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Sub-decadal submarine landslides are important drivers of deltaic sediment flux: Insights from the Mississippi River Delta Front

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ABSTRACT

Submarine mass failures triggered by energetic forcing events such as hurricanes and earthquakes are relatively well studied due to the potential for infrastructure damage and tsunami generation; such failures are common on heavily sedimented margins where underconsolidated deposits are preconditioned to fail. However, studies of seafloor sediment movement between large events remain scarce. Using repeat bathymetric surveys of the Mississippi River Delta Front (MRDF), we document substantial seafloor movement in absence of major hurricanes. About 1 m/yr of deepening was observed within preexisting failures, with downslope sediment transport on the order of 10^5 m^3/yr. Outside failure features, seafloor depths remained stable or showed minor (<20 cm/yr) accretion. MRDF volumetric sediment flux during hurricane-driven mass failures is an order of magnitude greater than the annual flux during a quiescent interval. When normalized by time, however, sediment flux during the quiescent interval (5.5×10^5 m^3/yr) was half that of hurricane-driven mass failures (1.1×10^6 m^3/yr). These observations corroborate our wave modeling results, which infer that even waves of 1 yr recurrence interval can generate differential seafloor pressures sufficient to trigger submarine landslides; this does not exclude the possibility of river floods also being agents of failure. These findings indicate that sub-decadal submarine landslides are important to MRDF dynamics, comparable to the role of major hurricanes, and observation during seemingly quiescent periods is necessary to holistically assess sediment flux. The periodicity and prevalence of moderate-scale mass transport documented here corroborates similar recent studies offshore other deltas globally, indicating that highstand mass and time budgets of shelf to deep-sea sediment flux, in addition to organic carbon and bioreactive particles, may need to be revised.

INTRODUCTION

Submarine landslides are processes that transport sediment downslope, can dramatically alter seafloor morphology, and are important links in the global source-to-sink sediment system. Large landslides can transport more sediment in a day than a decade of global river discharge (Talling, 2014). Submarine landslides have been the subject of numerous studies because they influence many sedimentary environments worldwide. Such mass transport occurs at a range of scales on subaqueous portions of river deltas, including systems with extensive subaqueous clinothems that are shaped by waves, tides, and gravity (e.g., Amazon, South America; Atchafalaya, USA; Fly, Papua New Guinea; Yangtze, China) (Denommee et al., 2016), and deltas with more proximal accumulation within river-dominated systems (Fraser, Canada; Yellow, China) (Walsh and Nittrouer, 2009). Submarine mass failures are also well documented on the modern subaqueous Mississippi River Delta Front (MRDF) and can potentially damage human infrastructure such as oil platforms and pipelines (Coleman et al., 1980; Hooper and Suhayda, 2005).

The MRDF is prone to submarine landslides despite its overall gentle gradient (mostly <1.5°; Abbott et al., 1985) due to multiple factors, including rapid deposition of relatively impermeable fine-grained sediment, abundant organic material, and subsequent biogenic gas production (Anderson and Bryant, 1990; Goñi et al., 1997). These factors promote oversteepening, hinder sediment consolidation, and can produce elevated pore pressures that precondition seabed failure. The northern Gulf of Mexico is subject to frequent tropical cyclones, and during their passage, wave heights can exceed 15 m (Wang et al., 2005). Cyclic seafloor loading-unloading conditions can exceed yield strength of underconsolidated, gas-charged sediments, resulting in failures (Prior and Coleman, 1984). Most studies to date document seafloor movement caused by major hurricanes (Landsea, 1993) of category 3 or greater (Bea and Aurora, 1981; Wang et al., 2005; Walsh et al., 2006; Hitchcock et al., 2008), with few studies addressing sub-decadal triggering events such as river floods, non-major hurricanes, and tropical storms (Son-Hindmarsh et al., 1984; Allison et al., 2005). Analytical modeling of major tropical storm waves by Henkel (1970) and Bea and Aurora (1981) evaluated potential failures based on the assumption of sinusoidal waves. These studies did not account for effects of nonlinear waveforms, where the transition from wave crest to trough occurs across a shorter horizontal distance than in a linear waveform. To assess the magnitude of sub-decadal mass failures compared with those triggered by decadal-scale events, we use nonlinear wave modeling in combination with data from three MRDF bathymetric surveys collected during a quiescent period (with respect to tropical cyclones: October 2005 to June 2014) and during one interval that captures major hurricanes (March 1979 to October 2005).

GEOMORPHIC SETTING

MRDF geomorphic features were first described by Coleman et al. (1980) as characteristic of river-dominated deltas. Mudflow gullies are elongate seafloor depressions tens of kilometers long, hundreds of meters wide, and tens of meters high. Mudflow lobes form at downslope termini of mudflow gullies and have similar dimensions to gullies, but positive relief (Prior and Coleman, 1978). Mudflow gullies and lobes are typically concentrated in the delta front (0.5°–1.5° slope, ~5–80 m water depth); the prodelta is downslope of the delta front and has a smaller gradient and greater distance from the distributary mouth that results in far less seafloor disturbance (Coleman et al., 1980).

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METHODS

The study site is an ~55 km^2 area ~10 km southwest of Southwest Pass (Fig. 1). Water depth spans 15–80 m and covers delta front and prodelta environments. Data used include: single-beam bathymetry of Coleman et al. (1980), multibeam bathymetry collected in October 2005 by Walsh et al. (2006), multibeam bathymetry collected by Fugro Geoservices Inc. (Lafayette, Louisiana) in February 2009, and interferometric swath bathymetry collected for this study in June 2014. No hurricanes of category 3 or greater passed within 100 km of the MRDF during the 9 yr period from October 2005 to June 2014 (NOAA, 2016), while the 1979 and 2005 surveys bracket two major (category 3–5) hurricanes: Ivan (in 2004) and Katrina (in 2005). Bathymetric data were gridded to 25 m^2 horizontal resolution and subtracted from one another, producing difference of depth (DoD) grids. The cut/fill tool in ESRI ArcGIS v. 10.1 (http://www.esri.com/arcgis/about-arcgis) was used to assess volumetric flux between surveys.

To evaluate wave forcing on failures, a nonlinear wave model was used to propagate waves over the study area and calculate local wave properties and pressure gradients under the influence of 1 yr return-period waves. Results and observations from Guidroz (2009) were used to generate Stokes waves at the marine boundary using the Fenton (1999) approach. Model results were then compared with an earlier linear-wave-model approach (Henkel, 1970). For further details, see the GSA Data Repository[1].

RESULTS

MRDF sub-decadal–scale mass failures transported on the order of 10^6 m^3 of sediment between 2005 and 2009 in the study area (comparable to sub-decadal failures on other deltas worldwide; Table 1); the volume of sediment transported by major hurricanes in the study area during 1979–2005 is on the order of 10^7 m^3. Normalized for time between surveys, annual transport during a quiescent period (5.5×10^5 m^3/yr for 2005–2009) is ~50% of that during a period that contained major hurricanes (1.1×10^6 m^3/yr for 1979–2005).

Outside mudflow features, the seafloor showed small positive elevation change (Fig. 2), which was generally within the uncertainty range (±0.5 m for 2009–2005 DoD) and rarely exceeded 1 m. The most drastic deepening (+4 m) occurred in shallow (15–40 m) parts of mudflow gullies (Fig. 3A), while the largest shoaling (–3.5 m) was observed in a narrow band at the mudflow lobe downslope terminus. Minimal lateral movement (<200 m) of the gully/lobe "footprint" was observed from 2005 to 2014 (Fig. 3B). Seafloor movement during 1979–2005 exceeded 10 m in the gully/lobe complexes, and downslope progradation of mudflow lobes exceeded 1 km (Walsh et al., 2006).

Our modeling shows that smaller nonlinear waves (4.5–6.5 m) with a return period of 1 yr produce pressure differentials comparable to larger hurricane waves (8.5–10.5 m) that were evaluated using the linear theory (Fig. 4B). Local wave heights remained near their boundary value (~6.5 m) and experienced little transformation in depths of >20 m, but reduced to ~6 m in depths of <20 m (Fig. 4A).

DISCUSSION

This study confirms that appreciable MRDF seafloor movement occurred between October 2005 and June 2014 in the absence of major hurricanes. The snapshot nature of bathymetric surveys does not elucidate whether observed movement was triggered by smaller-scale impulse events, such as extratropical cyclones, tropical storms, or river floods, or whether sediment exhibited continuous creep-like motion under the influence of gravity, as has been suggested (Adams and Roberts, 1993). Repeat geophysical surveys can quantify seafloor movement and numerical models can provide a simplified idea of triggering mechanisms, but in situ observation of gully/lobe rheology akin to the Fraser River Delta Observatory (Prior et al., 1989; Clare et al., 2016) is necessary to truly understand mudflow kinematics.

The absence of large hurricanes during the 2005–2014 period of our study (significant wave height H_s << 10 m) suggests that the seafloor movement observed in bathymetric data was not triggered by major hurricane waves. Simulated

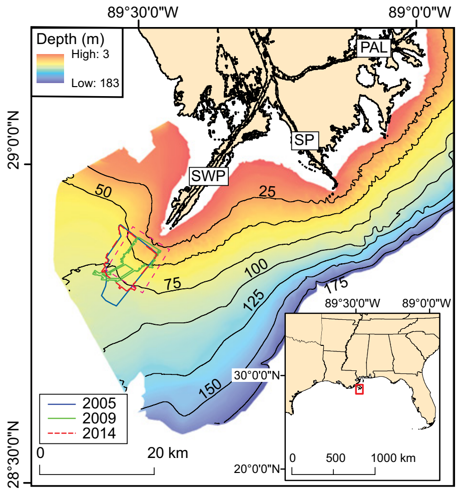

Figure 1. Base map showing survey area, Mississippi River Delta front, offshore Louisiana, USA. Bathymetry from Coleman et al. (1980); isobaths are at 25 m intervals. SWP—Southwest Pass; SP—South Pass; PAL—Pass A Loutre. Blue (for 2005), green (for 2009), and red (for 2014) polygons are spatial extents of bathymetric grids used in this study. Pink dashed rectangle demarcates extent of Figure 2.

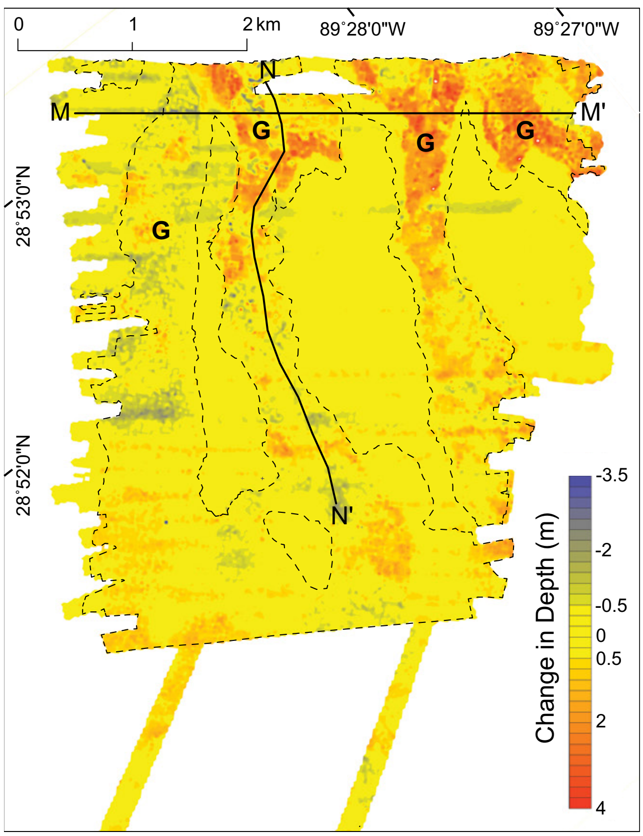

Figure 2. Difference of depth calculated by subtracting the 2005 (Walsh et al., 2006) digital elevation model (DEM) from the 2009 DEM (Fugro Geoservices, Lafayette, Louisiana). Cell size is 25 m². Red values indicate depth increase and blue values indicate depth decrease (depth notation is down-positive). Yellow pixels are values within uncertainty range (95% confidence interval, ±0.5 m). Dashed lines and bold letter "G"s mark mudflow gullies delineated in 2009 survey data. Lines M-M′ and N-N′ show extents of Figures 3A and 3B, respectively.

[1]GSA Data Repository item 2017227, methodology and supplemental figures, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

TABLE 1. COMPARISON OF DELTAIC SUBMARINE LANDSLIDES

Location*	Foreset gradient	Presumed failure trigger(s)	Time between surveys	Magnitude of volume transported (10^6 m^3)	Magnitude of vertical change (m)	References
Fraser River Delta	1°–3°	Current undercutting, cycling loading via earthquake, storm waves leading to liquefaction	~2 mo	0.075–1	4–12	McKenna et al. (1992)
Squamish River Delta	3°–6°	Summer freshet flood	24 h	>0.02	1–12	Hughes Clarke et al. (2014); Clare et al. (2016)
Ogooué River Delta	3°–8°	Oversteepening	1 yr	0.02–2	4–15	Biscara et al. (2012)
Mississippi River Delta front	<0.5°	River flood, tropical storm or extratropical cyclone passage	4 yr	2.2	1–4	This study
Mississippi River Delta front	<0.5°	Major hurricane passage (2005 Katrina)	24 yr	28	3–12	Walsh et al. (2006); this study

Note: Comparison of worldwide submarine landslides studied via repeat bathymetric surveys. Relevant parameters including foreset gradient, triggering factors, and volume displaced by failures are included.
*River locations: Fraser and Squamish—British Columbia, Canada; Ogooué —Gabon, Africa; Mississippi—Louisiana, USA.

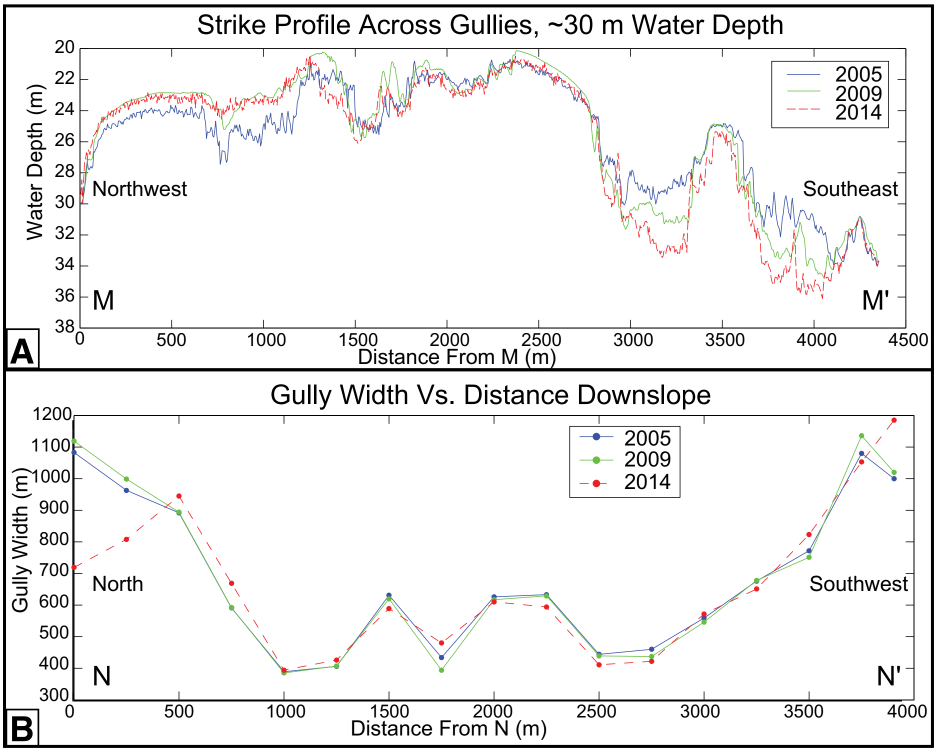

Figure 3. A: Profile M-M′ across survey area showing change in gully depth between surveys. Gully depth decreases in westernmost gully, but increases in all other gullies. B: Width of Mississippi River delta front gully plotted against distance from origin along profile N-N′. Note this origin is not head of gully, but shallowest depth common to all three data sets. See Figure 2 for locations of profiles M-M′ and N-N′.

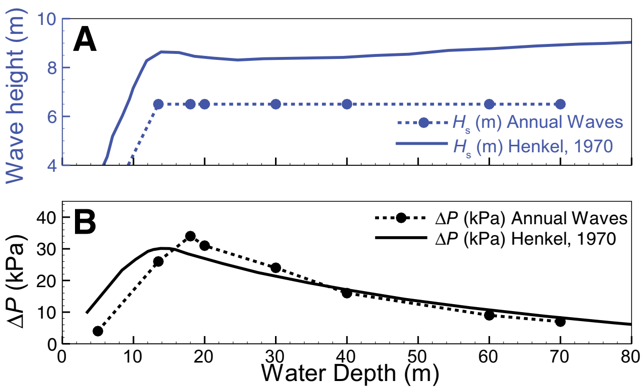

Figure 4. Relationship between water depth, wave height (blue), and pressure change (black) on sea bottom. A: Wave heights (H_s) plotted against water depth, with results of Henkel (1970) as solid line and this study's results as dashed. B: Seafloor ΔP (pressure differential) compared to water depth, with results of Henkel (1970) as solid line and this study's results as dashed. Evolution of pressure change from water depths between 5 and 70 m appears similar between linear sinusoidal and fully nonlinear waves.

peak pressure differentials at the seabed (ΔP ~35 kPa) in the study area generated by 1 yr waves (H_s ~6.5 m; Fig. 4B) reached similar peak conditions to those produced by simulated hurricane waves, suggesting that movement can be triggered by 1 yr waves if nonlinear effects are considered. In depths of 14–50 m, 1 yr nonlinear waves (~6.5 m; Fig. 4A) produce pressure differentials that exceed pressure differentials of linear waves simulated for hurricanes by >15%.

Regardless of the exact triggering factor(s), sub-decadal–scale MRDF submarine landslides mobilize volumes of sediment comparable to those of more catastrophic counterparts, when averaged over multi-decadal time scales. While the calculated volume fluxes are not precise due to large uncertainties and assumptions (see the Data Repository), they agree with results from another recent study (Kelner et al., 2016) that indicates that smaller, sub-decadal landslides provide major forcing for shelf-to-slope sediment flux as important as larger, better-studied catastrophic landslides. Submarine landslides are also an important conduit for shelf to deep-sea transport of organic carbon, heavy metals, and bioreactive particles (Panieri et al., 2012); the fact that these landslides occur more frequently than previously conceived on margins as disparate as the northern Gulf of Mexico and southern France (Kelner et al., 2016) suggests that the presently accepted flux estimates for these materials are probably incomplete in other locations as well.

This study documents depth change and substantial (10^5 m^3/yr) volumetric flux within MRDF mudflow gully-and-lobe complexes during a relatively quiescent period of ocean-wave climate. These failures may be triggered by extratropical cyclones, tropical storm passage, or river floods (Prior and Coleman, 1981); nonlinear wave modeling results presented here demonstrate that storms with a return interval of at least 1 yr could cause such failures. Regardless of the forcing mechanism, volumetric analysis of sediment displaced during the 2005–2009 quiescent period indicates that "fair weather" subaqueous MRDF movement may be an important driver of sediment transport comparable to the better-studied major hurricane-forced failures. These findings have widespread mass-flux implications not only for the MRDF, but also for margins worldwide because the present understanding for event-scale dispersal of sediment, organic carbon, and bioreactive particles from shelf to deep sea may be skewed toward low-frequency, high-magnitude events. These results also underscore the need for in situ monitoring programs in tandem with sub-annual repeat surveys in order to elucidate the drivers, periodicity, and magnitude of sediment flux on the MRDF and other deltas worldwide.

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