Hurricane-associated ebb-tidal delta sediment dynamics

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ABSTRACT

Bathymetric surveys conducted before and after the 2005 hurricane season at Little Pass Timbalier in the Mississippi River delta plain, United States, demonstrate that 9.1 (±2.4) × 10^6 m^3 of sediment was eroded from a 47.9 km^2 area. Between the two surveys, Hurricanes Cindy, Katrina, and Rita passed within 300 km of the tidal inlet. Comparison of before and after bathymetric data sets shows that the distal portion of the ebb-tidal delta (ETD) was the site of 63% of the total erosion, locally resulting in 400 m of shoreface retreat. Shoaling (0.75–1.0 m) in the seawardmost portion of the ebb channel and erosion in the landward portion (~1.5 m) resulted in a 160 m landward shift of the inlet throat. Collectively, these processes forced the landward migration of the entire tidal inlet and ETD system. There has been considerable discussion about large volumes of mineral sediment deposited on the Mississippi River delta plain interior marsh surface as a result of hurricanes; however, the origin of this sediment is unknown. We identify the distal portion of an ETD as one possible sediment source and hypothesize that ETD and shoreface sediment is mobilized by hurricane waves and transported landward by surge-induced currents. Our results emphasize the role of frequent and intense hurricanes in long-term coastal evolution and as a mechanism for regional sediment retention within the transgressive system beyond typical barrier overwash processes.

INTRODUCTION

The 2005 hurricane season along the Louisiana coast of the United States, encompassing the landfall of Hurricanes Cindy, Katrina, and Rita, provided an opportunity to document the effects of large-magnitude storms on barrier systems. The impact of short-term events is particularly relevant to Louisiana coastal evolution, where long-term historical analyses have recorded rapid degradation of barriers (List et al., 1997; Williams et al., 1992). This study is the first to quantify tidal inlet–ETD morphologic response to hurricane impact, a short-term condition that has not been isolated from the Louisiana historic trends. Our data show that erosion of the shoreface and ETD region during storms can mobilize large volumes of sediment for possible redeposition at a more landward location. Increased storm frequency and intensity in the Gulf of Mexico during the past decade (Goldenberg et al., 2001; Emanuel, 2005; Webster et al., 2005) and possible future increase in storm intensity (Mann and Emanuel, 2006) may accelerate the rate of coastal evolution in Louisiana beyond predictions based primarily on historical land loss trends (Williams et al., 1992).

The passage of large-magnitude tropical cyclones produces rapid morphological changes to barrier islands (Nummedal et al., 1980; Sallenger et al., 2007). The largest and least predictable of these changes occur at tidal inlets due to their complex bathymetry and resulting wave refraction patterns, as well as increased wave-generated and tidal current–induced sediment transport. It is during these events that large volumes of sand are exchanged among the ETD, tidal channels, and adjacent beach (FitzGerald, 1984; Morton et al., 1995). For the Louisiana coastal zone, rapid changes produced by frequent hurricanes are not followed by gradual recovery to pre-storm conditions as reported for Atlantic coast inlets (Sexton, 1995; Zhang et al., 2002). In contrast, major storms produce an enduring signature that contributes to the long-term evolution of the inlet-barrier system due to limited sand supply along the Mississippi River delta plain coast.

Barrier island coasts of the Mississippi River delta plain are rapidly degrading due to (1) a rapid rate of relative sea-level rise (locally ~1 cm/a) (Penland and Ramsey, 1990; González and Törnqvist, 2006), (2) diminishing sand resources (Williams et al., 1992), and (3) expanding tidal prism due to wetland loss, which causes an increase in the size and number of tidal inlets (List et al., 1997; FitzGerald et al., 2004; Miner et al., 2007).

Although relative sea-level rise, increasing tidal prism, and antecedent geology are purported to be the dominant factors controlling long-term tidal inlet evolution for Mississippi River delta plain barrier systems (FitzGerald et al., 2004), we show here that comparable changes can occur during a major tropical cyclone. The integrity of barrier island and tidal inlet systems, including their short-term response to major storms, dictates their ability to attenuate storm surge and wave energy (Stone et al., 2005) and ultimately reduce hurricane impacts to inland communities of southern Louisiana. One benefit of major storms is that they suspend mud and blanket marsh platforms with a layer of inorganic sediment, thereby contributing to marsh accretion and their ability to keep pace with relative sea-level rise (Reed, 2002). For example, Turner et al. (2006) calculated that 131 × 10^6 t of inorganic sediment was deposited on marsh surfaces as a result of Hurricanes Katrina and Rita; however, the origin of this sediment is unknown. In this paper we document that large quantities of sediment were eroded from the nearshore during the 2005 hurricanes. An intriguing question is whether this sediment is a possible source of the wetland sedimentation documented by Turner et al. (2006).

Using pre-hurricane and post-hurricane season bathymetric data at Little Pass Timbalier, we capture the effects of three closely spaced storms, and report on erosional and accretionary patterns as well as quantify hurricane-induced sediment transport at a tidal inlet.

GEOMORPHIC SETTING

Little Pass Timbalier is a tidal inlet located between Timbalier and East Timbalier Islands that provides a conduit for tidal exchange between Timbalier Bay and the Gulf of Mexico (Fig. 1). Between 1880 and 2005

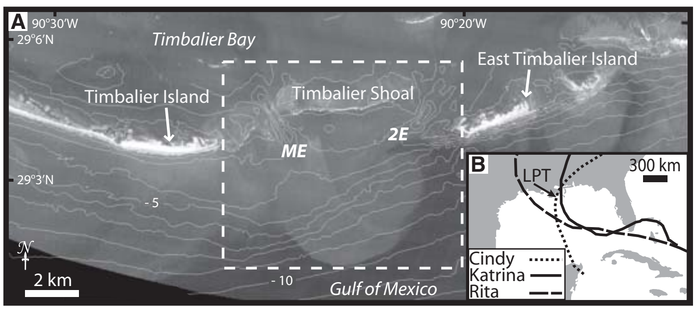

Figure 1. A: Satellite image of Little Pass Timbalier (LPT) and Timbalier Shoreline from 2005 with 1 m bathymetric contours. Note main ebb channel (ME) and secondary ebb channel (2E) separated by Timbalier Shoal. Dashed box indicates study area shown in Figure 2. B: Map of storm tracks for hurricanes affecting LPT in 2005.

the inlet throat and adjacent barrier system migrated landward a remarkable 4.9 km (Miner et al., 2007). Timbalier Shoal, an ephemeral barrier island that separates two ebb channels, builds and becomes subaerially exposed during calm weather and is denuded of sand during major storms (Fig. 1). In 2004, ~3.5 × 10^6 m^3 of sediment was excavated from the ETD of Little Pass Timbalier to nourish the downdrift barrier, producing a large borrow pit (Fig. 2A; Shaw Coastal Inc., 2005).

BATHYMETRIC CHANGE: JUNE 2005 TO NOVEMBER 2005

The study area covered a swath of coast (47.9 km^2) from the western spit platform of East Timbalier Island to the eastern spit platform of Timbalier Island (8.5 km) and extending 6 km offshore (Figs. 1 and 2). Single-beam bathymetric surveys were conducted in June and November 2005, pre-storm and post-storm, respectively. Surface grids for each survey were constructed with identical node locations (100 m grid-node spacing) so that seafloor elevation changes could be calculated. A new grid resulting from the comparison of the two bathymetric surveys shows negative and positive values, reflecting erosion and accretion, respectively. Details of methods and bathymetry data and grid interpolation uncertainty analyses results are available in the GSA Data Repository.[1] A detailed meteorological account of Hurricanes Cindy, Katrina, and Rita can be found in Stewart (2006) and Knabb et al. (2005, 2006). Tidal inlet terminology follows that of Hayes (1979).

Bathymetric change analysis shows that the combined effects of the three hurricanes decreased sediment volume by 9.1 (±2.4) × 10^6 m^3 at the study area (Fig. 2C). Zones of erosion were concentrated at the distal ETD [6.2(±0.7) × 10^6 m^3], swash platform [0.5(±0.9) × 10^6 m^3], Timbalier Shoal [1.4(±0.2) × 10^6 m^3], and proximal back barrier [1.8(±0.3) × 10^6 m^3]. Deposition of ~0.7(±0.3) × 10^6 m^3 of sediment occurred in pre-storm (June 2005) bathymetric lows such as the ebb channels, flood channels, and the dredge borrow pit on the ETD.

Erosion of the distal portion of the ETD, between the 4.5 and 8 m isobaths, accounts for 63% of the sediment lost from the study area, which is ~10% of the total volume of sediment composing the ETD. Within the distal portion of the ETD, concentrated erosion (1.0–1.5 m vertically) occurred seaward of the dredge borrow pit. Conversely, the borrow pit shoaled locally up to 0.75 m, having a net increase in sediment volume of 4.31 × 10^5 m^3.

Timbalier Shoal contained a vegetated dune platform prior to June 2005, but was almost completely destroyed by the hurricanes eroding 0.5–1.5 m vertically. In addition, landward flow over the island excavated the area behind the shoal (0.25–0.75 m) (Fig. 2C). Volumetrically, erosion of Timbalier Shoal and the surrounding area account for 32% of the total loss of sediment in the study area.

The 2005 hurricanes produced a 160 m landward migration of the main ebb channel due to a combination of shoaling (0.75–1.0 m) in the seaward portion of the channel and erosion (0.5–0.75 m) in the landward reach (Fig. 3). This compares with the long-term (1930–2005) rate of landward throat migration of 44 m/a (Miner et al., 2007).

The secondary (easternmost) ebb channel also shoaled in the seaward portion of the channel (1.5–2.0 m) and eroded landward of the throat (1.0–1.5 m), causing an ~120 m landward movement of this secondary channel.

DISTAL EBB TIDAL DELTA STRATIGRAPHY

Vibracores and chirp sonar high-resolution subbottom profiler data were collected in June 2005 at Little Pass Timbalier prior to storm impact

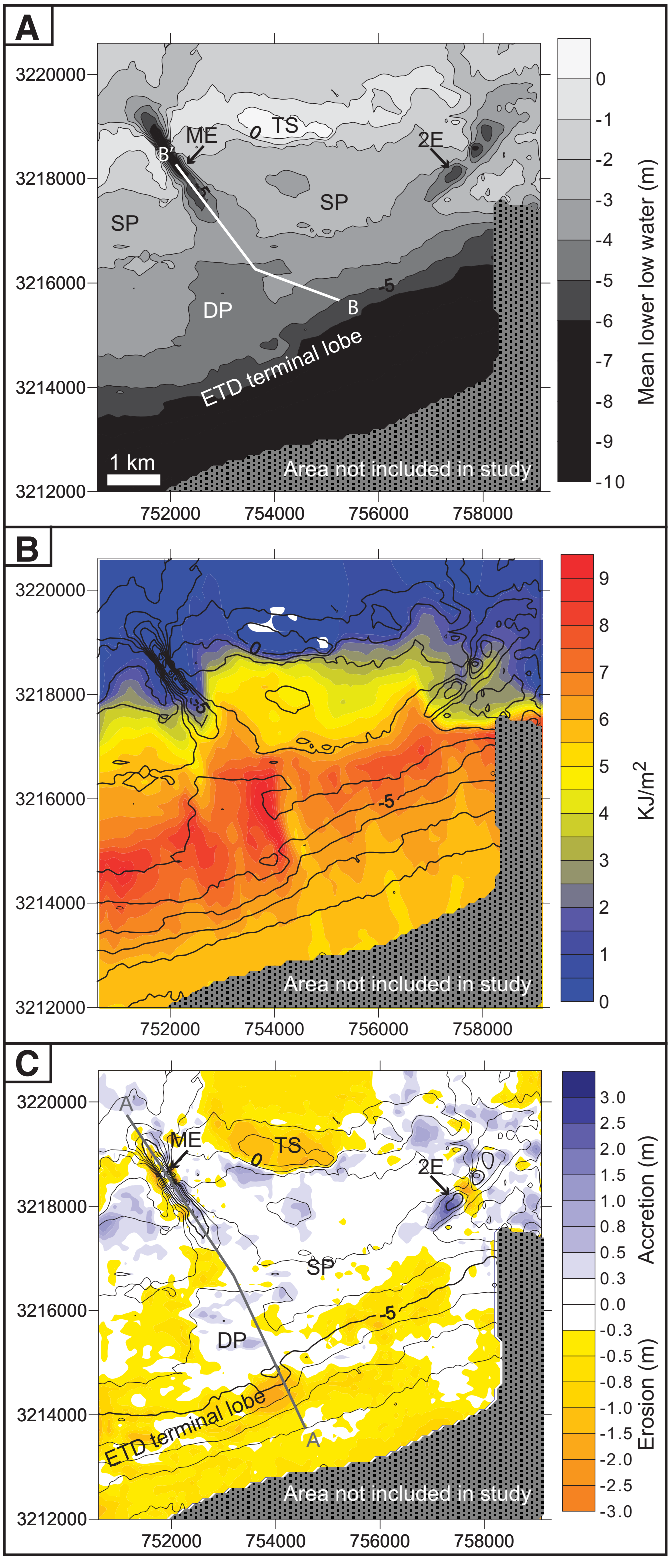

Figure 2. A: June 2005 bathymetric map for Little Pass Timbalier (LPT). Note locations of dredge borrow pit (DP), Timbalier Shoal (TS), spit platform (SP), main ebb channel (ME), secondary ebb channel (2E), and ebb tidal delta (ETD) terminal lobe. This map is used as base map in B and C. B: Simulated maximum wave energy for Hurricane Rita at LPT. Note maximum energy along ETD terminal lobe. C: Seafloor change between June and November 2005. Note erosion along ETD terminal lobe. Isobaths in C are thinner, with exception of the –5 m isobath, so that change patterns are not obscured. Coordinates are in Universal Transverse Mercator (UTM) Zone 15N.

[1]GSA Data Repository item 2009206, detailed methods, bathymetric survey coverage, and grid uncertainty analysis results, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

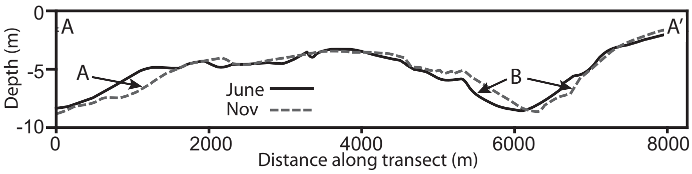

Figure 3. Shore-normal bathymetric profiles for June and November 2005 trending offshore through main ebb channel (ME) and across ebb tidal delta (ETD). Note ~400 m of shoreface erosion at distal ETD (A). Deposition in seawardmost and erosion in landwardmost portions of the channel that resulted in ~160 m of landward channel migration (B). Location of transect is shown in Figure 2C.

(Fig. 4). The subsurface data show that the upper sand unit of the ETD pinches out in an offshore direction at a depth of 6–6.5 m and is underlain by muddy distal ETD deposits (sensu FitzGerald et al., 2004). The ETD unit overlies clayey delta front deposits associated with progradation of the Lafourche delta complex (Kulp et al., 2005).

SIMULATED WAVES AND SAND TRANSPORT

A steady-state, wave numerical model (STWAVE v. 4; Smith et al., 2001) using pre-storm bathymetry and hindcast wave simulations for Hurricanes Katrina (Smith, 2007) and Rita (Oceanweather Inc., 2006) provided a means of analyzing the distribution of wave energy across the ETD and determining sediment transport rates. Wave simulations were performed using a 23-m-resolution grid in order to obtain the distribution of significant wave heights, periods, energy (Fig. 2B), and breaker indices for sediment transport calculations. Longshore transport rates at the terminal lobe, where storm wave energy was concentrated, were evaluated based on wave breaking criteria defined by Sverdrup and Munk (1946) and Komar's (1998) nearshore transport equation. Utilizing Komar's (1998) longshore current velocity at the mid-surf position, the volumetric transport rate for quartz sand was estimated as 2.5×10^5 m^3 for a 40 h event; peak potential sand transport rates were >15,000 m^3/h (see the Data Repository for details).

DISCUSSION

The bathymetric change analysis and stratigraphic data show that the hurricanes removed a total of 2.9×10^6 m^3 of sediment from the ETD terminal lobe, of which $\sim 1.19 \times 10^6$ m^3 was the upper sand unit and the rest was underlying fine-grained deposits (Fig. 4). The wave and sediment transport modeling of the 2005 storm conditions show a potential longshore sediment transport rate of 2.5×10^5 m^3 along the periphery of the ETD during a 40 h storm event. Assuming average conditions for the three storms (see the Data Repository), collectively they had the potential to transport 7.5×10^5 m^3. The deficit between these predicted and measured volumes can be attributed to the onshore transport of sand that filled the dredge pit (4.3×10^5 m^3) (Fig. 2C).

Whereas the sediment transport modeling accounts for the sand budget of the ETD, the disposition of the fine-grained sediment underlying the sand facies and composing much of the distal ETD volume that was eroded during the storms is unknown. Fine-grained sediment is an important constituent of Mississippi River delta plain wetlands and its influx helps marshes accrete vertically and keep pace with relative sea-level rise (Day et al., 2007). Turner et al. (2006) documented that 131×10^6 t of inorganic sediments accumulated in Mississippi River delta plain coastal wetlands as a result of the 2005 hurricanes; however, these investigators did not identify the source of the wetland sediment. Allison et al. (2007) showed that Hurricanes Katrina and Rita eroded the inner shelf (2–8 cm) inside the 40 m isobath and that little post-storm deposition occurred one year later. We suggest that the fine-grained component removed from Little Pass Timbalier and other similar ETDs, as well as mud eroded from the inner shelf (Allison et al., 2007), may have contributed to the large areal extent and volume of fine sediment deposited in interior wetlands during Hurricanes Rita and Katrina (Turner et al., 2006).

The transfer of muddy sediment from the inner shelf, shoreface, and ETDs to the interior bays and marsh during a storm event can be explained by high-velocity, landward-directed currents that are associated with surge inundation as storms make landfall. Murray (1970) measured wind-driven coastal currents with velocities of as much as 1.6 m/s during Hurricane Camille (1969) along the Florida Panhandle, 160 km east of the landfall location. Using hindcast data from Camille, Keen et al. (2004) calculated that steady current velocities of >0.9 m/s in Lake Borgne and >2 m/s in Breton Sound, Louisiana, existed during peak storm conditions. Our seafloor change data coupled with the high-velocity, landward-directed currents that would have accompanied the hurricane storm surge inundation suggest a possible source and mechanism for transporting the fine-grained sediment that blanketed the Louisiana wetlands (Turner et al., 2006). Mobilization of mud within the bays between the barriers and mainland is another obvious source of fine-grained sediment.

Our study has documented the significant hurricane-induced erosion of Little Pass Timbalier, which not only released large quantities of fine-grained sediment to surrounding waters, but also resulted in almost instantaneous landward migration of the inlet channel. While barriers migrate onshore by means of overwash processes followed by post-storm recovery and shoreline development landward of the pre-storm position, tidal inlets along the Mississippi River delta plain undergo a similar cycle of rapid landward migration during major hurricanes, followed by long periods of semiquiescence when they reestablish their dynamic equilibrium, dominated by a regime of increasing tidal prism. An increase in magnitude of storm-generated currents at tidal inlets during passage of tropical cyclones produces bottom shear that erodes the

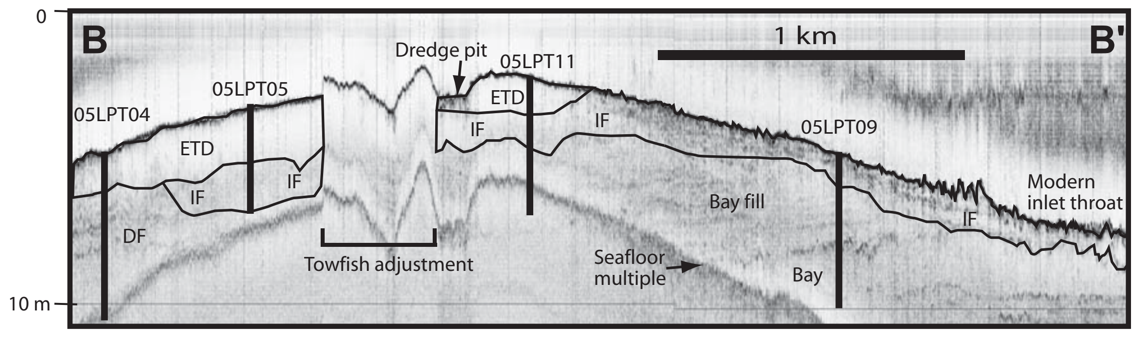

Figure 4. Chirp sonar profile with Vibracore control (black vertical lines) along shore-normal transect that extends from inlet throat offshore across ebb tidal delta (ETD). Stratigraphic units along inlet retreat path include inlet fill (IF), delta front (DF), bay fill, and bay deposits. Upper portion of Vibracore 05LPT04 contains ETD massive fine sand, and a storm scour depth of 0.22 m at that location was used to estimate sand component eroded from ETD as a result of the storms. Location of cross section is shown in Figure 2A.

landward portions of the ebb channel, drastically increasing the rate of inlet channel landward migration.

The significant erosion of sediment from the ETD—which is likely a proxy for the shoreface in general—not only emphasizes that storms drive shoreface retreat during transgression, but we speculate that they also play an important role in regional sediment retention during transgression by transferring fine-grained sediment eroded from the shoreface onshore to the marsh surface.

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