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The impacts of the great Mississippi/Atchafalaya River flood on the oceanography of the Atchafalaya Shelf

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ABSTRACT

Rivers are the primary means by which water, sediment, and dissolved material are transported from the continents to the ocean. Despite previous advances, much remains to be learned about the dynamics of large shelf-discharging rivers, and their functional differences with deep water-discharging rivers, particularly with respect to the distribution of sediments in the coastal zone. The great Mississippi/Atchafalaya River flood of 2011 provided an excellent opportunity to examine the impacts of a large, shelf-discharging river on the coastal ocean, and the role that event pulses from such rivers play in the delivery of sediment to the inner continental shelf. Vessel-based surveys were conducted on the inner-continental shelf within the Atchafalaya and Mississippi River plume regions, providing *in situ* measurements of salinity, temperature, dissolved oxygen, turbidity, particle size, and current velocity profiles. MODIS satellite images and ^{7}Be measurements were used to assist in data interpretation.

We demonstrate that the Atchafalaya River plume produced intense vertical gradients in temperature, salinity, oxygen and turbidity. This occurred despite the shallow bathymetry of this system and the presence of winds, which alternated between onshore to offshore, and that might have otherwise mixed systems with less freshwater. Sedimentation rates along the inner-continental shelf were about 5–10 times greater than those measured previously during smaller "typical" floods. This large deposit is likely to be preserved, at least in the near term, because sedimentation occurred beyond normal depths of wave reworking and the intense stratification induced by this flood likely reduced mixing at the time of sedimentation. A sediment budget for this system reveals that sediment fluxes to the coastal zone during 2011 were similar to those observed in previous years, suggesting that this system is supply limited, rather than transport limited. As such, we postulate that the major impact of this flood was to change the location of the depocenter of Atchafalaya River sediments, rather than increase the annual flux of sediments to the coastal zone. These findings imply that extreme flood events may not be an ideal analog for coastal restoration along this deltaic coast.

1. Introduction

Rivers are the primary means by which water, particles and dissolved materials are transported from the continents to the ocean. On average, rivers deliver 45,000 km^3 of water, 13×10^9–18×10^9 t of sediment, and 378×10^8 t of carbon to the ocean every year (Milliman and Meade, 1983; Oki and Kanae, 2006). Given the magnitude of these fluxes, the fate of this material in the ocean is a matter of considerable interest. Over the past several decades, numerous studies have examined how river-derived nutrients, sediments, and freshwater are processed in the coastal ocean and whether they are transported directly to the deep sea or sequestered to the continental shelf (Nittrouer et al., 2007). River/ocean systems that have generated substantial attention include small mountainous rivers, such as the Eel and the Po, which discharge into deep water; large mountainous rivers, such as the Fly, which deliver sediments into long, shallow deltas; or large rivers, such as the main stem of the Mississippi, which discharge directly into deep water. Despite significant studies along the Amazon River Shelf (Aller et al., 2004; Anthony et al., 2010) and

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the Atchafalaya River Shelf (Draut et al., 2005b; Huh et al., 2001; Neill and Allison, 2005; Walker and Hammack, 2000), much remains unknown about the dynamics of large shelf-discharging rivers, and the differences between shelf-discharging and deep-water discharging rivers, particularly with respect to the distribution of sediments in the coastal zone.

The great Mississippi/Atchafalaya River flood of 2011, one of the largest floods on record, provided an excellent opportunity to understand how large, shelf-discharging rivers can impact the distribution of water and sediment in river-influenced regions of the inner continental shelf of the Gulf of Mexico. The flux of water in the lower Mississippi River as measured at Vicksburg reached 65,940 $m^3\ s^{-1}$, which rivaled the historic floods of 1927 and 1973 (waterdata.usgs.gov). This extreme high-water event prompted the opening of a flood control structure, the Morganza Spillway, to relieve pressure on levees across the lower Mississippi River Valley. This release diverted additional water down the already swollen Atchafalaya River, temporarily creating one of the largest shelf-discharging rivers in North America. It also created an ephemeral opportunity to study a significant and well-studied continental shelf under unique hydrodynamic conditions.

These special hydrographic conditions allowed us to test two hypotheses. First, we hypothesize that physical gradients and patterns of sediment distribution produced by large shallow shelf-discharging rivers and large rivers discharging into deeper waters are a function of 1) the geometry of the outlet channel, 2) the buoyancy difference between the freshwater plume and marine waters, and 3) the return period of the flood. Second, we hypothesize that the primary sedimentological impact of a large flood in a supply-limited system will be to change the location of the depocenter, rather than the overall annual flux of sediment to the coastal zone. This second hypothesis can be derived from first principles; supply-limited systems by definition lack sediment, and therefore flood pulses can redistribute sediment, but not increase its availability. It can also be derived empirically; dams and flood control structures along the Mississippi River and its tributaries trap more sediment than they do water (Meade and Moody, 2010), suggesting flood pulses are not likely to bring new sediments into the lower reaches of the system. We tested these hypotheses using data collected from the shallow ($<$ 10 m in many locations) Atchafalaya River inner-continental shelf during near-peak discharge in 2011. We contrast these data to similar measurements conducted from the continental shelf fronting Southwest Pass, the largest distributary of the lower Mississippi River, which discharges onto an irregularly shaped, but narrow continental shelf that leads into water of $>$500 m over a distance of $<$50 km. We provide analyses of the distribution of salt, temperature, turbidity, and particle size in these systems, and add river gauge on the flux of water and sediment to the coastal zone and *in situ* hydro-acoustic data on circulation patterns during high discharge conditions. These measurements are given a broader environmental context using satellite imagery analyses, *in situ* cores that illustrate the extent of sediments in surface waters and their subsequent deposition on the continental shelf and nearby deltaic environments.

2. Study location

This study was conducted on the inner-continental shelf seaward of Atchafalaya Bay and the Southwest Pass of the Mississippi Balize Delta, Louisiana (Fig. 1). The drainage basin of the two rivers totals 3.27×10^6 km^2, making this the third largest drainage basin on Earth (McKee et al., 2004). At 485 km above Head of Passes (near the mouth of the main stem of Mississippi River), the Old River Control Structure diverts water from the Mississippi River into the Atchafalaya Basin, where it mixes with the Red River to form the Atchafalaya River. This structure is regulated such that on average, 30% of the combined flow of the Mississippi and Red Rivers are directed into the Atchafalaya River (Allison et al., 2012; Huh et al., 2001; Meade and Moody, 2010). There is a secondary structure, the Morganza Spillway (located 448 km above Head of Passes) that diverts additional water into the Atchafalaya River. These structures are part of a series of flood-control structures that include the Bonnet Carré Spillway, located about 19 km upstream of New Orleans, and the Birds Point Levee, located near Cairo, Illinois. The Morganza spillway has only been open twice since its construction was completed in 1954, in 1973, and again in 2011, when this study was conducted. The 2011 flood marks the only occasion when all three of these major flood-control structures were opened.

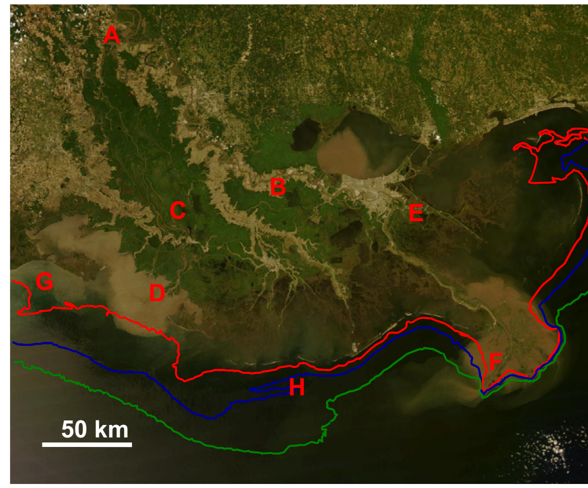

Fig. 1. MODIS true color image depicting the Mississippi and Atchafalaya rivers in flood, discharging into the Gulf of Mexico on May 17, 2011. The red, blue and green contour lines correspond to the 5, 10 and 20 m isobaths. The following locations are noted: (A) Old River Control Structure; (B) main stem of the Mississippi River; (C) Atchafalaya River; (D) Wax Lake and Atchafalaya River deltas; (E) Belle Chasse Mississippi River gauge; (F) Southwest Pass of the Mississippi River G, LSU/Wavcis CSI-3 gauge; and (H) LSU/Wavcis CSI-6 gauge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The Atchafalaya River reaches the coastal zone through two main channels; the main stem of Atchafalaya River, which is gauged at Morgan City, Louisiana, and a conveyance channel called the Wax Lake Outlet, which is gauged at Calumet, Louisiana (Fig. 1). At the mouth of these channels are deltas that first became subaerial following a series of high water events in the early 1970s (Coleman et al., 1998a; Roberts, 1997). The rapid rate of formation of these sedimentary systems, and particularly the unmanaged nature of the Wax Lake Delta, has contributed to their use as models for delta growth (Coleman et al., 1998a; Kim et al., 2009; Paola et al., 2011; Roberts, 1997). Water from these deltas reaches the continental shelf through a 45 km passage at the mouth of Atchafalaya Bay. In contrast, the Mississippi River reaches the coastal zone through a variety of outlets in the lower river. The dominant features distributing Mississippi River water are the passes that begin at Head of Passes and which make up the “bird's foot” distributary-channel network of the delta. The largest of these outlets is Southwest Pass, a ~1.5-km wide pass that opens water that is ~10 m deep, but which reaches a depth of 50 m–5 km offshore. While the distribution of water varies with discharge, during the years 2008, 2009 and 2010 an average of 163 km^3 (30%) of the total discharge of the Mississippi River (541 km^3) reached the Mississippi River through Southwest Pass (Allison et al., 2012).