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ORIGINAL

Hurricane impact and recovery shoreline change analysis of the Chandeleur Islands, Louisiana, USA: 1855 to 2005

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Abstract Results from historical (1855–2005) shoreline change analysis conducted along the Chandeleur Islands, Louisiana demonstrate that tropical cyclone frequency dominates the long-term evolution of this barrier island chain. Island area decreased at a rate of −0.16 km^2/year for the relatively quiescent time period up until 1996, when an increase in tropical cyclone frequency accelerated this island area reduction to a rate of −1.01 km^2/year. More frequent hurricanes also affected shoreline retreat rates, which increased from −11.4 m/year between 1922 and 1996 to −41.9 m/year between 1982 and 2005. The erosional impact caused by the passage of Hurricane Katrina in 2005 was unprecedented. Between 2004 and 2005, the shoreline of the northern islands retreated −201.5 m/year, compared with an average retreat rate of −38.4 m/year between 1922 and 2004. A linear regression analysis of shoreline change predicts that, as early as 2013, the backbarrier marsh that serves to stabilize the barrier island chain will be completely destroyed if 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. 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 characterize the entire island chain.

Shea Penland – deceased

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Introduction

The Chandeleur Islands are composed of 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 important because they (1) attenuate storm impacts for mainland Louisiana and Mississippi (Stone and Orford 2004; Stone et al. 2005), (2) regulate estuarine salinity and circulation (Reyes et al. 2005) for an approx. 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, brown pelicans, piping plovers, and least terns (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 to 1,800 years B.P. (Frazier 1967; Törnqvist et al. 1996). They are separated from the Louisiana mainland wetlands by the approx. 40-km-wide Breton and Chandeleur Sounds. As a result of this geographic position, they are susceptible to the effects of almost any major storm entering the northern Gulf of Mexico, and have been impacted by ~42 hurricanes since the early 1900s.

It has been suggested that the long-term evolution of the Chandeleur Islands is governed by tropical cyclone impacts, which result in a long-term net land loss driven by insufficient post-storm recovery, leading to the islands' conversion into an inner shelf shoal through transgressive submergence (Kahn and Roberts 1982; Penland et al. 1983, 1988; Kahn 1986; Suter et al. 1988). McBride et al. (1992) proposed 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. However, these predictions did not account for the increase in northern Gulf of Mexico storm

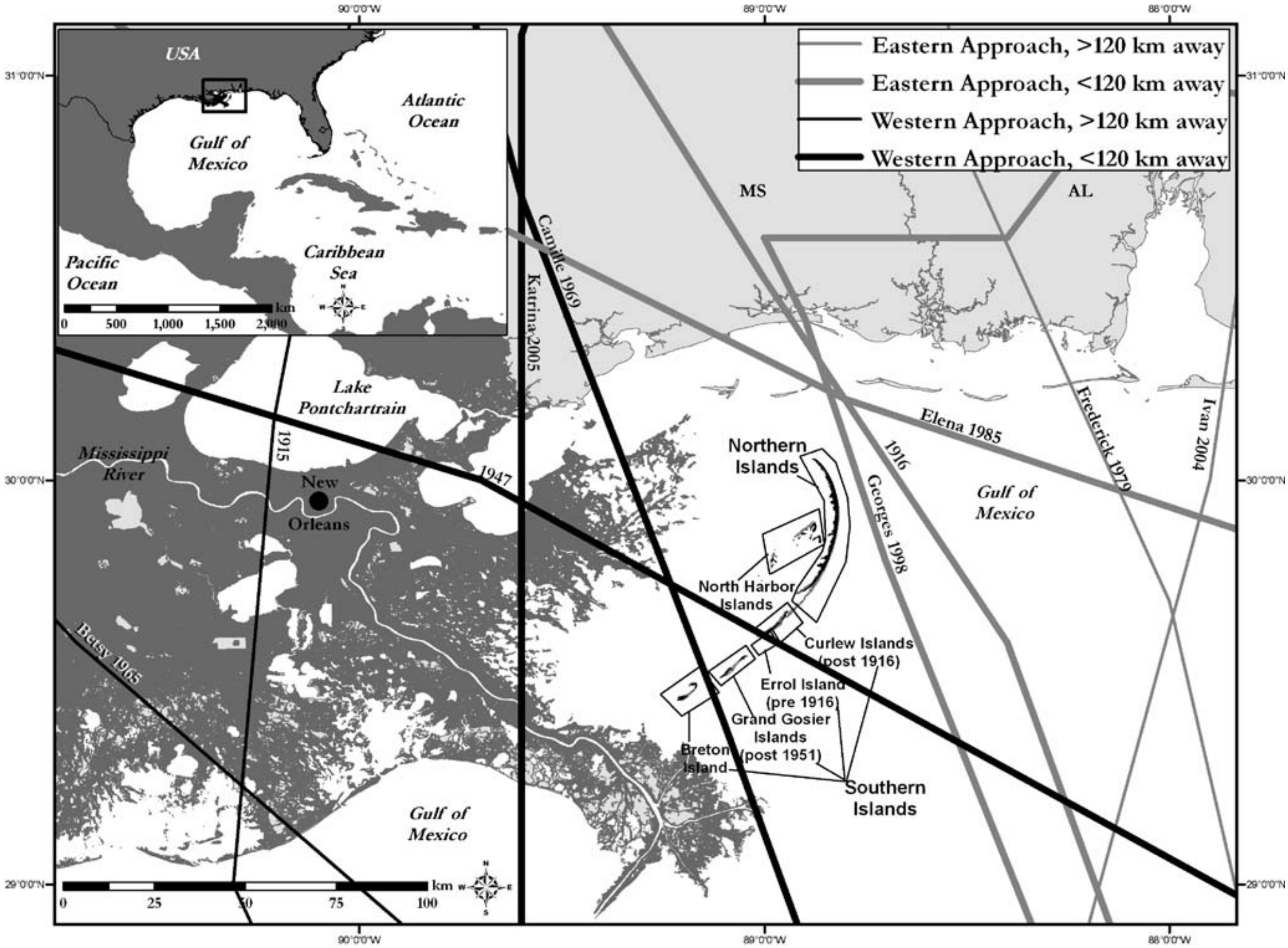

Fig. 1 Map depicting the storm paths of ten major storms impacting the Chandeleur Islands in southeastern Louisiana during the 20th century. The Chandeleur Islands are shown in *black* near the center of the figure, and the individual islands that make up the island arc are outlined in *boxes and labeled*.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

frequency and intensity that ensued in the decade following their analysis.

Recent increased storminess associated with the impacts of Hurricanes Georges, Ivan, and Katrina during the past decade is unprecedented for the Chandeleur Islands during the historic record. These multiple, closely spaced (temporally) storm impacts culminated with Hurricane Katrina (Aug. 2005), completely inundating the islands, removing >90% of the sand, exposing backbarrier marsh along the gulf shoreline to wave attack (Miner et al. 2009), and reducing total island area by ~50%. 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 historic shoreline position and island area changes for several time periods (dating to 1855) to hurricane impact frequency and storm intensity. The overall goal is to forecast the timeframe of island conversion into an inner shelf shoal. This study is a component of a more comprehensive investigation into the past, present, and future evolution and geomorphology of the Chandeleur Islands (Lavoie 2009).

Hurricane history

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

Table 1 A list and description of the major hurricanes to impact the Chandeleur Islands in the 20th century, and the dates of the pre- and post-storm imagery used for this analysis

Year	Date	Name	Description (data sources)	Pre-storm imagery date	Post-storm imagery date
1915	29 Sep.	#6	4-m storm surge was reported in New Orleans. Grand Isle's storm surge was estimated at 3 m; nearly the entire island was under water (1)[a]	1855	1922
1916	5 Jul.	#2	Hurricane #2 made landfall near Gulfport, MS with >190 km/h winds, crossing the Chandeleur Islands as a strong Category 3 storm (2)	1855	1922
1947	19 Sep.	#4	Over 2.5 m of water flooded New Orleans from a September hurricane that tracked directly over the city, generating a surge that easily overtopped the region's protective levees (1)	1922	1951
1965	8 Sep.	Betsy	Hurricane Betsy passed into Louisiana on 8 September with winds over 250 km/h after passing over southern Florida. Grand Isle was inundated with nearly a 3 m surge height. The entire island was covered, and the rest of the inundated area in Louisiana exceeded 12,000 km^2 (1)	1951	1965
1969	17 Aug.	Camille	Hurricane 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 (1)	1969	1969
1979	12 Sep.	Frederick	Hurricane Frederick made landfall in southern Alabama, crossing within 16 km east of the Chandeleur Islands (1)	1978	1982
1998	28 Sep.	Georges	Hurricane Georges made final U.S. landfall near Biloxi, MS with maximum sustained surface winds of 167 km/h; the minimum central pressure was 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 (3)	1996	1998
2004	16 Sep.	Ivan	Hurricane Ivan made landfall immediately west of Gulf shores, AL with winds of >190 km/h and an eye wall diameter of 60–80 km. The storm passed approx. 160 km to the east of the Chandeleur Islands (4)	2004	2005
2005	29 Aug.	Katrina	Hurricane Katrina made landfall on the southern tip of Florida as a Category 1 storm before re-strengthening in the gulf and passing into southern Louisiana as a Category 3 storm. Katrina made landfall crossing the Mississippi River at Buras, LA and then continued north, making a third landfall along the LA/MS border; however, hurricane force winds extended for 320 km from the center of a massive 225-km-wide eye. The surge that peaked along the Mississippi Gulf Coast at over 8 m also flooded 80% of the city of New Orleans, Louisiana when several levees were breached (5)	2004	2005

[a] Data sources: (1) Williams et al. (1992), (2) National Hurricane Center (2008), (3) Yamazaki and Penland (2001), (4) Stewart (2004), (5) Knabb et al. (2005)

excluded, because it passed directly over the southern Chandeleur Islands (Fig. 1).

Hurricanes Frederic (1979), Elena (1985), Georges (1998), and the 1916 hurricane 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 wind speeds are the greatest, was seaward (east) of the islands. The 1915 hurricane, 1947 hurricane,

Table 2 Sources of imagery used in the determination of shoreline position for each of the analysis years

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
13 Oct. 1965	B&W aerial photography	National Oceanic and Atmospheric Administration
Apr. 1969	B&W aerial photography	Louisiana State University—School of the Coast and Environment
Oct. 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

and Hurricanes Camille (1969) and Katrina (2005) passed landward (west) of 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 is expected to have occurred 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 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, was used to complete all shoreline measurements 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. 2). Comprehensive documentation of methods, uncertainty analysis, and measurement accuracy can be found in McBride et al. (1992), Morton et al. (2004), and Martinez et al. (2009).

Island area calculation

Island area was determined for the Chandeleur Islands for all years in which a polygon shoreline was available. The polygons represent portions of the entire island 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 into 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 followed by the second period of higher storm frequency.

Uncertainty analysis and accuracy of measurements

Morton et al. (2004) attribute error to three categories in this type of shoreline change analysis, including (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 due to 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 with long time periods between analysis years (McBride et al. 1992). Measurement and sampling errors for more shorelines produced from more recent satellite imagery decrease to ±1 m, which takes into account both

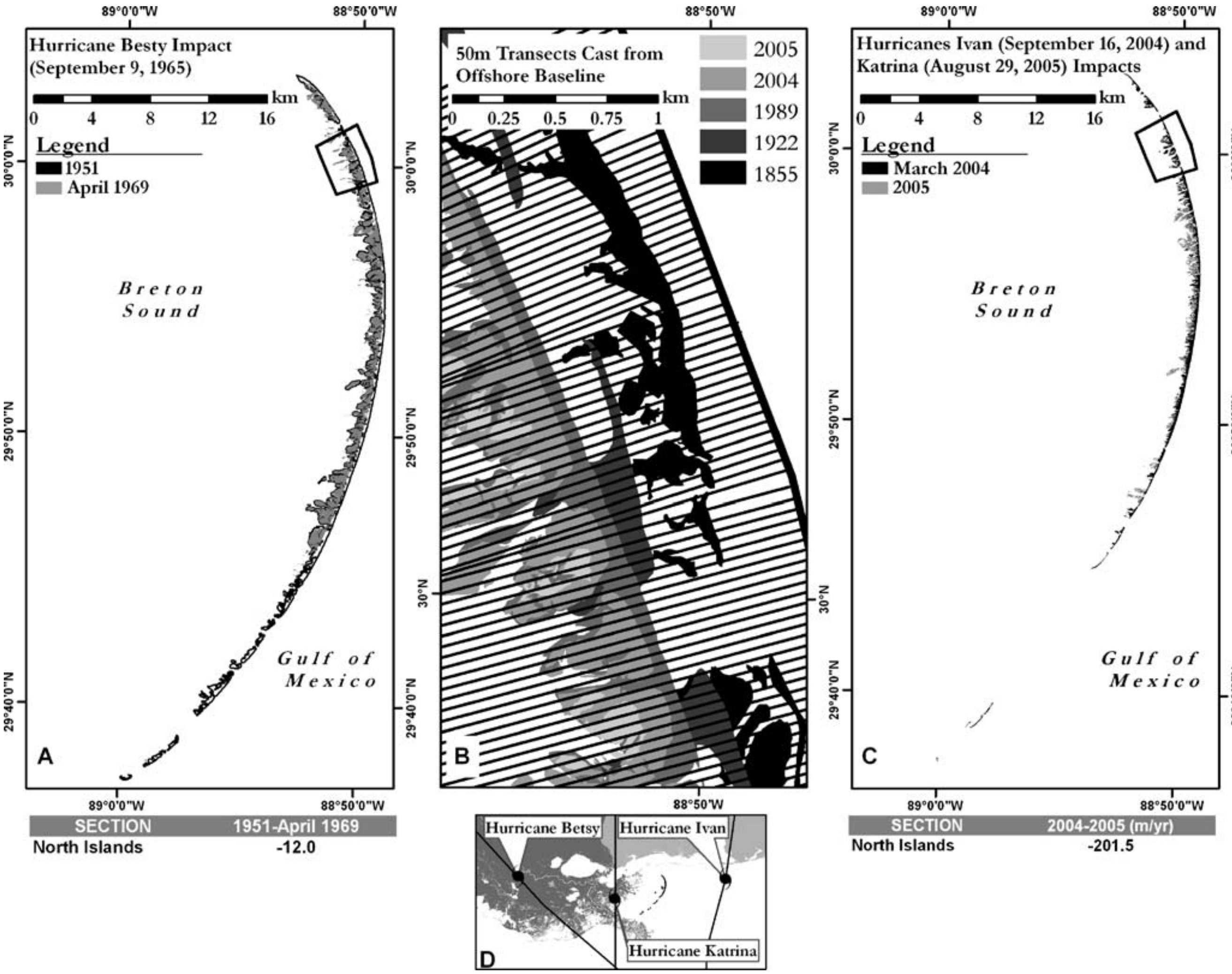

Fig. 2 Linear shoreline change map of the northern Chandeleur Islands for the time periods 1951 to 1969 and 2004 to 2005, during which time Hurricanes Betsy and Katrina impacted the islands, respectively. Also shown is a depiction of transects established from the offshore baseline and extending landward perpendicular to the position of the shoreline

GPS positioning errors and errors resulting from the resolution of the imagery (Martinez et al. 2009). Error associated with statistical averaging of transect measurements is accounted for using the standard deviation of the data.

Results

Northern Chandeleur Islands

Storm impact and post-storm 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 long term (1855 to 2005). There are two periods where the distance between the shoreline and the offshore baseline increased: (1) 1965 to 1969 during the recovery period between Hurricanes Betsy and Camille, and (2) between 2002 and 2004 during the post-Hurricane Georges recovery period, immediately prior to the impact of Hurricane Ivan in 2004 (Fig. 3).

The average rate of linear shoreline loss predicts 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 2033 (Fig. 3). At this time, the shoreline will erode to the bayside position of the islands, and the acreages of marsh area are expected to be zero. Transgressive sand bodies will remain for some time after, behaving much like the ephemeral southern Chandeleur Islands (Fig. 4; Miner et al. 2009). Conversion of the

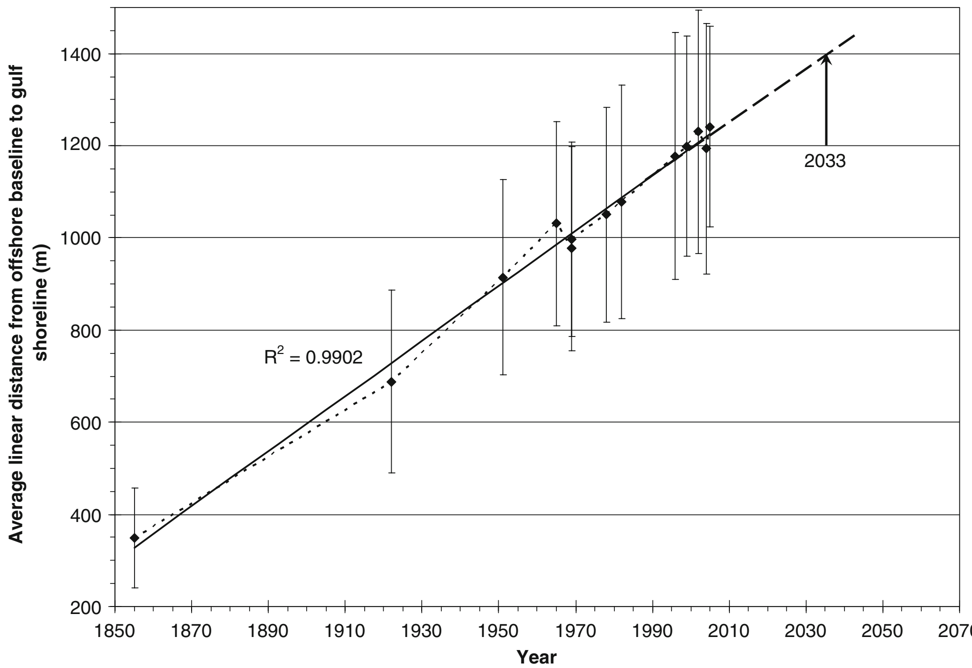

Fig. 3 Average linear distance of the northern islands shoreline from the offshore baseline for 13 time periods between 1855 and 2005. 2033 is the date at which the rate of linear shoreline loss predicts that the distance from the shoreline to the offshore baseline will be equal to the distance from the 2005 bayside backbarrier marsh shoreline to the offshore baseline. At this time, 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 (2033) corresponds well with the estimated date of disappearance computed from the area change measurements (2037)

northern Chandeleur Islands into an ephemeral shoal/barrier island chain, based on the long-term averages in shoreline retreat rates (Fig. 3) and average decreasing rate in their aerial extend (footprint; Fig. 5), is predicted to occur during the mid to late 2030s.

The rate of average annual shoreline change per year between storm impact and in the inter-storm periods (recovery phase) demonstrates a relatively constant rate (−2.0 m/year) of shoreline retreat during calm periods that accelerates abruptly (>−45.0 m/year) after storm impacts (Fig. 6). Interestingly, the islands maintain a steady rate of erosion of ~12 m/year between 1922 and 2004. Brief periods of accretion occurred pre-Hurricane Camille and post-Hurricane Georges/pre-Hurricanes Ivan and Katrina. However, because recovery periods do not reverse the trend of erosion for long periods of time, 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

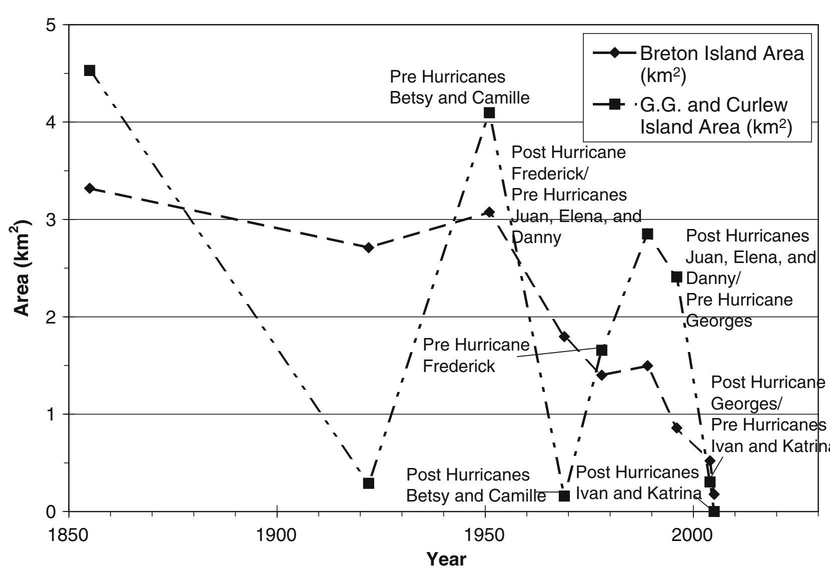

Fig. 4 The southern Chandeleur Islands' (Breton, Grand Gosier *G.G.*, and Curlew) average island area in square kilometers, based on the measured average annual amount of land change between 1869 and 2005

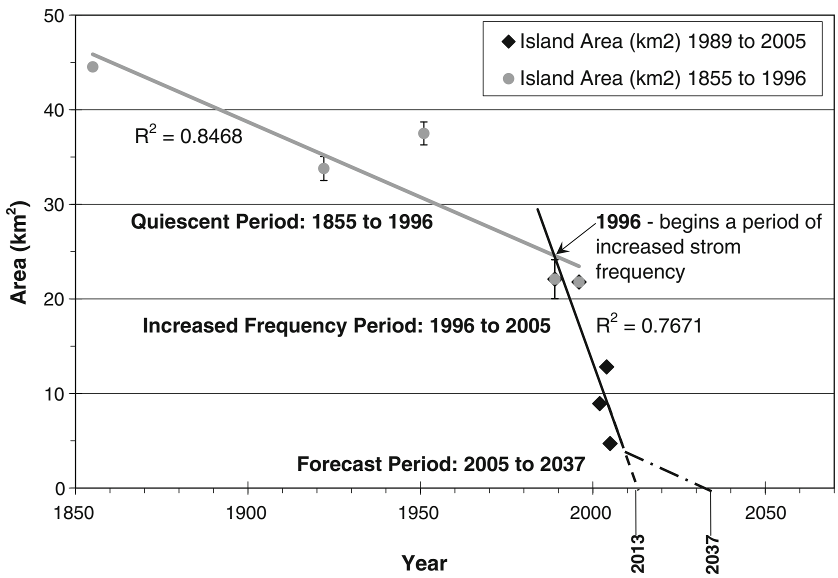

Fig. 5 Northern islands area (in square kilometers) and trend lines for the two time periods 1855 to 1996 (*grey line*) and 1989 to 2005 (*black line*), which depicts two different trajectories for island survival based on the frequency of storm activity. The *dash-dot-dash line* depicts the trajectory 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

(Miner et al. 2009; Fig. 2). Material eroded from the Gulf shoreline and nearshore is transported laterally to the north and south (Miner et al. 2009). Shoreface and Gulf shoreline erosion is not balanced by increased land area in the backbarrier or a landward migration of the backbarrier shoreline (Miner et al. 2009); therefore, the islands have undergone thinning, producing a net decrease in area of 44.5 km^2 in 1855 to 4.7 km^2 in 2005.

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/year) was unmatched throughout the rest of the time period (1855 to 2004). This includes the effects of Hurricane Camille, which was a Category 5 storm when it passed directly over the southern Chandeleur Islands, but which resulted in an average rate of linear erosion of −58.5 m/year (Fig. 5). When the collective impact of Hurricanes Ivan and Katrina is included in the long-term shoreline change analysis (1855–2005), the rate of erosion exceeds −27 m/year, more than twice the average rate of linear shoreline erosion (−12 m/year) that was calculated for the time period prior to Hurricane Katrina (1855–2004).

The extraordinary shoreline erosion rates resulting from the impact of Hurricane Katrina were a consequence of both the intensity of the storm (i.e., wind speed, wave

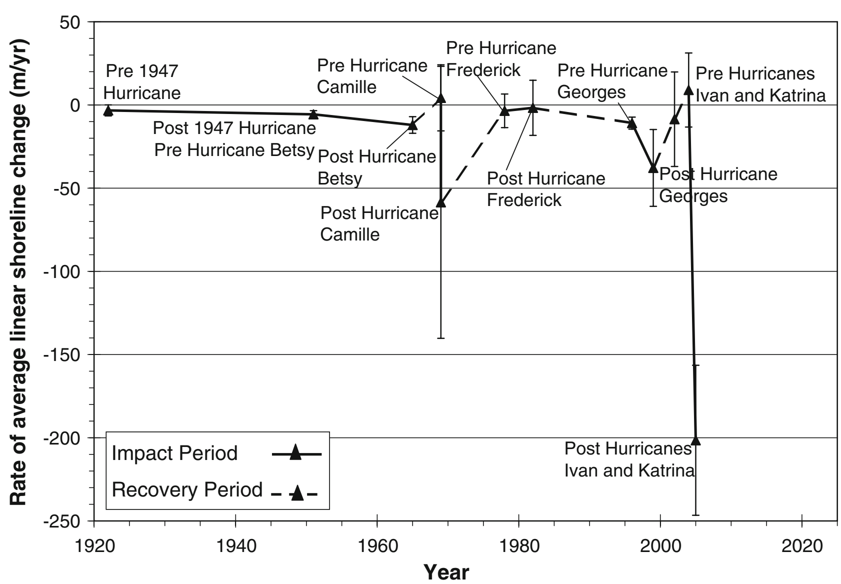

Fig. 6 Northern islands average linear shoreline change (in meters per year) beginning in 1922 through the Hurricane Katrina impact in 2005. The *solid portions* of the line indicate periods of storm impact, and reflect periods of increased shoreline erosion (average >−35.0 m/year). The *dashed portions* of the line indicate periods of recovery between storm impacts. The recovery periods do not always signify an accreationary shoreline during these time periods but often represent a period of less severe shoreline erosion rates than during the previous impact period, and average −4.7 m/year

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 immediately west of the islands causes the most shoreline erosion (Fig. 7).

Island area through time

For time periods where polygon shoreline data are available, island area change was calculated and related to storm impact frequency (Fig. 5). Results from a linear regression analysis of the data demonstrate a land loss rate of -0.16 km^2/year between 1922 and 1996, and a land loss rate of -1.01 km^2/year 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 9-year period. By projecting trends calculated from the linear regression analysis of island area change through time, the expected date of the northern Chandeleur Islands' conversion into an inner shelf shoal falls between 2013 and 2037 (Fig. 5). 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 the northern Chandeleur Islands (Fig. 4). 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 into inner shelf shoals. During extended periods of calm weather following storm impacts, new islands reemerge 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. However, during long-term periods (>100 years), the rate of shoreline retreat was approx. −15 m/year for the time period from 1869 to 1996. Island area decreased from 48.3 km^2 to 1.7 km^2 between the years 1869 to 2005. The following subsections provide the results of the shoreline change analysis in terms of 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. After the three major hurricanes, the 1922 shoreline configuration shows a discontinuous series of intertidal shoals. The combined island area for the southern Chandeleurs decreased from 7.8 km^2 to 3.0 km^2 during this time period.

1922–1951 By 1951, a new set of islands (Grand Gosier and Curlew) had emerged along this stretch of shoreline. Between 1916 and 1951, the 1947 hurricane (Category 2)

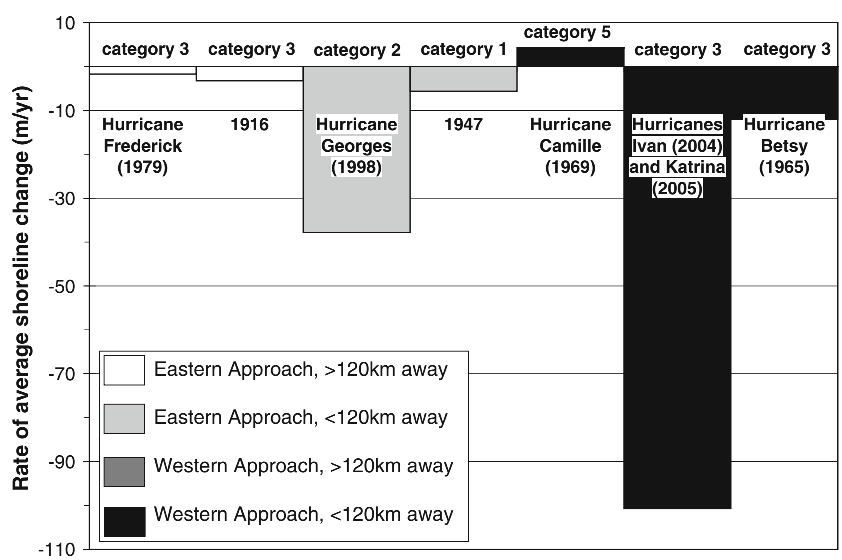

Fig. 7 Northern islands average shoreline change (m/year) for storms of varying intensities and storm tracks. Storms depicted in *black* approach the islands from within 120 km to the west, and cause the most severe shoreline erosion. Storms depicted in *dark grey* pass the islands from >120 km to the west, and are slightly less devastating than those passing within 120 km to the west. Storm tracks from the east within 120 km are even less devastating to the islands (*light grey*), and the least amount of shoreline erosion can be expected to occur when storms pass more than 120 km to the east of the islands (*white*)

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 to 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.

1951–1969 The time period covering 1951 to 1969 included two major hurricanes Betsy (1965) and Camille (1969). Shoreline data from 1969 (post-Camille) show that, once again, the formerly 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.

1969–1978 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.

1978–1989 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 Nummedal et al. (1980) and Kahn and Roberts (1982). However, by 1989 the islands resembled the form of the 1978 configuration. Island area increased from 3.1 km^2 to 4.3 km^2.

1989–1996 1989 to 1996 was another relatively calm period. Hurricane Opal in 1994 made landfall along the Florida Panhandle and was the only major storm that impacted the Chandeleur Islands. 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 the 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 the area was reduced from 1.5 km^2 in 1989 to 0.9 km^2 in 1996; it has remained segmented to the present.

1996–2005 Between 1996 and 2005 Hurricanes Georges (1998), Ivan (2004), Katrina (2005), and Tropical Storm Isidore (2002) 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 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; because of this, the geomorphic response to each storm and subsequent recovery are highly variable. However, the long-term (1855–2005) evolution of the northern islands has been characterized by a continual decrease in island area from 44.5 km^2 to 4.7 km^2, an area reduction that is 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 pre-storm conditions as sediment is removed from the active sediment transport system (Georgiou and Schindler 2009; Miner et al. 2009).

The highly variable geomorphic response of the Chandeleur Islands to storm impacts was documented by Penland et al. (1989) when they classified island response for three separate 1985 storms, Hurricanes Danny, Elena, and Juan. Each of these storms had a different track, distance from the Chandeleurs, and intensity. Hurricane Danny crossed the central Gulf and made landfall on the Louisiana Chenier Plain coast as a Category 1 hurricane, with estimated surge levels at the Chandeleur Islands of ~1 m (Penland et al. 1989). Hurricane Elena passed to the north of the Chandeleur Islands, making landfall near Biloxi, MS as a strong Category 3 storm with estimated surge elevations in excess of 2 m for the Chandeleur Islands (Penland et al. 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 >2 m at the Chandeleur Islands (Penland et al. 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, sand dune scarping, overwash scour, and island breaching. Hurricane Juan produced major beach erosion, landward-directed overwash fans, island breaching, overwash scour, and severe sand dune destruction (Penland et al. 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 previous two storms. The results from Penland et al. (1989) emphasize 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 these storm characteristics.

Storm track emerged from this investigation as a key factor in estimating shoreline erosion rates from a given storm (Fig. 7). Hurricanes Camille and Katrina caused the most severe rates of shoreline erosion on the northern islands, −58.5 and −201.5 m/year, respectively (Fig. 7). The high rates of erosion are attributed to the storms' trajectories and proximity to the Chandeleur Islands. These storm paths (Katrina and Camille) 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, 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 >120 km to the west of the islands, did not result in shoreline erosion rates of magnitudes similar to 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. 6). A second period of erosion reversal 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 (post-Hurricane Camille to pre-Hurricane Frederick, post-Hurricane Frederick to pre-Hurricane Georges, and post-Hurricane Georges to pre-Hurricane Ivan).

The amount of shoreline erosion of the northern Chandeleur Islands during the combined impact of Hurricanes Ivan and Katrina (−201.5 m/year) is unprecedented for earlier time periods, which average −38.4 m/year between 1922 and 2004 (Fig. 6). As a result of the lack of similarity to other storms on 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. 5), 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 past decades' level of storm frequency persists (Fig. 4). However, if storm frequency decreases to levels similar to the 1955 to 1998 period, the islands may remain exposed until 2037. At present sediment availability (Flocks et al. 2009; Miner et al. 2009; Twichell et al. 2009), the northern Chandeleur Islands will transition to ephemeral barrier island/shoal sand bodies between 2013 and 2037 (Fig. 4).

The range of projected dates of island conversion into ephemeral barrier islands/shoals are all within the next 30 years, stressing the Chandeleur Islands' vulnerability to future storm impacts. These predictions are as much as an order of magnitude more rapid (30 versus 300 years) than those made only over a decade ago using the same methods (McBride et al. 1992). The differences between predictions made a decade ago and those resulting from our analysis are 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 into an inner shelf shoal (Miner et al. 2009). Storm intensity and frequency are the major controls on island/shoal evolution. The islands are destroyed and converted into 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 (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 seafloor 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 once again resulted in the destruction and submergence of these islands.

The submergence of the southern islands after storms and subsequent reemergence at a location landward of their pre-storm position 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 is in contrast to the northern islands where minimal landward translation of the subaerial barrier occurs (Miner et al. 2009). The disparity between the northern and southern island response 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 et al. 2009). 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 with regard to the rest of the dataset that spans the entire 20th century. The Hurricane Katrina impact 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 into 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 this threshold crossing is 2037. The trajectory of the storm track with respect to the position of the islands stands out as a key determinant governing 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 >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 emerge during periods of calmer weather. The ephemeral nature of these islands is attributed to the absence of a stabilizing backbarrier marsh (Miner et al. 2009). 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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