovery

Shoreline change data documenting shoreline response to storm impacts of varying intensities and orientations were compiled for nine storms that affected the Chandeleur Islands between the years 1855 and 2005. Shoreline retreat distance from the baseline versus time is linear for the longest period used in this study (1855–2005). There are two periods during which the distance between the shoreline and the offshore baseline increased: (1) 1965–69 during the recovery period between Hurricanes Betsy and Camille and (2) between 2002 and 2004 just prior to the impact of Hurricane Ivan in 2004 (fig. 7).

The average rate of linear shoreline loss indicates that the distance from the shoreline to the offshore baseline will be equal to the distance from the bayside backbarrier marshes in 2005 to the baseline in 2035 (fig. 7). At this time, 2035, the shoreline will erode to the bayside position of the islands, and the marsh area is predicted to be zero. Transgressive sand bodies will remain for some time after, behaving much like the southern Chandeleur Islands (fig. 8; Miner and others, this volume). Conversion of the northern Chandeleur Islands to an inner shelf shoal, on the basis of the long-term averages in shoreline retreat rates (fig. 7) and average decreasing area of their extent (footprint) (fig. 9), is predicted to occur during the mid to late 2030s.

The rate of average annual shoreline change per year between storm impacts and in the interstorm periods (recovery phase) demonstrates a relatively constant rate (-2.0 m/yr) of shoreline retreat during calm periods that accelerates abruptly after storm impacts (fig. 10). Interestingly, the islands maintained a steady rate of erosion of about 12 m/yr between 1922 and 2004. There were brief periods of accretion in the period before Hurricane Camille and in the period after Hurricane Georges but before Hurricanes Ivan and Katrina. Because recovery periods do not reverse the trend of erosion for long periods of time, however, the storm impacts serve to accelerate the long-term retreat rate and have a lasting effect on barrier evolution.

Besides gulf shoreline erosion, the long-term evolution of the northern Chandeleur Islands is characterized by island arc rotation, a reflection of variability in rates of erosion along the shoreline that is possibly a response to altered wave climate associated with progradation of the modern Balize Delta Complex of the Mississippi River (Georgiou and Schindler, this volume; fig. 2). Material eroded from the gulf shoreline and nearshore is transported laterally to the north and south (Miner and others, this volume). Shoreface and gulf shoreline erosion is not balanced by increased land area in the backbarrier or a landward migration of the backbarrier shoreline (Miner and others, this volume); therefore, the islands have undergone thinning, causing a net decrease in area of 44.5 km^2 in 1855 to 4.7 km^2 in 2005.

The impacts of Hurricanes Ivan and Katrina along the northern Chandeleur Islands were extreme erosional events, and the average amount of linear shoreline erosion for the two storms combined (-201.5 m/yr) was unprecedented throughout the rest of the analysis time period (1855–2004). This period includes the effects of Hurricane Camille, which was a Category 5 storm when it passed directly over the southern Chandeleur Islands but only resulted in an average rate of linear erosion of -58.5 m/yr (fig. 9). When the collective impact of Hurricanes Ivan and Katrina is included in the long-term shoreline change analysis (1855–2005), the rate of erosion is in excess of -27 m/yr, more than twice the average rate of linear shoreline erosion (-12 m/yr) that was calculated for the time period prior to Hurricane Katrina (1855–2005).

The extraordinary shoreline erosion rates resulting from the impact of Hurricane Katrina were a consequence of both the intensity of the storm (windspeed, wave heights, current velocity, and storm surge elevation) and the storm track west of the islands. The analysis of hurricane impacts and shoreline data indicates that a major hurricane (Category 3 or stronger) crossing just west of the islands causes the most shoreline erosion (fig. 11).

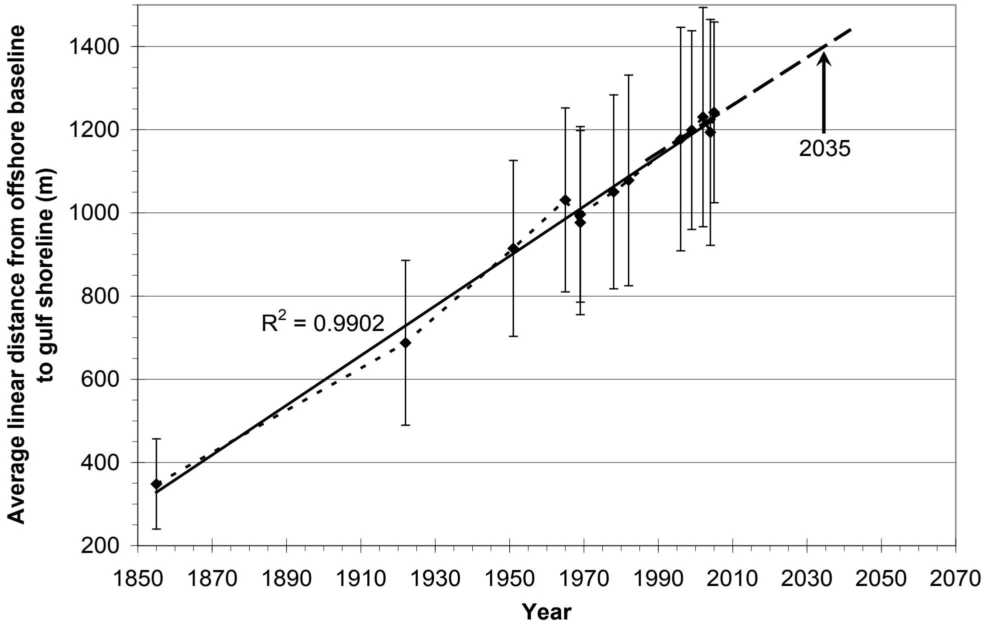

Figure 7. Average linear distance of the shoreline of the northern Chandeleur Islands, La., from the offshore baseline for 13 time periods between 1855 and 2005. The year 2035 is the date at which the rate of linear shoreline loss predicts that the distance from the shoreline to the offshore baseline will be equal to the distance from the 2005 bayside backbarrier marsh shoreline to the offshore baseline. At this time, 2035, the shoreline will erode to the bayside position of the islands, and the area of marsh is expected to be zero. The estimated date of disappearance for the northern Chandeleurs from the shoreline change data (2035) corresponds well with the estimated date of disappearance computed from the area change measurements (2037).

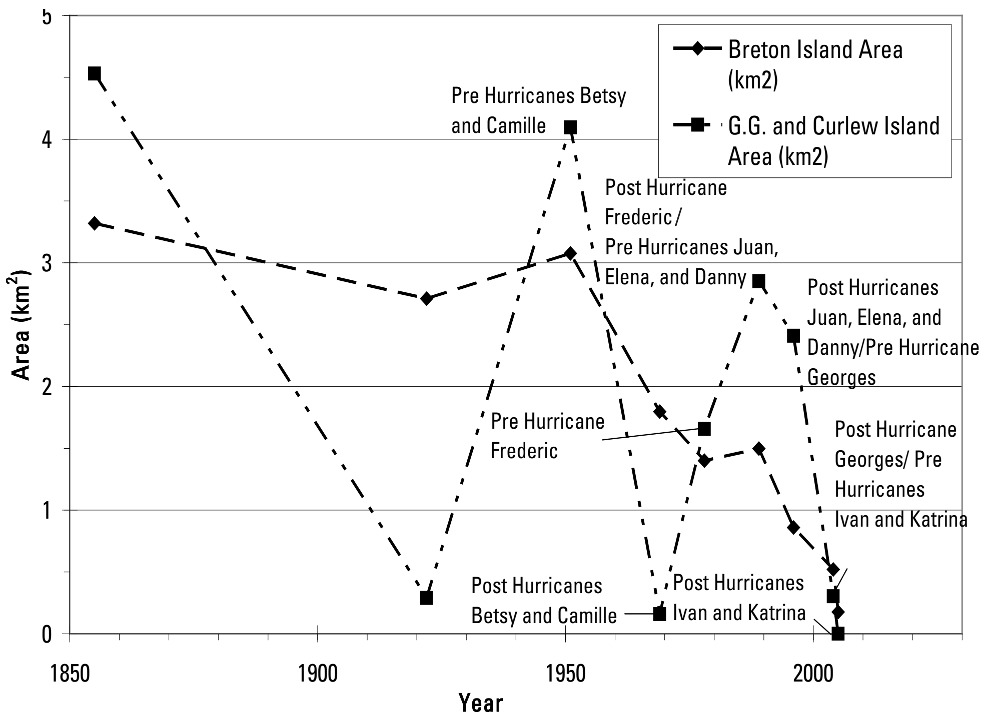

Figure 8. Average island area of the southern Chandeleur Islands, La. (Breton, Grand Gosier [G.G.], and Curlew), based on the measured average annual amount of land change between 1869 and 2005.

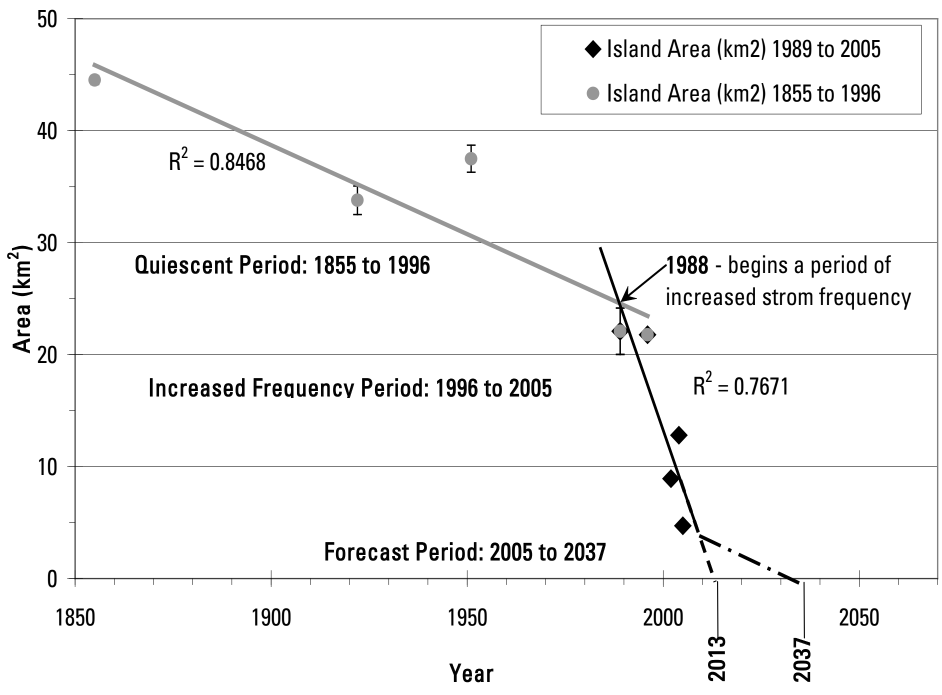

Figure 9. Area of the northern Chandeleur Islands, La., and trend lines for the two time periods 1855–1996 (gray line) and 1989–2005 (black line), which depicts two different trajectories for island survival on the basis of the frequency of storm activity. The dash-dot-dash line depicts the trajectory of the islands in their current state under lower frequency storm conditions such as existed during the earlier half of the 20th century and indicates a disappearance date of 2037.

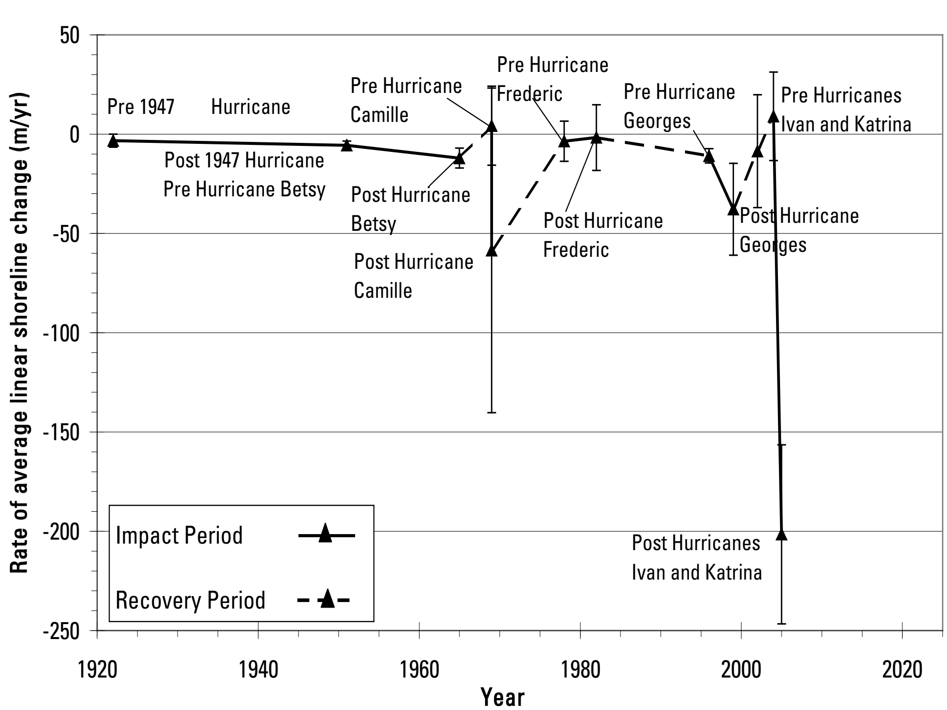

Figure 10. Average linear shoreline change of the northern Chandeleur Islands, La., beginning in 1922 and through the impact period of Hurricane Katrina in 2005. The solid portions of the line indicate periods of storm impact and reflect periods of increased shoreline erosion (average of more than -35.0 m/yr). The dashed portions of the line indicate periods of recovery between storm impacts. The recovery periods do not always signify an accretionary shoreline but often represent a period of less severe shoreline erosion rates than during previous impact periods and average -4.7m/yr.

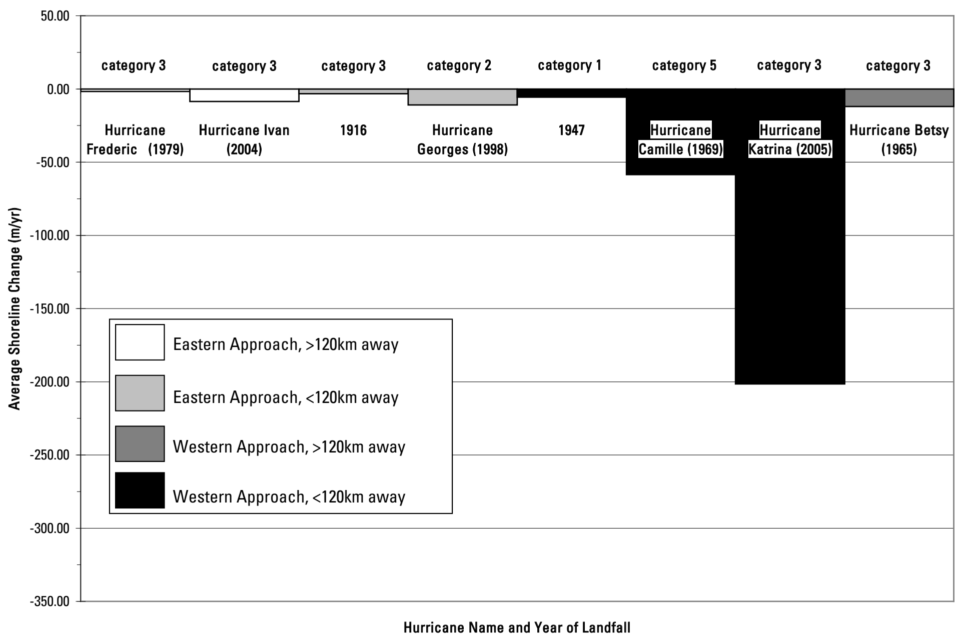

Figure 11. Average shoreline change of the northern Chandeleur Islands, La., of storms of varying intensities and storm tracks. Storms represented by black bars approached the islands from within 120 km to the west and caused the most severe shoreline erosion. Storms represented by dark gray bars passed the islands from more than 120 km to the west and were slightly less devastating than those that passed within 120 km to the west (in black). Storm tracks from the east within 120 km were even less devastating to the islands (represented by light gray bars), and the least amount of shoreline erosion occurred when storms passed more than 120 km to the east of the islands (represented by white bars).

Island Area Through Time

For time periods for which polygon shoreline data are available, island area change was calculated and related to storm impact frequency (fig. 9). Results from a linear regression analysis of the data demonstrate a land loss rate of -0.16 km^2/yr between 1922 and 1996 and a land loss rate of -1.01 km^2/yr between 1996 and 2005. There is an inflection point at 1996 that indicates a shift from a relatively quiescent period with a storm recurrence interval of five storms within a period of 141 years to a period of high-frequency storms between 1996 and 2005 with a storm recurrence interval of five storms within a period of 9 years. By projecting trends calculated from the linear regression analysis of island area change through time, the expected date of the conversion of the northern Chandeleur Islands to an inner shelf shoal falls between 2013 and 2037 (fig. 9). The earlier date is based on a projected storm frequency consistent with that of the past decade, whereas the later date represents a projected low storm recurrence interval similar to that for the period from 1922 to 1996.

Southern Chandeleur Islands

Storm Impact and Recovery

The southern Chandeleur Islands (fig. 2), which include Breton Island, Grand Gosier Islands, Curlew Island, and Errol Island (historical), encompass a different storm impact response and mode of recovery than do the northern Chandeleur Islands (fig. 8). Like the northern barrier arc, the southern Chandeleur Islands are characterized by shoreface retreat; however, major storm impacts result in almost complete island destruction and conversion to inner shelf shoals. During extended periods of calm weather following storm impacts, new islands emerge along this sector. Because the islands are completely destroyed during storms, it is difficult to relate storm impacts to shoreline position. Moreover, island area change through time has not been linear because relatively long periods of calm weather produce more robust islands. During long-term periods (more than 100 years), however, the rate of shoreline retreat was approximately -15 m/yr for the time period from 1869 to

1996. Between 1869 and 2005 island area decreased from 48.3 km^2 to 1.7 km^2. The following sections provide the results of the shoreline change analysis in reference to storm impact frequency and are presented on the basis of the time periods for which shoreline data exist.

1855–1922

The southern Chandeleurs were impacted by three major hurricanes (1889, 1915, and 1916) between 1855 and 1922. Shoreline data from 1869 show a robust Errol Island (later named Curlew Island) with a sandy shoreline backed by mangrove swamp. As a result of the three major hurricanes, the 1922 shoreline configuration comprised a discontinuous series of intertidal shoals. Combined island area for the southern Chandeleurs decreased from 7.8 km^2 to 3.0 km^2 during this time period.

1922–51

By 1951, a new set of islands (Grand Gosier and Curlew) had emerged along this southern stretch of shoreline. Between 1922 and 1951, the 1947 hurricane (Category 2) made landfall along the southern Chandeleur Islands, the only major storm during this time period to impact the islands. The 1947 hurricane did not result in total island destruction and submergence, similar to the multiple hurricane impacts during the 1855–1922 time period. Island area for the southern Chandeleurs increased more than twofold from 3.0 km^2 in 1922 to 7.2 km^2 in 1951.

1951–69

The time period covering 1951–69 included two major hurricanes, Betsy (1965) and Camille (1969). Shoreline data from 1969 (post-Camille) show that once again the robust barrier islands were segmented into an intertidal shoal dotted with small sandy islets. Island area decreased more than threefold during this time period from 7.2 km^2 to 2.0 km^2.

1969–78

During the time period between 1969 and 1978, no major storms impacted the study area. The islands responded to this calm period by expanding laterally, broadening, and gaining elevation (Otvos, 1981). Island area increased from 2.0 km^2 in 1969 to 3.1 km^2 in 1978.

1978–89

The time period between 1978 and 1989 was characterized by smaller storms that did not have major impacts on the southern Chandeleurs. Hurricane Frederic in 1979 had the greatest impact, which is well documented by Kahn and Roberts (1982) and Nummedal and others (1980). By 1989, however, the islands resembled the form of the 1978 configuration. Island area increased from 3.1 km^2 to 4.3 km^2.

1989–96

The timespan from 1989 to 1996 was another relatively calm period. Hurricane Opal in 1995 made landfall along the Florida Panhandle and was the only major storm that impacted the Chandeleur Islands during this period. The 1996 shoreline shows that Curlew Island maintained much of its area and remained fixed. The downdrift spits on Grand Gosier Islands were destroyed, decreasing island area along this sector from 4.3 km^2 in 1989 to 3.3 km^2 in 1996. Breton Island was breached into three segments, and area was reduced from 1.5 km^2 in 1989 to 0.9 km^2 in 1996 and has remained segmented since.

1996–2005

Between 1996 and 2005 Hurricanes Georges (1998), Isidore (2002), Ivan (2004), and Katrina (2005) had major impacts on the southern Chandeleur Islands. In 1996 the total area for the southern Chandeleur Islands was 3.3 km^2. Shoreline data from 1999 (post-Georges) show that once again the southern islands were reduced to a series of small islets. By 2004 Curlew Island was supratidal as a thin linear barrier, but that same year Ivan transformed the shoreline into sparse sandy islets. The following year, Hurricane Katrina destroyed Curlew and Grand Gosier Islands, leaving only 1.8 km^2 of Breton Island supratidal along the southern Chandeleur Islands.

Discussion

Hurricane Frequency, Trajectory, and Intensity

Hurricane impact to the Chandeleur Islands is dependent upon storm intensity, path, and duration, and because of this, the geomorphic response to each storm and subsequent recovery are highly variable. The long-term (1855–2005) evolution of the northern islands documented in this study, however, has been characterized by a continual decrease in island area from 44.5 km^2 to 4.7 km^2, a reduction that was driven by storm impacts. Almost instantaneously, major hurricanes substantially increase the rates of shoreline retreat and reduction in island area. Any increase in storm frequency and intensity rapidly accelerates the land loss, and with each storm impact the islands become less capable of a recovery to prestorm conditions as sediment is removed from the active sediment transport system (Miner and others, this volume; Georgiou and others, this volume).

The highly variable geomorphic response of the Chandeleur Islands to storm impacts was documented by Penland and others (1989) when they classified island response for three separate storms, Hurricanes Danny, Elena, and Juan, in 1985. Each of these storms had a different track, distance from the Chandeleurs, and intensity. Hurricane Danny crossed the central Gulf of Mexico and made landfall on the "Chenier Plain" (Kulp and others, 2005) portion of the Louisiana coast as a Category 1 hurricane with estimated surge levels at the Chandeleur Islands of about 1 m (Penland and others, 1989). Hurricane Elena passed to the north of the Chandeleur Islands making landfall near Biloxi, Miss., as a strong Category 3 storm with estimated surge elevations of more than 2 m at the Chandeleur Islands (Penland and others, 1989). Hurricane Juan was downgraded to a tropical storm as it headed east across the Mississippi River Delta and passed to the east of the Chandeleurs making landfall along the Alabama coast with estimated surge levels of more than 2 m at the Chandeleur Islands (Penland and others, 1989).

Hurricane Danny resulted in minor beach erosion, dune scarping, and landward-directed overwash fans. Hurricane Elena resulted in beach erosion, seaward-directed overwash fans, dune scarping, overwash scour, and island breaching. Hurricane Juan produced major beach erosion, landward-directed overwash fans, island breaching, overwash scour, and severe dune destruction (Penland and others, 1989). It is interesting to note that, even though Juan was a weak tropical storm when it passed the Chandeleurs, the storm response was characterized by severe dune erosion, possibly attributable to the short recovery time between Juan and the two previous storms. The results from Penland and others (1989) emphasized the control that storm track, intensity, and frequency have on barrier geomorphic response and provide a means to understand and predict geomorphic response on the basis of the storm characteristics.

In this investigation the storm track was identified as a key factor in estimating shoreline erosion rates from a given storm (fig. 11). Hurricanes Camille and Katrina caused the most severe rates of shoreline erosion on the northern islands, -58.5 and -201.5 m/yr, respectively (fig. 11). The high rates of erosion are attributed to the storms' trajectories and proximity to the Chandeleur Islands. These storm paths (Camille and Katrina) placed the eastern eye wall (where winds are strongest and surge elevations are highest) directly over the northern islands, causing extensive shoreline erosion. Because the storm path was landward of the islands, after the eye wall continued to track north, hurricane-force winds were directed in an offshore direction. This pattern, coupled with the ebbing surge, resulted in a net offshore transfer of sand. Other Category 3 storms of similar size to Katrina (such as Hurricane Betsy, which passed more than 120 km to the west of the islands) did not result in shoreline erosion rates of magnitudes similar to those caused by Hurricanes Camille and Katrina.

Historical Shoreline Evolution, Storm Impacts, and Future Scenarios

Northern Chandeleur Islands

In the midst of increasing rates of relative sea level rise and overall reduced sediment supply, as well as continual storm impacts, the northern Chandeleur Islands have been in a constant state of shoreline retreat and decreasing island area during the past century. A temporary reversal of shoreline erosion trends did take place between 1965 (post-Betsy) and 1969 (pre-Camille), and the shoreline prograded seaward (fig. 10). A second period of accretion occurred between the analysis years 2002 and 2004 during a recovery period following the impact of Hurricane Georges in 1998 and prior to the impacts of Hurricane Ivan in late 2004. During other recovery time periods between major storm events, the average rate of linear shoreline erosion slows considerably when compared to storm impact periods.

The amount of shoreline erosion of the northern Chandeleur Islands during the combined impact of Hurricanes Ivan and Katrina (-201.5 m/yr) is unprecedented for earlier time periods, which average -38.4 m/yr between 1922 and 2004 (fig. 10). As a result of the lack of similarity to other storms of record, it is unknown whether another erosional event of similar magnitude will take place again. On the basis of the entire available dataset for island area measurements (fig. 9), the northern islands will persist until 2037.

The northern Chandeleur Islands may reach a threshold of erosion that results in the transition to ephemeral sand bodies as early as 2013 if the level of storm frequency seen in recent decades persists (fig. 9). If storm frequency decreases to levels similar to the 1955–98 period, however, the islands may remain subaerial until 2037. At present sediment availability (Miner and others, this volume; Twichell and others, this volume; Flocks and others, this volume), the northern Chandeleur Islands will transition to ephemeral barrier island/shoal sand bodies between 2013 and 2037 (fig. 9).

The range of projected dates of island conversion to inner shelf shoal is within the next 30 years, stressing the vulnerability of the Chandeleur Islands to future storm impacts. These predictions are as much as an order of magnitude more rapid (30 versus 300 years) than those made just over decade ago by using the same methods (McBride and others, 1992). The differences between predictions made a decade ago and those resulting from our analysis are the increased storm frequency during the past decade and, specifically, the catastrophic erosional event associated with Hurricane Katrina in 2005 that greatly accelerated the rate of island area reduction and shoreline retreat.

Southern Chandeleur Islands

The southern Chandeleur Islands are ephemeral barrier islands undergoing early stages of transgressive submergence and conversion to an inner shelf shoal (Miner and others, this volume). Storm intensity and frequency are the major controls on island/shoal evolution. The islands are destroyed and converted to submerged shoals during periods of high storm frequency and historically have emerged and naturally rebuilt as relatively robust barrier shorelines during extended periods of calm weather. The time between 1969 (post-Camille) and 1998 (pre-Hurricane Georges) was a period of relative quiescence, during which Curlew and Grand Gosier Islands were able to recover from complete destruction and increase in area from 0.03 km^2 to 5.9 km^2. During this time, backbarrier marsh and mangrove swamp accreted in the shelter of the sandy shoreline, and extensive submerged grass bed meadows blanketed the sea floor landward of the islands (based on aerial photography used during this study). This period of relative quiescence was followed by the stormiest period on record for the northern Gulf of Mexico, during which four major hurricanes resulted in the destruction and submergence once again of these islands.

The submergence of the southern islands after storms and subsequent reemergence at a location landward of their prestorm positions result in the landward translation of the entire barrier island. This landward barrier retreat in response to relative sea level rise is not driven by storm-induced overwash processes; instead, fair weather hydrodynamics and attendant sediment transport processes reorganize the islands into subaerial features. This trend is in contrast to the northern islands, where minimal landward translation of the subaerial barrier occurs (Miner and others, this volume). The disparity between the responses of the northern islands and the southern islands to storms, storm recovery periods, and sea level rise is attributable to the absence of a well-established backbarrier marsh along the southern chain (with the exception of small portions of Breton Island) (Miner and others, this volume). As the northern islands erode and are stripped of sand during storms, this backbarrier marsh becomes exposed, and because it is composed of a thick organic root mat within a cohesive fine-grained sediment matrix, it resists rapid erosion and prohibits island submergence.

Conclusions

The erosional impact of Hurricane Katrina on the northern Chandeleur Islands is unprecedented within the rest of the dataset used in this study. The impact of Hurricane Katrina highlights the vulnerability of the northern Chandeleur Islands to major storm events. Island area measurements available between 1855 and 2005 indicate that the northern Chandeleur Islands can be expected to be completely converted to ephemeral barrier island/shoals between 2013 and 2037. In an environment of frequent storm impacts, such as has been occurring during the past two decades, the projected date of transition to ephemeral sand bodies is 2013. In their present state, if storm frequency subsides to conditions such as existed during the early part of the 20th century, the projected date of island transition is 2037. The trajectory of the storm track with respect to the position of the islands stands out as a key determinant of shoreline response to a storm impact. Storms that pass within 120 km to the west of the islands result in the highest rates of shoreline erosion, and storms that pass more than 120 km to the east result in a relatively small amount of shoreline erosion.

As a result of the high storm recurrence interval during the past decade, the southern Chandeleur Islands of Curlew and Grand Gosier have been reduced to submerged shoals. These ephemeral islands have undergone submergence in the past as a result of storm impacts and subsequently emerged during periods of calmer weather. The ephemeral nature of these islands is attributed to the absence of a stabilizing backbarrier marsh (Miner and others, this volume). As the northern islands erode and island area is reduced to include only the sandy shoreline deposits, with no backbarrier marsh, they will begin to behave similarly to the southern ephemeral islands.

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Appendix A–1. Shoreline Change Final Report
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