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Effect of wind, river discharge, and outer-shelf phenomena on circulation dynamics of the Atchafalaya Bay and shelf

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ABSTRACT

The influence of wind, river discharge, and outer-shelf variations on the circulation of the Atchafalaya Bay and the adjoining inner shelf were examined using a 3-dimensional circulation model. Current and water level data from three stations along a transect off the Marsh Island were used for model calibration and skill assessment. Coastal current and its spatial distribution were significantly affected by open boundary conditions. Model sensitivity analysis suggested that the vertical eddy viscosity has a substantial impact on the energy and momentum transfer across the water column in this shallow bay-shelf environment. It was also shown that westward to northwestward currents dominated in the study area during the non-summer months and that would transport westward large volume of sediments discharged from rivers during the spring flood season. This sediment load is contributing to the progradation of the Chenier Plain along the southwestern Louisiana coast. A particle tracking Lagrangian model validates the westward migration of suspended sediments originating from the river mouth area during the spring season.

1. Introduction

The Atchafalaya Bay, located on the western flank of Louisiana inner shelf, forms part of the greater Mississippi River drainage system. The Bay and the adjoining shelf are strongly influenced by the sheer volume of fresh water and sediment plume discharged from rivers, particularly during the spring flood season with circulation in the shallow shelf mainly driven by the wind (Allahdadi et al., 2011). About 19–29% of the river water and 30–40% of sediment load from the Mississippi River is diverted through the Atchafalaya River to the Atchafalaya-Vermillion Bay and then to the Gulf of Mexico (Mossa and Roberts, 1990; Allison et al., 2000; Walker and Hammack, 2000). Fresh water and sediment load are discharged through two main outlets, viz., Wax Lake outlet and Morgan City channel (Roberts and Sneider, 2000). For the inner Atchafalaya shelf, water quality is highly affected by seasonal hydrodynamics and morphology of the shelf, which modulates the salinity in the shelf and along the shoreline (Cobb et al., 2008a; Allahdadi et al., 2011). In this context, understanding the hydrodynamics within the Atchafalaya Bay and the adjoining inner shelf is essential for studies aiming to determine the fate and dispersal of fresh water and sediment load from the Atchafalaya River. For instance, strong southward currents associated with passage of cold fronts during winter/spring season have been identified for their significant effect on sediment transport inside and outside of the Atchafalaya Bay (Feng and Li, 2010).
Currents in the Atchafalaya shelf follow the general circulation pattern of Louisiana coast (Cochrane and Kelley, 1986) and is influenced by seasonal wind, tides, river discharge, and outer-shelf variations induced by the Loop Current Eddies (Oey, 1995; Allahdadi et al., 2011). However, depending on the location, relative contribution of each individual forcing on the circulation is different and difficult to differentiate. A modeling study for the Louisiana shelf by Oey (1995) concluded that wind forcing accounts for up to 50% of the transport over the inner shelf with river discharge and outer shelf eddies contributing to the rest. Tide-generated currents are very weak due to the small tidal range over the Louisiana shelf (average of 0.4 m) and are of mixed-diurnal in nature (Wright et al., 1997). The dominant wind effect with varying direction for different seasons results in different circulation patterns. Easterly to south-easterly winds during most of the year (September to May) produce mostly westward (down-coast) currents over the inner-shelf (Cochrane and Kelly, 1986; Li et al., 1997; Allahdadi et al., 2013). A simultaneous eastward current produced by anticyclonic Loop Current eddies along the shelf break can generate a cyclonic gyre

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circulation within the broad inner-shelf with a sustained down-coast current (Cochrane and Kelley, 1986). A shift in the wind direction to southwest during the summer produces a persistent, albeit weak, eastward current over the inner-shelf. At a shorter time scale, the frequent passage of cold fronts from late September to May, generates episodic offshore directed shelf currents (Rego, 2008; Cobb et al., 2008b; Feng and Li, 2010). Based on the analysis of met-ocean data from different bays along the Louisiana coast, Feng and Li (2010) observed that during the passage of cold fronts, northerly wind would generate strong southward (offshore directed) currents that could flush out about 40% of bay waters over a short period of time. This flushing can substantially modulate sediment transport characteristics and their depositional pattern over the Atchafalaya shelf (D'Sa et al., 2011;Tehrani et al., 2013).

Although several studies have already addressed wave dynamics and its interaction with the muddy bed of the Atchafalaya Bay and shelf (Siadatmousavi et al., 2012, 2013; Sheremet and Stone, 2003; Sheremet et al., 2005; Allison et al., 2000), a detailed study of shelf hydrodynamics and coastal current regime has been lacking. Cobb et al. (2008a, 2008b) used a northern Gulf of Mexico model to investigate the effect of cold fronts on salinity distribution and to some extent the circulation of the Atchafalaya Bay. They reported that during the pre-frontal phase, westward currents were amplified which could contribute to the transport of river sediments to the Chenier plains. The westward currents could also be modulated by river plume deflection as a result of the Coriolis effect (Kourafalou et al., 1996). Although that comprehensive study addressed some aspects of circulation over the inner Atchafalaya shelf, the focus was on the fate of fresh water discharged from the river. The present study uses a 3-dimensional hydrodynamic model implemented on a high-resolution flexible mesh to address the hydrodynamics of the extended Atchafalaya Bay-shelf system while also assessing the impact of different forcing and their sensitivity on the circulation. One key aspect of this study is to simulate the dispersal pathways of freshwater and sediment plumes coming out of the rivers during the peak flood season and to show how they are influenced by the prevailing wind and remote outer-shelf forcing. Outcome of this study can provide a proper base to evaluate the seasonal contribution of sediment load originating from the Atchafalaya River towards the buildup of Chenier coastline farther west of the study area.

Another objective of this study is to statistically quantify the relative contribution of different forcing (local as well as remote) in the shelf circulation. Although wind has been identified as the main forcing in driving the currents in the region (e.g., Allahdadi et al., 2011), the effect of outer-shelf variations in modulating the current field has not been thoroughly determined. A study of the hydrodynamics of the narrow eastern Louisiana shelf using outputs from a northern Gulf of Mexico model nested in a regional Intra-Americas Sea model (IASNFS; Ko et al., 2003; Ko and Wang, 2014) appropriately resolved the Loop Current eddies and their interaction with the currents on the Louisiana Shelf (Chaichitehrani et al., 2014). That study demonstrated the modulating effect of deep water eddies on the coastal currents in the vicinity of the Birds-Foot Delta and the adjoining shelf west of the delta. The present study attempts to numerically evaluate similar effects for the broad Atchafalaya bay/shelf region.

2. Study area and approach

The focus of the present study is the Atchafalaya Bay and the adjoining shelf (Fig. 1). Marsh Island, located along the southern fringe of the bay, is a rapidly eroding low lying barrier island that protects the northern bay (Vermillion Bay) from the open Gulf of Mexico. The shallow coastal zone is strongly impacted by the discharge from the Atchafalaya River system, which brings high amounts of mud (consolidated and partially settled) that accumulates on the shelf (Sheremet and Stone, 2003; Jose et al., 2014; Siadatmousavi et al., 2012).

3. Model specifications

3.1. Numerical model

The 3-D hydrodynamics model, Mike3 FLOW MODEL-FM, developed by *DHI water and Environment* (DHI, 2014) was utilized to simulate the coastal currents and its spatial/temporal variability in response to wind, river discharge and tide/outer-shelf variations. The model solves Reynolds averaged Navier-Stokes and continuity equations based on a finite volume scheme on a domain composed of triangular elements on a horizontal plane.

For model discretization along the vertical direction, a finite difference approach using either z or σ coordinate or their combination is applied. Time varying 2-D wind data can be used for forcing the model with wind energy transferred through the water column via shear stress. There are different approaches for considering the effect of bottom friction on the current. Bottom friction parameter as well as the surface friction coefficient regulate the atmosphere-ocean coupling and can be fine-tuned for model calibration. A particle tracking tool based on a Lagrangian approach has been incorporated in Mike Zero module of the DHI software. This tool is used in this study for further analysis of simulated currents.

3.2. Model setup

3.2.1. Data

3.2.1.1. Bathymetry data. Compared to the narrow shelf adjoining the Mississippi Bird-foot delta, the mid Louisiana shelf, especially the Atchafalaya shelf, is very wide with extensive shallow shoals off the Atchafalaya Bay (Fig. 1). Although the study area (Atchafalaya shelf and bay) encompasses only a smaller part of the Louisiana coast, a large modeling domain extending from the Mississippi Bird-foot delta to the western boundary of the Atchafalaya shelf was considered for simulating the effect of Louisiana coastal currents on the study area as well as accounting for the complex interaction of the shallow shelf with the outer continental shelf dynamics. Shelf-wide bathymetry data were obtained from NGDC (NOAA). Additionally, high resolution bathymetry survey data collected during 2008 from Tiger and Trinity Shoal Complex (Roberts et al., 2010) were used to refine the model grid for the shoal complex. Based on the available bathymetry data, the average depth within the Atchafalaya Bay is about 2.5 m. Water depth is 10 m at a distance of 35 km south of the bay entrance, while the 30 m isobath is located at a distance of ~70 km.

3.2.1.2. NARR (NCEP) wind. - NCEP North American Regional Reanalysis (NARR) wind data were extracted from the NCEP archives and used for the study. The NARR wind data with ~32 km spatial resolution has been extensively validated for the Gulf of Mexico (Jose and Stone 2006).

3.2.1.3. NCOM/Navy Hydrodynamic data for boundary forcing. The forcing from outside of the shallow Atchafalaya model domain could significantly affect the dynamics (e.g., current pattern) of the inner-shelf, especially along the eastern and southern boundaries. In order to take into account these far-field effects, boundary conditions along the open boundaries were extracted from archives of a coastal model based on NCOM (Navy Coastal Ocean Model). NCOM is a 3-D, free surface, primitive equations ocean model applying the hydrostatic, Boussinesq, and incompressible approximations (Martin, 2000; Barron et al.,