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Contribution of river floods, hurricanes, and cold fronts to elevation change in a deltaic floodplain, northern Gulf of Mexico, USA

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Abstract

Deltas are globally important locations of diverse ecosystems, human settlement and economic activity that are threatened by reductions in sediment delivery, accelerated sea level rise, and subsidence. Here we investigated the relative contribution of river flooding, hurricanes and cold fronts on elevation change in the prograding Wax Lake Delta (WLD). Sediment surface elevation was measured across 87 plots, eight times from February 2008 to August 2011. The high peak discharge river floods in 2008 and 2011 resulted in the greatest mean net elevation gain of 5.4 to 4.9 cm over each flood season, respectively. The highest deltaic wetland sediment retention (16.3% of total sediment discharge) occurred during the 2008 river flood despite lower total and peak discharge compared to 2011. Hurricanes Gustav and Ike resulted in a total net elevation gain of 1.2 cm, but the long-term contribution of hurricane derived sediments to deltaic wetlands was estimated to be just 22% of the long-term contribution of large river floods. Winter cold front passage resulted in a net loss in elevation that is equal to the elevation gain from lower discharge river floods and was consistent across years. This amount of annual loss in elevation from cold fronts could effectively negate the long-term land building capacity within the delta without the added elevation gain from both high and low discharge river floods. The current lack of inclusion of cold front elevation loss in most predictive numerical models likely overestimates the land building capacity in areas that experience similar forcings to WLD.

Keywords

deltas; sedimentation; cold fronts; hurricanes; river floods; deltaic floodplain wetlands; USA, Louisiana, Wax Lake Delta

1. Introduction

Land building by both progradation and aggradation in coastal deltaic wetlands is largely controlled by sediment delivery and deposition from terrestrial sources via fluvial sediment transport and marine sources, such as offshore bay bottom deposits resuspended by waves, tides and storms. Understanding the relative contribution of these sediment delivery processes to net elevation change is important for prediction and management of deltas in the 21st century (Georgiou et al. 2005; Day et al. 2007; Paola et al. 2011). Coastal deltas are globally important as population centers, (Ericson et al. 2006; Syvitski et al. 2009) and also include extensive and diverse ecological communities, including mangrove forests, salt, brackish and fresh marshes (Day et al. 2008). The processes that have controlled delta formation throughout the Holocene are changing, including accelerated sea level rise, sediment trapping in river basins by dams and reservoirs, human induced increases in compaction and subsidence due to fluid extraction, reduction of distributary channels and an increase in storm intensity and frequency, altering the ability of deltas to persist and grow (Day et al. 2008; Syvitski 2008 Syvitski et al. 2009, Vörösmarty et al. 2009).

River discharge and sediment delivery control a large portion of the land-building in deltaic systems, for example the shift from progradation to retrogradation that was observed in the Danube Delta as a result of a decrease in sediment delivery of 30-40% due to dam construction within the past 40 yr (Panin and Jipa 1997). A loss in wetland area in the Yellow River Delta has also been attributed to decreases in water and sediment delivery (Li et al 2009). Marine processes can also have strong effects on delta growth; the Ebro Delta in Spain is a sediment limited system where waves, tides and storms primarily shape delta morphology

(Jiménez et al. 1997, Valdemoro et al. 2007). The physical processes that shape the Mississippi River Delta (MRD), in the northern Gulf of Mexico, include river flooding, frequent winter cold front passage (20-30/yr), tropical cyclone landfall (return interval of 3-10 yr) and a predominantly east to west longshore current. Wave energy is typically very low, with wave heights between 0.5 to 1 m with a period of 5 to 6 s and a mean tidal range of 0.35 to 0.43 m (Hardy and Henderson 2003, Georgiou et al. 2005, Keim et al. 2007). Given the low energy of these coastal forcings relative to river discharge, the MRD is considered a fluvial-dominated system in the classic ternary diagram (Galloway 1975).

There has been much recent analysis looking at the variability in the amount of sediment reaching the coastal zone and its capacity to reduce land loss that is occurring there (Turner et al. 2006, Tornqvist et al. 2007, Blum and Roberts 2009, Allison et al. 2010, CPRA 2012, Rosen and Xu 2014, Nittrouer and Viparelli 2014, Roberts et al. 2015). Previous studies have generally focused on one type of forcing (e.g. floods, storms or cold fronts) and lack direct comparisons of the contribution of multiple forcings to coastal land loss and gain. Here we used observations made in the Wax Lake Delta (WLD), a young (<50 yr) prograding delta lobe of the Mississippi River, to investigate the relative contribution of three seasonally distinct hydrologic forcings on sediment surface vertical elevation change. River flooding, hurricanes and repeated cold front passage occur within this system during distinct times of the year and will be referred to throughout as seasonal forcings. We investigated the variability between seasons and among years, as well as in terms of the long-term return period of rare events such as large floods and hurricanes, to better understand and predict how modern progradational deltas build over long timescales. This study is the first to directly compare the empirically measured contribution of all three forcings to elevation change in coastal deltaic wetlands.

Large river floods generally result in appreciable land building along the remaining unveeved Mississippi River distributaries, and account for the majority of land building observed in deltaic wetlands (Rouse et al. 1978; Roberts and Adams 1980; Majersky et al. 1997). The loss of flood derived overbank sedimentation is a major factor in increasing rates of wetland subsidence and land loss within the MRD (Baumann et al. 1984; Day et al. 2007; Day et al. 2008; Syvitski et al. 2009; Vörösmarty et al. 2009).

The influence of tropical cyclone passage (both tropical storms and hurricanes) on deltaic sedimentary processes can be large, though they are generally too rare to result in total readjustment of the delta morphology (Syvitski 2008). The factors that determine the severity of hurricane storm surge include aspects of the storm itself, including but not limited to direction of approach, forward speed, wind speed, integrated kinetic energy of the surface wind field, and central pressure (Georgiou et al. 2005; Powell and Reinhold 2007; Irish and Resio 2010). The coastal morphology is also a strong factor in the resulting severity and pattern of hurricane surge inundation, with the broad low-lying MRD acting to enhance storm surge (Westerink et al. 2008; Dietrich et al. 2011). The return period of all tropical cyclones (wind speed ≥ 63 km hr⁻¹) in the vicinity of the MRD is every 3 yr and for hurricanes (winds speed ≥ 119 km hr⁻¹) is every 7 to 10 yr (Keim et al. 2007).

Sediment redistribution and deposition on the surface of coastal wetlands as a result of the large hurricane storm surges has been reported across the northern Gulf of Mexico, with deposition ranging from washover of sandy beaches and barrier islands that extends 100s of meters from the coast (Williams 2009; Morton and Barras 2011) to widespread redistribution of fine grain sediment and organic root mats that extends to interior marshes 10s of km from the

coast. While a few studies focused solely on deposition (Turner et al. 2006; Tweel and Turner 2012), many have also reported on the widespread erosion that resulted from tropical cyclone passage (Baumann et al. 1984; Rejmánek et al. 1988; Guntenspergen et al. 1995; Nyman et al. 1995; Cahoon 2006; McKee and Cherry 2009; Morton and Barras 2011). It is very difficult to determine both erosional and depositional processes associated with these storms across the entire coast because the effects of each storm are unique based on factors such as angle of approach, size, wind speed, wave height, storm surge, and tidal stage, as well as the variability in coastal wetland morphology, dominant vegetation type and density, sediment characteristics and coastal built infrastructure such as levees, canals, and impoundments, which can affect sedimentary processes.

Cold front passage is a common occurrence during the late fall through early spring in the southeastern U.S. A cold front is the common term for the transition zone between two atmospheric air masses of different densities that generates a predictable set of wind, wave and current conditions as it moves through the coastal zone (Mossa and Roberts 1990). Generally the cold front passages that affect the northern Gulf of Mexico are 25 to 250 km wide and pass from a northwest to southeast direction every 4-7 days through between October and April, with highest occurrence in January and February. No significant variation in frequency or timing of cold fronts occurs between years, therefore their effect on coastal processes is expected to be consistent year to year (Hardy and Henderson 2003). The pre-frontal phase, typically 24-48 hours before the front passes, is defined by strong southerly and easterly winds, producing waves and currents that push water toward the coast, resulting in water level increases of 0.5 to 1 m over predicted levels and resuspension of sediment from coastal bays and low organic matter deltaic wetlands (Rouse et al. 1978; Roberts and Adams 1980; Mossa and Roberts 1990; Feng

and Li 2010; Li et al. 2011). As the front passes the coastal zone there is a sudden decrease in barometric pressure and an increase in precipitation and wind speed. This is followed by the post-frontal phase in which the barometric pressure rises, temperature and humidity drop and winds shift to northwesterly and northerly direction. These strong post-frontal winds move water out of coastal bays, rapidly decreasing water levels and transporting suspended sediments onto the continental shelf (Walker and Hammack 2000). The resuspension and transport of sediment from shallow bay bottoms in the vicinity of both the WLD and the nearby Atchafalaya Delta has been well established with predominant westward longshore sediment transport and deposition on the shallow continental shelf and coast of the Chenier Plain located in western Louisiana (Roberts et al. 1989; Mossa and Roberts 1990; Allison et al. 2000; Draut et al. 2005; Neill and Allison 2005; Kineke et al. 2006; Moeller et al. 2012). Water level changes due to cold front wind conditions are often referred to as meteorological tides, defined as the difference between the predicted astronomical tide and the total observed water level (Pugh 1996). In the northern Gulf of Mexico this large change in water levels of 1 m or more over 24-48 hr and their frequent reoccurrence from October to April can have a much greater effect on coastal morphodynamics and sediment transfer than astronomical tides alone (Georgiou et al. 2005).

Here we used the WLD as a long-term experimental system, which allowed us to isolate the effects of distinct seasonal forcings. Due to its relatively protected location within Atchafalaya Bay (Fig. 1) and the micro-tidal regime, the effects of astronomical tides and wave action are minimal (Georgiou et al. 2005), allowing for the seasonally distinct processes of river floods, cold fronts, and hurricanes to be isolated in time. In other coastal deltaic systems the confounding effects of continuous and higher magnitude marine forcings would make it more difficult to clearly attribute observations to a single forcing. Our original research objective was

to compare the sediment surface elevation change during the spring flood period and the winter cold front period with the timing and location of sampling transects designed to measure a distinct seasonal interval over which each forcing was dominant and to compare seasonal and interannual patterns in elevation change across the WLD. While we did not plan this *a priori* we were also able to measure the effects of Hurricanes Gustav and Ike in September 2008. This long-term sampling design has allowed us to investigate a number of questions regarding the relative effect of the three dominant seasonal forcings, river floods, hurricanes, and cold fronts, on sediment surface elevation change.

2. Methods

2.1 Study area and seasonal intervals

The WLD is a prograding delta forming at the terminus of the Wax Lake Outlet (WLO), a constructed distributary channel of the Atchafalaya River, which is a major distributary of the Mississippi River (Fig. 1). The water discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled by the Army Corps of Engineers at the Old River Control Structure (ORCS). The WLO was originally constructed in 1942 as a flood control conduit from the Lower Atchafalaya River (Shlemon 1975). As the WLO discharges into the shallow (2-3 m) Atchafalaya Bay the resulting bed friction forms distributary mouth bars with coarse grain deposition at the bar crest (upstream end) and along the lateral boundaries and finer grain sediments in the interior portions. Bars are separated by bifurcating distributary channels. Over time the mouth bars increase in elevation to greater than mean low low water (-0.14 m NAVD88) and become deltaic islands (Wright 1977; Wellner et al. 2005; Fagherazzi et al. 2015).

WLD is a relatively young deltaic system with prodelta deposits and subaqueous expansion first observed in 1952. However the majority of the fine grain sediment bypassed the bay and was deposited on the continental shelf prior to the early 1970s (Shlemon 1975). Small subaerial bars that first began to appear in the WLD in 1973 grew rapidly following high river flooding and infilling of shallow lakes upstream and adjacent to the WLO (Roberts and Adams 1980; Wellner et al. 2005). Due to its unique occurrence as a constructed river outlet that has been allowed to build land under natural hydrologic conditions, this system represents an extremely valuable analogue to many MRD coastal restoration strategies, which propose diverting river water and sediment into shallow coastal basins to reduce present wetland degradation rates (Parker and Sequeiros 2006; Kim et al. 2009; Allison and Meselhe 2010; Paola et al. 2011; CPRA 2012).

The WLD currently receives approximately 30-40% of the total water and sediment discharge of the Atchafalaya River (Allison et al. 2012), equivalent to 10-12% of the total Mississippi and Red River discharge. Areal land growth rates within WLD range between 1.0 to 3.3 km² yr⁻¹ (Majersky et al. 1997; Allen et al. 2011). A delta front expansion rate of 0.3 km yr⁻¹ has been estimated (Parker and Sequeiros 2006), with a vertical elevation change rate estimated at 2.7 cm yr⁻¹ from 1981 to 1994 (Majersky et al. 1997). Sediment transport in the WLD is influenced by seasonal water exchange from river flooding, tidal exchange, cold fronts, and tropical cyclones (Mossa and Roberts 1990; Walker and Hammack 2000; Walker 2001; Roberts et al. 2015). During late fall, winter and

Figure 1. Northern Gulf of Mexico with location of study site at Wax Lake Delta. Tracks of Hurricanes Gustav and Ike are also shown (top). Sediment surface elevation map of Wax Lake Delta, LA, with 10 cm elevation ranges from 2012 LiDAR survey. Location of sampling transects indicated by black lines and letters (bottom).

162 early spring the inshore to offshore exchange of water and sediments is influenced by winds
163 associated with cold-front passage. In spring water movement is strongly controlled by the
164 increasing river discharge as the spring river flooding occurs. As river discharge decreases in the
165 summer, the microtidal regime (amplitude ~ 35-43 cm) becomes the dominant means of water
166 movement on the delta islands; however the channel discharge is maintained in a downstream
167 direction even at rising tide. The lowest river discharge normally occurs during late summer and
168 fall. This is also when tropical cyclones are most likely to occur (Walker 2001). With the
169 exception of storm surges associated with passing hurricanes and tropical storms, the WLD is an
170 entirely freshwater tidal system (Holm and Sasser 2001).

171 The deltaic floodplain wetlands are composed of low organic matter, highly mineral
172 sediments, primarily fine sand and silt, and are colonized by woody, shrub/scrub and herbaceous
173 fresh marsh species that exhibit zonation along the elevation gradient (Visser 1989). Similar
174 vegetation patterns have also been documented in the Atchafalaya Delta (Johnson et al. 1985;
175 Shaffer et al. 1992). Higher elevation delta islands often have a mixed canopy composed of
176 woody *Salix nigra*, *Baccharis halimifolia* and *Sesbania* spp. with an herbaceous understory
177 dominated by *Colocasia esculenta*. At slightly lower elevations mixed communities of *C.*
178 *esculenta*, *Phragmites australis*, *Polygonum punctatum*, *Typha* spp., *Schoenoplectus* spp., and
179 *Zizaniopsis miliacea* occur. Low elevation intertidal and subtidal emergent and submerged
180 herbaceous communities are dominated by *Nelumbo lutea*, *Sagittaria platyphylla* and
181 *Potamogeton nodosus* (Johnson et al., 1985; Shaffer et al., 1992, Bevington, 2016).

182 It is likely that sedimentary processes and therefore elevation change on delta island tops
183 are related to and controlled to some extent by the presence and morphology of vegetation

(Viparelli et al. 2011; Nardin and Edmonds 2014). However these effects are extremely complex due to the high degree of heterogeneity of vegetation community composition in these freshwater tidal wetlands, as well as the drastic seasonal shifts in aboveground herbaceous biomass. It is likely that the lack of aboveground herbaceous cover during both the later part of the winter cold front season and the early spring flood season may play a role in sediment surface elevation change, however it occurs at a spatial and temporal scale that was not feasible to address within the experimental design of this study.

2.2 Sampling and analytical methods

Between February 2008 and August 2011 elevation surveys were conducted before the spring river flood (February/March) and after water levels returned to non-flood levels (July/August) in all years. Sampling intervals were chosen to capture the period of spring river flooding and fall/winter cold front passage. Additional surveys followed the passage of Hurricanes Gustav and Ike in September 2008. Due to logistical and weather constraints, field surveys often consisted of 2 to 3 field days and the start and end of each season interval is defined by the median field date, for example in winter 2008 field surveys were conducted on January 30 and February 13, and the beginning of that interval is reported as February 7, 2008. The number of days between pre-season and post-season sampling dates is referred to as the sampling interval duration (Table 1). During each survey we measured the sediment surface elevation along seven transects (Fig. 1, Table 2), for a total length of 1,950 m. Transects and plot locations were established starting at the distributary channel edge and extended into the interior of the deltaic island, This orientation was selected in order to capture a large portion of the elevation gradient, which includes fringe and interior wetlands. The number of 1 m² sampling

plots per transect ranged from 9 to 14, distance between plots was 10, 20 or 40 m, and total transect lengths ranged from 130 to 400 m (Table 2). The spacing and length of transects was variable to accommodate the elevation gradient at each transect location. The location and number of plots within each elevation range were limited by the feasibility and field logistics associated with covering the large distances and completing the surveys within the allotted field campaign.

Table 1. Seasonal sampling intervals, all transects sampled pre-season and post-season, change over season interval is defined as the elevation difference between the two samplings.

Seasonal interval	Pre-season sampling	Post-season sampling	Seasonal interval duration (days)
Flood 2008	Feb. 7 2008	Aug. 3 2008	179
Hurricanes 2008	Aug. 3 2008	Sept. 16 2008	44
Cold Fronts 2008-09	Sept. 16 2008	Feb. 15 2009	152
Flood 2009	Feb. 15 2009	July 16 2009	151
Cold Fronts 2009-10	July 16 2009	Mar. 9 2010	236
Flood 2010	Mar. 9 2010	Aug. 19 2010	162
Cold Fronts 2010-11	Aug. 19 2010	Mar. 1 2011	194
Flood 2011*	Mar. 1 2011	Aug. 21 2011	173

* Benchmark was eroded so transect F was not surveyed in summer 2011.

Sediment surface elevation was measured with a Class I laser level (Sokkia LP30A; accuracy: ± 1.5 mm @ 100 m) and a stadia rod fit with a laser receiver (Sokkia LP100). The maximum range surveyed along any transect was 300 m, resulting in a maximum vertical error of ± 0.45 cm. Soil elevation measurements were corrected relative to temporary benchmarks, which consisted of 3.8 cm diameter pipes driven approximately 3-4 m into the sediment, to the point of refusal. This was likely the consolidated pre-delta bay bottom mud (Roberts et al. 2005; Shaw et al. 2013; Shaw and Mohrig 2013). Based on the age and consolidation of the bay bottom

sediments, it was assumed that any subsidence below the depth of the benchmarks was minimal over the 3.5 years of sampling. Two replicate sediment surface elevation measurements were taken randomly within each 1 m² plot, and the mean value was reported as the elevation of that plot. There was very little variation between plot replicates, with a mean difference of only 1.1 ±0.09 cm across 640 individual plot measurements. To prevent the stadia rod from sinking into the sediment the bottom was fitted with a 10 cm diameter plastic plate. All elevation measurements were taken on bare sediment; when wrack deposits were present they were carefully removed to not disturb the surface of the sediment. Bulk density cores were also collected to a depth of 10 cm at a known volume from each elevation sampling plot, these cores were oven dried to constant mass at 60° C and weighed to determine sediment bulk density.

In order to compare elevation surveys taken at different times and different locations throughout the delta, all elevation values were corrected first to the transect benchmark. Each benchmark was corrected to the NOAA tidal datum, in July 2008 by linear regression analysis of 30 minute water levels at each benchmark and verified water level data from Amerada Pass (NOAA 8764227), which is approximately 10 km from the transects. There was significant correlation for all benchmarks ($r^2 > 0.98$). Elevations were then converted from the NOAA tidal datum to NAVD88 geodetic datum, using vdatum software. It was determined that mean sea level based on the NOAA tidal datum at Amerada Pass is equivalent to -0.12 m NAVD88 (Parker et al. 2003; Shaw et al. 2013). The consistent use of the NAVD88 datum allows for direct comparison to water level and elevation datasets not directly tied to the Amerada Pass NOAA tide gauge.

The elevation change over each seasonal interval was calculated by subtracting the pre-season corrected elevation from the post-season corrected elevation. The elevation change values for each plot for each seasonal interval were used to calculate net elevation change (the mean of all positive and negative change values), mean elevation gain (mean of only positive change values) and mean elevation loss (mean of only negative change values) for each seasonal interval across the entire dataset. These values were used to compare the patterns observed during the different seasonal events. We also calculated mean elevation change values for 10 cm pre-event elevation ranges for each river flood interval. Statistical analyses of elevation change were conducted using SAS 9.1 (SAS Institute, Cary NC, USA), primarily one-way ANOVA unless otherwise noted. Tukey's pairwise comparison with $\alpha = 0.05$ was used as post hoc test, and significant differences are indicated with letter values.

Table 2. Length of elevation survey transects, with location of first plot (located closest to channel edge) all transects extended into island interior perpendicularly to channel edge.

Transect ID	Latitude (decimal degrees)	Longitude (decimal degrees)	Total length (m)	Number of sampling plots
A	29.49560	-91.44735	360	11
B	29.50113	-91.45125	400	13
C	29.51051	-91.44493	160	13
D	29.50171	-91.47941	380	13
E	29.51151	-91.43311	130	10
F	29.50315	-91.43520	230	15
G	29.49283	-91.44085	290	12

Water levels over the entire sampling period were downloaded from the U.S. Geological Survey (USGS) 07381590 gauge on the WLO at Calumet, LA (<http://waterdata.usgs.gov>), which is located in the WLO channel 19 km upstream of the first bifurcating distributary channel of the WLD, and will hereafter be referred to as WLO water level. Water levels from the NOAA

Amerada Pass gauge located in the Atchafalaya Bay approximately 10 km southeast of the WLD, more accurately represent the water level within the delta and the bay and will hereafter be referred to as the WLD water level (Fig. 1). Mean daily total suspended sediment discharge in short tons per day was calculated with the rating curve equation (Eq. 1) developed for USGS Calumet station on the WLO (Allison et al., 2012; Allison pers. comm.). This was converted to metric tons per day and used to calculate the total suspended sediment discharge for WLO over each seasonal interval.

$$Y=Y_0+a(1-e^{-bX}), \quad (Eq. 1)$$

where Y = total suspended sediment load (shorts tons/day), and X = mean daily sediment discharge (cfs). Coefficients in Eq. 1 are as follows: $Y_0 = 2.057 \times 10^4$, $a = 3.580 \times 10^7$, and $b = 1.883 \times 10^{-8}$.

A LiDAR digital elevation model (DEM) derived from the USGS Atchafalaya 2 LiDAR Survey (<http://coast.noaa.gov/digitalcoast/>) was used to create a histogram of the deltaic wetland area within 10 cm elevation bins. We calculated the total area within each 10 cm elevation bin for the entire delta top equal to and over -0.5 m NAVD88. This elevation range includes the majority of subtidal, intertidal and supratidal vegetated wetland habitats. The histogram of 10 cm elevation bins was generated using ArcGIS 10.2 (ESRI, Redlands, CA). While the 2012 LiDAR DEM was collected shortly after the period of field sampling we consider this as a reasonable estimate of vertical elevation within the delta for the time period of 2008 through 2011. Using the areal estimates for 10 cm elevation bins based on the LiDAR DEM, the total mass of sediment that was deposited in the deltaic wetlands at elevation ≥ -0.5 m NAVD88 was estimated based on the total area of each 10 cm elevation range multiplied by the mean depth of

sediment deposited from each spring flood within that range. This volume was multiplied by the post-flood sediment bulk density estimated from the mean of 87 homogenized sediment cores collected in July of 2009.

3. Results

3.1 Seasonal net elevation change

Analysis of the elevation change across all the measured plots indicated that all river floods resulted in net elevation gain, with the largest net elevation change occurring in 2008 and 2011 (Fig. 2). These years also exhibited similar river floods, with one main large discharge peak and only a few smaller ancillary peaks. The spring river flood of 2009 had lower total discharge and resulted in less net elevation gain than in 2008 or 2011, but was not significantly different from 2011. In 2010 while positive elevation change was observed it was close to zero and the pattern of river flood peaks was markedly different than other years, consisting of a sequence of smaller peaks beginning in October 2009 and continuing through June 2010. The overlap of the river flood with the season of winter cold front passage of 2009/10 resulted in a net elevation change of close to zero for both these seasonal intervals (Fig. 2). A very different pattern was observed in 2008/09 and 2010/11, when the cold front seasonal interval was distinct from the river flood and resulted in net elevation loss in both years (-2.2 cm and -2.1 cm, respectively). Hurricane Gustav made landfall on the coast of Louisiana, passing 25 km to the northeast of WLD on September 1 2008, and Hurricane Ike passed 275 km southwest of the delta on a northwesterly track on September 12 2008, making landfall in Galveston, TX on September 13 2008, 315 km from WLD (Fig. 1). Both hurricanes resulted in storm surges that affected the study site (Fig. 2). Despite the much closer proximity of the eye, Hurricane Gustav resulted in a

smaller surge with WLD water level 1.1 m above predicted as the storm surge came ashore,
 (NOAA 8764227 Fig. 2). The passage of the very large Hurricane Ike 275 km to the south of
 WLD resulted in an increase in water level of 2.0 m above predicted, despite the storm

Figure 2. Mean $\pm$ 1 standard error (SE) net elevation change (cm) across all the measured plots for each seasonal interval with results of one-way ANOVA (Tukey's pairwise comparison significant differences at $\alpha = 0.05$, indicated by letters). The spacing of bars is based on pre- and post-season sampling dates, which determined length of seasonal interval; see Table 1 for sampling dates and interval durations. Corresponding water levels reported relative to NAVD88, measured at Wax Lake Outlet gauge (USGS 07381590) shown with thin line and Amerada Pass gauge (NOAA 8764227) represented by thicker line.

not making landfall in Louisiana (NOAA 8764227). These two hurricanes resulted in 1.2 cm net elevation gain, illustrating that hurricanes can deliver sediments, presumably resuspended from offshore, into coastal wetlands. The two storms resulted in about as much sediment elevation gain as a moderately large river flood (e.g. 2009). The passage of these two category 2 hurricanes occurred within a two-week time period, restricting our ability to sample between the storms. Therefore, the two hurricanes have been grouped into one seasonal interval. Estimating a return period for the hurricanes was therefore complicated by the probability of two storms in such a short period of time. The actual return period for two hurricanes within two weeks is likely much greater than the estimate for one hurricane in this area of the northern Gulf of Mexico of every 7 to 10 yr (Keim et al. 2007). Due to the inability to sample the effect of each storm, we attributed half of the elevation gain to each hurricane to estimate long-term contributions. Based on the return period for one hurricane of 7 to 10 yr, we estimate that the net elevation gain that we observed from Hurricanes Gustav and Ike in 2008 of 1.2 cm would result in an annual contribution of 0.06 to 0.09 cm yr⁻¹.

We also investigated the differences in the depositional capacity of each seasonal forcing by comparing the mean of only elevation loss plots and only elevation gain plots separately for each season. Sampling plots with no change in elevation were not included in this analysis (Fig. 3). We found no significant difference in the mean of elevation loss plots from any seasonal forcing, indicating that the capacity to cause elevation loss either through sediment removal or compaction is consistent across all types of seasonal forcing and all years (Fig. 3). However significant differences were observed between the seasonal interval means of the elevation gain plots, with significantly higher elevation gain as a result of large river floods (Fig. 3). These results indicated that while all seasonal forcings result in comparable sediment elevation loss, the

340 depositional capacity of the river floods and hurricanes occurs as a result of the availability of
 341 suspended sediment brought in from outside of the system.

342

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Figure 3. Mean $\pm$ 1 standard error (SE) of only elevation gain (cm) and elevation loss (cm) for each seasonal interval, including results of one-way ANOVA (Tukey's pairwise comparison significant differences at $\alpha = 0.05$, indicated by letters). There was no significant difference in elevation loss plots. The differences between seasonal events are only seen in elevation gain plots

3.2 Discharge and sediment supply

The total water discharge and total suspended sediment discharge are based on the riverine sediment discharge rating curve (Eq. 1; Allison et al. 2012) and do not include the suspended sediment load from offshore sediments that are likely resuspended and delivered to the delta during hurricanes and possibly cold fronts, therefore underestimating the total sediment delivery from these types of events (Fig. 4) The total WLO water and suspended sediment discharge was higher during the 2008 river flood, with the 2011 river flood discharge just slightly lower (Fig. 4). This likely accounted for the greater net mean elevation change observed during the 2008 river flood compared to 2011 (Fig. 2). During the 2009/10 cold front seasonal interval, which had the third highest water and total sediment discharge of all seasonal forcings (Fig. 4), the mean net elevation change was close to zero (Fig. 2). This is due to the overlap of the cold front seasonal interval with the multiple low discharge river flood peaks. (Fig. 2).

Sediment surface elevation change across the deltaic island elevation gradient

The largest net elevation change across the whole delta occurred as a result of river floods in 2008 and 2011. In both years there was a clear trend in elevation gain relative to the pre-season elevation gradient (Fig. 5). The direction of the trends differed from one another; in 2008 there was more net deposition at lower elevations, with the peak at -0.3 m NAVD88 and a

Figure 4. Total water discharge (cubic km) on left axis and total suspended sediment discharge (million metric tons) on right axis at Wax Lake Outlet for each seasonal interval.

gradual decline to 0.1 m NAVD88 (Fig. 5a). The opposite trend was observed in 2011, with little or no net elevation gain at elevations < 0 m NAVD88 and a gradual increase at higher elevations with a peak at 0.3 m NAVD88 (Fig. 5d). The difference in the location of the net elevation gain maxima between the 2008 and 2011 river floods may be due to the different patterns and duration of flooding that occurred during each seasonal interval. In 2009 and 2010, when the river flood discharge was lower, there were similar levels of net elevation gain across the whole deltaic island top elevation gradient (Fig. 5b & c).

A. 2008 flood

B. 2009 flood

C. 2010 flood

D. 2011 flood

378

379 Figure 5. Mean $\pm$ 1 standard error (SE) net elevation change (cm) within 10 cm elevation ranges
 380 for all river flood seasonal intervals. Color of bars corresponds to 10 cm elevation ranges shown
 381 on map of Wax Lake Delta in Fig. 1.

The distribution of total area of floodplain wetlands within each 10 cm elevation range (Fig. 6) illustrates that a larger portion of the deltaic wetlands (≥ -0.5 m NAVD88) occur at lower elevations. During the 2008 flood, the highest elevation gain was seen at lower elevations, resulting in much greater estimates of total sediment deposition than was observed from the 2011 river flood when the majority of elevation gain occurred at high elevations (Fig. 6). There was an estimated 2,082,000 metric tons (T) deposited on deltaic wetlands in 2008, compared to 1,133,000 T in 2011 (Table 3). River flood intervals in 2009 and 2010 both had similar estimates of 824,000 T and 711,000 T respectively, much lower than the two large flood years (Table 3).

Figure 6. Total area (km²) of deltaic wetlands within each 10 cm elevation range, based on USGS Atchafalaya 2 LiDAR Survey December 2012. Color of bars corresponds to 10 cm elevation ranges shown on map of Wax Lake Delta in Fig. 1

3.3 Deltaic wetland sediment retention efficiency

The sediment retention efficiency of the deltaic wetlands is estimated as the proportion of total suspended sediment discharge through WLO over the flood seasonal interval that was deposited on the deltaic wetlands at elevations greater than -0.5 m NAVD88. The retention efficiency during the 2008 river flood was higher than in any other year at 13.5%, much higher than the 7.6% retention efficiency from the 2011 river flood. The spring river flood seasonal interval of 2009 and 2010 had 7.4% and 6.7%, respectively (Fig. 7 & Table 3). This analysis did not include the trapping of sediment that likely occurred in the deeper portions of the delta (<-0.5 m NAVD88), which would increase the overall retention efficiency for the delta as a whole. These results indicate that large floods with lower peak discharge but longer flood duration, as was seen in 2008, maximize sediment retention efficiency and deltaic island top elevation gain. The portion of the total suspended sediment discharge that is trapped and deposited in the deltaic wetlands is critical for land building and the maintenance of the deltaic floodplain in response to sea level rise and subsidence.

4. Discussion

4.1 Estimates of deltaic sediment retention efficiency during spring river floods

The greatest net elevation gain occurred during river flood intervals, compared to all other seasonal forcings (Fig. 2), and is likely related to increased fluvial sediment delivery. The amount of sediment delivered during river floods varied between years in relation to water discharge (Fig. 7). We utilized the results of the field measurements to refine previous estimates of sediment retention efficiency for WLD, reported as 23% by Törnqvist and others (2007), which is double what we estimated for deltaic wetlands. However, their estimate was based on retention for the whole delta topset, which includes both deltaic wetlands and deeper subaqueous

channels, a total area of 104.6 km², approximately double the deltaic wetland area at elevations greater than or equal to -0.5 m NAVD88 used in this study of 53.2 km². Therefore if we scale their original retention efficiency estimate of 23% to the smaller delta area used in this study (limited to wetlands $\geq$ -0.5 m NAVD88) which amounted to 50.8% of their entire delta topset area, the resulting 11.7% retention efficiency (Törnqvist et al. 2007) is very similar to our estimate of 6.7 to 13.5%. The large difference in sediment retention efficiency observed during the 2008 compared to the 2011 river floods of 13.5% and 7.6%, respectively, was surprising as we personally observed many areas of large sandy deposits immediately after the 2011 flood. However, based on our results it is likely these were restricted to higher elevations (Fig. 5d) and less elevation gain occurred at lower elevations (Fig. 6). Analyses by Kolker et al. (2014) found evidence of a shift in the location of the primary sediment depocenter, from nearshore deltaic wetlands and the Atchafalaya Bay bottom, to the continental shelf during the 2011 flood, postulating that the higher discharge of this large flood was able to move suspended sediments further offshore. We observed a mean net elevation gain of 4.8 cm from the 2011 flood mainly in higher elevation areas (Fig. 5d), while the 2008 river flood had higher mean net elevation gain (5.4 cm) spread across a greater range of elevations and larger area (Fig. 5a). This coupled with the observed increased elevation loss at lower elevations and bank collapse in 2011 (personal observations and those of Shaw and Mohrig 2013) supports the shifting of the majority of sediment deposition to locations further offshore. This is consistent with suggestion that the extreme flooding event observed in 2011 was not an ideal model for deltaic restoration and management in open bay environments (Kolker et al. 2014). If the goal is to increase sediment delivery to nearshore deltaic wetlands, high total discharge floods, which extended over a longer duration, as occurred in the 2008 spring flood, seem to better optimize water levels, sediment

delivery and discharge, resulting in the greatest net elevation gain and retention on deltaic wetlands. In doing these calculations we assume that the spatial and temporal coverage of our dataset is adequate to do rough estimates; however we acknowledge that there are assumptions inherent in these data specifically related to the small sampling size across the 10 cm elevation bins. We contend that these estimates should be used as a basis for hypothesis development for more robust experimental designs in order to better refine sediment retention estimates and the overall sediment budget in the WLD.

Figure 7. Total suspended sediment discharge (million metric tons) at Wax Lake Outlet over each river flood seasonal interval and total mass of sediment deposited on deltaic island tops at elevation ≥ -0.5 m NAVD88 during each seasonal interval. Retention efficiency for each river flood seasonal interval is also shown.

4.2 Hurricane storm surge contribution to elevation gain

We measured a net elevation gain of 1.2 ± 0.41 cm following the passage of Hurricanes Gustav and Ike in September 2008. This is consistent with observations by other studies that have shown that there is a resuspension of sediment which occurs as a result of the waves, currents and storm surge associated with hurricane passage (Walker 2001). These sediments are re-deposited as the surge moves inland into coastal wetlands, resulting in measurable elevation gain attributed to hurricanes (Rejmánek et al. 1988; Guntenspergen et al. 1995; Nyman et al. 1995; Cahoon 2006; Turner et al. 2006; McKee and Cherry 2009; Morton and Barras 2011; Tweel and Turner 2012). Recent studies have measured deposition rates resulting from hurricanes (Turner et al. 2006; Tweel and Turner 2012). While both of these studies adequately measure sediment deposition, they fail to also quantify erosion, essentially reporting gross deposition. These gross deposition rates are then used to interpolate to a landscape scale the amount of hurricane derive sediment accumulation across the northern Gulf of Mexico coastal zone. We contend that by using only a measure of deposition (i.e. positive elevation change) the landscape scale values reported in these studies are overestimates the total sediment attributable to hurricanes along the Northern Gulf of Mexico coast (Turner et al. 2006; Tweel and Turner 2012). In order to accurately interpolate their deposition estimates as they did over thousands of square km of coastal wetlands and open water, they would need to include a factor that represents the erosional component resulting from the hurricanes as well. Our analysis provides an estimate of this erosional component. Of the 85 plots measured in replicate after the passage of Hurricanes Gustav and Ike, 53 exhibited a mean deposition of 3.14 ± 0.36 cm, 27 exhibited elevation loss with a mean of -2.35 ± 0.64 cm and 5 exhibited no change in elevation. The estimate of gross elevation gain (3.14 ± 0.36 cm) is 2.6 times larger than the final estimate of net

477 elevation gain (1.21 ± 0.41 cm). Therefore, we suggest that the overestimates reported for the
478 contribution of hurricanes sediments across the coastal zone reported in Turner et al. 2006, and
479 Tweel and Turner 2012, should be adjusted downward by including an erosional component
480 factor of 0.385 in order to get a more accurate representation of net sediment accumulation
481 resulting from hurricanes across the northern Gulf of Mexico Coastal zone. While this is still an
482 appreciable sediment subsidy for coastal wetlands, especially in abandoned delta lobes that
483 receive very little riverine sediment input (McKee and Cherry 2009; Baustian and Mendelssohn
484 2015), it is only a small contribution in wetlands that receive appreciable riverine sediment
485 delivery (Törnqvist et al. 2007).

486 Table 3. Total surface area for delta island top 10 cm elevation ranges ≥ -0.5 m NAVD88, estimate of volume of sediment deposited
487 over each river flood seasonal interval, and total suspended sediment (TSS) discharge from Wax Lake Outlet over each river flood
488 interval. Retention efficiency is determined as the proportion of TSS discharge that is retained on delta island tops. Estimates of
489 sediment mass are based on a mean post river flood bulk density of 0.86 ± 0.02 g/cm³ from 10 cm deep sediment cores collected
490 following 2009 spring river flood.

Elevation ranges (m NAVD88)	2008 Flood			2009 flood		2010 Flood		2011 flood	
	Total surface area (km ²)	Mean sediment elevation change (cm)	Estimate of mass of sediment (metric tons) <small>based on mean bulk density of 0.71 g/cm³</small>	Mean sediment elevation change (cm)	Estimate of mass of sediment (metric tons) <small>based on mean bulk density of 0.86 g/cm³</small>	Mean sediment elevation change (cm)	Estimate of mass of sediment (metric tons) <small>based on mean bulk density of 0.71 g/cm³</small>	Mean sediment elevation change (cm)	Estimate of mass of sediment (metric tons) <small>based on mean bulk density of 0.72 g/cm³</small>
-0.50 to -0.41	4.11	--	--	-1.8	-64,000	-1.1	-32,000	-0.5	-15000
-0.40 to -0.31	5.69	0.5 $\pm$ 2.0	20,000	3.9 $\pm$ 4.2	190,000	1.7	69,000	-2.1	-86000
-0.30 to -0.21	7.32	12.5 $\pm$ 7.0	650,000	-0.2 $\pm$ 0.3	-13,000	0.4 $\pm$ 0.2	21,000	3.3 $\pm$ 0.4	170000
-0.20 to -0.11	7.27	10.1 $\pm$ 3.6	520,000	--	--	5.3 $\pm$ 2.8	270,000	-0.3	-16000
-0.10 to -0.01	6.17	7.8 $\pm$ 2.1	340,000	7.3 $\pm$ 6.1	390,000	3.3 $\pm$ 1.1	140,000	0.9 $\pm$ 0.6	40000
0.0 to 0.09	5.05	6.4 $\pm$ 1.8	230,000	0.8 $\pm$ 1.1	35,000	0.1 $\pm$ 0.7	3,600	4.0 $\pm$ 1.9	150000
0.10 to 0.19	4.8	0.9 $\pm$ 2.2	31,000	3.2 $\pm$ 2.1	130,000	1.4 $\pm$ 1.2	48,000	8.1 $\pm$ 4	280000
0.20 to 0.29	4.18	2.8 $\pm$ 3.1	83,000	0.5 $\pm$ 2.1	18,000	1.6 $\pm$ 1.5	47,000	7.9 $\pm$ 4.4	240000
0.30 to 0.39	3.42	6.2 $\pm$ 1.2	150,000	1.3 $\pm$ 1.8	38,000	4.9 $\pm$ 3.2	120,000	14.3 $\pm$ 0.6	350000
0.40 to 0.49	3.59	1.6 $\pm$ 0.5	41,000	1.8 $\pm$ 1.3	56,000	0.8 $\pm$ 1.0	20,000	-1.1 $\pm$ 0.9	-28000
>0.50 m	1.55	1.5	17,000	3.3 $\pm$ 0.4	44,000	0.4 $\pm$ 0.5	4,400	4.3 $\pm$ 1.8	48000
Total surface area	53.2								
Total mass of sediment deposited on island tops (≥ -0.5 m NAVD88) by flood (metric tons)			2,082,000		824,000		711,000		1,133,000
Percentage of total suspended sediment discharge over seasonal interval			13.5%		7.4%		6.7%		7.6%

4.3 Long-term contribution of large river floods and hurricanes to delta growth

Here we use the synoptic results obtained from the passage of Hurricanes Gustav and Ike to estimate the long-term contribution of hurricanes to sediment elevation gain in the WLD, particularly relative to large river floods. While the reported return period for hurricanes ($\geq$ category 1) along the MRD is one every 7-10 years (Keim et al. 2007), the hurricane passage that occurred during this study is unusual in that it included the passage of two category 2 storms within two weeks. From an ecological and sediment transport perspective it is likely that Hurricane Ike, with its larger shifts in water level, had a much greater effect on the ecology and geomorphology of deltaic wetlands. However this cannot be determined from our data because no sampling occurred during the time between the two storms. We estimate that the net elevation gain that we observed from Hurricanes Gustav and Ike in 2008 of 1.21 cm would result in an annual contribution of 0.06 to 0.09 cm yr⁻¹. This long-term estimate is much lower than the vertical accretion rate of 1.4 to 2 cm yr⁻¹ estimated from ¹³⁷Cs peaks in nearby wetland and bay bottoms that are also receiving riverine mineral sediment inflow (DeLaune et al. 1987; Mossa and Roberts 1990). The return period for large river floods equal or greater in water level than the 2008 flood is once every 12 yr based on the entire record of the Atchafalaya River at Simmesport LA (USGS 07381490) which extends from 1932 to 2015. Using this estimated return period and a mean net deposition of 5.4 cm and 4.9 cm in 2008 and 2011, respectively, the long-term estimate of mineral sediment contribution from large river floods is 0.42 to 0.46 cm yr⁻¹. Direct comparison of the long-term sediment elevation gain from large floods and hurricanes shows that long-term hurricane derived contribution to delta wetland elevation gain is less than 22% of that from large river floods.

4.4 Elevation loss due to cold front passage

The net loss of elevation resulting from annual cold front passage can effectively cancel out flood elevation gain except in large river flood years, which occur about once every 12 yr. There is little variability in number and pattern of cold front occurrence from year to year (Hardy and Henderson 2003). Therefore the effects of cold fronts on elevation loss are occurring to the same degree every year. This pattern of elevation loss, due to cold front seasonal forcings in the WLD and Atchafalaya Delta has been reported in a number of other studies (Rouse et al. 1978; Kemp et al. 1980; Roberts and Adams 1980; Mossa and Roberts 1990). This has important implications for land building capacity of this type of system as the need to offset this annual elevation loss is critical for continual net elevation gain. While cold front elevation loss is significant within the wetlands within the WLD itself, it has been reported that resuspended sediments from cold front passage as well as river floods have resulted in appreciable sediment deposition along tidal creeks in nearby organic headland marshes, brackish marshes along Fourleague Bay and near shore bay bottoms (DeLaune et al. 1987; Perez et al. 2000; Roberts et al. 2015). Transport of suspended sediment via cold front water level fluctuations in areas that do not receive direct river inflow has also been shown, such as salt marshes in sediment limited Terrebone Basins (Reed 1989). Also, cold front resuspension and transport of sediments westward from the Atchafalaya Bay via longshore current results in accretion of mudflats in the Louisiana Chenier Plain (Roberts et al. 1989; Mossa and Roberts 1990; Kineke et al. 2006). Therefore fluvial sediments initially deposited on the deltaic wetlands of WLD during river floods may act as a sediment source during winter cold front resuspension events and support secondary sediment transport to far field wetlands throughout the coastal zone.

While two large river floods (2008 and 2011) occurred within only four years during our sampling, the return period of river floods this size is historically one every 12 years. The large river floods resulted in net annual elevation gain. The moderate and smaller river floods, like 2009 and 2010, seem to be offset on an annual basis by cold front elevation loss, resulting in no net change in elevation across the delta for the year (Fig. 2). This pattern of vertical elevation gain in which there is no net growth of deltaic island elevation for a number of years (with small to moderate river floods), punctuated by net elevation gain from periodic large river floods (approximately once every 12 yr), may be important for understanding previous long term estimates of vertical delta growth and predicting future elevation gain. Previous delta land building predictions for both the WLD and Atchafalaya Deltas have been over-estimated with some researchers predicting that both deltas would merge and fill the Atchafalaya Bay within the early part of the 21st century (Shlemon 1975; Roberts and Adams 1980; van Heerden et al. 1983; DeLaune et al. 1987; Majersky et al. 1997). This may be due to the lack of inclusion of elevation loss resulting from cold fronts in these predictive models. It is likely that numerical models currently used for restoration planning that do not take cold front removal into account will also overestimate land building rates (Parker and Sequeiros 2006; Hanegan 2011). Inclusion of this net degradational process in future delta models is critical for accurate prediction of delta morphodynamics and development.

5. Conclusions and implications for coastal restoration

Coastal Louisiana is an area where dynamic marine and riverine forces shape deltaic landforms. This study in an actively prograding delta allows us to better understand the relative contributions of three major forcings, river floods, cold fronts and hurricanes to delta growth.

River floods are the main drivers of elevation gain in the WLD, with the highest discharge floods resulting in significantly more elevation gain than lower discharge floods; however without the combined elevation gain attributed to both large and small floods, net positive elevation gain would not be possible over the long-term, due to consistent annual loss in elevation due to cold fronts. We also found that while hurricanes do deliver a net elevation gain to the deltaic floodplain wetlands, they also result in appreciable elevation loss, equal to 39% of the gross elevation gain. This is an important consideration that is often left out of other studies of hurricane sediment subsidy. The long-term annual contribution of hurricane derived sediments to these deltaic wetlands based on a return period of one every 7-10 years is less than 22% of the sediment delivered by large river floods in the WLD. River diversions designed for suspended sediment delivery have been proposed as a potential means to offset wetland loss in coastal Louisiana (CPRA 2012). We conclude that in locations that experience similar hydrological forcings to the WLD, the operation of these diversions would need to be designed with these findings in mind. It is also crucial to include cold front elevation loss in numerical models of delta building to accurately predict future land building.

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