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Dispersal of Mississippi and Atchafalaya sediment on the Texas–Louisiana shelf: Model estimates for the year 1993

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ABSTRACT

A three-dimensional coupled hydrodynamic-sediment transport model for the Texas–Louisiana continental shelf was developed using the Regional Ocean Modeling System (ROMS) and used to represent fluvial sediment transport and deposition for the year 1993. The model included water and sediment discharge from the Mississippi River and Atchafalaya Bay, seabed resuspension, and suspended transport by currents. Input wave properties were provided by the Simulating WAves Nearshore (SWAN) model so that ROMS could estimate wave-driven bed stresses, critical to shallow-water sediment suspension. The model used temporally variable but spatially uniform winds, spatially variable seabed grain size distributions, and six sediment tracers from rivers and seabed.

At the end of the year 1993, much of the modeled fluvial sediment accumulation was localized with deposition focused near sediment sources. Mississippi sediment remained within 20–40 km of the Mississippi Delta. Most Atchafalaya sediment remained landward of the 10-m isobath in the inner-most shelf south of Atchafalaya Bay. Atchafalaya sediment displayed an elongated westward dispersal pattern toward the Chenier Plain, reflecting the importance of wave resuspension and perennially westward depth-averaged currents in the shallow waters (<10 m). Due to relatively high settling velocities assumed for sediment from the Mississippi River as well as the shallowness of the shelf south of Atchafalaya Bay, most sediment traveled only a short distance before initial deposition. Little fluvial sediment could be transported into the vicinity of the "Dead Zone" (low-oxygen area) within a seasonal–annual timeframe. Near the Mississippi Delta and Atchafalaya Bay, alongshore sediment-transport fluxes always exceeded cross-shore fluxes. Estimated cumulative sediment fluxes next to Atchafalaya Bay were episodic and "stepwise-like" compared to the relatively gradual transport around the Mississippi Delta. During a large storm in March 1993, strong winds helped vertically mix the water column over the entire shelf (up to 100-m isobath), and wave shear stress dominated total bed stress. During fair-weather conditions in May 1993, however, the freshwater plumes spread onto a stratified water column, and combined wave–current shear stress only exceeded the threshold for suspending sediment in the inner-most part of the shelf.

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1. Introduction

1.1. Background

Large rivers play a key role in delivering freshwater, sediment, and nutrients to the ocean (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Large-river deltas and associated coastlines are especially important interfaces between continents and oceans for material fluxes that globally impact oceanographic processes (Bianchi and Allison, 2009). The Mississippi River, the largest in North America, drains 41% of the continental United States before entering the northern Gulf of Mexico (Fig. 1A). The State of Louisiana contains about 40% of the nation's coastal and estuarine wetlands which are vital to recreational and agricultural interests, and is home to the state's \$1 billion per year seafood industry (Stone and McBride, 1998). The Mississippi Delta, its associated wetlands and barrier islands developed over geological timescales in response to continuous accumulation of fluvial sediment and reworking by physical oceanographic processes

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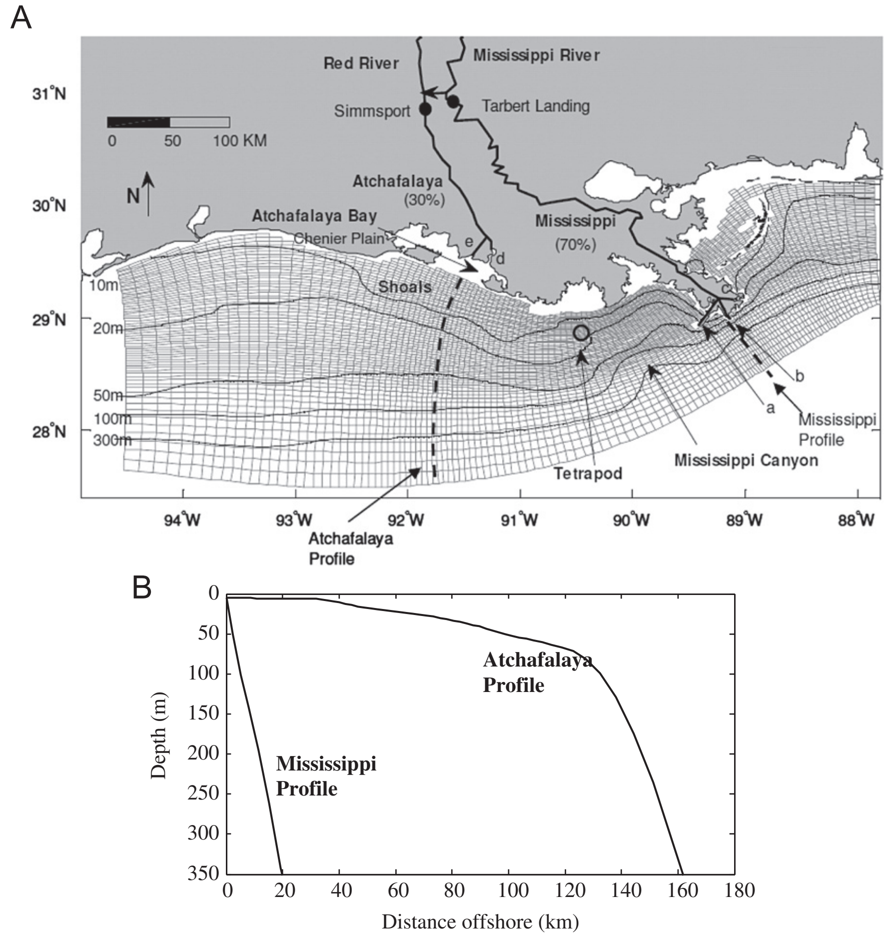

Fig. 1. (A) Curvilinear model grid for the Texas–Louisiana shelf. Isobaths contoured at 10, 20, 50, 100, and 300 m. The open circle is the tetrapod location for the LATEX sediment transport observation in spring, 1993 (Wright et al., 1997). Shown on the Mississippi Delta are Southwest Pass (a), South Pass (b) and Pass a Loutre (c). Both Atchafalaya (d) and Wax Lake (e) Deltas are being built in Atchafalaya Bay. (B) Bathymetric profiles south of the Mississippi Delta and Atchafalaya Bay. Locations of profiles shown as dashed lines in (A).

(e.g., waves and currents). Since the early Holocene ($\sim$8000 years BP), the Mississippi River has built six delta complexes, including the two most recent ones: the Balize (modern Mississippi Bird-foot Delta) and Atchafalaya–Wax Lake Deltas (Coleman et al., 1998).

The Atchafalaya has served as a distributary of the Mississippi since as early as the 1500s (Fisk, 1952), but the volume of diverted flow increased significantly during the past century when the Mississippi River begun to abandon the Balize course in favor of the Atchafalaya (Roberts, 1998). Since installation of a control structure in 1963, approximately 70% of the combined discharge of Mississippi and Red Rivers has entered the Gulf of Mexico through the modern Mississippi mainstem, while 30% went through the Atchafalaya (Meade and Moody, 2010; Fig. 1A). During the past two decades, the Mississippi and Atchafalaya carried an average of 115 and 57 Mt (Million tons)/year of sediment into coastal Louisiana, respectively (Meade and Moody, 2010).

The geomorphology of the areas offshore of the Mississippi and Atchafalaya Rivers differ. Though coastal morphological settings can greatly impact fluvial sediment dispersal, few recent studies have compared the sediment transport mechanisms or sediment accumulation patterns in the areas offshore of these two rivers. In response to high fluvial sediment discharge and relatively modest waves and tides, the Mississippi developed a river-dominated bird-foot shaped delta on the eastern Louisiana shelf (Fig. 1A). Near this prominent delta, high sediment supply has led rapid delta progradation, developing a narrow and steep shelf ($<$20 km wide south of the delta, a gradient of $\sim$0.4°, Fig. 1B). Along the western Louisiana shelf, however, the relatively young Atchafalaya River has been building bird-foot Atchafalaya and Wax Lake deltas inside the shallow and semi-enclosed Atchafalaya Bay (Fig. 1A). Because only a small portion of sediment from the Atchafalaya River can reach deep water (Allison et al., 2000), the modern sediment supply to the middle and outer shelf is minimal and the shelf south of Atchafalaya Bay is broad, smooth, and gently sloped ($\sim$200 km wide, a gradient of 0.02°) (Fig. 1B).

1.2. Physical oceanographic setting

Wind-driven low-frequency currents on the Texas–Louisiana shelf have distinct modes during summer (June–August) compared to non-summer periods (Cho et al., 1998). During the summer when winds are generally from the west and thus upwelling favorable, the fresh water introduced by the Mississippi and Atchafalaya Rivers combines with intense solar radiation, stratifying the shelf water column (Cochrane and Kelly, 1986); during the non-summer months, downwelling-favorable winds blow predominately from the northeast, enhancing westward currents (Rhodes et al., 1985). Tidal fluctuations in the area are diurnal or mixed diurnal types with amplitudes generally less than 0.4 m (Wright et al., 1997; DiMarco and Reid, 1998).

The northern Gulf of Mexico has low wave action except during storms (Curray, 1960). Typical deep-water waves show a range of wave periods averaging from 3 to 8 s with heights rarely exceeding 1 m. Such waves are capable of mobilizing the sea bed only in the surf zone and nearshore areas (Curray, 1960). Wave energy episodically increases during storm and hurricane conditions, during which wave shear stresses are capable of suspending sediment from sea bed. Based on measurements on the inner shelf south of Atchafalaya Bay, for example, Sheremet et al. (2005) found that waves and currents resuspended large quantities of sediment during Hurricane Claudette in 2003, with concentrations reaching 0.5 kg/m^3 throughout the water column.

1.3. Sedimentary environment

Around the Mississippi Delta, the close proximity of a large fluvial sediment source facilitates accumulation, as does the fact that the hydrodynamic regime of the inner shelf is characterized as low energy under fair-weather conditions (Wright and Nittrouer, 1995). The Mississippi Delta contains several passes that deliver sediment and freshwater to the northern Gulf of Mexico, the largest being Southwest Pass, South Pass and Pass a Loutre (a, b, and c in Fig. 1A). Based on bottom-boundary layer observations of sediment transport at 20.5-m water depth about 100 km west of Southwest Pass (Fig. 1A), Wright et al. (1997) found near-bed flows to be very weak under fair-weather conditions. In the absence of wave activity the bed was hydraulically very smooth, and the combined wave–current shear stress was insufficient to suspend sediment; sediment concentrations during these observations peaked at about 80 mg/L.

Using short-lived radionuclides, Corbett et al. (2004) showed that river-borne sediment was transported less than ~30 km from the river mouth before initial deposition; however, seasonal variations in ^{7}Be and ^{137}Cs indicated significant remobilization and potential export of sediment out of the Mississippi subaqueous delta during high-energy winter months. Based on high-frequency surveys of radionuclides, Corbett et al. (2006) further demonstrated that monthly ^{7}Be inventories showed a significant positive relationship to river discharge at the *proximal* site, ~10 km offshore of the Southwest Pass, but no relationship at the *distal* site, ~120 km southwest of the Southwest Pass (next to the Mississippi Canyon, Fig. 1A). Instead, monthly ^{7}Be inventories at the distal site had a significant positive relationship with wave orbital velocity, which indicated that high wave orbital velocities potentially maintained particles in suspension longer so that they traveled farther before initial deposition (Corbett et al., 2006). In addition, Walsh et al. (2006) found evidence of mudflow activities near the Mississippi subaqueous delta after hurricanes Katrina and Rita in 2005, revealing that storm remobilization and gravity-driven transport might be an important mechanism transferring sediment to deep water.

Sediment dispersal processes offshore of Atchafalaya Bay differ from those offshore of the Mississippi Delta. Based on observations offshore of Atchafalaya Bay in 2001, Kineke et al. (2006) reported that as cold fronts passed the region, fine-sediment transport was to the west and shoreward, mainly due to suspension and mixing with increased wave energy during pre-front conditions and stratification and upwelling during post-front conditions. Based on sediment cores and ^{210}Pb/^{7}Be geochronology, Allison et al. (2000) found 1–3-cm-thick deposits on the inner shelf offshore of Atchafalaya Bay, but they suggested that these were produced by sediment redistributed from the shallower parts of the shelf during storms in the non-flood season. Using CHIRP seismic profiling, Neill and Allison (2005) identified an early-stage subaqueous delta accumulating on the inner shelf south of the Atchafalaya Bay mouth. This muddy subaqueous clinoform extends across the entire bay front, reaches a maximum thickness of 3 m at the 6-m isobath, and pinches out around the 10-m isobath (Neill and Allison, 2005). ^{210}Pb and ^{137}Cs geochronology showed maximum sediment accumulation rates (>3 cm/year) corresponded to the foreset and bottomset of this clinoform, while rates decreased to as low as 0.9 cm/year on the shelf and its extension inside Atchafalaya Bay (Neill and Allison, 2005).

These differences in sedimentary environments offshore Mississippi Delta and Atchafalaya Bay motivates, in part, our comparison of the influence of physical oceanographic conditions (waves and currents) on sediment dispersal there. Using results from a three-dimensional numerical model, we will contrast the processes responsible for alongshore and cross-shore sediment-transport fluxes in these two areas.

1.4. Modeling studies of the Gulf of Mexico

A number of numerical and statistical models have been used to hindcast, nowcast and forecast the oceanographic processes in the northern Gulf of Mexico (see review in Justić et al., 2007). Using a three-dimensional model, Oey (1995) studied the relationships among convergence and divergence, shelf break currents and Loop Current eddies in the northwest Gulf of Mexico. Chen et al. (1997) applied a physical–biological coupled model to study the impact of fluvial discharge on biological production in the inner Texas–Louisiana shelf. Zavala-Hidalgo et al. (2003) further investigated seasonal circulation on the western shelf of the Gulf of Mexico and found that the along-shelf currents and low-frequency variability of the atmospheric sea level pressure explained up to 80% of seasonal sea level variability. Morey et al. (2003, 2005) found that the primarily wind-driven circulation in the Gulf of Mexico governs the salinity field on the shelves by transporting fresh water along seasonally shifting pathways.

Despite these extensive studies, there have been few numerical modeling studies of *sediment transport* processes on the Texas–Louisiana shelf. Though some three-dimensional hydrodynamic models have been used to study sediment transport processes in the area next to the bird-foot delta (Keen et al., 2004) and within the Atchafalaya prodelta channel (Teeter and Johnson, 2005), published models have not considered sediment transport on the entire Texas–Louisiana shelf. The timescales over which, and mechanisms by which sediment is transported from the Mississippi and Atchafalaya Rivers to the Texas–Louisiana Shelf remain poorly understood. With a three-dimensional numerical model, we can address gaps in the knowledge base that has been developed from field observations that are limited in spatial or temporal scope. For example, our numerical model can be used to evaluate the relative contributions of waves and currents to sediment transport during storm and fair-weather conditions from the inner to outer shelf. Additionally, model estimates can quantify the relative importance of alongshore and cross-shore sediment transport fluxes, and compare dispersal mechanisms on the Mississippi shelf to those on the Atchafalaya shelf.

1.5. Hypoxia on the Texas–Louisiana shelf

A well-known problem in the northern Gulf of Mexico, hypoxia is defined as an episode where dissolved oxygen content in bottom water falls below 2 mg/L, potentially causing habitat loss, stressing marine organisms, and degrading the health of the impacted ecosystems. Known as the "Dead Zone", an area of hypoxic water recurs during summer, covering on average 8000–9000 km^2 of the northern Gulf's continental shelf between water depths of 5–30 m (Rabalais et al, 2002). Some years, however, the size covered by hypoxic waters has been observed to exceed 20,000 km^2, and in 1993 it exceeded 16,000 km^2 (Rabalais et al., 2002). Hypoxia is believed to be exacerbated by nutrient enrichment of Mississippi River water from terrestrial sources (Rabalais et al., 2007) and its location is tied to that of fresh water plumes that inhibit mixing (Hetland and DiMarco, 2008). During the past several years, extensive studies have focused on hypoxic processes in the Dead Zone. Hetland and DiMarco (2008) isolated the effects of stratification and circulation on the formation and maintenance of hypoxic water using an implementation of ROMS that included several simplified respiration models. DiMarco et al. (2010) reported that local topography plays a role in the hypoxia formation and that the area between sandy shoals south the Atchafalaya Bay coincides with areas of more frequent hypoxia.

Sediment processes impact hypoxia in the northern Gulf of Mexico via sediment-induced light attenuation, and modify benthic diagenetic processes (Wainright and Hopkinson, 1997; McKee et al., 2004). Turbid Mississippi and Atchafalaya freshwater plumes, permanent features on satellite imagery (personal communication with Dr. Nan Walker, LSU), play a key role in light attenuation that inhibits photosynthesis and controls primary production (Bierman et al., 1994; Lehrter et al., 2009). Based on integrated measurements of sediment oxygen consumption on the sea bed and bottom water-column respiration rates during eight cruises from 2003 to 2007 along the hypoxic zone (between 5 and 30 m isobath) in the Gulf of Mexico, Murrell and Lehrter (2010) found that sediment oxygen demand contributed to 20% of total below-pycnocline respiration. Based on a mass balance model and a few in-situ measurements on the Texas–Louisiana shelf, Bierman et al. (1994) found sediment oxygen demand to be between 22 and 30% of the total summertime oxygen consumption in the bottom layer of hypoxic water. Using oxygen stable isotopes, Quiñones-Rivera et al. (2007) attributed 73% of the oxygen consumption in the lower water column of the northern Gulf during summer 2001 to benthic respiration. Moreover, Turner et al. (2006, 2008) reported an increase in oxygen demand of marine sediment that arose from the addition of organic matter to the seabed, concluding that accumulation in a flood year could precondition the system to be more sensitive to nitrogen loading in following years. To fully investigate the mechanisms controlling hypoxia therefore requires a better understanding of temporal and spatial variations of both the dispersal of Mississippi and Atchafalaya sediment and resuspension.

2. Objectives

By analyzing model estimates of Mississippi and Atchafalaya sediment dispersal, we develop a quantitative and comprehensive understanding of the *spatial* and *temporal* variations of sediment transport processes on the Texas–Louisiana shelf. In the northern Gulf of Mexico, the spatial coverage of most past sediment observations (e.g., grabs, cores, tetrapods, and sediment traps) was limited to the vicinities of either the Southwest Pass of the Mississippi Delta or south of the Atchafalaya Bay. The timescales covered by tetrapod observations and short-lived radionuclides was weeks to months, while longer-term radionuclides (^{210}Pb) and modern seismic stratigraphy (e.g., Neill and Allison, 2005) average over timescales of 100 years or longer. Our modeling effort fills the spatial and temporal gap in the previous observational studies, covering a large portion of the Texas–Louisiana shelf and focusing on daily to yearly time scales.

Using a high-resolution three-dimensional model, this paper addresses three specific questions for the Texas–Louisiana shelf: (a) To what degree can suspension by waves and currents disperse sediment from the Mississippi and Atchafalaya Rivers in a year? (b) How do sediment-transport mechanisms differ offshore of the Mississippi and Atchafalaya Rivers? (c) What are the direction and relative importance of alongshore and cross-shore transport fluxes of Mississippi and Atchafalaya sediments? This study also provides a baseline for future three-dimensional sediment-transport studies of the Texas–Louisiana shelf. Our longer term goal, as discussed in Section 7.2, is to investigate the role of sediment processes on the formation and duration of hypoxic water in the Northern Gulf of Mexico.

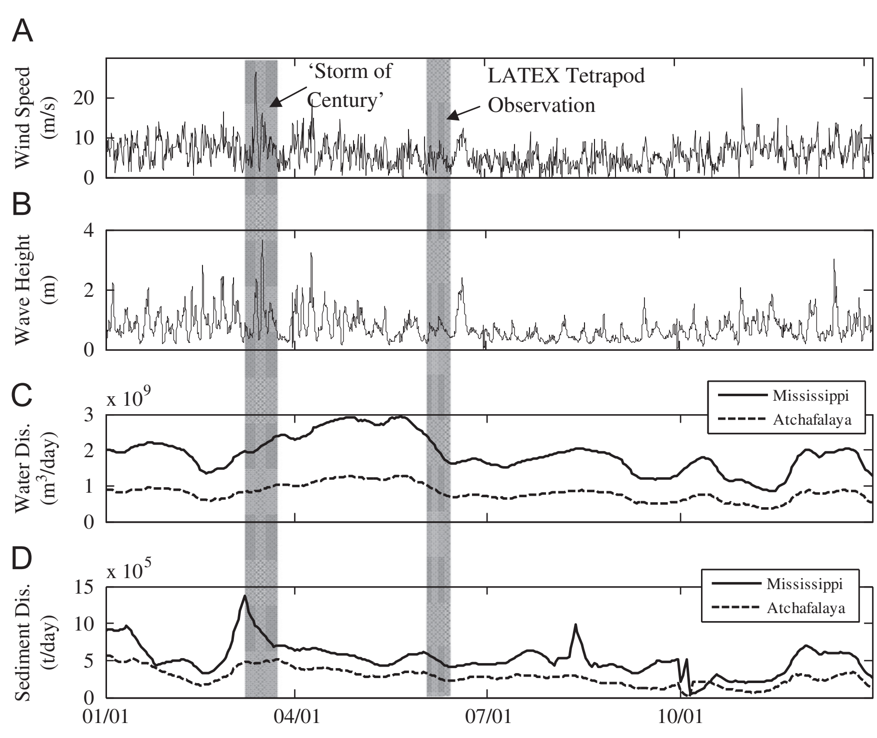

Fig. 2. (A) Observed wind speed from BURL 1 C-MAN weather station near the Southwest Pass of the Mississippi Delta. (B) SWAN-modeled wave height at the LATEX tetrapod location (see Fig. 1). (C and D) Water and sediment discharge from the Mississippi and Atchafalaya Rivers. This paper focused on the following two periods in 1993 (shaded): the storm in March and the fair-weather conditions during LATEX observation in May.

In this paper we modeled the year 1993. Annual water and sediment discharge of the Mississippi River in 1993 was highest of the decade (1990 to 1999), and was 32% and 33% greater than 10-year (1990–1999) averages, respectively (data from USGS, not shown here). This year contained several wind and wave events and a large storm in March, after which river discharge rose (Fig. 2). Moreover, the LATEX projects (DiMarco et al., 1997; Wright et al., 1997) provided extensive oceanographic observations (including CTD casts, buoys, and tetrapods), which facilitated model-observation comparisons.

3. Methods and model inputs

3.1. The coupled hydrodynamic-sediment transport model

The three-dimensional, open-source Regional Ocean Modeling System, ROMS (Haidvogel et al., 2008; http://www.myroms.org/), formed the foundation of our numerical model. The Community Sediment Transport Modeling System (CSTMS; http://www.cstms.org/) provided a mature sediment-transport module within ROMS (Warner et al., 2008). Combined wave–current bottom boundary layer (BBL) calculations were based on Styles and Glenn (2000) along with moveable bed routines proposed by Wiberg and Harris (1994) and Harris and Wiberg (2001). More detailed descriptions of sediment transport calculations are in Warner et al. (2008).

ROMS solved the Reynolds-averaged Navier–Stokes equation (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008); configured to use fourth-order horizontal advection of tracers, third-order upwind advection of momentum, conservative splines to calculate vertical gradients, and Mellor and Yamada (1974) turbulence closure with the Galperin et al. (1988) stability functions. Radiation conditions were used on the eastern and southern open boundaries. The model used a gradient condition on the western boundary to minimize impedance when westward currents hit the boundary, and to effectively avoid the creation of artificial plumes along that boundary. We neglected tides since tidal ranges are small (less than 0.4 m). The model was initialized on January 1, 1993 with an averaged climatological profile of temperature and salinity. Boundary conditions of temperature, salinity and momentum were based on horizontally uniform climatological fields derived from regional hydrographic surveys. The model used time steps of 60 s, and had a maximum horizontal resolution of $\sim$1 km on the inner shelf and a relatively lower resolution (up to $\sim$20 km) on the southern boundary (Fig. 1). Twenty layers were stretched in an *s*-coordinate vertical grid to have increased resolution near the water surface and seabed. Water depths resolved by the model ranged from 5 to 410 m.

3.2. Input winds and waves

The model used spatially uniform but temporally variable winds based on hourly measurements from the BURL 1 C-MAN weather station near the mouth of Southwest Pass (28°54′18″N 89°25′42″W; Fig. 1; http://www.ndbc.noaa.gov/station_page.php?station=BURL1). This was appropriate given the spatial and temporal scales of the local wind field. Based on meteorological observations over the northwestern Gulf of Mexico from April 1992 to November 1994, Wang et al. (1998) found that the meso-scale (100 km, 6 h) monthly wind field was fairly uniform in space in the $\sim$300-km long focus area of this study between the Mississippi Delta and Atchafalaya Bay. Wind speed in 1993 remained low (3–7 m/s) throughout the summer from May to August, but was high (6–12 m/s) in other seasons. Peak winds for the year reached 27 m/s during the storm in middle March (Fig. 2A).

The widely used SWAN (Simulating WAves Nearshore) model (Booij et al., 1999) provided wave inputs to ROMS. Bathymetry for SWAN was taken from the Coastal Relief Model provided by the National Geophysical Data Center (Divins and Metzger, retrieved in, 2008). Two wave model domains were used in SWAN simulations. To estimate the production of swell, the larger grid represented the overall Gulf of Mexico, spanning from 18°N, 98°W to 30.5°N, 80°W, with a resolution of 2 min. Input wind fields for this grid were obtained from the North American Regional Reanalysis (Mesinger et al., 2006) at 0.3° resolution. An inner nest then represented the Texas–Louisiana shelf, spanning from 27°N, 95°W to 30.33°N, 87.5°W, with a resolution of 30 s. Estimated wave properties from the larger scale Gulf of Mexico SWAN model were used as open boundary conditions for the nested model, thereby accounting for remote swell. Local wave generation in the inner domain was specified by applying winds from the BURL 1 C-MAN station uniformly over the grid, consistent with ROMS runs. The SWAN model then provided wave properties (e.g., height, period, direction, and near-bed orbital velocity) as input to ROMS for the estimation of bed shear stresses. SWAN wave height in 20.5 m deep water at the Tetrapod (Fig. 1) was closely associated with wind speed, with the largest wave height of 3.8 m calculated during the storm in March 1993 (Fig. 2).

3.3. Fluvial discharge

Fresh water input from the Mississippi and Atchafalaya Rivers was specified using daily measurements from Tarbert Landing and Simmsport gauging stations (Fig. 1A) maintained by the U.S. Army Corps of Engineers and U.S. Geological Survey (USGS). Sediment was sampled approximately once every two weeks at both stations, and daily sediment discharges were calculated by USGS (data from Dr. Charles Demas, USGS). The measurements made at these stations provide the best available indication of the total amount of sediment being delivered by the combined Red and mainstem Mississippi Rivers to coastal Louisiana (Meade and Moody, 2010).

Tarbert Landing has long been used as the representative station of Mississippi River discharge, but it is 525 km upstream of the mouth of Southwest Pass of the Mississippi Delta (Fig. 1). It takes about 3–7 days for the suspended sediment to be transported from this station to the sea, depending on the flow and antecedent conditions (personal communication with Dr. Charles Demas). In our model, however, we neglected this time-lag because (a) the two rivers' discharge changes relatively gradually (Fig. 2C and D), (b) the time-lag is relatively short compared with annual/seasonal variations, and (c) our calculations seems insensitive to the timing of arrival of fluvial discharge based on our model experiments.

Data from Simmsport represent the discharge from diverted Mississippi flow and the Red River to Atchafalaya Bay (Fig. 1A). In 1993, on average 30% of sediment passing Simmsport Station was sand and 70% was mud (data from USGS, not shown here). Sand content of sediment deposited on the Atchafalaya and Wax Lake deltas exceeded 50% (Roberts, 1998), but decreased rapidly to $<5\%$ at the 5-m isobath south of Atchafalaya Bay (Neill and Allison, 2005). Because of the shallowness of Atchafalaya Bay (an average depth of only 2 m), and its close proximity to high sediment supply, most of the coarse sediment preferentially deposits on the Wax Lake and Atchafalaya Deltas, leaving finer sediment to be resuspended and exported to the inner shelf (Wells et al., 1984; Allison et al., 2000). Based on volumetric calculations using bathymetric data, Atchafalaya Bay seems to retain about 27% of sediment delivered to it (Wells et al., 1984; Draut et al., 2005), while the remaining 73% is exported from the bay into the northern Gulf of Mexico. Our model neglected the processes in Atchafalaya Bay because we focused on the continental shelf. We therefore adjusted the measured Simmsport sediment by 73% and delivered it in a line source directly south the Atchafalaya Bay mouth (Fig. 1A).

3.4. Initial sediment bed

More than 50,000 historical surficial grain-size data from the study site were archived by the usSEABED project (Williams et al., 2006). For each sample, the database included the fraction of sand, silt, and clay. These data were interpolated to generate the initial bed fractions of sand and mud for the model, where the mud fraction was assigned the sum of the silt and clay fractions (Fig. 3). At most locations in the inner and middle shelf, the sediment contained more than 80% mud except at the sandy Trinity and Ship Shoals (20–30% mud) between 5- and 10-m isobaths south of Atchafalaya Bay (Fig. 3). Along the southern boundary of the model where water depth exceeds 300 m, the sea bed was mainly consolidated mud. This area was represented as sandy in the model to simplify the sediment transport calculations and to avoid unrealistically high erosion there (Fig. 3). This was appropriate given (a) this paper focused on the shelf area shallower than 100 m, and (b) sediment movement by wave resuspension in deep water there only occurs once every 5–20 years (Curray, 1960). Four 10-cm-thick vertical layers were used to represent the initial sediment bed. Sediment density was set to be 2650 kg/m^3 and porosity was 0.8 based on measurements by Draut et al. (2005) and Allison et al. (2007).

3.5. Treatment of sediment classes

The model used a total of six sediment classes: two each for Mississippi River material, Atchafalaya River sediment, and the seabed. The model required a settling velocity (w_s) and critical shear stress for erosion (τ_{cr}) for each sediment class, and held both constant. The model neglected aggregation and disaggregation of flocs and there was no exchange between the six sediment tracers in model runs. Flocculation critically impacts settling velocity and sediment transport near river-dominated muddy deltas (Geyer et al., 2004); however, there have been no in-situ measurements of floc settling velocity on the Texas–Louisiana shelf. We therefore chose settling velocities as outlined below. Likewise, the model neglected bed consolidation and swelling and held τ_{cr} constant. Hydrodynamic properties were chosen based on comparison of model estimates to observations (see Section 4), and were consistent with past modeling studies (Bever et al., 2009; Harris et al., 2008).

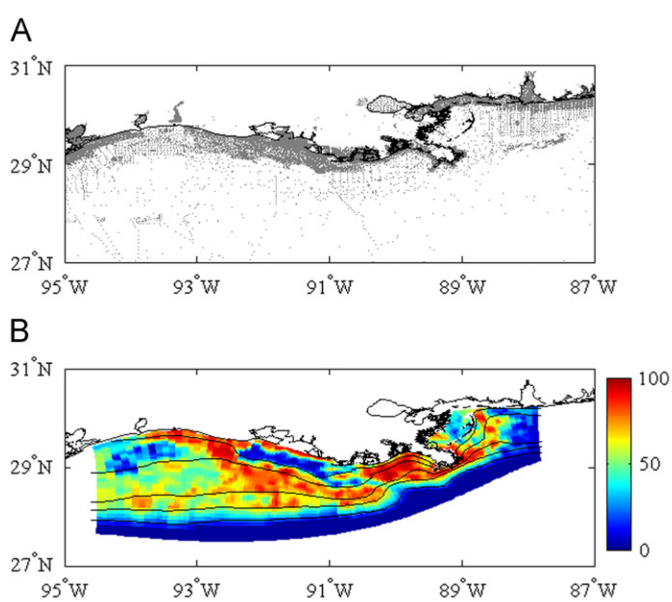

Fig. 3. (A) Locations of >50,000 grain size data points from usSEABED (Williams et al., 2006). (B) Interpolated mud fraction within the model grid based on usSEABED data. Isobaths contoured at 10, 20, 50, 100, 300 m. Shoals shallower than 10m south of Atchafalaya Bay are sandy. Area deeper than 300 m was modeled as sand to minimize southern boundary effects.

Table 1
Properties of six sediment tracers in the model.

Sediment	Type	τ_{cr} (Pa)	W_s (mm/s)	Fraction
Mississippi	Large flocs	0.11	1	50%
	Small flocs	0.11	0.1	50%
Atchafalaya	Large flocs	0.03	1	10%
	Small flocs	0.03	0.1	90%
Sea bed	Sand	0.13	10	Spatially variable,
	Mud	0.11	1	see Fig. 3B

Based on model sensitivity to the choice of settling velocities (see Section 4.2) and comparison to observations (see Section 4.3), the model assumed settling velocities of 0.1, 1, and 10 mm/s. For sediment discharged from the Mississippi River, we specified 50% as large flocs with a fast settling velocity of 1 mm/s, and 50% as small flocs with a slower settling velocity of 0.1 mm/s (Table 1). Critical shear stress for both types was 0.11 Pa, a value derived by Wright et al. (1997). The treatment of Atchafalaya sediment differed from that of Mississippi sediment. Assuming a low floc settling velocity at 0.1 mm/s, a mean depth of 2 m, and mean current at 0.2 m/s, sediment exported from the Atchafalaya and Wax Lake deltas would only travel 4 km (0.2 m/s × 2 m/0.1 mm/s) before initial deposition. In reality, however, 73% of this sediment escapes Atchafalaya Bay, traveling more than 20 km to the inner shelf of the northern Gulf of Mexico. Thus Atchafalaya sediment either experiences multiple settling-resuspension cycles before leaving the Bay, or more energetic conditions (e.g., strong waves) retain sediment in suspension for a longer time period. In addition, Sheremet and Stone (2003) and Sheremet et al. (2005) found fluid muds south of Atchafalaya Bay. High sediment concentrations formed in fluid muds may hinder the settling of sediment and thus facilitate initial dispersal. Our model thus assumed that 10% of Atchafalaya sediment was large flocs with a settling velocity of 1 mm/s, while the remaining 90% was small flocs with a settling velocity of 0.1 mm/s (Table 1). A lower critical shear stress of 0.03 Pa was assumed for Atchafalaya sediment to facilitate the suspension. Sea-bed sediment included fast-settling mud (1 mm/s) and very-fast-settling sand (10 mm/s). Their critical shear stresses were assumed to be 0.11 and 0.13 Pa, respectively. Fractions of sea bed mud and sand were based on the initial sea bed map discussed in Section 3.4.

4. Model validation

These sections compared currents, gyres, waves, and sediment estimates to observations. Hetland and DiMarco (2008) reported further validation of the hydrodynamic model.

4.1. Hydrodynamic processes

Based on long-term observations from Atchafalaya Bay, winds from the east predominate on the Texas–Louisiana shelf throughout the year, occurring 64% of the time (Walker and Hammack, 2000; Walker et al., 2005). These strengthen the westward coastal current along the inner shelf (Cochrane and Kelly, 1986; Wang and Justić, 2009). Curray (1960) characterized the coastal current as a ~0.2 m/s persistent westward flow on the inner Texas–Louisiana shelf. Additionally, both drifter trajectory studies

(Yang et al., 1999) and heavy mineral analysis (Van Andel and Poole, 1960) demonstrated broad westward water and sediment flux on the Texas–Louisiana shelf. Consistent with these studies, our time- and depth-averaged mean currents on the inner-middle shelf were westward at a speed of 0.1–0.2 m/s (Fig. 4A).

A semi-permanent, clockwise gyre west of the Mississippi Delta appears frequently in satellite imageries (personal communication with Dr. Nan Walker, Louisiana State University). Although influenced by winds, high discharge in spring and summer tends to enhance this feature, which carries a large amount of fresh water shoreward to the north, rather than directly westward off the Southwest Pass, and increases the residence time of freshwater here. This gyre also was documented in the recent modeling work by Wang and Justić (2009), with validation by ADCP current measurements. Our time- and depth-averaged mean currents also reproduced this circulation pattern west of the Mississippi Delta (Fig. 4A).

In May, 1993, Wright et al. (1997) observed wave orbital velocities using tetrapod-mounted electromagnetic current meters (EMCMs) at 20.5 m deep water about 100 km west of Southwest Pass (Fig. 1). During this fair-weather period wind speeds remained low and measured wave orbital velocities reached only 12 cm/s (Fig. 5). Our modeled near-bed wave orbital velocity matched the observed velocity, in terms of both timing and magnitude (Fig. 5).

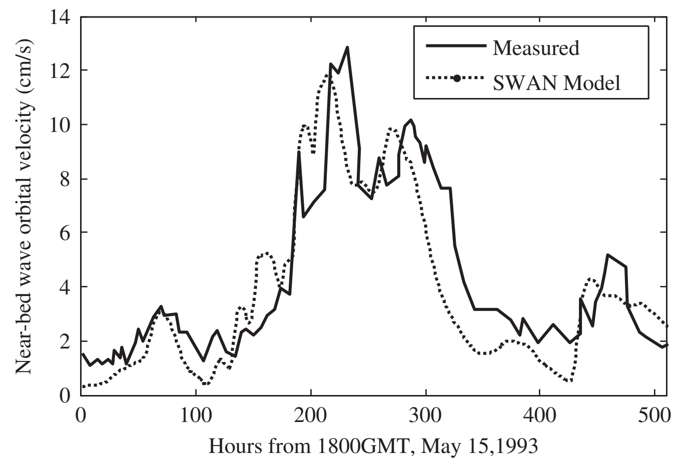

Fig. 5. Comparison between measured (Wright et al., 1997) and modeled near-bed wave orbital velocity at the LATEX Tetrapod location (see Fig. 1) for May 1993.

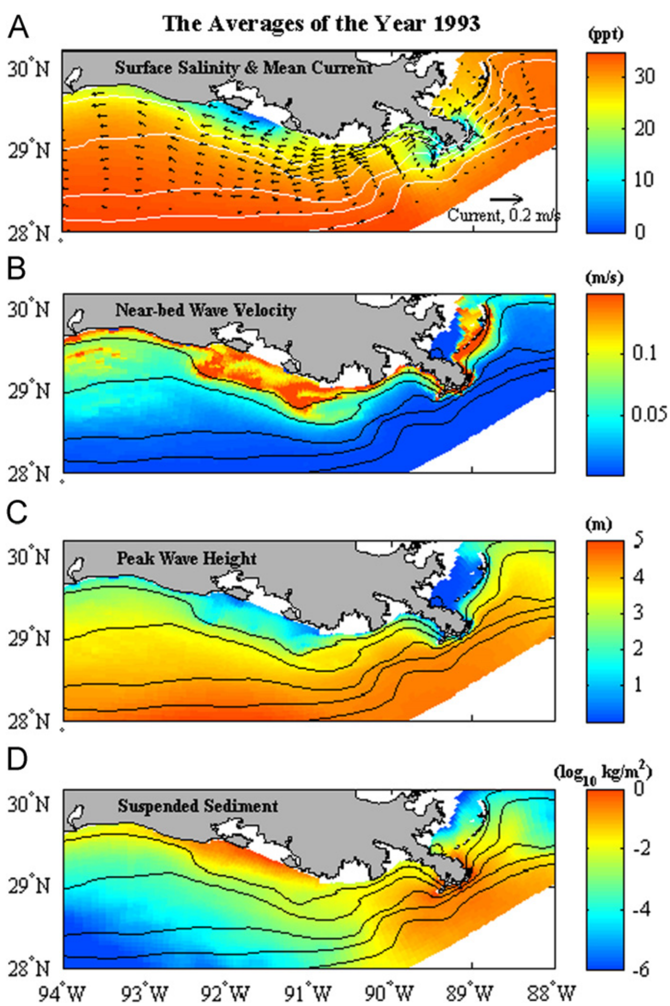

Fig. 4. (A) Time-averaged surface salinity (ppt, color) and mean current (m/s) calculated for the year 1993. (B) Time-averaged near-bed wave orbital velocity (m/s) and (C) peak significant wave height (m) estimated by SWAN. (D) Time-averaged and depth-integrated fluvial suspended sediment (kg/m^2 in logarithmic scale) in the water column calculated for 1993. Isobaths drawn at 10, 20, 50, 100, 300 m water depths (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4.2. Sensitivity to settling velocity

Sediment transport calculations are extremely sensitive to the settling velocities used to represent silts and clays which often form aggregates in coastal water. Unfortunately in-situ measurements of settling velocity for the Texas–Louisiana shelf were unavailable. We chose settling velocities (Table 1) similar to measurements from, and values used in models of, other muddy study sites (Eel River, Harris et al., 2005; York River, Rinehimer et al., 2008; Po River, Fox et al., 2004, Mikkelsen et al., 2007, Harris et al., 2008). To evaluate the sensitivity of our calculations to uncertainties in settling velocity, we ran the model using w_s=1, 0.1 and 0.01 mm/s. During this sensitivity test, other model parameters were held constant, including critical shear stresses used for the Mississippi (0.11 Pa) and Atchafalaya (0.03 Pa) sediment types.

As settling velocity decreased, the dispersal radius of fluvial sediment increased. Using a settling velocity of 1 mm/s, much of modeled sediment accumulated within a 5-km radius of the mouths of the Mississippi River and Atchafalaya Bay. Negligible sediment deposited in other areas, and essentially none was transported toward the Chenier Plain (Fig. 6A). Decreasing settling velocity to 0.1 mm/s, the dispersal radius increased to 20–40 km, with Mississippi sediment more widely broadcast, traveling as far as the middle shelf (Fig. 6B). When settling velocity decreased further to 0.01 mm/s, the dispersal extents increased greatly and accumulation at the two sources decreased dramatically (Fig. 6C). Deposition no longer followed the bird-foot shaped subaqueous delta around the Mississippi Delta and a large amount of Atchafalaya sediment moved to the middle and even outer shelf (Fig. 6C).

Comparison of depositional patterns estimated by these model runs to observed accumulation patterns (Section 4.3) supported the values selected (Table 1). The smallest value considered, w_s=0.01 mm/s, settled too slowly to create reasonable depositional patterns. We therefore restricted w_s for fluvial discharge to 1 and 0.1 mm/s, and varied the fluvial floc proportions from 90% of 1 mm/s and 10% of 0.1 mm/s, to 10% of 1 mm/s and 90% of 0.1 mm/s, with a decrement/increment of 10% each time. Thus this sensitivity test involved a total of twelve model runs for the year 1993.

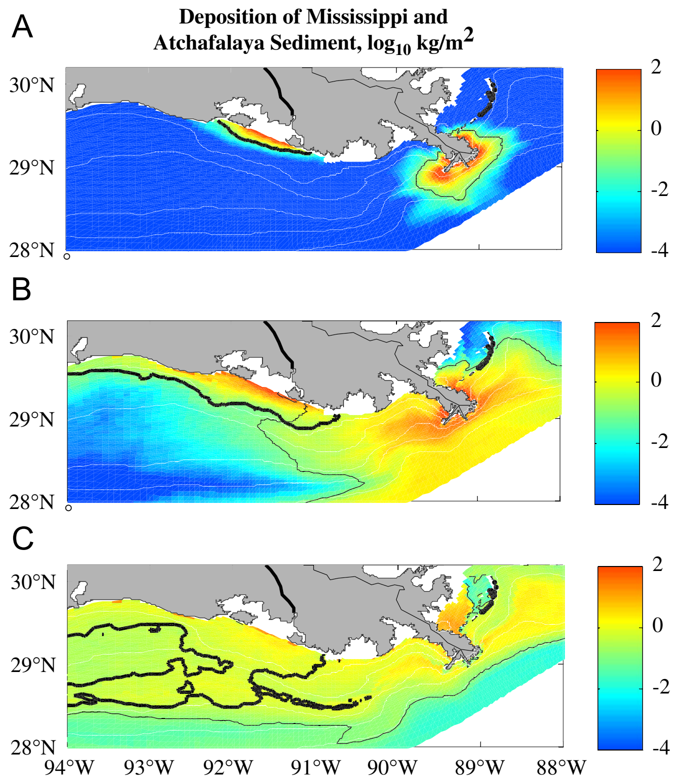

Fig. 6. Calculated deposition where the model assumed settling velocity (w_s) to be (A) 1, (B) 0.1, and (C) 0.01 mm/s. Dispersal extents (at a level of $10^{-1.5}$ kg/m^2) delineated for Mississippi (regular lines) and Atchafalaya (bold lines) sediment.

4.3. Sediment accumulation

Profiles of short-lived radionuclides with depth in the bed have been widely used to estimate sediment accumulation rates. Profiles of ^{234}Th, and ^{7}Be can be analyzed to estimate short-term rates (order of months to seasons) while those of ^{137}Cs and ^{210}Pb provide accumulation averaged over longer timescales (decades to century). Rates derived from ^{210}Pb and those from ^{137}Cs/^{7}Be, however, can differ by an order of magnitude. For instance, accumulation rates derived from ^{234}Th and ^{7}Be near the Mississippi subaqueous delta were 0.8–3.9 cm/month which were about one order of magnitude greater than those observed via ^{210}Pb (1.3–2.0 cm/year) at the same sites (Corbett et al., 2004). The discrepancy between short- and long-term accumulation rates might be due to rapid deposition in flood seasons followed by extensive reworking or redistribution processes (like episodic hurricanes). Radionuclides samples were not collected in 1993, so we used values from the literature for different years.

We finalized the partitioning between large and small floc classes (w_s=1 and 0.1 mm/s, respectively, see Table 1) based on the model's ability to reproduce observed depositional patterns. Since the model represented a year, we preferred to compare our estimates to available short-timescale accumulation rates, and near the Mississippi Delta used ^{137}Cs accumulation rates derived by Allison et al. (2007). Offshore of Atchafalaya Bay, short-timescale rates were unavailable, and we therefore used ^{210}Pb from Draut et al. (2005).

Based on the model estimates (blue italic numbers and contour lines in Fig. 7A), at the end the model year the highest sediment accumulation (> 5 cm/year) was adjacent to the mouth of Southwest Pass of the Mississippi Delta, the rate decreasing rapidly to 1 cm/year about 20–40 km offshore. The depositional pattern near the Mississippi Delta was localized and had a

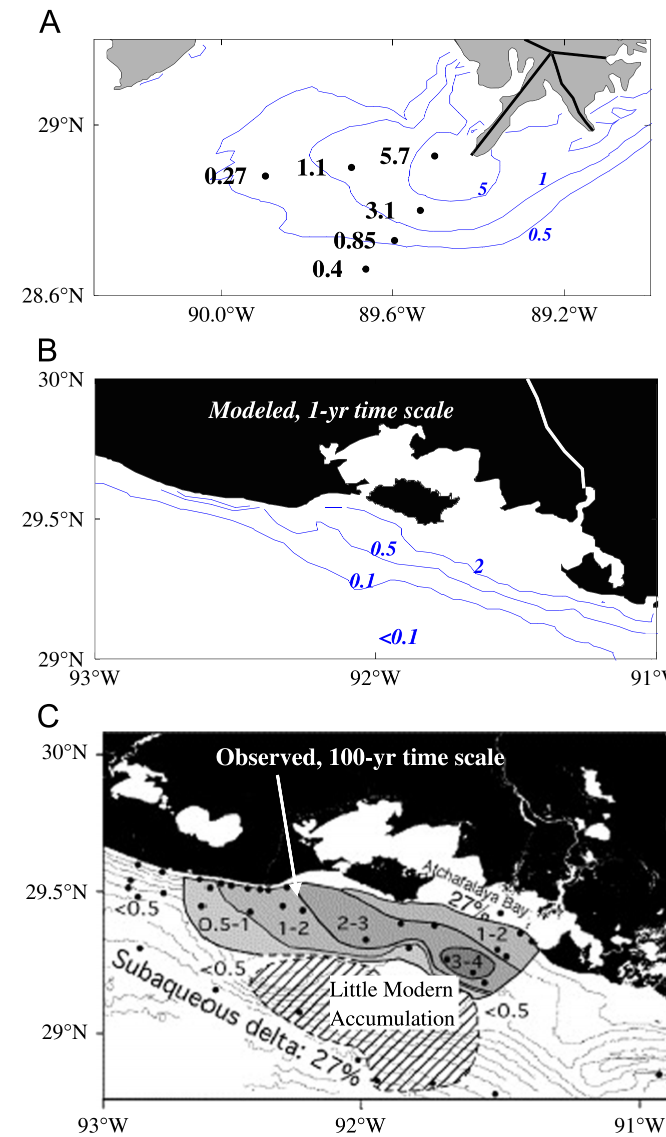

Fig. 7. (A) Comparison between modeled sediment accumulation (contours of 0.5, 1, and 5 cm/year in italic) with the rates derived from ^{137}Cs geochronology (in bold) at six sites by Allison et al. (2007). (B) Modeled 1-year time scale sediment accumulation south of Atchafalaya Bay (contours of 0.1, 0.5, and 2 cm/year). (C) Sediment accumulation rate (cm/year) based on ^{210}Pb geochronology (100-year time scale) and acoustic transacts by Draut et al. (2005). The hatched area indicates shoals having exposed relict sediment where Atchafalaya sediment accumulation is heterogeneous and poorly defined (for interpretation of the references to color in this figure (color mentioned in the text), the reader is referred to the web version of this article).

"bird-foot" shape. The modeled accumulation rates matched the observations obtained using ^{137}Cs radionuclide analysis of box cores collected in July 2003 (Allison et al., 2007). The slight differences between model and observation might be due to the fact that the year 1993 was a flood year while 2003 experienced normal discharge.

South of Atchafalaya Bay, modeled sediment accumulation rates decreased rapidly from > 2 cm/year near the bay mouth to 0.1 cm/year around the 5 m isobath (Fig. 7B). In this region, ^{210}Pb accumulation rates (Draut et al., 2005; Allison et al., 2005) indicated that the inner shelf immediately adjacent to the bay mouth effectively sequestered fine-grained sediment (3–4 cm/year), and that much of the Atchafalaya sediment remained confined to the inner shelf landward of the 10 m isobath (Fig. 7C). Modeled accumulation patterns were similar to ^{210}Pb, but more concentrated near the bay mouth. The difference might be due to (a) the year 1993 was a flood year and saw higher accumulation than in normal years; (b) as explained above, the model represented only a one-year time scale while ^{210}Pb characterized 100 years, and longer-term redistribution and reworking during severe hurricanes (like Katrina and Rita) did not happen in 1993; (c) our neglect of processes within Atchafalaya Bay might enhance sediment accumulation directly offshore of the Bay mouth.

5. Results

5.1. Time averages for the year 1993

For the year 1993, the model estimated that time-averaged surface salinity was low close to the mouths of Mississippi River and Atchafalaya Bay, with a buoyant plume extending westward from both freshwater sources (Fig. 4A). Currents flowed westward at 0.1–0.2 m/s, being relatively strong on the shelf and weakening offshore. Peak wave height during the entire year increased from about 1 m at the 10 m isobath to 4–5 m at 100 m isobath (Fig. 4C). Time-averaged near-bed wave orbital velocities rarely exceeded 0.15 m/s, and decreased rapidly offshore (Fig. 4B). Time-averaged and depth-integrated suspended fluvial sediment in the water column was estimated to be as high as 1 kg/m^2 close to the mouths of Mississippi River and Atchafalaya Bay. Mississippi suspended sediment spread around the delta and reached water depths of 300 m in the south. In contrast most Atchafalaya suspended sediment was confined to the inner-most part of the shelf to the west of the bay mouth (Fig. 4D).

5.2. Deposition at the end of year 1993

The model's estimate of cumulative deposition for the year 1993 resembled the pattern of suspended fluvial sediment (Figs. 4D and 8A). Because of the high settling velocities assumed for it, the majority of Mississippi sediment accumulated within 20 km of the radius of the Delta, and most stayed within 50 km. Most Atchafalaya sediment deposited landward of the 10-m isobath, settling quickly to the sea bed in the shallow water. The coastal current carried some Atchafalaya sediment westward where it deposited along the Chenier Plain (Figs. 1A and 8A).

To evaluate the alongshore sediment distribution, net deposition of Mississippi and Atchafalaya sediment for 1993 was integrated for the entire model grid from the coastline to the southern domain boundary along shore-perpendicular transects (Fig. 8B). Estimated accumulation decreased rapidly from 2 to 6 Mt/km near the sediment sources to less than 0.01 Mt/km at distances of 50 km from the sources. Near the Mississippi Delta, deposition peaked at three locations; the tip of Southwest Pass, western and eastern side of delta (Fig. 8B). Southeast of Atchafalaya Bay, there was a "mixing area" where both the Mississippi and Atchafalaya contribute to the deposition over the twelve-month timescale (Fig. 8A).

During 1993, a total of 190 and 101 Mt of suspended sediment passed Tarbert Landing and Simmsport Stations, respectively (data from USGS). Only 73% of sediment passing Simmsport was assumed to be transferred through the Atchafalaya Bay mouth (Wells et al., 1984). Thus a total of 264 Mt of fluvial sediment was actually delivered into our model grid. At the end of the year 1993, 259 Mt of fluvial sediment accumulated on sea bed, 4 Mt of sediment remained suspended, and the rest 1 Mt escaped the model grid. Of total *accumulated* fluvial sediment (four sediment tracers from two rivers, 259 Mt), 60% stayed around the Mississippi Delta and 29% deposited next to the Atchafalaya Bay mouth or Chenier Plain. About 5% was inside the "hypoxic box",

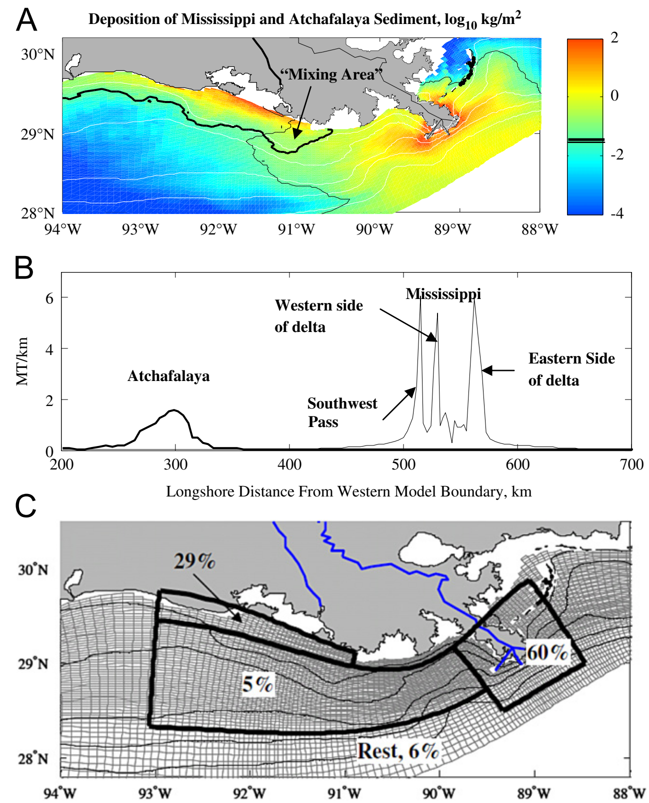

Fig. 8. (A) Estimated deposition of both Mississippi and Atchafalaya sediment on the sea bed, overlaid by dispersal extents (at a level of $10^{-1.5}$ kg/m^2, in regular and bold lines respectively). Isobaths at 10, 20, 50, 100, 300 m. (B) Longshore sediment deposition (Mt/km) of Mississippi and Atchafalaya sediment. Net deposition was integrated for the entire model grid from the coastline to the southern domain boundary. (C) Sediment budget of total fluvial sediment accumulation on the sea bed calculated for the end of 1993. The "hypoxic box" was based on hypoxia observed by Rabalais et al. (2001), shown in Fig. 16D.

an area roughly corresponding to observed hypoxic water in 1993 (See Section 6.4), and 6% of sediment was distributed to the rest model grid cells (Fig. 8C).

5.3. The storm in March 1993

From March 12–17, 1993, a large cyclonic storm passed the Gulf of Mexico and east coast of North America. Called the "Storm of the Century" or "93 Super Storm", it was unique for its intensive snow fall, massive size, and wide-reaching effects along the eastern seaboard of the United States. While it was not exceptionally intense on the Texas–Louisiana shelf, it did produce the biggest winds and waves of that year. The wind speed recorded at the Southwest Pass of the Mississippi Delta reached 27 m/s, and wave height calculated for the LATEX tetrapod location peaked at 3.7 m (Fig. 2). During the storm, wind direction was mainly from the northwest and then rotated to be from the east (details in Section 6.3). This storm coincided with the onset of flood water discharge from the Mississippi and Atchafalaya Rivers, but the antecedent water discharge was relatively low (Fig. 2).

Model estimates were analyzed to characterize flow and sediment transport under storm conditions. Over the six days from 12 to 17 March, 1993, the model estimated surface currents to be mainly toward the southwest, with fresh water (<30 ppt) confined to the inner and middle shelf (Fig. 9A). Upwelling created strong seaward surface flow (as high as 0.3 m/s) and shoreward bottom flow (Fig. 9C). Peak wave orbital velocity reached nearly $\sim$1 m/s in water shallower than 20 m (Fig. 9B).

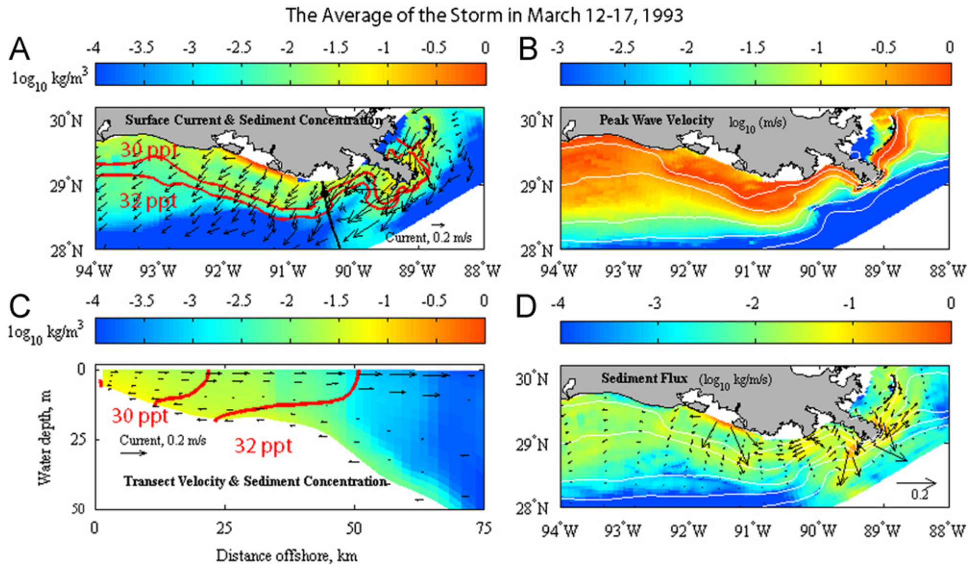

Fig. 9. (A) Surface current (arrows, cm/s), sea surface sediment concentration (color, kg/m^3 on a logarithmic scale) with surface salinity contour lines at 30 and 32 ppt. (B) Peak near-bed wave orbital velocity in m/s (logarithmic scale). (C) Current velocity (arrows) and sediment concentration (color, kg/m^3, on a logarithmic scale) for a cross-shelf transect that goes through the LATEX tetrapod (transect shown as a black line and tetrapod location shown as a black dot in panel A). Salinity contoured at 30 and 32 ppt. (D). Sediment flux in kg/m/s. White isobaths in (B) and (D) are 10, 20, 50, 100, 300 m. (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Under the influence of strong winds, energetic currents created turbulence sufficient to vertically mix the water column. Sea surface sediment concentration was highest ($\sim$0.3 kg/m^3) next to fluvial sources and remained elevated (0.1 kg/m^3) over most of the shelf (Fig. 9A). During these six days, the largest sediment fluxes were around the Mississippi Delta and Atchafalaya Bay (Fig. 9D). Mississippi sediment was transported offshore of the Mississippi Delta, indicating extensive storm remobilization of previously deposited sediment on the delta front (Fig. 9D). As discussed in Section 6.4, during the storm, the maximum erosion was estimated to be about 5 cm around the Mississippi Delta and 3 cm south of Atchafalaya Bay.

Total bed shear stress peaked along the inner Texas–Louisiana shelf landward of the 20 m isobath during the storm, reaching values of 1.8 Pa (Fig. 10). Current-generated shear stress was highest in shallow water, sometimes reaching the critical level (0.11 Pa) to suspend sediment (Fig. 10). Shear stresses due to currents were at least one order of magnitude smaller than those generated by waves, however, and most resuspension occurred in areas of high wave shear stresses (Fig. 10). Wave-generated shear stress was reduced in the shallow water northeast of the Mississippi Delta due to shielding by the Chandelier Islands, but in other shallow waters the model indicated that wave-generated shear stresses reached 1.6 Pa.

5.4. Fair-weather conditions in May 1993

For comparison to the storm period, we considered hydrodynamics and sediment processes during the May 1993 LATEX experiment, when the weather was free of rain or storms (Wright et al., 1997). At this time, winds were very weak in the northern Gulf of Mexico, barely reaching 10 m/s (Fig. 2). Floodwaters from the Mississippi and Atchafalaya Rivers were receding, but were at levels similar to those during the storm (Fig. 2C). Sediment discharge in May was lower than that in March (Fig. 2D). Between May 11 and 22, 1993, surface currents were estimated to be weak and mainly offshore, impacted by seaward movement of freshwater. Because of high antecedent water discharge, surface water was fresher than normal. The area having salinity less than 30 ppt

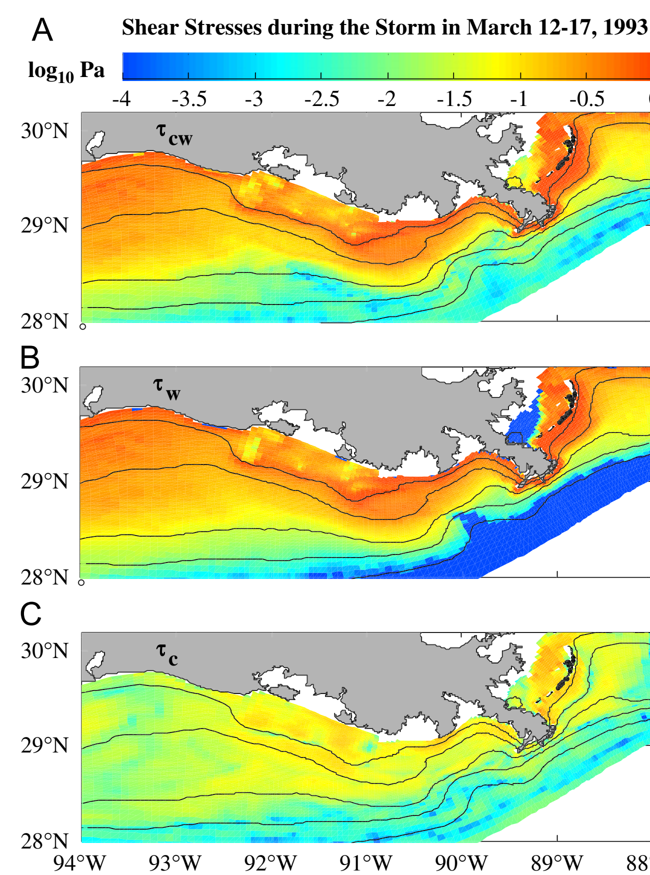

Fig. 10. Bed shear stresses (Pa, on a logarithmic scale) calculated for the storm period in March 12–17, 1993: (A) combined wave–current stress (τ_{cw}), (B) wave component (τ_w), and (C) current component (τ_c). Isobaths are 10, 20, 50, 100, 300 m.

expanded compared to storm conditions, helping to stratify larger portions of the water column (Figs. 9A and 11A). Sediment concentration was estimated to be very low in most areas. Only areas

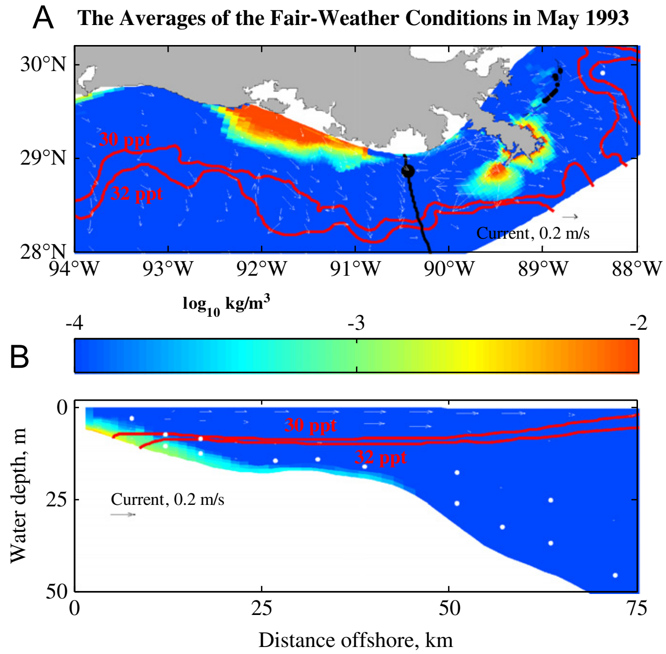

Fig. 11. Averages calculated during the fair-weather period of May 11–21, 1993. (A) Surface current (arrows, cm/s), sediment concentration (color, kg/m^3 on a logarithmic scale), and surface salinity contoured at 30 and 32 ppt. (B) Current velocity (arrows) and sediment concentration (color, kg/m^3, on a logarithmic scale) for a cross-shelf transect that goes through the LATEX tetrapod (transect shown as a black line and tetrapod location shown as a black dot in panel A). Salinity contoured at 30 and 32 ppt. (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

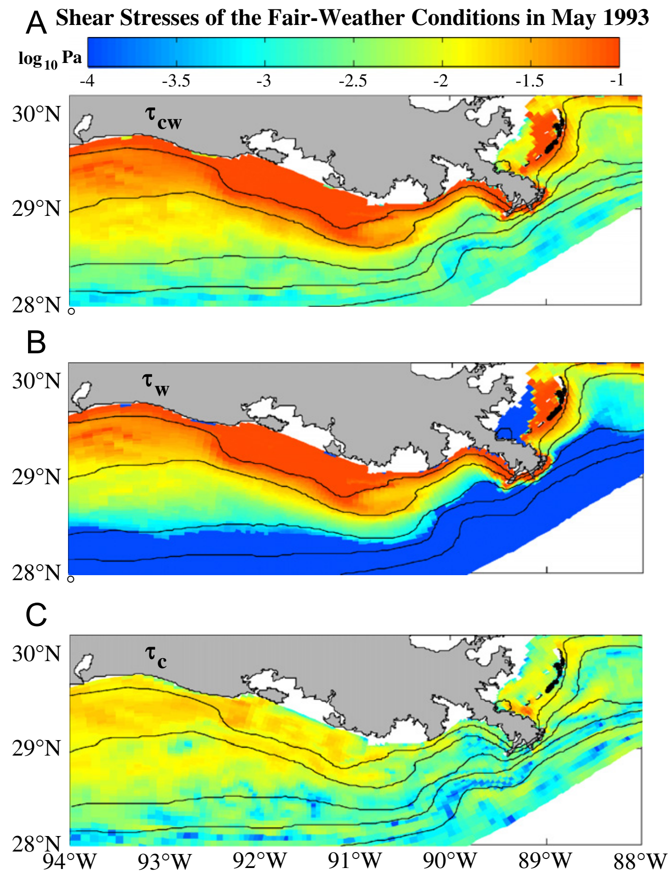

Fig. 12. Bed shear stresses (Pa, on a logarithmic scale) calculated for the fair-weather period, May 11–21, 1993: (A) combined wave–current stress (τ_{cw}), (B) wave component (τ_w), and (C) current component (τ_c). Isobaths drawn at 10, 20, 50, 100, 300 m water depths.

shallower than 10m near the Mississippi Delta and Atchafalaya Bay had concentrations as high as 0.01 kg/m^3, at least an order of magnitude smaller than the storm average (0.1 kg/m^3). Some sediment was estimated to be carried horizontally by fresh water plumes but the distances traveled did not generally exceed 50 km (Fig. 11). Wave–current-combined shear velocity only reached the critical level of 0.11 Pa in water shallower than 10 m (Fig. 12). In the inner shelf, waves still dominated shear stresses, but in some mid-shelf areas between the 20- and 50-m isobaths, waves and currents contributed equally to bed stresses.

6. Discussion

6.1. Sediment dispersal

Our model indicated that on the Texas–Louisiana shelf, short term sediment accumulation rates vary by at least two orders of magnitude, from >5 cm/year near sediment sources to less than 0.01 cm/year in other areas (Figs. 7 and 8). Thus sediment accumulation in this area is highly localized. Our estimated accumulation pattern agreed with past studies. Shokes (1976) and Rotter (1985) concluded that the region of highest Mississippi accumulation was confined to a 20 km radius of distributary mouths. Retention of sediment near sources helps maintain features like the bird-foot delta, but creates sediment-starved conditions elsewhere. Allison et al. (2000), for example, found that a 10-m deep station approximately midway between Atchafalaya Bay and the Southwest Pass of the Mississippi Delta exhibited essentially no long-term accumulation, indicating minimal direct influence from either Mississippi or Atchafalaya River sediment.

Although some modeled sediment from both the Mississippi and Atchafalaya Rivers deposited in a "mixing area" southeast of Atchafalaya Bay (Fig. 8A), accumulation there within the 1-year timeframe accounted for a very small part of sediment budget, less than 1% of the total fluvial sediment input. It is unclear whether longer timescale model runs would continue to estimate extremely low accumulation rates in this "mixing area". Evaluating this issue with a numerical model would require consideration of a longer period (e.g., tens to hundreds of years).

6.2. Comparison of sediment-transport on the Mississippi and Atchafalaya shelves

Based on sediment deposition in Fig. 8A, the pattern of Mississippi deposition was bird-foot shaped, being rounded around the Mississippi Delta. Mississippi River sediment that was transported away from the delta was dispersed widely, on the middle shelf to the east and west of the delta as well as in water deeper than 100 m (Fig. 8A). In contrast, Atchafalaya deposition was narrow and elongated, being confined to the inner-most part of the shelf. This section discusses shelf morphology, waves and currents to investigate the differences in sediment-transport mechanisms on these two distinct shelves.

As explained in Section 1.1, the Mississippi shelf is steeper (0.4° vs. 0.02°) and narrower (20 vs. 200 km) than the Atchafalaya shelf (Fig. 1B). About 20 km offshore of the Mississippi Delta, sediment must settle 350 m before reaching the sea bed. In contrast the area 20 km south of the Atchafalaya Bay mouth is shallower than 10 m. Shelf morphology thus aids dispersal of Mississippi sediment because it experiences a settling depth that is roughly 35 times longer than sediment from the Atchafalaya.

Waves south of Atchafalaya Bay tended to be stronger than those around the Mississippi Delta, with time-averaged orbital velocities of ~0.15 m/s on top of the two sandy shoals (Fig. 4B). Total bed stresses reflected the increased wave energy south of the Atchafalaya Bay mouth, compared to these offshore of the Mississippi Delta. Bed Stresses 10 km south of the bay, for example, exceeded a threshold of 0.11 Pa about 48% of the time of the year 1993 and a lower threshold of 0.03 Pa about 85%, but they exceeded 0.11 Pa only 9% of the time 10 km west of the Southwest Pass of Mississippi Delta. Within the model, we used a lower critical shear stress for Atchafalaya sediment (0.03 Pa) compared to Mississippi sediment (0.11 Pa). Conditions offshore of the Atchafalaya more effectively suspended the available sediment than offshore of the Mississippi. Through enhancing resuspension, wave energy prevented the sandy shoals offshore of Atchafalaya Bay from accumulating fine sediment in our one-year model run.

The depth-averaged currents offshore of the Atchafalaya Bay were estimated to be northwestward for ~85% of the time in our model run (Fig. 13A). These persistent westward currents carried sediment toward the Chenier Plain. During three periods (January–April, May–August and September–December) of the year 1993, the westward direction did not change much and the speed was about 0.1 m/s (Fig. 13). The depth-averaged mean currents offshore of the Mississippi Delta had much lower speeds (about 0.02 m/s), and highly variable directions (Fig. 13B).

Thus the westward, elongated dispersal of Atchafalaya sediment can be explained as due to: (a) shallow water depth that prevented significant seaward flux before settling, (b) strong wave energy that kept sediment in suspension, and (c) perennially westward depth-average mean currents south of Atchafalaya Bay with little cross-shelf flux (discussed below). In contrast, Mississippi sediment dispersal was directed radially away from the Delta because of (1) deep water's proximity to the sediment source, (2) directionally variable currents, and (3) multiple dispersal passes surrounding the delta.

6.3. Alongshore and cross-shore sediment fluxes

Alongshore and cross-shore sediment fluxes were calculated south and west of the Mississippi Delta and Atchafalaya Bay,

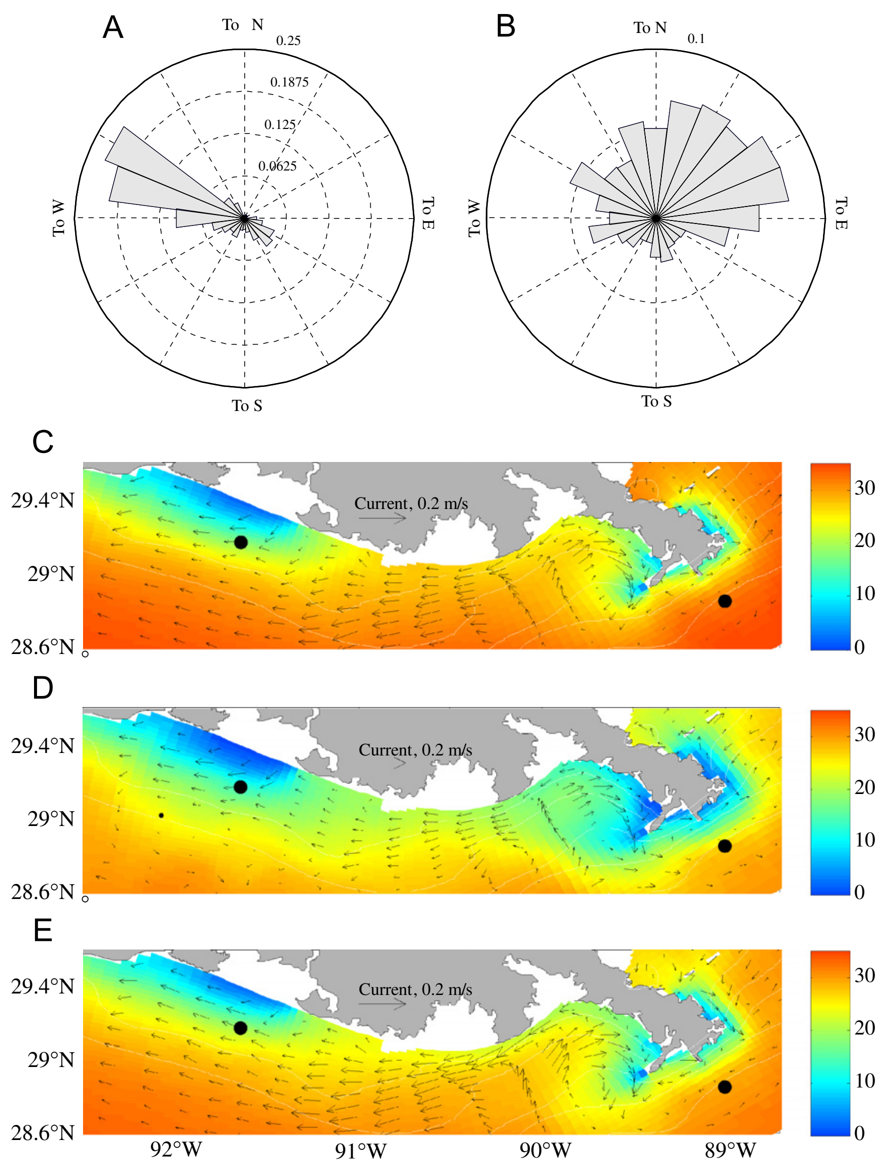

Fig. 13. Direction frequency of annual time-averaged, depth-averaged current south of the Atchafalaya Bay (A) and the Mississippi Delta (B) (locations shown as black dots on panels C–E). Mean current (arrows) and sea surface salinity (color) for January–April (C), May–August (D) and September–December (E) of 1993 (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

respectively, by integrating modeled sediment fluxes along transects shown in Fig. 14A. The magnitudes of alongshore sediment fluxes always exceeded those of cross-shore fluxes offshore of both sediment sources (Fig. 14B and C). Transport offshore of Atchafalaya Bay was episodic, with most flux occurring during short-lived events. In contrast, cumulative flux estimated at the Mississippi Delta changed more gradually. This indicated that sediment in the shallow waters offshore of Atchafalaya Bay, subjected to high wave orbital-velocities and shear stress, responded more quickly to episodic wind events than sediment debouched to deep water offshore of the Mississippi Delta.

Though alongshore flux was generally westward (Fig. 14B), at times winds reversed, creating eastward flux. During early stages of the "Storm of the Century" from March 12–15, for example,

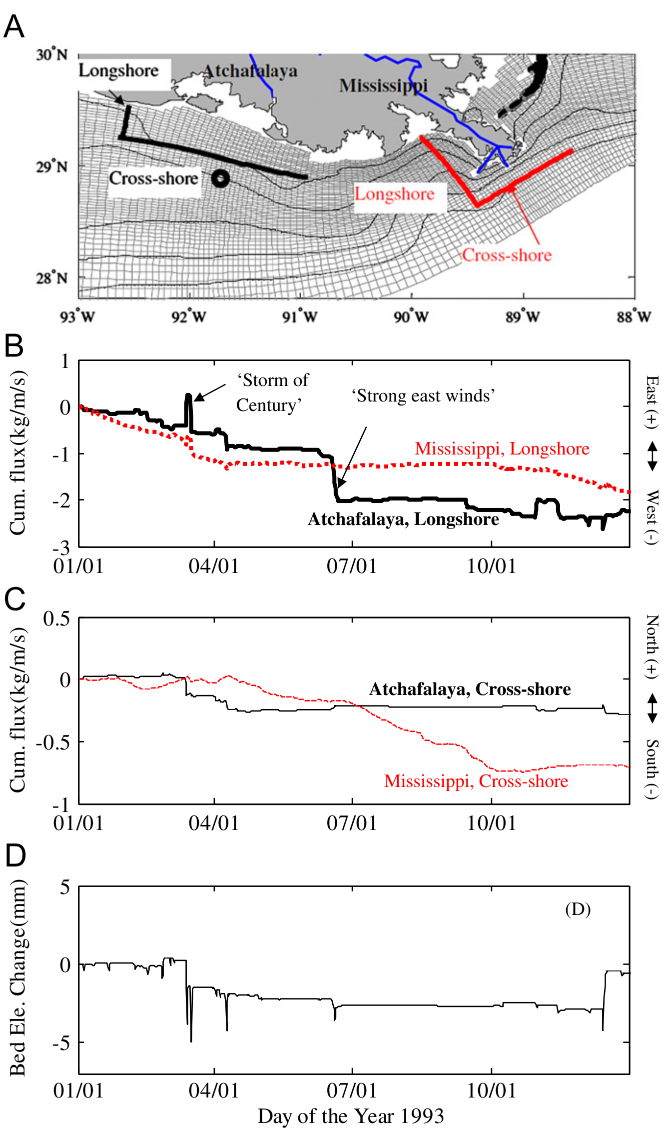

Fig. 14. (A) Transects for alongshore and cross-shore sediment flux calculations south and west of the Mississippi Delta (red) and Atchafalaya Bay (black), respectively. Cumulative sediment fluxes (in kg/m/s) offshore of the Mississippi Delta and Atchafalaya Bay for longshore (B) and cross-shore (C) transects. For Atchafalaya alongshore flux, there were two major events, the "Storm of the Century" in March, and a period of strong east winds in June, whose winds are shown in detail in Fig. 15. (D) Bed elevation change (mm) at a site on the 20 m isobath south of Atchafalaya Bay (circle in A). Maximum erosional depth at this site is shown in Fig. 16C (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

high eastward flux of ~0.8 kg/m/s occurred during periods of extremely strong southeastward (27 m/s) winds (Fig. 15). Westward fluxes resumed once winds relaxed and reversed to come from the east, leading to small *net* sediment transport for the storm (Fig. 14B). From June 15 to 22, the antecedent sediment discharge of the Atchafalaya River was high (Fig. 2), and steady and energetic eastern winds generated large westward sediment fluxes of 1 kg/m/s (Fig. 14B). Despite the lower wind speed (12 vs. 27 m/s) and bed stresses (1.0 vs 1.8 Pa), net sediment flux during June 15–22 actually exceeded that of the "Storm of the Century".

The mainly southward estimated cross-shore sediment-transport flux offshore of the Mississippi Delta accounted for ~30% of the total flux, while the cross-shelf flux offshore of the Atchafalaya only accounted for ~10% of the total (Fig. 14). Opposing the net seaward cross-shelf flux offshore of the Atchafalaya, several shoreward (to the north) sediment transport events occurred, but these had relatively small magnitudes (Fig. 14C). During the "Storm of the Century" in March 12–17, winds were initially from the northwest but later rotated to become from the east (Fig. 15) and modeled depth-integrated cross-shore flux was seaward during March 12–17. Kineke et al. (2006) studied sediment transport processes during a cold front passage in 2001 when wind direction was from the south in advance of the cold front but then veered to become from the north. They observed that sediment transport south of Atchafalaya Bay was to the west and shoreward mainly due to suspension and mixing with increased wave energy and stratification and upwelling during post-front conditions. As noted, wind fields during the March, 1993 storm differed significantly from those during the cold front studied by Kineke et al. (2006). Within our model of the "Storm of the Century", upwelling did occur that caused shoreward fluxes along sea bed (Fig. 9C), but the depth-averaged value remained seaward because the dominantly northwest winds from March 13–14 (Fig. 15) created more energetic, seaward surface currents and a well-mixed turbid water column (Fig. 9A). The highest seaward flux was adjacent to the Atchafalaya Bay mouth plume, a direct result of turbid discharge.

6.4. Potential impact on hypoxia

As reviewed in Section 1.5, sediment influences the development of hypoxia by light attenuation by suspended sediment, and sediment oxygen demand created by the respiration of organic matter associated with suspended or seabed sediment. Shelf-wide average light attenuation has been strongly correlated to freshwater discharge from the Atchafalaya and Mississippi Rivers and light availability was recognized as critical in structuring the distribution of phytoplankton productivity in the water column (Lehrter et al., 2009). Based on eight-year model simulations for Texas–Louisiana shelf, Fennel et al. (2011) found light limitation to be strongest near the Mississippi Delta and weakest in far-field regions. In stratified systems with low light attenuation, sub-pycnocline production can provide significant amounts of oxygen and organic carbon to bottom waters, decoupled from surface nutrient inputs (Murrell et al., 2009). Organic matter can bind to sediment flocs and thus be transported via sediment settling, deposition and suspension. Sediment therefore may impact the generation of hypoxia when it carries labile organic matter that, when microbially respired, consumes significant amounts of oxygen. Using a mechanism simulation model of a closed coupled sediment/water column system, Wainright and Hopkinson (1997) concluded that resuspended organic material from the seabed could enhance the demand of dissolved oxygen, and that water column respiration increased relative to benthic respiration

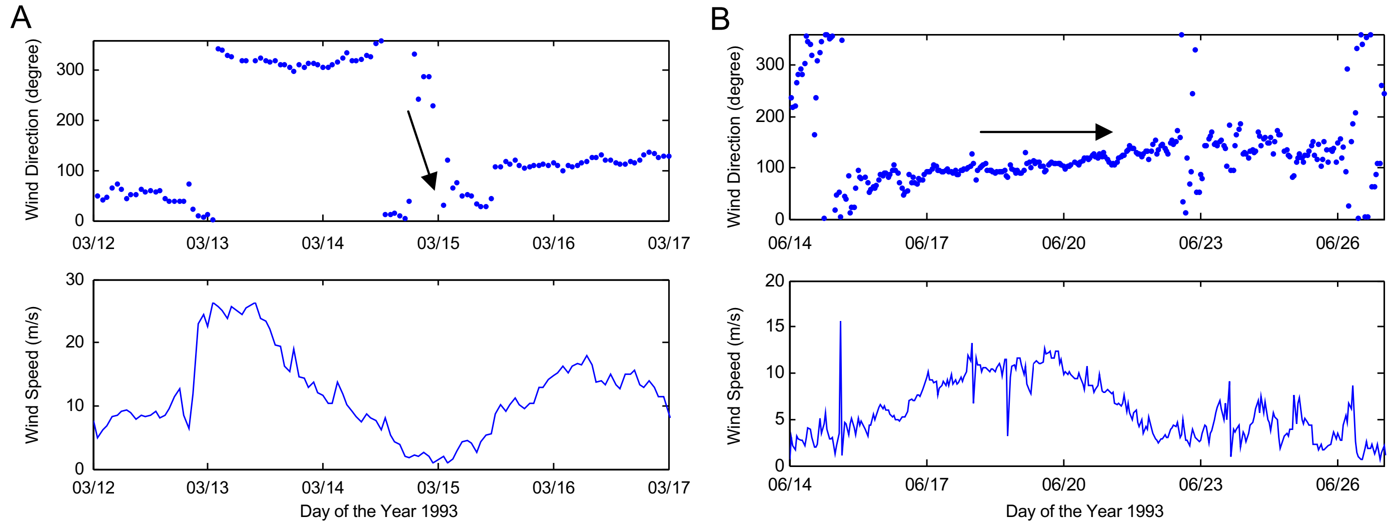

Fig. 15. Wind speed (m/s) and direction (degrees from which the winds blew, relative to north) at BURL 1 C-MAN weather station near the mouth of Southwest Pass of Mississippi Delta during "Storm of the Century" in March and "strong east winds" in June, 1993.

as sediment resuspension events became more frequent or intense.

Though our model did not include biogeochemistry, our calculations shed some light into the potential for sediment processes to impact the formation and persistence of hypoxia offshore of the Texas–Louisiana coast. Considering the potential time lag between cause and effect, we compared modeled physical and suspended sediment conditions between June 15 and July 15, 1993 to the distribution of hypoxia observed in mid-July, 1993 (Fig. 16). Estimated stratification, defined as the density difference (kg/m^3) between surface and bottom water, dominated the Texas–Louisiana shelf, occurring in the plumes of the Mississippi and Atchafalaya Rivers and over the mid-shelf (Fig. 16A). Areas of two sandy shoals on the inner shelf, to the southeast and southwest of Atchafalaya Bay, however, were fairly well mixed. Depth-integrated suspended sediment concentrations (including all six fluvial and sea bed sediment classes) for this period were high near the river and bay mouths, and shoreward of the 10m isobath (Fig. 16B). Fair-weather conditions occurred between June 15 and July 15, so Fig. 16B mainly represents fluvial sediment dispersal, without little contribution of sediment suspended from the seabed.

Next, we considered the potential for the seabed to provide organic matter that fuels water column respiration. Because the time lag between organic matter burial and later resuspension can be as long as a year (Turner et al. 2006, 2008), we calculated the maximum erosional depth from January 1 to July 15, 1993, to evaluate the potential for resuspended organic matter to impact oxygen consumption. During this period, the maximum seabed erosion occurred next to the Mississippi Delta (5 cm) and Atchafalaya Bay (3 cm), and happened mainly during the large storm in March 1993 (Fig. 16C). A mud band exists between the 10 and 50 m isobaths, centered along the 20 m isobath. The mud band had enhanced erosion depths relative to sediment seaward and shoreward of it. On its shallow boundary, sediment texture played a key role; the shoals offshore of Atchafalaya Bay resisted erosion because of the higher critical shear stress assumed for the sands there (Figs. 3 and 16C). Seaward of 50 m, wave energy attenuated, decreasing the frequency and magnitude of erosion. Interestingly, the boundaries of the more erodible mud band follow the landward and seaward boundary of hypoxia, especially along the sand-mud boundary south of the sandy shoals (Figs. 3 and 16C), implying that resuspension may impact the formation and duration of hypoxia on the Texas–Louisiana shelf.

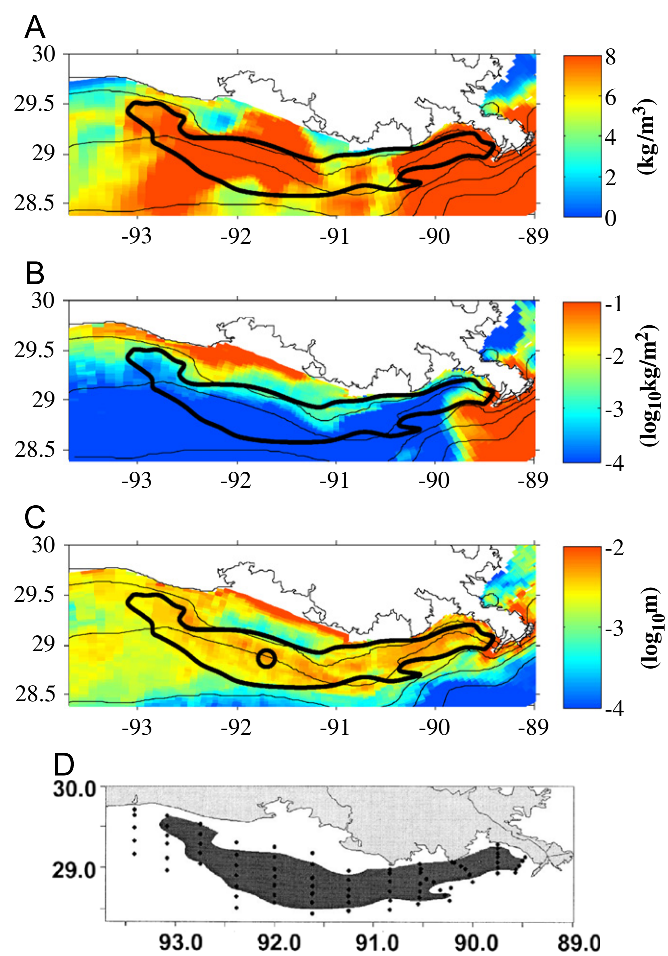

Fig. 16. (A) Stratification (kg/m^3) calculated by subtracting surface from bottom water density for June 15–July 15, 1993. (B) Time-averaged and depth-integrated total suspended fluvial and sea bed sediment (kg/m^2 in logarithmic scale) in the water column calculated for June 15–July 15, 1993. (C) Maximum erosional depth on the sea bed from January 1–July 15, 1993. Time series bed elevation change at a site on the 20 m isobath south of Atchafalaya Bay (circle) is in Fig. 14D. (D) Hypoxic water (oxygen concentration less than 2 mg/L) observed around mid-July 1993 (from Rabalais et al., 2001). The boundary of hypoxic water is overlaid for comparison in panels A–C. (Used with permission, from Journal of Environmental Quality 30:320–329 (2001)).

Diagenetic models account for remineralization of organic matter within the sediment bed, but routinely assume burial rates to be slow and steady (e.g. Boudreau, 1996; Soetaert et al., 1996), thus neglecting resuspension and the episodicity of exchange between the seabed and near-bed waters. Time series changes of seabed elevation in the middle of the mud band (Fig. 14D) demonstrate its episodic nature, with erosion and deposition dominated by a few energetic events. Additionally, although net deposition at the site in the mud bed was only 1 mm, erosion during single events could be as high as 4 mm. Resuspension depths during events were therefore several times larger than indicated by net deposition rates. Neglect of resuspension may greatly underestimate the sediment bed's ability to exchange organic matter with overlying water.

6.5. Fluid mud processes and gravity-driven sediment transport

Fluid mud, defined as a high turbidity layer (concentrations exceeding ~10 g/L; Kineke and Sternberg, 1995) having a distinct lutocline, has been found both within and directly offshore and west of the Atchafalaya Bay mouth (Sheremet et al., 2005; Kineke et al., 2006). These fluid muds occurred in locations having energetic waves and available fine sediment, namely the shallow (< 10 m) inner shelf offshore of and to the west of the Atchafalaya Bay mouth. Corbett et al. (2004) also observed 2–6 cm thick layers of mobilized mud in the vicinity of the Mississippi Delta. Our recent measurements in the hypoxic area indicated sediment there to be relatively consolidated, however. The role of fluid mud therefore seems potentially important for the immediate dispersal of Atchafalaya and Mississippi sediment, but seems less likely to play a key role within the hypoxic area. Our model neglected fluid mud processes (sediment induced stratification and gravitational forcing, hindered settling, consolidation, and wave damping), yet produced reasonable dispersal patterns for Atchafalaya sediment. Since the Mississippi shelf is steep (Fig. 1B), gravity-driven sediment transport may play a role offshore of Mississippi Delta, especially on the delta front and inside Mississippi Canyon, as reported by Walsh et al. (2006).

Depending on the needs of future projects, some fluid mud processes may be added to our model, and ROMS is well equipped for incorporating them. The CSTMS can include sediment's contribution to density, and therefore account for sediment-induced stratification and gravitational forcing. A primary problem with including fluid mud effects has been in achieving vertical resolution necessary to represent the lutocline, but recent modifications to ROMS' grid formulations have achieved very high resolution near the bed (Chen, 2011). Furthermore, the wave-supported gravity flow formulation originally designed for the northern California shelf within the ECOM-SED model (Harris et al., 2004, 2005) is being added to ROMS to allow it to account for strong stratification on the top of the wave boundary layer interface. Additionally, our ROMS model is coupled to SWAN, and wave-damping by suspended sediment might be pursued within SWAN as is being done by other researchers (Winterwerp et al., 2007).

7. Ongoing and future work

Our model proved useful for evaluating shelf-wide dispersal patterns and investigating links between meteorological forcing, circulation, and sediment transport. Our long-term goal is to integrate the sediment model into biogeochemical models to explore the role that sediment processes play in organic matter cycling and hypoxia. Toward that goal, we are pursuing model refinements and field–based measurements as described below.

7.1. Critical shear stress

Critical shear stress is a key parameter in controlling sediment suspension from the sea bed. To our knowledge, in-situ measurements of critical shear stress have not been published from the study area. Critical shear stress may vary significantly on the sea bed, however, both in response to sediment size changes, and for muddy sediment, in response to consolidation and swelling processes (Sanford and Maa, 2001). Based on our model estimates, about 5% of fluvial sediment reaches the hypoxic area defined in Fig. 8C within a year. Thus resuspension and sediment's interaction with biogeochemical cycles within the hypoxic area depend especially on the critical shear stress of the seabed sediment there, consisting of *relict* material originally derived from the Mississippi or Atchafalaya Rivers.

The model presented here neglected the effects of consolidation and swelling, instead parameterizing erodibility and erosion rates as dependent on a critical shear stress for each grain type that was held constant. Other approaches have incorporated time- and depth-dependent critical shear stress to account for bed consolidation and swelling (Sanford, 2008). ROMS now includes an option to account for cohesive sediment bed processes that relies on field-based measurements of critical shear stress as a function of depth in a sediment core (Rinehimer et al., 2008). We did not use this option, however, because of the lack of erodibility data from the study site. In August, 2010 a Gust sediment erosion chamber (Gust and Muller, 1997) was used at eight sites on the Texas–Louisiana shelf between the 20 m and 50 m isobaths to measure sediment erodibility and consolidation. Preliminary results indicated that sediment on the mid Texas–Louisiana shelf was much less erodible than those from the Chesapeake Bay and Mediterranean (preliminary data of Xu, compared to published erodibilities from Dickhudt et al., 2009, In Press and Stevens et al., 2007). Additional measurements will be performed during four future research cruises in 2011 and 2012. These measured critical shear stresses will be applied in later generations of our ROMS sediment model, and used to inform sensitivity tests of shear stress.

7.2. Toward a realistic coupled hydrodynamic-biogeochemical-sediment model

Several numerical models have been developed within collaborative efforts to study the mechanisms controlling hypoxia in the northern Gulf of Mexico. A biogeochemical model based on Fennel et al. (2006, 2011) included nitrate, nitrite, ammonium, phytoplankton, zooplankton, detritus, primary production, and oxygen. Results from this model demonstrated the importance of upwelling favorable summer-time winds in determining the size and duration of hypoxic events (Feng et al., 2010). A simplified model of respiration has been incorporated within a ROMS-based physical model for the Texas–Louisiana shelf, and results from this showed that freshwater input and stratification can explain much of the spatial patterns of hypoxia (Hetland and DiMarco, 2008). We used the same physical hydrodynamic model as both of these, but they simplified sediment processes by assuming either that organic matter instantly remineralized upon reaching the seafloor (Fennel et al., 2006; Feng et al., 2010), or that remineralization in the water column was limited only by temperature (Hetland and DiMarco, 2008). Our analysis of sediment dispersal from the Mississippi and Atchafalaya Rivers has been motivated by the need to build the capability to include sediment processes and better account for the transport and remineralization of particulate organic matter. The long-term goal for these studies is to produce a realistic coupled hydrodynamic-biogeochemical-sediment model to better study three-dimensional temporal and spatial variations of hypoxia in the northern Gulf.

Toward this, we are coupling the sediment and biological modules within ROMS. This includes linkages both in the water column model, whereby the organic detritus created within Fennel et al.'s (2006) model is linked to particulate classes in the sediment transport model; and within the sediment bed model, whereby the remineralization of organic matter on the seabed is represented by a sediment-bed-layer diagenetic model modified from Soetaert et al. (1996). To date, the coupling between the sediment and biological models has been linked within an one-dimensional test case that includes aspects of the diagenetic model such as diffusive mixing within the seabed, degradation of organic matter and oxygen consumption (Harris et al., 2010).

8. Conclusions

A numerical model that included hydrodynamics, waves, and sediment transport was used to estimate the dispersal of Mississippi and Atchafalaya sediment on the Texas–Louisiana Shelf. Our modeled year 1993 included a large storm, high discharge during the spring and summer, followed by a typical fair-weather summer period. Based on model estimates, we concluded the following:

(a) For the year 1993, the model successfully reproduced both hydrodynamic conditions and sediment dispersal patterns on the Texas–Louisiana Shelf.
(b) Sediment deposition was highly localized: Mississippi deposition retained a bird-foot shape whereas narrow and elongated accumulation occurred offshore of Atchafalaya Bay. Mississippi sediment was more widely broadcast than Atchafalaya sediment due the highly variable current directions and relatively steep slopes offshore of the Mississippi River mouth. The presence of deep water directly offshore of the birdfoot delta increased sediment settling times and transport distances. The presence of perennially westward depth-averaged currents south of Atchafalaya Bay confined Atchafalaya sediment to the inner-shelf. The shallow water depth there enhanced wave suspension which facilitated the westward dispersal of Atchafalaya sediment.
(c) During fair-weather conditions, river plumes spread onto a stratified shelf water column. Wave–current-combined shear stress episodically reached the critical level sufficient to resuspend sediment at depths shallower than 10 m. During the storm of March, 1993, sediment flux peaked near the Mississippi subaqueous delta and Atchafalaya Bay mouth. Most resuspension occurred in areas where wave shear stresses dominated total bed stresses; these sometime resuspended sediment to water depths of 100 m.
(d) Model results indicated that relatively little fluvial sediment can be transported into the vicinity of the hypoxic area within a year. More than half ($\sim$60%) remained near the Mississippi Delta and about one-third (29%) deposited next to the Atchafalaya Bay mouth or Chenier Plain.
(e) Alongshore sediment-transport fluxes generally exceeded cross-shore fluxes offshore of both the Mississippi Delta and Atchafalaya Bay. Offshore of the Atchafalaya, most sediment-transport flux occurred episodically during short intervals. In contrast, cumulative flux offshore of the Mississippi changed more gradually.
(f) Sediment processes impact the formation of hypoxia through light attenuation and sediment oxygen demand. The extent of the hypoxic area in 1993 showed a relationship to model estimates of both the extent of turbid fluvial plumes (light attenuation) and seabed resuspension. Specifically, intermittent mobilization of the mud bed present on the middle Texas–Louisiana shelf during storms may facilitate the development of later hypoxia.

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