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NUMERICAL MODELING OF WAVE DYNAMICS AND SEDIMENT TRANSPORT NEAR THE MISSISSIPPI BIRDFOOT DELTA AND BARATARIA ESTUARY

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Oceanography and Coastal Sciences

by

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August 2019
To

my wife, Soha,

For all her sacrificial support
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ABSTRACT

The Barataria Basin is a large estuarine system in Southeastern Louisiana, connected to the Gulf of Mexico through a number of inlets, the most important of which is the Barataria Pass. This research examines, during April-June 2010 including both cold front passage and calm summer-time wind regimes, the wave dynamics in this basin and in its major inlets, morphological evolution near the Barataria Pass, and the budgeting and dispersal of the Mississippi River sediment in the birdfoot delta region. An unstructured grid, terrain following, high resolution coupled FVCOM-SWAVE-SED model is employed and validated in this study. The numerical model results reveal that locally generated wind-seas are the main source of the wave field inside the Barataria Basin, especially for waves with significant wave height greater than 0.1 m and during cold front passage events. Moreover, the model predicts an almost instantaneous response of the wave field to the change in the wind direction. The impact of cold front passage on shoreline erosion is also attested by wave exposure analysis, i.e. frequency of occurrence of wind waves with significant wave height greater than 0.1 m.

In tidal inlets, an analysis indicates a dual nature of the wave field: locally generated seas and swells from the Gulf of Mexico. We assessed the contribution of hydrodynamic forces and found them to be more important in the inlets rather than inside the basin. FVCOM-SWAVE predicts a decrease in significant wave height inside the Louisiana Bight due to current-induced refraction and wave stretching effects caused by the clockwise gyre from the Mississippi River plume. The modulation of significant wave height at the Barataria Pass due to partial wave blocking from the opposing current, and wave stretching for the following current can be up to 20%. The effect of depth-induced breaking and bottom friction overshadows that from wave-current interaction at other shallower inlets.
The analysis of the water and suspended sediment concentration fluxes among six major outlets of the Mississippi birdfoot delta indicates that 64% and 40% of the flow and SSC passes through the Southwest Pass during the three-month simulation time, respectively. Due to the more energetic flow field at this pass, the sediment dispersal and deposition is more elongated and large suspended sediment concentration (> $10^{-2}$ kg/m$^3$) is retained in the upper four meters of the water column for ~ 8 km offshore of the Southwest Pass.

A study on morphological evolution near the Barataria Pass demonstrates an erosional area mainly located at the shelf side of the Barataria Pass, and two depositional regions at the shelf and the bay side of the pass. Tidal forcing is shown to be the dominant forcing during the modeling period. Because the location of the transect across the pass is located almost on the northern edge of the erosional area, the net sediment flux is bayward while the net water flux in this ebb-dominated inlet is seaward. The largest sediment flux into the bay occurs during the pre-frontal phase of cold front events.
CHAPTER 1. INTRODUCTION

Since the emergence of the Mississippi Delta about 6000-7000 years ago, the Mississippi River has changed its main course six times, forming a series of overlapping delta lobes (Roberts, 1997; Day et al., 2007). The most recent channel formed a progradational “birdfoot” delta over the past 550 years (Day et al., 2007) that protrudes southward into the Gulf of Mexico by ~ 60 km. The advancement of the birdfoot delta was possible due to sufficient amount of fluvial sediment supply that was transported and deposited through a series of outlets, as well as overbank flooding, crevasse formation and distributary switch (Roberts, 1997). Due to human intervention, nowadays the birdfoot delta is no longer growing and is in a retreat stage (Blum and Roberts, 2009).

Wetlands in Coastal Louisiana, formed by the Mississippi River Delta and its lobe-switching over the centuries, are considered as the seventh largest in the world (Couvillion et al., 2011). These wetlands worth more than 3 billion US Dollars per year for the US seafood industry (Restore the Mississippi Delta Coalition, 2012) and host infrastructures for a substantial amount of oil and gas industry (90%) and fisheries (20%) of the United States (Coastal Protection and Restoration Authority of Louisiana, 2017). Louisiana wetlands and barrier islands, in particular, also act as multiple levels of defense for coastal cities against hurricanes and associated storm surges.

However, wetland loss in coastal estuaries and bays has emerged as a major threat to the environment, ecology, and economy of the State of Louisiana and United States at large. Though Louisiana estuarine wetlands constitute 40% of the wetlands in the United States, Louisiana suffers from 80% of the wetland losses in the whole country (USGS, 2018). On one hand, this land loss is caused by anthropogenic activities that either deprived the wetlands from natural
fluvial sediment input from the Mississippi River (e.g. by building of levees on the banks of the Mississippi River) or made areas more susceptible to erosion (e.g. by dredging of oil and gas canals that channelize the marshes and cause marsh edge erosion). On the other hand, natural causes such as sea level rise, subsidence and wave action contributed to Louisiana coastal and wetland erosion.

The Barataria Basin is located in the northern Gulf of Mexico, bounded by the gulf in the south, Bayou Lafourche in the west, and the Mississippi River proper in the east. The Gulf Intracoastal Waterway (GIWW) passes through the Barataria Basin and divides it into two groups of water body: the northern part includes Lake Salvador, Lake Cataouatche, and Lac des Allemands; and the southern part consists of Barataria Bay, Little Lake, and Caminada Bay. The exchange of water, nutrients and sediment between the inner shelf and the Barataria Basin is through a number of tidal inlets. The Barataria Pass is the major inlet in terms of size and depth. More than two-third of the exchange of water between the Barataria estuary and the Louisiana Bight is through this inlet (Marmer, 1948). Other notable inlets are Caminada Pass, Pass Abel, Quatre Bayou Pass.

Apart from the problem of coastal erosion, a failure occurred in Deep Watr Horizon (DWH) drilling rig on 20 April 2010 near the coast of Louisiana, releasing large amount of light sweet crude oil from a depth of ~ 1525 m. On 24 May, 2010 British Petroleum (BP) committed $500 million over a 10-year period to create a broad, independent research program studying the the dynamics of this catastrophic event and its environmental impacts, known as the Gulf of Mexico Research Initiative (GoMRI). As a part of the GoMRI, Coastal Water Consortium II (CWC-II) project was inaugurated in 2015 consisting of 14 collaborative institutions and 194 research team members (GoMRI, 2019) to continue the study of the effect of oil pollution on
wetland ecosystems and food web structures. One of the objectives of this project was to investigate the dispersion and transport of oil contaminants under the combined influence of hydrodynamic and wave forces, primarily associated with the transport of sediments. Moreover, the resuspension and deposition processes in the Barataria estuarine system and the dispersion pattern of sediments were to be examined. The hydrodynamic aspect of this study was accomplished by Cui (2018). This research aims to further the scope of the CWC-II research including wave dynamics and sediment transport in the Barataria Basin, Mississippi birdfoot delta and the major passes connecting the Barataria estuary and the continental shelf. Moreover, all three components, i.e. hydrodynamic, wave and sediment transport, are coupled.

The chain of barrier islands, namely, West Grand Terre, East Grand Terre, Grand Pierre, and Cheniere Ronquille have suffered from severe erosion in the past decades. The combined area of aforementioned barrier islands have dwindled by 45% from 1990 to 2015 with a projected disappearance of East Grand Terre and Grand Pierre by 2045 (LaCoast, 2002). This will expose the Barataria Basin to even larger waves from the continental shelf, and consequently exacerbate the erosion in this estuarine system. So long as inlet opening plays a major role in energy and momentum transfer in an inlet-barrier-island system (Olabarrieta et al., 2014), understanding of the inlet hydrodynamic, wave action and the effect of wave-current interaction on wave dynamics is crucial to gain insight into forcing on bed. Processes such as wave-current interaction, alongshore current, ocean swells, wind intensity, bottom friction and depth-dependent wave breaking contribute to inlet wave dynamics (Olabarrieta et al., 2011; Ganju et al., 2017). Waves can be modified by the current through current-induced refraction and wave blocking. The strong tidal jets near varios passes alter wave direction due to current-induced refraction (Wolf and Prandle, 1999). Smith et al. (2000) applied a coupled
hydrodynamic-wave model to Willapa Bay, WA to show the increase and decrease of wave height at strong (> 2 m/s) opposing ebb and subsequent flood current by 80% and 20%, respectively. The numerical modeling investigation of Dodet et al. (2013) reported the retarding of wave height during ebb flow and increase in wave height by 20% in Albufeira inlet, Portugal due to partial wave blocking and wave-induced refraction. In chapter 2, a fully-coupled unstructured-grid, three-dimensional, FVCOM-SWAVE model is employed to address the wave characteristics and wave-current interaction in the Louisiana Bight and the six tidal inlets connecting the Barataria Basin to the northern Gulf of Mexico (Fig. 1.1) during the spring-summer time period when both cold front passages and persistent southeast wind events exist.

Fig. 1.1. The study area in the northern Gulf of Mexico and the locations studied in each of the chapters.
Apart from barrier islands, the Barataria Basin itself has been prone to very high rates of land loss and marsh erosion in the Grande Cheniere and Bay Regions, amassing nearly 23.1 km\(^2\) between 1974 and 1990 (LaCoast, 2002). The total land loss from 1932 to 2010 in this estuarine system is estimated as 1092 km\(^2\) (Couvillion et al., 2011). Specifically, wave action is considered to be one of the prime causes of marsh edge erosion. It has been estimated that 26% of the wetland loss in this estuarine system is caused by the wave-induced erosion (Penland, 2000).

Wave exposure, defined as frequency of occurrence of wind waves with heights above a certain threshold value (e.g. 0.15 m in Seibt et al., 2013), is used to estimate the potential for edge erosion (Hoffmann et al., 2011). Therefore, proper understanding of wave dynamics within the Barataria Basin would be imperative to gain insight to and further mitigate the land loss problem in this estuarine system. In chapter 3, the causality between wind and wave and the relative contribution of seas and swells in six major water bodies of the Barataria estuarine system are investigated for the same three-month period as in chapter 2, using the numerical modeling approach. The significant impact of extratropical storms (i.e., cold frontal passage events) on shoreline erosion inside the basin is also demonstrated in this chapter.

The man-made interference on the Mississippi River, such as damming, building of levees and other river control systems and land use change, has reduced the sediment load to half over the past century (Corbett et al., 2004; Blum and Roberts, 2009). The decrease in fluvial sediment input is considered as one of the prime reasons for dire wetland loss in coastal Louisiana (Barras et al., 2003; Barras, 2006). Therefore, proper management of the available sediment resource from the Mississippi River, beginning with an accurate estimation of water and sediment budgets from various Mississippi Delta passes, is indispensable to make a strategic restoration plan to mitigate the chronic Louisiana coastal and wetland loss. Although some
experimental studies have been performed to estimate the water and sediment budget for the lower Mississippi system and the Mississippi birdfoot outlets (Li et al., 2011; Allison et al., 2012), collecting simultaneous data from various exits of the Mississippi birdfoot is costly and logistically challenging. Therefore, a numerical model, with accurate hydrodynamics and high fidelity to real world geometry and bathymetry, can provide an alternative way to calculate the sediment and water budgets through various passes. A number of numerical studies have focused on dispersion and accumulation of sediment from the Mississippi River on the continental shelf (e.g. Keen et al., 2004; Xu et al., 2011). However, none of the aforementioned numerical models have the appropriate spatial resolution of the Mississippi birdfoot delta to capture the details of the partitioning of flow and suspended sediment concentration from each of the outlets as well as sediment dispersal and deposition near each outlet. The complex and irregular boundaries of the Mississippi birdfoot delta can only be precisely resolved by an unstructured grid numerical model. In chapter 4, a three-dimensional high-resolution coupled hydrodynamic-wave-sediment numerical modeling system is developed to quantify the water and sediment budgeting and the dispersion and accumulation of riverine sediment around the the Mississippi Delta (Fig. 1.1). Moreover, in this chapter the mechanisms for the shelf-estuary sediment exchange at the Barataria Pass during normal and cold front passage conditions are investigated (Fig. 1.1).

The overall summary and general conclusions are presented in chapter 5.
Coastal wetlands and estuarine systems are invaluable from economic and ecological perspectives. In many parts of the world, tidal inlets between barrier islands connect an estuarine system with the coastal ocean. Thus, they are crucial routes for estuarine-shelf exchanges of water and nutrients (Allen et al., 2007; Ferrarine et al., 2013; Umgiesser et al., 2014), fish and larvae migration (Joyeux, 1999), as well as acting as outlets of freshwater plumes (Spydell et al., 2015; Li et al., 2017). Louisiana wetlands and barrier islands, in particular, also act as multiple levels of defense for coastal cities against hurricanes and associated storm surges. The area hosts infrastructures for a substantial amount of oil and gas industry (90%) and fisheries (20%) of the United States (Coastal Protection and Restoration Authority of Louisiana, 2017). However, local subsidence, sea level rise, and significant reduction in sediment input due to anthropogenic activities (such as construction of dams on rivers and distributaries of the Mississippi Basin) resulted in severe land loss along the Louisiana Coast.

The Barataria Basin, one of the major coastal bays in the northern Gulf of Mexico, has suffered from the highest rate of land loss, losing about 23.1 km$^2$ between 1974 and 1990 (LaCoast, 2002). The chain of barrier islands that protect the basin against the coastal wave action are also subjected to substantial erosion. Four major barrier islands defending Barataria Basin, i.e. West Grand Terre, East Grand Terre, Grand Pierre, and Cheniere Ronquille, have been reduced by about 45% area from 1990 to 2015 with a projected disappearance of East Grand Terre and Grand Pierre by 2045 (LaCoast, 2002). This will expose the Barataria Basin to
even larger waves from the continental shelf, and consequently exacerbate the erosion in this estuarine system.

In an inlet-barrier-island system, the inlet opening plays a major role in energy and momentum transfer as affected by local bathymetry, tidal forcing, wind-generated surface gravity waves, and wave-current interaction (Olabarrieta et al., 2014). Therefore, understanding of the inlet hydrodynamics is crucial for establishing a science-based sustainable management framework to protect and restore the estuarine system, such as the Barataria Basin. In this paper, the focus is mainly on wind wave dynamics and the impact of wave-current interaction on wave dynamics.

Wave dynamics in tidal inlets have been extensively studied using analytical methods (Ismail and Wiegel, 1983), flume experiments (Ismail, 1980), in situ measurements (Wargula et al., 2014; Orescanin et al., 2014), remote sensing observations (Díaz Méndez et al., 2015) and numerical modeling (Bertin et al., 2009; de Swart and Zimmerman, 2009; Kumar et al., 2011; Olabarrieta et al., 2011, Keshtpoor et al., 2014). Processes such as wave-current interaction, alongshore current, ocean swells, wind intensity, bottom friction and depth-dependent wave breaking contribute to inlet wave dynamics (Olabarrieta et al., 2011; Ganju et al., 2017). In shallow inlets for instance, the depth-induced breaking becomes important in wave action balance and can even overshadow wave-current interaction in modulation of wave height (Bertin et al., 2009; Malhadas et al., 2009; Chen et al., 2015; Ghader et al., 2016; Haghshenas et al., 2018).

Waves can be modified by current through current-induced refraction and wave blocking. A strong jet can alter wave direction due to current-induced refraction (Wolf and Prandle, 1999). An opposing current can block the advancement of wave and transfer the wave energy to higher
wave numbers provided that the current speed scales the wave group velocity (Chen et al., 1998; Chawla and Kirby, 2002). Gonzales et al. (1985) conducted an observational study at the Columbia River entrance and demonstrated wave steepening and wave height increase during opposing currents, and elongation of wavelength in the presence of a following current. Smith et al. (2000) applied the coupled STWAVE steady state wave model and ADCIRC circulation model to Willapa Bay, WA, to show the increase and decrease of wave height at strong (> 2 m/s) opposing ebb and subsequent flood current by 80% and 20%, respectively. Using the SELFE hydrodynamic model and the Simulating WAve Nearshore (SWAN) (Booij et al., 1999) wave model, Dodet et al. (2013) reported a retarding of wave during ebb flow and increase in wave height by 20% in Albufeira inlet, Portugal, due to partial wave blocking and current-induced refraction. The results of the numerical study from Chen et al. (2015) proved the onshore decrease of wave height and offshore decay of current velocities.

In spite of recent developments in remote sensing techniques to measure wave height in coastal environment, and in absence of sufficient field measurements, numerical modeling is still the main tool to tackle complex inlet wave and hydrodynamics (Chen et al., 2015). Two categories of numerical wave models exist: phase-resolving and phase-averaging (spectral) models. The application of phase-resolving models is limited to relatively small domains due to their computational burden. On the other hand, spectral action balance models, though losing phase information of waves, are more practical in medium- and large-scale domains. The wave spectral models have been extensively applied to two-dimensional wave models, and two-dimensional, quasi-three-dimensional and three-dimensional coupled wave-current modeling systems on complex coastal and inlet regions (e.g. Özkan-Haller and Li, 2003; Newberger and Allen, 2007; Banijamali et al., 2009; Haas and Warner, 2009; Uchiyama et al., 2010; Kumar et
al., 2011; Siadatmousavi et al., 2012a; van der Westhuysen et al., 2012; Dodet et al., 2013; Olabarrieta et al., 2014; Allahdadi et al., 2017; Mao and Xia, 2018). Nonetheless, none of the above-mentioned studies tackled inlet wave dynamics under extratropical storms. Further, the inlets of Barataria Basin are different from a typical inlet system in that they are under the influence of strong Mississippi River plume and the circulation in the Louisiana Bight.

The cold front (i.e. extratropical storm) is a mid-latitude atmospheric circulation system in which cold, high pressure air moving towards the south encounters warm, low pressure, maritime air. A rotational wind pattern accompanies each cold front passage frequent the northern Gulf of Mexico every three to seven days in winter and spring seasons (Stone and Wang, 1999) and sweep through the coastal estuaries of the region especially from the northern sector. Cold fronts can be categorized into three stages: prefrontal, frontal and post-frontal. During the prefrontal stage, southerly winds prevail, causing coastal water level setup and prolonged wave action from southerly sectors (Walker, 1996). A decrease in barometric pressure, a rise in air temperature and an increase in wind speed are common characteristics of this phase (Roberts et al., 2015). Frontal passage is a short-lived event during which barometric pressure drops and wind direction suddenly changes from southerly to northerly. The post-frontal stage corresponds to strong wind from northerly quadrants accompanied by a quick set down in coastal water level, rapid drop in air temperature and an increase in barometric pressure (Roberts et al., 2015). Though cold fronts are less energetic compared to hurricanes, their impact is more pronounced on the Louisiana coast owing to their frequent occurrence (Roberts et al., 1989; Mossa and Roberts, 1990). Walker and Hammack (2000) showed that water level in the Louisiana bays could increase by more than 0.5 m at frontal stage. They also found that the turbid coastal plume generated during cold front events could extend 180 km alongshore and 75
km seaward of the Atchafalaya Bay section of the Louisiana coast. Feng and Li (2010) reported that cold fronts flushed up to 40% of water from coastal bays into the continental shelf during post-frontal stage in less than 40 hours.

In spite of several hydrodynamic studies in the northern Gulf of Mexico and Barataria Basin (Chen et al., 1997; Justic et al., 2007; Li et al., 2011; Das et al., 2012), few studies focused on coupled wave-current modeling of the Louisiana coast and estuaries, especially during cold front events. Xu et al. (2011) studied the coupled wave-current-sediment modeling using the ROMS model, but their study was confined to the continental shelf without sufficient resolution to capture the advection from the Mississippi River plume. Liu (2016) applied the coupled circulation-wave Delft3D model to the Terrebonne and Barataria Basins, but his work only addressed the wave and sediment dynamics under Hurricane Gustav (2008). Everett (2016) applied the SWAN wave model to investigate the wave field in Terrebonne Bay. None of the aforementioned studies, per contra, were dedicated to study the wave field and its interaction with current in the tidal inlets of the Barataria Basin.

The present study investigates the causality of waves at major inlets of the Barataria Basin, and the current induced wave transformations in the Louisiana Bight in front of the inlets. It is based on a three-month (April, May, and June 2010) numerical simulation using a high-resolution, finite-volume, 3-D, FVCOM-SWAVE (Finite-Volume Community Ocean Model/Surface WAVE; Chen et al., 2013) model. The motivation to select this spring-summer time span is that it comprises two typical wind regimes in the northern Gulf of Mexico, i.e. cold front passage events in April 2010 (called CF event hereafter), and persistent wind blowing from the south and southeast directions during June 2010 (SE event). Nevertheless, the intensity and frequency of extratropical storms in late spring are relatively less than those in winter and early
spring. Following the introduction section, the remaining of the present paper is organized as follows: Section 2.2 describes the study area. Section 2.3 introduces the methodology including the model grid and setup, modeling system for waves and hydrodynamics and, coupling method between the components. Section 2.4 elaborates on model validation. The results are presented and discussed in section 2.5 coping with causality of wave in six major inlets and in their bay and shelf-side regions during the whole three-month simulation, cold-front event, and persistent southeast wind event, respectively. In addition, the effect of coastal current, the tidal jet near the Barataria Pass, and the influence of the Mississippi River plume are also discussed in this section. Section 2.6 briefly summarizes the major findings of present study.

2.2 Study area

The Barataria Basin is a deltaic estuarine system located on the west side of Mississippi bird foot delta, formed by lobe-switching of the Mississippi River over the past two thousand years (Rejmanek et al., 1987). It is comprised of several lakes and water bodies (Fig. 2.1a), among which Barataria Bay is the largest one, with average depth of \( \sim 2.4 \) m. Several smaller and shallower bays, such as Caminada Bay, Bay Melville, Bay Ronquille, Bay Long, and Bastian Bay, are also distinguished in the southern Barataria Basin (Fig. 2.1b). Wetlands, which are prone to inundation due to their small elevation, are also depicted as grey-filled areas in Fig. 2.1. The basin opens to a mild slope continental shelf of the Louisiana Bight and Mississippi bird foot delta, which is created by progradational river-dominated delta with a gradient of about \( 0.4^o \) (Xu et al., 2011).

The exchange of water and material between Barataria Basin and the continental shelf is through a number of tidal inlets as presented in Fig. 2.1b. In this study six major tidal inlets, namely, Caminada Pass, Barataria Pass, Pass Abel, Quatre Bayou Pass, Bay Long Pass, and
Grand Bayou Pass, are studied. Among them, Barataria Pass is the main entrance to Barataria Basin between Grand Isle and Grand Terre Island with width, length and maximum depth of about 800 m, 430 m and 40 m, respectively. Marmer (1948) estimated that ~ 66% of water exchange between Barataria Bay and Louisiana Bight went through Barataria Pass. The rest of the outlets are shallower with the maximum depth of 1.5 m.

The circulation in the Louisiana Bight is mainly governed by confluence of buoyancy forcing, wind forcing, tidal forcing, and the buoyant tidal jet from the Barataria Pass. The major buoyancy forcing is from Southwest Pass of the Mississippi River and from various crevasses along the western levee of the bird foot delta. The Mississippi River exports about 530 km$^3$/yr freshwater into the continental shelf (Rong et al., 2014), 45% of which enters through the Southwest Pass (Etter et al., 2004). The average and maximum Mississippi River discharge during April-June 2010 was 19730 and 28880 m$^3$/s, respectively (USGS data). The width of Southwest Pass is much narrower (in the order of 700 m) than other river systems, resulting in a supercritical flow near the mouth of the pass with velocity greater than 2 m/s. Moreover, construction of jetties, which has been included in our numerical grid, and channel dredging in this outlet amplifies the effect of the river plume and generates a prominent clockwise gyre circulation in the Louisiana Bight (Rouse and Coleman, 1976; Wiseman et al., 1976; Walker et al., 2005). The river runoff from various crevasses induces a westward alongshore current just south of the barrier islands (Walker, 1996). Under special occasions, Loop Current filaments or eddies may influence the circulation patterns adjacent to the bird-foot delta (Wiseman and Dinnel, 1988; Huh and Schaudt, 1990).

Fig. 2.1c presents the wind rose for the whole 2010 year from National Data Buoy Center (NDBC) Station 42040 (https://www.ndbc.noaa.gov/, see Fig 1a for location). It has been
pointed out that there are two major wind regimes in this region (Chuang and Wiseman, 1983): one is wind blowing from northwest to southeast that are more frequent in the winter time (October to April) and are mainly associated with cold front passages. The other is southerly winds that prevail in the summer season. The wind rose for the three-month modeling period (April-June 2010) is shown in Fig. 2.1d demonstrating prevalent summer wind patterns. The dominant southeasterly winds during this period presumably enforce westward surface current that reinforces the buoyancy-induced westward current (Walker, 1996). Wind also modulates the Mississippi plume. This downwelling favorable wind from east and southeast sector pushes the plume closer to the coastline and downcoast (Zhang et al., 2014). As will be shown later, this summer wind pattern mostly occurred in June 2010 while the cold front passage events occurred during April 2010.

Over the Louisiana continental shelf, as well as inside the Barataria Basin, $K_1$ and $O_1$ are the dominant tidal constituents, each having an amplitude of ~ 0.11 m at the NDBC Grand Isle station. Due to the microtidal condition, tidal currents are relatively weak over the continental shelf, averaging ~ 0.15 m/s (Murray, 1972). At the Barataria Pass averaged tidal currents are ~ 0.5 m/s due to the narrowness of the pass (Snedden, 2006). Maximum tidal currents reach as high as 2 m/s during tropic tides (Li et al., 2011). Inside the Barataria Basin, the tidal range is ~ 0.4 m near the Barataria Pass and is attenuated by 68% in the northern basin (Byrne et al., 1976; Conner et al., 1987).

Except for the extreme events such as hurricanes and extratropical storms, the wave regime over the continental shelf is a low wave action. The calculated wave parameters for a 23-year time span (1995-2017) at NDBC Station 42040 (Fig. 2.1a) show that the mean and standard deviation for significant wave height ($H_s$) and peak wave period ($T_p$) are $0.99 \pm 0.71$ m and
5.64±1.55 s, respectively. However, the maximum values of the same parameters during this period reaches 16.91 m and 23.55 s, respectively, which must be during a hurricane event. In cold front events, $H_s$ in the open coast can exceed 2-3 m (Dingler et al., 1993).

Fig. 2.1. (a) The FVCOM-SWAVE model domain of Alabama-Louisiana-Texas continental shelf and the Barataria Basin, and location of wave observation stations. The thick black line denotes the model open boundary. (b) Zoomed area of major bays in south of Barataria Basin and six major inlets connecting this estuarine system and continental shelf. The color contours illustrate bathymetry. The black, red and green dots show the location of representative stations at each of the six pass locations and their shelf- and bay side, respectively. (c) Wind rose for the whole 2010 year. (d) Wind rose for April, May, and June 2010.
2.3 The modeling system

2.3.1 FVCOM hydrodynamic model

FVCOM is a triangular-grid, 3-D, primitive equation ocean model (Chen et al., 2013), which has been extensively applied to coastal and estuarine environments (Chen et al., 2006, 2007; Huang et al., 2008). It solves the governing equations with flux-based finite-volume discrete algorithms on a horizontal triangular mesh that ensure conservations of mass and momentum in both the whole domain and individual mesh. FVCOM combines the best of finite-difference models for simple code structures and finite-element models for geometric flexibility. The latter is essential for complex coastal and estuarine modeling. Modified Mellor and Yamada level 2.5 (Galperin et al., 1988) and Smagorinsky (1963) turbulent closure schemes are incorporated for vertical and horizontal viscosity and diffusivity, respectively. The governing equations can be numerically solved using either explicit mode-splitting scheme or semi-implicit scheme (Chen et al., 2013).

2.3.2 FVCOM-SWAVE wave model

FVCOM-SWAVE is a triangular-grid, SWAN-based phase-averaged wave model developed by Qi et al (2009). The model employs the wave action balance equation to calculate the wave spectrum evolution in temporal, geographical and spectral spaces (Booij et al., 1999; SWAN Group, 2018). The numerical discretization of the equation, using the same finite-volume scheme on the same triangular mesh as the FVCOM model, makes it particularly appropriate for coastal and estuarine applications under the wave-current interaction condition (Qi et al., 2009). This wave action balance equation, in presence of ambient current, is written as:

$$\frac{\partial N}{\partial t} + \nabla \cdot [(C_g + U)N] + \frac{\partial C_{\theta}N}{\partial \theta} + \frac{\partial C_{\sigma}N}{\partial \sigma} = \frac{S_{tot}}{\sigma}$$

(1)
where $N$ is the wave action density spectrum; $t$ is the time, $\theta$ is the wave direction taken counterclockwise from the geographical east; $\sigma$ is intrinsic radian frequency, $C_\sigma$ and $C_\theta$ are the wave propagation velocities in spectral space $(\sigma, \theta)$, $C_g$ is the group velocity, $U$ is the ambient water current vector., and $\nabla \cdot ( )$ is the horizontal divergence operator in geographic space. The propagation velocities are defined as (Mei, 1983; Dietrich et al., 2013):

$$c_\sigma = \frac{\partial \sigma}{\partial H} \left( \frac{\partial H}{\partial t} + U \nabla H \right) - c_g k \cdot \frac{\partial u}{\partial s}$$  \hspace{1cm} (2)

$$c_\theta = -\frac{1}{|k|} \left( \frac{\partial \sigma}{\partial H} \frac{\partial H}{\partial m} + k \cdot \frac{\partial u}{\partial m} \right)$$  \hspace{1cm} (3)

Herein, the $\vec{k}$ is the wave number vector, $(s,m)$ are left-turning spatial coordinates in the wave direction $\theta$ and perpendicular to it, and $H$ is the total water depth.

The right-hand-side of Eq. 1 includes the source and sink terms that balance the change of wave action in temporal, geographical and spectral space and can be described as:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{wc} + S_{br} + S_{bot}$$  \hspace{1cm} (4)

where $S_{in}$ determines the growth of the wind waves due to energy input from wind stresses. $S_{nl3}$ and $S_{nl4}$ characterize nonlinear triad (three-wave) and quadruplet (four-wave) interaction between spectral components. The last three terms in right-hand-side of Eq. 4 represent the dissipation due to whitecapping, shallow-water depth-induced breaking, and bottom friction, respectively.

The triad wave interaction transfers energy from higher frequencies to the lower ones in shallow water. The Lumped Triad Approximation (LTA) formulation (Eldeberky, 1996) that approximates this process in SWAVE model calculates the directionally-decoupled propagation of energy through the spectrum from lower to higher frequencies. The LTA formulation expresses the three-wave interaction using bi-phase of the self-interactions of the peak frequency
components that is parameterized in terms of Ursell Number with the following formulation (Eldeberky, 1996):

\[
\beta = \frac{\pi}{2} \left[ \tanh \left( \frac{0.2}{U_r} \right) - 1 \right]
\]  

(5)

where \( \beta \) is the bi-phase of wave and \( U_r \) is the Ursell number expressed as:

\[
U_r = \frac{g}{g\sqrt{2\pi}} \frac{H_{m0} \tau_{m01}^2}{\kappa^2}
\]  

(6)

where \( H_{m0} \) is the zero-moment wave height, \( T_{m01} \) is the mean period using zero and first moment of spectrum, and \( H \) is the water depth. The bi-phase value varies from \( \beta \to 0 \) (symmetrical wave) to \( \beta \to -\frac{\pi}{2} \) (asymmetric wave) and is a measure of wave nonlinearity. The \( |\sin\beta| \) governs LTA-based calculation of three-wave interaction.

2.3.3 Model coupling and wave-current interaction

The FVCOM and SWAVE models exchange information at each wave time-step to maximize accuracy of wave-current interactions (wave time step is always the product of current time step and an integer number). Upon initialization, SWAVE calculates the wave action and determines wave parameters, namely, \( H_s, T_p \), mean wave direction, average wave-length, and bottom wave orbital velocity. Wave radiation stress is thus calculated based on these parameter values and passed to FVCOM. In the next step, FVCOM computes current and surface elevation fields using momentum and continuity equations with added radiation stress terms. Then, wave action is calculated in SWAVE for the next time step, including the feedback of current and surface elevation of the previous time step from FVCOM (Wu et al., 2011).

The momentum transfer between wave and circulation models is treated through excess momentum flux in the surf zone expressed as radiation stress gradients, as formulated by
Longuet-Higgins and Stewart (1964) and implemented by Mellor (2008). The 3D radiation stress is implemented into FVCOM-SWAVE as (Wu et al., 2011):

\[
S_{xx} = kE \left( \frac{k_x k_x}{k^2} F_{CS} F_{CC} - F_{SC} F_{SS} \right) + \frac{k_x k_x}{k^2} A_R R_z \\
S_{yy} = kE \left( \frac{k_y k_y}{k^2} F_{CS} F_{CC} - F_{SC} F_{SS} \right) + \frac{k_y k_y}{k^2} A_R R_z \\
S_{xy} = kE \left( \frac{k_x k_y}{k^2} F_{CS} F_{CC} \right)
\]

(7)

where \( S_{xx}, S_{yy} \) are vertically-integrated radiation stress in x and y directions, \( S_{xy} \) is lateral component of the radiation stress, \( E \) is the wave energy (\( E = \frac{gH^2}{16} \)), and \( k_x \) and \( k_y \) are components of wave number in x and y directions. The expressions for roller area \( A_R \), roller shape function \( R_z \), and vertical structure functions \( F_{CS}, F_{SC}, F_{CC} \) and \( F_{SS} \) can be found in Wu et al. (2011).

2.3.4 Numerical model setup

The computational domain, which encompasses most of Alabama-Mississippi-Louisiana-Texas continental shelf, is composed of an unstructured triangular grid with 143546 nodes and 278399 elements. The finest mesh resolution is ~ 15 m in shallow estuarine region and inside channels, and it gradually enlarges to ~ 8 km near the open boundary over the continental shelf. The setting of hydrodynamic model follows exactly Cui (2018), in which FVCOM is driven by winds at the surface, sea level elevation at the open boundary, and freshwater inflows from various Mississippi River and Atchafalaya River passes and the Davis Pond Diversion inside the Barataria Basin. Three-hourly 0.25°×0.25° gridded wind data are obtained from NOAA North American Regional Reanalysis (NARR) products and linearly interpolated to each time step and grid point. At the open boundary, six-min interval sea level time series at four stations are downloaded from NOAA tides and currents website, and piecewise linearly interpolated to prescribe sea surface elevations boundary condition at all open boundary nodes. USGS fifteen-
min freshwater discharge data are used to specify flux boundary conditions at river boundary nodes. All model forcing functions are ramped up from zero over a period of ten days. Periodic inundation in the wetlands is incorporated by activating the flooding-drying scheme with a threshold of 0.05 m (Huang et al., 2011). Salinity is also considered as a prognostic variable in the computation as discussed in Cui (2018).

SWAVE is forced by winds at the sea surface and JONSWAP wave spectra along the open boundary. Same NARR wind data are used in wave simulation. Wave spectrum is constructed from integral wave characteristics (e.g. $H_s$, $T_p$, and mean wave direction). In this study these parameters are interpolated along the open boundary from 10 arc minute North-East Atlantic WAVEWATCH III (WWIII) products (http://polar.ncep.noaa.gov/waves/). The wind-induced wave growth and whitecapping follows the formulation of Komen et al. (1984). Wave growth term of Cavaleri and Malanotte-Rizzoli (1981) is activated with proportionality coefficient of 0.0015. Both quadruplet (Hasselmann et al., 1985) and triad wave-wave interactions (Eldeberky, 1996) are included with parameters endorsed by van der Westhuysen et al. (2012). For bottom friction, the JONSWAP formulation (Hasselmann et al., 1973) is selected and wave breaking is according to Battjes and Janssen (1978). The phase-decoupled refraction-diffraction approximation (Holthuijsen et al., 2003) is not activated as recommended by van der Westhuysen et al. (2012). Other parameters in the wave model also follow van der Westhuysen et al. (2012). The wave spectrum simulation is divided into 36 intervals in directional space and 44 intervals in frequency, logarithmically distributed from 0.05-3.0 Hz. The maximum cut-off frequency in the model is larger than typical value of 0.5 Hz recommended for application in the Gulf of Mexico (Siadatmousavi et al., 2012b) that is to capture the anticipated higher frequencies in the interior of the Barataria Basin and shallow bay side of the inlets.
Three configurations of FVCOM-SWAVE are considered in this study: first, FVCOM and SWAVE are fully coupled which is called WC case hereinafter; second, only SWAVE runs excluding FVCOM, called WO case; third, a WC case, except excluding the sea level elevation forcing in FVCOM at the open boundary. The last case is named WC_ncWL, which is only used in section 2.5.1 to show the effect of water surface variation in changing the shape of Mississippi plume and discuss its effect on wave field inside Louisiana Bight.

2.4 Comparison between model simulations and observations

The evaluation of FVCOM performance is based on 19 NOAA and USGS water level stations on the continental shelf and inside the Barataria Basin, as elaborated in Cui (2018). In summary, all correlation coefficients between WC case and observations exceed 0.83 with an average of 0.91.

Characteristic wave parameters of the WC and WO cases are validated against 5 NDBC stations and 1 Coastal Studies Institute (CSI) station as depicted in Fig. 2.1a. The CSI-09 is part of the Wave-Current-Surge Information System (WAVCIS) observation network, initiated at Louisiana State University. It is 3.4 m deep and located inside the Louisiana Bight in front of the Barataria Bay. The depths at NDBC stations 42035, 42040, 42369, 42370 and 42887 are 15.5, 290.4, 1659.3, 1225.6 and 1849.8 m, respectively. The data for NDBC station 42035 and 42040 and CSI-09 were measured on an hourly basis, while it was measured every 20 minutes for the rest of the offshore stations.

The skill metrics selected in this study are scoring index (SI), relative bias (RBias), correlation coefficient (CC), mean absolute error (MAE), and index of agreement (IA). Their formulations are as follows:
\[ SI = \frac{\frac{1}{n} \sum_{i=1}^{N} (X_{ml} - X_{ol}^2)^2}{\frac{1}{n} \sum_{i=1}^{N} X_{ol}^2} \]  
(8)

\[ RBias = \frac{\sum_{i=1}^{N} (X_{ml} - X_{ol})}{\sum_{i=1}^{N} X_{ol}} \]  
(9)

\[ CC = \frac{\sum_{i=1}^{N} (X_{ml} - X_{ol})(X_{ol} - X_{ol}^2)}{\sqrt{\sum_{i=1}^{N} (X_{ml} - X_{ol})^2 \sum_{i=1}^{N} (X_{ol} - X_{ol}^2)^2}} \]  
(10)

\[ MAE = n^{-1} \sum_{i=1}^{N} |X_{ml} - X_{ol}| \]  
(11)

\[ IA = 1 - \frac{(X_{ml} - X_{ol})^2}{(|X_{ml} - X_{ml}| + |X_{ol} - X_{ol}|)^2} \]  
(12)

where \(X_{ml}\) and \(X_{ol}\) denote modeled and observed data, respectively, and overbars indicate the mean values. \(SI\) is the standard deviation of the observation from corresponding model result, normalized by mean observed data. The \(RBias\) denotes the relative difference between measured and modeled values. As for the deviation measure skill parameter, \(MAE\) is preferred over root-mean-square deviation as recommended by Willmott et al. (2012). The \(CC\) is the Pearson product-moment correlation coefficient and has its value between -1 and 1, with unit value indicating perfect correlation and 0 meaning no correlation. \(IA\) is regarded as a better performance measure than \(CC\) when used to compare model-predicted and observed variables (Willmott, 1981). Perfect agreement between model results and observations yields \(IA\) of 1 and complete disagreement gives \(IA\) of 0.

Further, due to angular nature of wind and mean wave direction, a circular correlation coefficient (CCC) is used to analyze the correlation between these two variables. The mathematical expression of CCC is as follows (Fisher and Lee, 1983):

\[ CCC = \frac{\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sin(x_i - x_j) \sin(y_i - y_j)}{\sqrt{\sum_{i=1}^{n} \sum_{j=i+1}^{n} \sin^2(x_i - x_j) \sum_{i=1}^{n} \sum_{j=i+1}^{n} \sin^2(y_i - y_j)}} \]  
(13)

where \(x\) and \(y\) are numerically calculated wind- and wave-directions.
Fig. 2.2. Left column: Time series of significant wave height calculated from numerical model for WC and WO cases as well as observation from NOAA and CSI stations during April to June 2010. Right column: The same time series comparison for peak wave period. Four extreme wave events are selected as A, B, C, and D. The shaded areas denote periods with no observational measurements.

The comparisons between observed and modeled $H_s$ and $T_p$ are tabulated in Table 2.1 and shown in Fig. 2.2. In general, the predictive skills of WC case are close to that of WO case, indicating that the influence of current and sea level variation over the continental shelf is
minimal at these stations. Owing to large CC and IA value and small MAE score, it can be concluded that both WC and WO are able to successfully reproduce $H_s$. The statistical scores for $T_p$ are also reasonable, bearing in mind the high sensitivity of measured $T_p$ and modeled $T_p$ being a stepwise function rather than a smooth one. Compared with other stations, NDBC 42887 station shows low CC and IA scores. This is mainly because of the substantial scatter in observed data, especially after 20 May (Fig. 2.2). It is believed that observed $T_p$ data at this station may be erroneous. The RBias and MAE scores for $T_p$ at nearshore stations (NDBC 42035, 42040, and CSI-09) are markedly better than the two offshore stations (NDBC 42369 and 42370). In addition, the RBias for $H_s$ at NDBC 42035 and CSI-09 is negative, indicating model under-estimates $H_s$. Otherwise, model over-estimates $H_s$.

Table 2.1. Statistical assessment between modeled and observed data for $H_s$ and $T_p$. SI: Scoring Index, RBias: Relative Bias, CC: Correlation Coefficient, MAE: Mean Absolute Error, IA: Index of agreement.

<table>
<thead>
<tr>
<th>Model</th>
<th>Station</th>
<th>Significant Wave Height</th>
<th>Peak Wave Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SI</td>
<td>RBias</td>
</tr>
<tr>
<td>WC</td>
<td>NDBC 42035</td>
<td>0.26</td>
<td>-0.09</td>
</tr>
<tr>
<td></td>
<td>NDBC 42040</td>
<td>0.39</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>NDBC 42369</td>
<td>0.33</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>NDBC 42370</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>CSI-09</td>
<td>0.33</td>
<td>-0.03</td>
</tr>
<tr>
<td>WC</td>
<td>NDBC 42035</td>
<td>0.26</td>
<td>-0.09</td>
</tr>
<tr>
<td></td>
<td>NDBC 42040</td>
<td>0.39</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>NDBC 42369</td>
<td>0.33</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>NDBC 42370</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>CSI-09</td>
<td>0.33</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>NDBC 42887</td>
<td>0.33</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>CSI-09</td>
<td>0.43</td>
<td>-0.11</td>
</tr>
</tbody>
</table>
2.5 Model results and discussion

Given a degree of model veracity established through observation and model simulation comparisons, wave characteristics in the various tidal inlets of the Barataria Basin is now being discussed as inferred from the FVCOM-SWAVE simulation. Since waves from the continental shelf may penetrate through these inlets, in order to differentiate swells from locally generated wind sea, sea state on the continental shelf will first be discussed.

2.5.1 The effect of Louisiana Bight circulation on wave field near the passes

The circulation in the Louisiana Bight strongly influences the height and direction of waves that approach various tidal inlets. Fig. 2.3 presents the distributions of surface current vectors and $H_s$ at a prefrontal stage during maximum flood, maximum ebb and slack water times for both WO and WC cases. Due to spatial and temporal uniformity of the wind field during these instances (red straight arrows in Fig. 2.3 left column), waves also uniformly propagate towards the barrier islands from a southeast direction in WO case (Fig. 2.3 mid-column). However, mean wave direction in the Louisiana Bight deviates greatly when wave-current interaction is added (green box in Fig. 2.3c and Fig. 2.3f). This change in mean wave direction is mainly caused by current-induced wave refraction because both clockwise and counterclockwise gyres inside the Louisiana Bight induce a gradient of current perpendicular to the wave direction ($k \cdot \frac{\partial \nu}{\partial m}$ term in Eq. 3). In addition, the WC case predicts a $H_s$ reduction in the Louisiana Bight and close to coast (green and red boxes in Fig. 2.3c and Fig. 2.3f) comparing to the WO case. Such a decrease in $H_s$ is attributed to the following current that stretches the wave height inside the bight. When the clockwise freshwater gyre bends toward the coast (red curve in Fig. 2.3a), strong following velocities extend closer to the coastline, lessening $H_s$ in front of the barrier.
islands east of Grand Bayou Pass (red box in Fig. 2.3c). As the clockwise gyre moves away from the coast, the wave elongation effect diminishes (Fig. 2.3f and Fig. 2.3i). A local $H_s$ shoal is also observed on the border of inner- and mid-shelf (green box in Fig. 2.3c and Fig. 2.3f), which could be explained by wave blocking induced by anticlockwise gyre near the mid-shelf (blue curved arrow in Fig. 2.3 left column).

Fig. 2.3. (a, d & g): Surface current vectors during (a) maximum flood, (d) slack water, and (g) maximum ebb. Representative wind vector is shown as a straight red arrow in each panel. Red, green, and blue curved arrows indicate major surface current pattern in the Louisiana Bight and adjacent continental shelf. (b, c, e, f, h & i): (Color) snapshot of significant wave height during maximum flood, slack water and maximum ebb for WO (b, e, and h) and WC (c, f, and i) cases. Black arrows represent mean wave direction. Red and black lines are contour lines for $H_s = 0.25$ and $H_s = 2.0$ m, respectively. Red and green rectangles indicate the regions in which wind waves change significantly due to wave-current interaction.
Fig. 2.4. Snapshots of difference of modeled significant wave height between WC and WO cases during (a) maximum flood, (b) maximum ebb and (c) a time instance with pronounced wave blocking in Louisiana Bight due to secondary counterclockwise gyres (green curved arrows). The black and magenta arrows represent surface ocean current and mean wave direction in WC case, respectively. The thick black arrow shows magnitude and direction of the wind on a representative point in Louisiana Bight.
In addition to the clockwise gyre from the Mississippi River plume, the runoff from the channels in west of bird foot delta induces an alongshore current that also changes the wave field on the east side of Barataria Pass. As a result of interaction between the clockwise gyre inside Louisiana bight (red curved arrow in Fig. 2.3 left-column) and westward alongshore current, smaller scale secondary anticlockwise gyres may form close to the barrier islands (green curved arrows in Fig. 2.4). Fig. 2.4a and Fig. 2.4b correspond to the maximum flood and ebb times, respectively, as presented in Fig. 2.3. The westward alongshore buoyancy-driven current in Fig. 2.4 is ~ 0.5 m/s. Such currents have a component that follows the mean wave direction and reduces the significant wave height. When the main clockwise gyre bends inside inward (maximum flood time in Fig. 2.3a), stronger secondary gyres are generated (green curved arrow in Fig. 2.4a) and the wave-stretching influence of alongshore current is more pronounced (stronger red-color zone in Fig. 2.4a compared with Fig. 2.4b and Fig. 2.4c). Depending on relative direction between ocean surface current and mean wave direction, these eddies can also block the wave propagation and enhance the significant wave height (blue regions in Fig. 2.4b and Fig. 2.4c).

The flow from Barataria Pass also alters the wave height at this pass and Caminada Pass. The results of the numerical model shows that a strong jet or potential flow from Barataria Pass halts the buoyancy-driven westward alongshore current (Fig. 2.4). The eddies formed downcoast of Barataria Pass changes the wave height in front of Grand Isle and Caminada Pass. The influence of jet flow from Barataria Pass will be further expounded in section 2.5.5.

Although tidal and subtidal forcing in Louisiana Bight is not as prominent as other abovementioned hydrodynamic forces, it can still affect the wave field in this region. Considering typical wave characteristics ($H_s = 1.5$ m & $T_p = 6$ s) and water level variation (~ 0.5
m) of the Louisiana continental shelf, applying linear wave theory for wave propagation on an average depth of 4 m results in a change of ~ 0.03 m in $H_s$ value. Sea level variation also changes the shape of Mississippi plume, which modifies the wave field inside Louisiana Bight. Fig. 2.5 presents the modeled $H_s$ and surface current vectors for the WC_noWL case at the same time instances for maximum flood and ebb as in Fig. 2.3. In absence of water level forcing, the clockwise Mississippi River plume is more contracted particularly during maximum ebb flow (Fig. 2.5b). During flood time, the gradient of surface current perpendicular to wave direction is dwindled and the effect of current-induced refraction is diminished (compare Fig. 2.5a with Fig. 2.3c). Contrastingly, because of the inward-bending of the Louisiana gyre the local shoal in wave height is shifted to the front of Southwest Pass (Fig. 2.5b) and wave stretching is stronger compared to Fig. 2.3i. Moreover, the anticlockwise gyre in the mid-shelf region (blue curved arrow in Fig. 2.3) is weaker in the WC-noWL case compared to the WC case that could affect the extension of Louisiana gyre and the formation of the shoal for significant wave height.

### 2.5.2 Wave field inside the Barataria Bay

The wave characteristics in the Barataria Basin are elaborated in a separate manuscript. There it is demonstrated that waves inside the Barataria Basin are mainly locally wind driven. For the sake of comparisons with wave characteristics in various tidal inlets, a station near the center of the Barataria Bay (station BB in Fig. 2.1) is selected as a representative bay station. Time series of wind vectors, vertically averaged current vectors and wave parameters at this station for the WC case are shown in Fig. 2.6. During the three-month simulation period, two distinct wind patterns were clearly distinguishable in Fig. 2.6a. First, a cold front (CF) passage event, which was characterized by clockwise rotation of wind, lasts from 23 April to 3 May 2010. Second, a wind event with relatively constant wind direction from south or southeast (SE)
A strong sector was seen, for example, from 2 June to 14 June 2010. The maximum wind speed reaches strong breeze to moderate gale (Beaufort wind scale 6-7) inside Barataria Bay during this period of time (Fig. 2.6a).

Fig. 2.6b depicts vertically averaged flow vectors, showing a dominant diurnal tidal current as commonly observed over the Louisiana-Texas continental shelf, as well as inside coastal bays and estuaries. The magnitude of the current rarely exceeds 0.1 m/s at this station. The seemingly diurnal variation in $H_s$ (Fig. 2.6c) is not caused by wave-current interaction since at this station WC and WO yield almost the same $H_s$ time series (figure not shown). As illustrated in Fig. 2.6e, the range of $T_p$, between 0.5 and 2.5 s, is much less than typical $T_p$ values over the continental shelf (~ 6 s), a confirmation that waves on the bay are locally generated.

Fig. 2.5. The modeled instantaneous significant wave height for the WC case excluding water level forcing at boundary (i.e., WC_noWL case) during (a) maximum flood, (b) maximum ebb. Black arrows indicate mean wave direction and white vectors indicate current magnitude and direction. The thick red arrow shows magnitude and direction of the wind on a representative point in Louisiana Bight. Green curved arrow indicates clockwise Louisiana gyre. Red and black lines are contour lines for $H_s = 0.25$ and $H_s = 2.0$ m, respectively.
Fig. 2.6. Timeseries of (a) wind stick plots, (b) vertically averaged current stick plots, (c) significant wave height, (d) mean wave direction, and (e) peak wave period for station BB in WC case, as well as scatter plots and statistics for wind direction vs mean wave direction and wind speed vs significant wave height at station BB during three-month simulation period (f1 and g1), cold front (CF) event (f2 and g2), and southeast (SE) wind event (f3 and g3). Four extreme wave events are selected as A, B, C, and D.
2.5.3 Dynamics of wave and current in inlet passes

2.5.3.1 Overall wave statistics

A distinct change in wave characteristics can be observed from shelf side to bay side of the Barataria Basin inlets. Therefore, for each inlet, three stations are chosen that represent inlet location and its shelf and bay sides, respectively (Fig. 2.1b). The shelf side station is influenced by waves from the deep Gulf of Mexico after transformations on the inner shelf and nearshore zone, while the station on the bay side follows more or less similar wave pattern as discussed in section 2.5.2.

Fig. 2.7 shows overall wind pattern, depth-averaged ocean current and wave parameters for Pass Abel and its shelf and bay sides. Similar to what has been shown in Fig. 2.6b, diurnal variation of depth-averaged tidal current is also detected at the inlet (I-3) and bay stations (I-3B) (Fig. 2.7b2 and Fig. 2.7b3). In spite of sporadic spikes in velocity on the shelf side (I-3S) (Fig. 2.7b1), the mean magnitude of depth-averaged current at the inlet is twice as large as that at the shelf side, which can be attributed to smaller cross sectional area at the pass.

The numerical model predicts a notable reduction in $H_s$ from shelf to pass and further inside the basin (Fig. 2.7c1 to Fig. 2.7c3). A comparison of mean and maximum value of $H_s$ and $T_p$ are summarized in Table 2.2. The decrease in mean $H_s$ is 53% and 75% at I-3 and I-3B compared to I-3S. Table 2.2 demonstrates approximately the same amount of $H_s$ reduction for all other passes. Reduction of $H_s$ at inlet locations, especially for I-3 which is 0.63 m deep, is probably due to wave dissipation resulting from depth induced breaking before shelf waves approach the inlets and bottom friction. The pattern of $H_s$ at I-3 is more jagged compared to I-3S and I-3B (Fig. 2.7c2) that is due to stronger ambient current along with tidal water surface variation. This will be further elaborated in section 2.5.5.
Fig. 2.7. Numerical model timeseries results for hydrodynamic and wave parameters for I-3S, I-3 and I-3B stations: (a) wind stick plots; (b1), (b2) and (b3) current stick plots; (c1), (c2) and (c3) significant wave height; (d1), (d2) and (d3) mean wave direction; (e1), (e2) and (e3) peak wave period. Four extreme wave events are selected as A, B, C, and D.
Table 2.2. Summary of significant wave height and peak wave period for the stations at six major passes.

<table>
<thead>
<tr>
<th>Pass Name</th>
<th>Station</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean</td>
<td>max</td>
</tr>
<tr>
<td>Caminada Pass</td>
<td>I-1S</td>
<td>0.400</td>
<td>0.958</td>
</tr>
<tr>
<td></td>
<td>I-1</td>
<td>0.198</td>
<td>0.598</td>
</tr>
<tr>
<td></td>
<td>I-1B</td>
<td>0.0783</td>
<td>0.600</td>
</tr>
<tr>
<td>Barataria Pass</td>
<td>I-2S</td>
<td>0.418</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>0.253</td>
<td>0.835</td>
</tr>
<tr>
<td></td>
<td>I-2B</td>
<td>0.158</td>
<td>0.507</td>
</tr>
<tr>
<td>Pass Abel</td>
<td>I-3S</td>
<td>0.378</td>
<td>0.905</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>0.166</td>
<td>0.502</td>
</tr>
<tr>
<td></td>
<td>I-3B</td>
<td>0.0938</td>
<td>0.324</td>
</tr>
<tr>
<td>Quatre Bayou Pass</td>
<td>I-4S</td>
<td>0.44</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>0.0911</td>
<td>0.348</td>
</tr>
<tr>
<td></td>
<td>I-4B</td>
<td>0.0918</td>
<td>0.308</td>
</tr>
<tr>
<td>Bay Long Pass</td>
<td>I-5S</td>
<td>0.3751</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>0.198</td>
<td>0.489</td>
</tr>
<tr>
<td></td>
<td>I-5B</td>
<td>0.0895</td>
<td>0.231</td>
</tr>
<tr>
<td>Grand Bayou Pass</td>
<td>I-6S</td>
<td>0.401</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>0.151</td>
<td>0.476</td>
</tr>
<tr>
<td></td>
<td>I-6B</td>
<td>0.0804</td>
<td>0.194</td>
</tr>
</tbody>
</table>

The mean wave direction on the shelf side follows somewhat a straight line, which is aligned with overall orientation of coastline, indicating the effect of refraction process (Fig. 2.7d1). The occasional spikes in mean wave direction are triggered at frontal stage of CF events associated with an abrupt change in wind direction from southeast to northwest. The jumps in mean wave direction become more frequent as we move to inlet or bay side locations (Fig. 2.7d2 and Fig. 2.7d3). This is because of the growing influence of the seas determined by local wind variability.

The average value of $T_p$ decreases from shelf- to pass-station by about 10% (Fig. 2.7e2 and Table 2.2), though this decrease can reach up to 40% in shallow inlets such as Quatre Bayou Pass. Such a reduction is in part attributed to redistribution of wave energy in shallow water due to triad wave interaction. The analysis of the bi-phase of the waves at the shelf side reveals
strong wave nonlinearity, especially during major wave events (Fig. 2.8). Therefore, transfer of energy to higher frequencies due to triad nonlinear wave interaction is more distinct at this region. Despite lower significant wave height at pass-stations compared with shelf-stations, yet the shallower depth at inlet location increases the Ursell number and bi-phase is decreased (Fig. 2.8). The only exception is Barataria Pass in which the water depth is greater than other passes by more than one order of magnitude. Therefore, the denominator in Eq. 6 is two to three orders of magnitude greater than the numerator resulting in formation of symmetrical wave at I-2 station.

Inside the inlet, $T_p$ is reduced up to four times, that characterizes locally generated waves on the bay side (Fig. 2.7e3). Here the contribution of three-wave interaction is minimal since low $H_s$ and $T_p$ forces small Ursell number. Therefore, wave is symmetric and $\beta \rightarrow 0$. Referring to Table 2.2, the maximum value of $T_p$ at Bay Long and Bastian Bay (Stations I-5B and I-6B) is much less than their counterparts at other passes, indicating that almost no wave from Gulf of Mexico can enter the Barataria Basin through these two passes. The geometry of Bay Long Pass has a major effect on preventing waves to enter Bay Long. On one hand, extension of the Barrier Island on the east of this pass blocks the more frequent waves from east to south direction and on the other hand, the mostly-dry wetlands on the north between Bay Long and Bay Ronquille (height of about 0.5 m above NAVD88) obstructs the waves from N and NW direction. Therefore, only small amplitude waves with high frequency are formed in this bay. Similarly, the I-6B station is also surrounded by shallow water with the average depth of about 0.25 m. Therefore, most of the wave from continental shelf is dissipated due to bottom friction and depth-induced breaking before reaching I-6B station.
2.5.3.2 Relationship between wind- and mean-wave-direction

The statistical relation between wind- and mean-wave-direction varies from coast to inside the bay at each pass. Fig. 2.9 provides the analysis for Barataria Pass and Quatre Bayou Pass as well as their shelf and bay sides. At the continental-shelf-stations the wave direction has a concentrated range. Examining all the waves for these stations (Fig. 2.9a1 and Fig. 2.9a4),
when winds are from 0° to 180° (wind and wave direction is to, zero is due east, counterclockwise), waves are mostly centered on a constant direction aligned with coastline orientation (130 and 105 for Barataria Pass and Quatre Bayou Pass, respectively). These near-coastline waves are not locally generated but rather depend on a large scale wind and wave in deep Gulf of Mexico. When wind is from 180° to 360°, i.e. relatively rare northerly wind, majority of waves are still refracted ones scattered around a constant wave direction. Nonetheless, in a number of instances local wind waves are predicted whose direction is linearly correlated to the wind direction.

Fig. 2.9a1 and Fig. 2.9a4 displays that locally generated wind waves are mostly observed when northerly winds are moderately strong between 5-8 m/s. Stronger waves, mainly from southern sector, has induced agitation wide range of mean wave direction in I2-S station. This could be due to current-induced wave refraction governed by circulation at Louisiana Bight, alongshore westward current and jet from Barataria Pass (section 2.5.1).

The wave field on the bay side (Fig. 2.9a3 and Fig. 2.9a6) follows a pattern akin to the wave field inside Barataria Basin (Fig. 2.6f1) with more pronounced linear relation between wind and wave directions, representing local seas. The metrics at bay side stations are superior to shelf-side stations as wind and wave direction does not obey a linear relationship at open coast (Fig. 2.10). Despite dominance of wind wave on the bay side, there still exist some swells in which waves are aligned with overall coastline orientation (Fig. 2.9a3), which will also be discussed in section 2.5.4.

Pass-stations are a transition zone between shelf- and bay-stations (Fig. 2.9a, middle column). Therefore, both wind-sea and swells from Gulf of Mexico are observed. Nevertheless,
comparing Quatre Bayou Pass vs. Barataria Pass, the scatter plot shows more contribution of wind seas in the former pass.

Fig. 2.9. Statistical analysis of wind vs. wave direction at continental shelf, tidal inlet and bay side for stations I-2 and I-4: (a1) to (a6) considering all the waves (b1) to (b6) considering large waves (≥ 0.5 m for the shelf-station and ≥ for inlet- and bay-station). The colorbar for (a1) to (a6) figures represent wind speed (m/s) and the one for (b1) to (b6) represent peak wave period (s).
Fig. 2.10. The numerical model metrics between wind- and mean-wave-direction for bay-, pass-, and shelf-stations corresponding six major inlets of Barataria Basin for three-month simulation, cold front passage and persistent SE event.
In order to investigate similar directional relationship between wind and wave direction for larger waves, a threshold was applied to filter out the small waves (Fig. 2.9b1 to Fig. 2.9b6). This threshold was considered as 0.1 m for pass- and bay-stations. In shelf side stations, since waves are much larger, the threshold was raised to 0.5 m. In coastal stations, the wave pattern becomes swell dominated (Fig. 2.9b1 and Fig. 2.9b4). On a contrary, Fig. 2.9b3 and Fig. 2.9b6 shows that model skill improve and linear relationship between wind and wave direction is enhanced. The CCC and IA in Bay Ranquille increase from 0.74 and 0.84 to 0.89 and 0.92, from all waves to large waves, respectively. MAE and SI in this pass are also reduced from 31.33 and 0.43 to 19.16 and 0.24, respectively. Similar amelioration is also observed for other inlets. Therefore, large waves more clearly follow the local wind that describes causality of wave on the bay side. The horizontal distribution of mean wave direction for large waves in I-2 emphasizes the more presence of swells at this pass (Fig. 2.9b2). On a contrary, larger waves at shallower Quatre Bayou Pass tend to establish a linear relationship similar to the bay side station (Fig. 2.9b5).

Fig. 2.9b1 and Fig. 2.9b4 also demonstrate that the direction of short-period waves are more correlated with the wind direction. Differently, for the waves with a period of larger than 5 s, wind direction shows an independency from wind direction attesting that these waves are not generated by ambient wind force. The results show a number of waves with a period of greater than 6 s inside Barataria Bay after Barataria Pass (Fig. 2.9b3). Such waves occur when wind direction is also southeast to south. Considering the lack of fetch on the bay side of the inlet, they are probably the swells entering the bay when wind direction is aligned with channel direction.
2.5.4 Wave characteristics under cold-front and persistent southeasterly-wind events

2.5.4.1 Wave characteristics during cold-front (CF) event

The wave spectral analysis in the inlets confirms wave energy dissipation right after the inlets. Fig. 2.11 illustrates time series of variance density spectra for a point on the continental shelf (CSI-09), one station inside Barataria Bay (BB), and two inlet locations at pass, shelf and bay region. In addition, three time instances associated with more energetic moments are singled out for which energy spectra is plotted for each station. The spectral analysis for all stations signify that peaks in wave spectra reside in three categories: \( f_1 = 0.1 – 0.125 \, \text{Hz} \) \( (T_p = 8 – 10 \, \text{s}) \), \( f_2 = 0.25 – 0.33 \, \text{Hz} \) \( (T_p = 3 – 4 \, \text{s}) \), and \( f_3 = 0.4 – 0.67 \, \text{Hz} \) (i.e. \( T_p = 1.5 – 2.5 \, \text{s} \) common inside Barataria Basin). These ranges are shaded in Fig. 2.11.

The wave spectra in open coast (Fig. 2.11a) and in the interior of Barataria Basin (Fig. 2.11b) are single-peaked ones, though the maximum frequency and peak energy is different in magnitude and corresponding frequency category. During extratropical storm event, the wave field in the continental shelf usually has a single peak at \( f_1 \) as could be seen for CSI-09 station in Fig. 2.11. Occasionally, a double-peaked spectrum is also perceived during this event as illustrated in time instance A in Fig. 2.11. Inside Barataria Basin the maximum peak period resides in \( f_3 \) range for the whole simulation time as depicted for BB station in Fig. 2.11.

The spectral density for the stations at the shelf side of the inlets are in the same order of magnitude as the one for CSI-09 station, though the magnitude is decreased due to wave energy dissipation from nearshore processes. In addition to the dominant frequency in \( f_1 \) category, a secondary peak frequency is also perceived. This demonstrates that even though shelf side of the inlets are determined by waves from continental shelf, yet still a small influence from wind seas exist in this region (Fig. 2.11c1 and Fig. 2.11d1).
Fig. 2.11. Left Panel: Time series of variance density spectra for CSI-09, BB, I-2S, I-2, I-2B, I-4S, I-4 and I4-B stations during CF event. Three time instances are selected as A, B, and C. Right Panel: Variance Density Spectra for time instances A, B, and C. Shaded areas pertain to $f_1 = 0.1-0.125$ Hz (grey), $f_2 = 0.25-0.33$ Hz (light green), and $f_3 = 0.4-0.67$ Hz (light blue).
The wave spectral energy drops by an order of magnitude at inlet locations compared with shelf-stations signifying significant energy dissipation in tidal inlets as presented in Fig. 2.11c2 and Fig. 2.11d2. The dual-peak shape in wave spectra is widely seen in pass-stations (Fig. 2.11c2). The magnitude of the energy corresponding \( f_3 \) category becomes as large as or even larger than the spectral density at other two categories (e.g. time instance A in Fig. 2.11c2). Therefore, the influence of local seas is increased at the passes.

The energy dissipation at the inlets in the I-4 pass is found to be greater in magnitude compared to I-2 station, presumably due to shallower depth in these inlets. Fig. 2.11 displays that although the spectral energy in I-4S is larger than the one at I-2S. The wave peak spectral energy in I-4 is about one fourth of the one in I-2 station.

Further reduction in peak spectral density is seen in bay-stations compared to pass-stations alluding to continued energy dissipation inside the inlets. However, the magnitude of peak spectral density is in the same order as the pass-station. Only in I-1B station (not shown here) this magnitude is reduced by an order of magnitude compared to the station at Caminada Pass, indicating the highest energy reduction among the passes.

The main peak frequency in bay side stations is shifted to \( f_3 \), similar to BB station, attesting the dominance of locally generated wind-waves right after the inlets. Nonetheless, in I-2B station during cold front passage a secondary peak at \( f_1 \) range is also seen (Fig. 2.11c3). The double peak pattern in wave spectra confirms that some swells from continental shelf can penetrate through this inlet due to its larger depth. The double-peak pattern is rarely seen in I-1B and I-3B stations as well. The range of spectral density in bay-stations is smaller compared to BB station further inside Barataria Bay, showing that local seas are relatively less developed on the bay-stations.
In general, the statistical measures of wind- vs. mean-wave-direction improved during cold front passage compared with the whole simulation time, denoting the locally generated wind-waves during this event (Fig. 2.10). Nonetheless, the model skills are still lower than the one for BB station inside Barataria Bay (Fig. 2.5f2). Contrastingly, The CCC magnitude in I-1S, I-1 and I-2 stations for CF event is less than the one for three-month simulation, which opposite to the trend in CC, MAE and IA parameters and also in other stations that is hard to explain.

2.5.4.2 Wave characteristics during persistent South-East (SE) event

Similar to the spectral analysis performed for CF event, the spectral analysis proves a single-peaked spectra for CSI-09 station (Fig. 2.12a). The maximum frequency in SE event, per contra, pertains to $f_2$ range. Comparing Fig. 2.11 and Fig. 2.12, the maximum spectral density pertinent to peak frequency is also an order of magnitude smaller than that of CF event denoting comparatively less energetic SE event.

The spectral density of the shelf-stations is on par with CSI-09 (Fig. 2.12c1 and Fig. 2.12d1). However, it is at least one order of magnitude smaller at the passes due to bottom friction and wave current interaction (Fig. 2.12c2 and Fig. 2.12d2). Similar to the discussion pertaining CF event, the rate of energy dissipation is larger in I-4 station compared to I-2. The concurrent contribution of local seas and swell especially in pass-stations is manifested through double-peak spectra with maximum frequencies at $f_2$ and $f_3$.

The peak spectral energy in bay-stations falls in the same category as BB station (Fig. 2.12c3 and Fig. 2.12d3 vs. Fig. 2.12b), attesting the growth of waves due to local wind. Alike the case of CF event, the double-peak shape is also predicted at some instances for I-2B station alluding to penetration of waves with characteristic peak frequency at $f_2$. Notwithstanding, the
The magnitude of maximum density spectra is larger in BB station, showing more wave development as we move further inside Barataria Bay.

Fig. 2.12. Left Panel: Time series of variance density spectra for CSI-09, BB, I-2S, I-2, I-2B, I-4S, I-4 and I4-B stations during SE event. Three time instances are selected as A, B, and C. Right Panel: Variance Density Spectra for time instances A, B, and C. Shaded areas pertain to $f_1 = 0.1-0.125$ Hz (grey), $f_2 = 0.25-0.33$ Hz (light green), and $f_3 = 0.4-0.67$ Hz (light blue).
2.5.5 Effect of wave-current interaction on wave field in front of inlets

Owing to geometrical restriction, current and wave direction at the inlet location are in line with each other where wave blocking/stretching is amplified. Fig. 2.13 depicts the difference between ocean surface current and mean wave direction for Barataria Pass and Bay Long Pass. The 0º and 180º of difference indicate following and opposing current, respectively. The analysis for other inlets follows the pattern as for Bay Long Pass. Fig. 2.13 demonstrates that opposing/following current is more pronounced at inlet-stations. In shelf side, such a pattern is weaker particularly up to first week of May when cold front passages prevail. The pattern is more scattered at I-2B and I-5B indicating less influence of ambient current on changing the wave height on the basin side (Fig. 2.13c and Fig. 2.13f). The analysis shows less scatter in Barataria Pass (Fig. 2.13 left panels) compared with Bay Long Pass (and other inlets though not shown here). This could be because of the stronger current at this pass. The surface current in Barataria Pass can reach 1.34 m/s, which is 72, 73, 36 and 93% larger than the modeled maximum surface current speed at Pass Abel, Quatre Bayou Pass, Bay Long Pass, and Grand Bayou Pass, respectively.

![Fig. 2.13. The difference between ocean surface current and mean wave direction at Barataria Pass and Bay Long Pass and their corresponding bay and shelf side stations.](image)
The contribution of water surface elevation and ocean surface current on changing the wave field can also be observed through contrasting the numerical model results between WO and WC cases. The significant wave height in WO case is smoother than the one in WC case. Further, the significant wave height in WO case is sometimes larger than the one in WC case. In shelf- and pass-stations, the major deviation in significant wave height between WC and WO cases occur at pre-frontal stage with moderate to large wind speed ($\geq 8$ m/s) from southerly quadrants associated with low tidal elevation (Fig. 2.14c1 and Fig. 2.14c2). On the shelf side, the difference in wave height is mainly due to the dynamics in Louisiana Bight as discussed in section 2.5.1. In the pass- and bay-stations, a confluence of propagation of smaller wave height from shelf side as well as additional water level and current in the coupled system is responsible for this discrepancy. Given a fixed breaking parameter according to Battjes and Janssen formulation (1985) ($\gamma = H_{\text{max}} / d$, in which $H_{\text{max}}$ is the maximum possible individual wave height and $d$ is the water depth), the lower water level during ebb tide would culminate in lower upper bound of maximum significant wave height.

The wave blocking/stretching phenomena can also be detected from instantaneous numerical model results as displayed in Fig. 2.15. During the flood period, the current direction aligned with wave direction stretches the wave length and therefore reduces the wave height on both sea side and basin side of Barataria Pass (Fig. 2.15b3). The model predicts a 15% decrease of significant wave height at following current that is close to the result from Smith et al. (2015) for Wallipa entrance channel (20%). However, during ebb period when the direction of jet is opposite to the prevalent wave direction, the blocking effect of opposing current is manifested in local enhancement of significant wave height about two kilometers offshore (blue zone in Fig. 2.15a3) followed by a rapid reduction of $H_s$ from I-2S to I-2 stations. Such pattern of onshore
decay in wave height is in conformity with findings of Chen et al. (2015). The numerical model predicts a 20% of increase in significant wave height that is less than the one predicted by Smith et al. (2000) (80%) but the same as the simulation results of Dodet et al. (2013) for Albufeira lagoonal inlet.

Fig. 2.14. Numerical model timeseries results and statistical analysis for stations I-1 and I-2: (a) wind stick plots at I-2 station, (b1) to (b3) depth-averaged current magnitude (solid black) and water surface elevation (solid grey), (c1) to (c4) significant wave height for WO (grey) and WC (black) cases, (d1) to (d4) mean wave direction for WO (grey) and WC (black) cases.
Aside from jet direction, direction and magnitude of local wind governs the pattern of wave-current interaction as well. For instance, though the time instance in Fig. 2.15c3 is associated with an ebb time, relatively strong northwest wind generates waves that are in the same direction as the jet flow and the resultant wave height on the sea side of the inlet reduces due to Doppler shift effect.

Fig. 2.15. (a1), (b1) and (c1): (color) snapshots of modeled water surface elevation at three time instances during ebb and flood around Barataria Pass. Small arrows illustrate direction and magnitude of ocean surface current. Thick white arrows denote direction and magnitude of wind speed for a representative point in vicinity of Barataria Pass at each time instance. The location of representative stations at Barataria Pass is illustrated in red dots. (a2), (b2), (c2): significant wave height and mean wave direction at each time instance pertaining WO case. (a3), (b3) and (c3): difference of significant wave height for WC case from that of WO case. Arrows denote mean wave direction for WC case.
The mean wave direction calculated from WC case is sometimes clearly different from the one predicted by WO case, especially in shelf-stations (Fig. 2.14d1). Such pattern can also be detected comparing modeled instantaneous mean wave direction for WO and WC simulations (Fig. 2.15, second and third row in front of the Barataria Pass). Current-induced wave refraction as a result of larger velocity in the main channel compared to adjacent shallower regions dictate such a deviation.

The dynamics of wave-current interaction is somewhat different in inlets other than Barataria Pass as the jet velocity diminishes in those passes and wave-current interaction plays a less important role. In shallower inlets, the significant wave height becomes more sensitive to variation in water surface elevation as depth-induced breaking plays a major role consistent with Kang and Di Iorio (2006) and Olabarrieta et al., (2011). In Caminada Pass, absence of a strong jet, obstruction of the east-to-west alongcoast current because of jet flow from Barataria Pass (See Fig. 2.4) and shallow depth resulted in abrupt change in significant wave height commensurate to local water depth (Fig. 2.14c4). Thus $H_s$ for WC case at tidal and subtidal peaks surpasses the one simulated by WO case.

2.6 Summary and conclusion

In this study, the wave dynamics and wave-current interaction for six major inlets connecting the Barataria Bay with Gulf of Mexico was investigated with a three-dimensional, wave-current coupled, wetting-drying activated model. The study was carried out for a three-month period in the late-spring and summer time period to include both cold front and persistent southeasterly winds common in northern Gulf of Mexico and the Louisiana Bight. The numerical
wave model was validated against observed data at five offshore stations and one coastal station, where the wave parameters in the region were successfully reproduced.

The validated model is used to address the causality of wave at each inlet and their shelf and bay side. The detailed spectral analysis and statistical evaluation of wind- vs. wave-direction demonstrate that the wave field on the bay side of the inlets is strongly dependent on the local wind intensity and direction. In contrast, the shelf side of the inlets is influenced by swells from the Gulf of Mexico. At the inlet, the contribution of both local seas and swells are perceived. In Barataria Pass due to its deeper depth, the effect of swell from Gulf of Mexico is more pronounced, while the shallow inlets on the east of Barataria Pass are more governed by locally generated waves.

The wind-driven nature of significant wave height is enhanced during cold front events with an increase in scores of wind- vs. wave-height. This result is attributed to rapidly-varying circulation inside Louisiana Bight during this event preventing distant waves to effectively approach coastline. Differently, the contribution of swells is boosted during southeasterly wind event.

All of the inlets effectively dissipate the wave energy as the wave spectral density dwindles by one order of magnitude from the shelf-side to the inlet location. The model predicts larger magnitude of wave spectral density during cold front (CF) event compared with persistent southeasterly (SE) wind event. Therefore, CF event is clearly revealed as a more energetic event. The peak frequency in CF event also corresponded to larger peak period.

The circulation pattern inside Louisiana Bight controlled by water level forcing, wind forcing, buoyancy- and wind-driven alongshore current and the Mississippi River plume affects the wave field inside the bight and in front of the inlets. As a result, current-induced refraction
and overall wave reduction in fully coupled system is noticed compared with wave-only simulation.

Both strong jet velocity and local wind direction impact the wave at the mouth of Barataria Pass through wave steepening and partial wave blocking during opposing current and decrease in wave height during following current. The opposing current could increase the wave height by about 20% during ebb flow, and the following current could decrease the wave height on sea side of Barataria Pass by up to 15%. The potential and jet flow at Barataria Pass blocks the westward movement of the alongshore current, reducing the effect of this current at Caminada Pass.

At inlets other than Barataria Pass, the wave field is more affected by bottom friction and depth-induced breaking rather than wave-current interaction. The redistribution of wave energy due to triad wave interaction is also more pronounced in these inlets compared with Barataria Pass, particularly during extreme wave events.
CHAPTER 3. UNSTRUCTURED GRID SPECTRAL WAVE MODELING DURING SPRING-SUMMER TIME IN A SHALLOW ESTUARY: THE BARATARIA BASIN

3.1 Introduction

Estuaries and wetlands constitute invaluable coastal environments for marine organisms and ecosystems. Wetlands in Coastal Louisiana, formed by Mississippi River Delta and its lobe-switching over the centuries, are considered as the seventh largest in the world (Couvillion et al., 2011). These wetlands worth more than 3 billion per year for US seafood industry (Restore the Mississippi Delta Coalition, 2012) and provide protection for infrastructures that supply 90% of the nation’s outer continental oil and gas and 20% of the nation’s annual waterborne commerce (Coastal Protection and Restoration Authority of Louisiana, 2017; Siverd et al, 2018). In addition, they act as a buffer zone to protect coastal Louisiana against hurricane damages.

However, wetland loss in coastal estuaries and bays has emerged as a major threat to the environment, ecology, and economy of the State of Louisiana and United States at large. Though Louisiana estuarine wetlands constitute 40% of the wetlands in the United States, it suffers from 80% of the wetland losses in the whole country (USGS, 2018). This land loss is caused by combined influence of sea level rise, subsidence, man-made levees that isolate riverine sediment input, and ocean waves.

Specifically, wave action is considered to be one of the prime causes of marsh edge erosion. It has been estimated that 26% of the wetland loss in Mississippi River Delta is caused by the wave-induced erosion (Penland, 2000). Wind waves in estuaries also contribute to bottom sediment resuspension (Hoffmann et al., 2011, Sorourian et al., 2017), establishment and survival of submerged aquatic vegetation (Chen et al., 2005), and change in behavior and distribution of benthic organisms and fish communities (Stoll et al., 2010).
Wave exposure, defined as frequency of occurrence of wind waves with heights above a certain threshold value (e.g. 0.15 m in Seibt et al., 2013), is used to estimate the potential for edge erosion (Hoffmann et al., 2011), release of pore-water constituents (Precht and Huettel, 2003), fluxes of nutrients to the shoreline, and adaptation of species to wave-induced disturbance (Lindegarth, 2007).

A number of observational, theoretical and modeling studies have tackled wave dynamics in estuarine and wetland environments. Agustin et al. (2009) employed laboratory measurement and Boussinesq-based wave model to investigate wave propagation and attenuation over shallow wetlands. Pratolongo et al. (2010) studied the wave dynamics on marshes and mudflats using field measurement. Lambrechts et al. (2010) incorporated a three-year field data and numerical modeling to address wave-induced liquefaction of the fine sediment under small waves in mudflats and estuaries. Some studies have utilized remote-sensing techniques such as high-frequency radar (Howarth et al., 2007; Siddons et al., 2009), X-band radar (van der Westhuysen et al., 2012) and synthetic aperture radar (SAR) (Gommenginger et al., 2010) to obtain wave spectra in shallow water and tidal inlets. Despite the aforementioned studies, long-term measurements of sea state in estuaries are scant. Thus, numerical modeling can be employed as a valuable alternative for wave field assessment and prediction, as well as estuarine resource management.

In shallow water regions, two types of wave model are available to evaluate wave action: phase-resolving and phase-averaging (spectral) models. Phase-resolving models are computationally expensive for large domains. Phase-averaging models, though losing phase information of waves, are more computationally efficient in medium- and large-scale domains (Siadatmousavi et al., 2012a; Allahdadi et al., 2017). Significant improvement has been applied
to the spectral models, enabling their application to complex coastal geometries (e.g. Chen et al., 2005; Banijamali et al., 2009; van der Westhuysen et al., 2012; Seibt et al., 2013; Dodet et al., 2013; Allahdadi et al., 2018). Among the spectral action-balanced models, Simulating WAve Nearshore (SWAN) model (Booij et al., 1999) has been used widely for both deep and shallow water applications. In shallow water region, SWAN has been employed to model wave field in lakes (Seibt et al., 2013), bays (Alari et al., 2008), tidal inlets (van der Westhuysen et al., 2012; Dodet et al., 2013) and estuaries (Chen et al., 2005). This research seeks to investigate the wave action in the Barataria Basin, a bar-built estuary in Coastal Louisiana, employing a SWAN-based phase-averaged wave model.

The motivation to select the Barataria Basin is because it is one of the largest estuaries in Mississippi River Delta and is comprised of several smaller lakes and bays. Alteration of circulation, wave, and morphology of this basin as a result of the construction of remedial projects such as river diversions, designed to mitigate the land loss issue and restore estuarine wetlands, necessitates thorough hydrodynamic, wave and morphodynamic studies.

The present study focuses on a three-month period from April to June 2010. This period includes two typical types of wind events in Gulf of Mexico, namely, cold front passage (also called extratropical storm) events that occurred in April 2010, and persistent southeasterly wind events that happened during June 2010. Nonetheless, the wind stress exerted by extratropical storms in the month of April is relatively weaker than the ones prevalent in the winter season.

Barataria Basin suffered from highest rate of land loss in the Grande Cheniere and Bay Regions, amassing nearly 23.1 km\(^2\) between 1974 and 1990 (LaCoast, 2002). The total land loss from 1932 to 2010 in this estuarine system has been 1092 km\(^2\) (Couvillion et al., 2011). In addition to land loss inside the basin, Barataria Basin is also prone to land loss in its defending
chain of barrier islands. The total area in main barrier islands, i.e. West Grand Terre, East Grand Terre, Grand Pierre, and Cheniere Ronquille have diminished from 7.28 km$^2$ in 1990 to 4.04 km$^2$ in 2015 and is expected to shrink to 1.62 km$^2$ by 2045 (LaCoast, 2002). Both land losses will expose the Barataria Basin to even larger waves because in one hand, erosion of barrier islands will allow stronger waves from Gulf of Mexico to enter the Barataria Basin, and on the other hand, land loss inside Barataria Basin results in larger fetch and, thus, larger wind-generated waves. Therefore, proper understanding of wave dynamics within the Barataria Basin and at its tidal inlets would be imperative to gain insight to and further mitigate the land loss problem in this estuarine system.

Numerous numerical studies have been launched to address the hydrodynamics and ocean processes in Northern Gulf of Mexico and Barataria Bay as reviews by Justic et al. (2007). These modeling studies range from simple prism models (Das et al., 2009) to more complicated two- (e.g. Das et al., 2012) or three-dimensional models (Chen et al., 1997; Li et al., 2011; Xu et al., 2011; Chaichitehrani, 2018). Although numerous hydrodynamic and nutrient modeling studies have embarked on and applied on the continental shelf and shallow water regions, but modeling research on wave dynamics in the Louisiana coastal bays are scant. Liu (2016) performed a coupled hydrodynamic and wave modeling to address storm surge, wave dynamics and sediment transport in Terrebonne and Barataria basins during Hurricane Gustav. Everett (2016) employed numerical model to address wind waves in Terrebonne Bay. However, a comprehensive wave modeling study for Barataria Basin, especially during cold front is yet to be done.

Present chapter aims at investigating causality between wind and wave and relative contribution of seas and swells inside the Barataria Estuary as well as at its tidal inlets. The paper
is organized as follows: Section 3.2 introduces the study area. Section 3.3 describes the numerical modeling system for waves and hydrodynamics, and the coupling method between the two components. The model validation is treated in section 3.4. Section 3.5 presents the model results and discussions. Specifically, two distinct events, namely, cold front passage and persistent southeasterly wind are described and wave dynamics contrasted; contributions of tidal elevation, ocean surface current, and riverine water discharge on the wave field are assessed by comparing the result of a wave-only model with that of a fully coupled hydrodynamic-wave model; wave exposure along the edges of major water bodies inside the Barataria Basin is calculated and erosion potential discussed. Finally, major findings of this study are summarized in section 3.6.

3.2 Study area

The study area, the Barataria Basin, is located in the northern Gulf of Mexico, bounded by the gulf in the south, Bayou Lafourche in the west, and the Mississippi River in the east (Fig. 3.2). The basin is approximately 100 km long, with a width ranging from 40 to 55 km. The basin is approximately 6300 km$^2$, of which 1380 km$^2$ (22%) are leveed or developed areas (LaCoast, 2002). This estuary was formed about 2000 years ago as a result of Mississippi Deltaic lobe switching (Rejmanek et al., 1987). The Gulf Intracoastal Waterway (GIWW) passes through the Barataria Basin and divides it into two groups of water body: the northern part includes Lake Salvador, Lake Cataouatche, and Lac des Allemands; and the southern part consists of Barataria Bay, Little Lake, and Caminada Bay (Fig. 3.2a). The estuarine system is connected to the Gulf of Mexico through a number of tidal inlets. Four major inlets, i.e. Caminada Pass, Barataria Pass, Pass Abel and Quatre Bayou Pass are singled out and depicted in Fig. 3.2b that will be further analyzed in this study.
Fig. 3.1 (a) Computational domain and bathymetry for hydrodynamic-wave modeling of Louisiana-Texas (LATEX) Continental Shelf and Barataria Estuarine Basin, and location of wave data (NDBC: National Data Buoy Center, CSI: Coastal Studies Institute), (b) Annual wind-rose in year 2010 for ST. 42040, (c) wind rose from April to June 2010 for ST. 42040.

The water depth in the model domain varies from above NAVD88 in wetlands to more than 1000 meters offshore. In the estuaries, the areas with elevation above mean sea level is included in the numerical mesh that is subject to periodic inundation due to water level oscillations. Such wetlands in Barataria Basin is depicted in Fig. 3.2 as magenta regions.

The annually averaged wind rose for National Data Buoy Center (NDBC) Station 42040 (https://www.ndbc.noaa.gov/) is presented in Fig. 3.1b signifying two major winds: one is winds from east and southeast sectors that prevail in the summer time, and the other northerly winds that are more frequent in fall and winter (October to April) due to cold front passages (Chuang
and Wiseman, 1983). The wind-rose corresponding the simulation time is displayed in Fig. 3.1c highlighting more frequent winds from southeast sector.

Fig. 3.2. (a) Major water bodies inside Barataria Basin along with six stations inside the estuarine system for numerical analysis, (b) name and location of main tidal inlets connecting Barataria Basin and the Gulf of Mexico.
The wave regime over the continental shelf of northern Gulf of Mexico is characterized by relatively small wave action. The analysis of significant wave height ($H_s$) and peak wave period ($T_p$) for NDBC Station 42040 from 1995 to 2017 yields $0.99 \pm 0.71$ m and $5.64 \pm 1.55$ s, respectively. However, wave parameters increase in extreme events, such as tropical storms, hurricanes, and cold front passages, which contribute to mobilization of large amount of sediments. The maximum value of NDBC-based $H_s$ and $T_p$ for the same 23 years of data and for the same station amounts $16.91$ m and $23.55$ s, respectively. Significant wave height during cold front passage in the continental shelf can reach 2-3 m inducing large energy in such a shallow water basin (Dingler et al., 1993).

The study of wind wave inside the Barataria Basin is scant and indirect. Booth et al. (2000) reported that waves generated by winds as low as 4 m/s were able to resuspend approximately 50% of bottom sediments. Such winds are present about more than 60% of the time between May to June 2010 or 75% for the whole year.

The tide in the Barataria Basin is small amplitude diurnal one with dominant $K_1$ and $O_1$ constituents, each with a range of about 0.15 m (reference). The total tidal range in the basin decreases from about 0.4 m in the barrier islands to 0.3 m in northern Barataria Bay and further attenuates as we move towards the northern water bodies. (Wright et al., 1997; DiMarco and Reid, 1998).

Apart from precipitation, water enters Barataria Basin from the Davis Pond Freshwater Diversion, stream runoff, GIWW and small amount of riverine input through the Naomi and West Pointe a la Hache siphons (LaCoast, 2002). In particular, the Davis Pond Diversion, located at the west bank of the Mississippi River in St. Charles Parish has been designed to usher sediment and nutrient-rich Mississippi River water into Lake Cataouatche to enrich the marshes,
lessen salt-water intrusion, and restore the ecological conditions in the northern Barataria Basin. Davis Pond Diversion, with a designed maximum discharge of 283.2 m$^3$/s (CoastalLA, 2018), is the only source of discharge inside the Barataria Basin that was considered in this study.

3.3 FVCOM hydrodynamic model

3.3.1 FVCOM hydrodynamic model

The hydrodynamic model used is the Finite Volume Community Ocean Model (FVCOM), which is an unstructured grid, finite volume, three-dimensional (3-D) primitive equation coastal ocean model, developed by Chen et al. (2007, 2013). FVCOM solves the continuity and momentum equations in their integral form to obtain fluxes over non-overlapping unstructured triangular grids that ensures conservation of mass both over the whole computational domain and on individual meshes. Either explicit mode-split or semi-implicit time stepping schemes can be selected. The finite volume method used combines the advantages of both finite difference methods for simple code structure and computational efficiency and finite-element methods for geometric flexibility.

3.3.2 FVCOM-SWAVE wave model

Similar to SWAN, FVCOM-SWAVE determines the evolution of wave spectra in time, geographical, and spectral spaces using balance of wave action density $N (= E/\sigma$, where $E$ is the variance density and $\sigma$ the intrinsic angular frequency). The reason of preferring $N$ is based on Bretherton and Garrett (1968), who showed that for linear waves on non-dispersive environment, wave action moving with group velocity is conserved in presence of ambient current. The wave action density spectrum balance equation derived and improved by Mei (1983), Christoffersen and Jonsson (1980) and Cristoffersen (1982) is the same as the one expressed in Chapter 2.
The wave action density in the SWAVE model is solved by four integral steps: the change of wave action density in spectral space, i.e. frequency and direction, the wave propagation in geographic space, and generation, transformation and decay of waves. The variation of action density in spectral space is solved by Flux Corrected Transport method (Boris and Book, 1973; Hsu et al., 2005) and the Crank and Nicolson method (Crank and Nicolson, 1947) for frequency and direction, respectively. For propagation of wave action density in geographic space, two options are available: explicit finite-volume upwind advection scheme and semi-implicit finite-volume upwind advection scheme. The growth, propagation and decay of wave energy by source/sink terms are numerically solved by semi-implicit integration scheme. Details of discretization of the wave action density equations are discussed in Qi et al. (2009).

3.3.3 Model coupling

The coupling of hydrodynamic, wave and sediment transport model for FVCOM is approached through radiation stress, bottom boundary layer, surface stress and morphology (Wu et al., 2011). In the circulation model, three-dimensional radiation stress is implemented in momentum equations to incorporate wave-driven motions and wave set-up. The bottom boundary layer (BBL) model works under wave-current-sediment interaction and follows the method developed by Warner et al. (2008). Three BBL models are available: the Styles and Glenn BBL model (SG_BBL), the Meinte Blaas BBL closure (MB_BBL) and the Sherwood/Signell/Warner BBL closure (SSW_BBL). In this study, SSW_BBL was incorporated. At sea surface, the roughness from wind speed is calculated from Donelan (1993). As for wave-current interaction, the depth-averaged current is calculated and weighted by wave parameters (Mellor, 2008). Regarding morphology, the morphological change is treated by equating the
bottom-boundary condition of the vertical velocity to the rate of change of elevation of the sea floor, which guarantees the mass conservation (Wu et al., 2011).

The hydrodynamic and wave models communicate and exchange information at each wave time-step to maximize the accuracy of wave-induced set-up calculation. Upon initialization, SWAVE calculates N first, then wave parameters, namely, significant wave height ($H_s$), peak wave period ($T_p$), mean wave direction, average wave-length, and bottom wave orbital velocity. Further, wave radiation stress (Mellor, 2008) is calculated and passed to the hydrodynamic model. In the next step, the ocean model utilizes the information received from wave model to compute current field and surface elevation. Finally, the wave model is run with feedback of current and surface elevation to calculate the wave field in the next time step (Wu et al., 2011).

3.3.4 Model setup

The model domain covers most of the Alabama-Mississippi-Louisiana-Texas (LATEX) Continental Shelf, which stretches from Mobile Bay in the east to Galveston Bay in the west (Fig. 3.1). Additionally, shallow water estuarine systems are incorporated dedicating high horizontal resolution to Barataria estuarine system.

The mesh grid for the simulation is comprised of 143546 and 278399 nodes and elements, respectively. The spatial resolution of the mesh grid varies between 8 km in the offshore to 15 m in the shallow bay area and inside small channels to ensure capturing wave and hydrodynamics details in both deep and shallow water.

The simulation starts as a cold-start condition with a ramping period of 10 days for circulation model and no ramping period for the wave model. As for the numerical scheme, the explicit scheme is adopted for both hydrodynamic and wave models. The time steps for
hydrodynamic model are 0.2 and 2 s for external and internal modes, respectively, and the time step for the wave model is 4 s.

All of the forcing at model boundary is considered as spatially and temporally varying. For FVCOM hydrodynamic model, water level variation is applied as a nested output from regional Gulf of Mexico model at the boundary, which is based on the method detailed in Cui (2018). Three rivers are included in the simulation, forcing discharge at every fifteen minutes over nineteen uniformly distributed vertical layers: the Mississippi River and Atchafalaya River that directly open to the continental shelf, and the Davis Pond Diversion, whose discharge is released into northwest of Barataria Basin in Lake Cataouatche. Wind forcing is interpolated from three-hourly North American Regional Reanalysis (NARR) with 0.25° × 0.25° spatial resolution. Wetting and drying treatment of the shallow intertidal zone is taken into account with the threshold of 0.05 m.

Wave boundary forcing parameters, namely $H_s$, $T_p$ and mean wave direction are interpolated as temporally and spatially variables from the 10 arc minute North-East Atlantic WAVEWATCH III (WWIII) spectral model product (Tolman, 1997), and enforced along the open boundary of the numerical model. The convention for wind and wave direction is to, with zero due to east, counterclockwise.

Among the tested cases, the parameters for SWAVE model corresponding the best model fit are as follows:

- Number of wave direction intervals: 36;
- Number of frequency intervals: 44, from 0.05 to 3.0 Hz;
- Quadruplet interaction using DIA formulation with $C_{nl4} = 3\times10^7$, $\lambda = 0.25$;
- Numerical method for Integrating quadruplets: explicit per sweep;
• Wave growth term of Cavaleri and Malanotte (1981) is activated with proportionality coefficient of 0.0015;
• Bottom friction from JONSWAP formulation with \( C_{\text{JON}} = 0.067 \text{ m}^2/\text{s}^3 \) for fully developed sea condition;
• Depth-induced wave breaking, \( \alpha = 1.0, \gamma = 0.73 \);
• Wave growth and whitecapping based on Komen et al. (1984), \( C_{\text{ds}} = 2.36 \times 10^{-5}, \bar{s}_{PM} = \sqrt{3.02 \times 10^{-3}}, p = 4, \delta = 1, q = 1 \);
• Energy transfer from triad wave-wave interaction using Lumped Triad Approximation (LTA) (Eldeberky, 1996) with \( \alpha = 0.10, f_{\text{max,EB}}/f_{\text{m01}} = 5.0 \);
• Limiter for Urshell number and breaking fraction not activated.

It is noted that Siadatmousavi et al. (2012b) recommended the cut-off frequency of 0.5 Hz for wave modeling in the Gulf of Mexico to improve the simulated bulk wave parameters. However, in application of phase-averaged wave models in shallow water region, waves with higher frequencies are anticipated to prevail inside Barataria Basin. Therefore, following some wave modeling studies in shallow water environments (e.g. cut-off frequency of 1.0 Hz in Lin et al., 2002; Moghimi et al., 2005; and 3.0 Hz in Seibt et al., 2013), the maximum frequency of 3.0 Hz is considered to capture high-frequency waves within shallow water bodies in Barataria Basin.

Regarding wave diffraction, the phase-averaged models are unable to capture this mechanism accurately. Yet, following SWAN model, FVCOM-SWAVE incorporates phase-decoupled refraction-diffraction approximation as introduced by Holthuijsen et al., 2003. In spite of that, the recommendation of Westhuysen et al. (2012) is followed to deactivate diffraction option.
Two modeling systems are employed in this study: the first one refers to an online-coupled hydrodynamic and wave model which is stated as WC case further on. Second configuration refers to a simulation with wave-only condition in which only FVCOM-SWAVE model runs. This configuration is called as WO case.

### 3.4 Model validation

The performance of the hydrodynamic model was validated against 19 National Oceanic and Atmospheric Administration (NOAA) and United States Geological Survey (USGS) for water surface elevation. The average Pearson correlation coefficient is 0.91. For a more detailed assessment of hydrodynamic model performance, see Cui (2018).

Five National Data Buoy Center (NDBC) stations and one WAVCIS CSI station are selected to validate the results of numerical model against measured data on the continental shelf (Fig. 3.1). The validation parameters are significant wave height and peak wave period. The validation is performed for the entire simulation time excluding the ramping period. The NDBC stations considered are stations 42035, 42040, 42369, 42370 and 42887 which are located at depths of 15.46, 290.4, 1659.3, 1225.6 and 1849.8 m, respectively. The wave data from first two stations are available hourly while that for the latter three stations are available at 20-min interval during the simulation period. In addition, stations 42369 and 42370 only have data from middle of May to June 30, 2010. The CSI-09 station is one of the coastal stations as a part of the WAVECIS (WAVE-Current-surge Information System) monitoring program (www.wavcis.lsu.edu). The depth of this station is 3.4 m which is the closest to the shoreline as well as to the Barataria Basin among all other stations.

Fig. 3.3 depicts the comparison between numerical model result and field data for both WC and WO simulations. Overall, WO and WC results are quite similar over the continental
shelf and both yield satisfactory prediction of $H_s$ and $T_p$ compared to the observations. Four relatively large wave events occurred during this period of time, in which significant wave height surpassed 2 m at outer continental shelf stations. They are labeled as A, B, C and D in Fig. 3.3.

In the offshore stations pertaining NDBC Buoys 42040 and 42887, the event C is over-predicted. This might be because of the accuracy of the input of wind forcing that is calculated from regional atmospheric models, which are coarse in resolution. Moreover, the improvement of the wind data using remote-sensing techniques from wave images fail to properly incorporate whitecapping of waves, culminating in relatively inaccurate wind forcing. The error in wind input would eventually influence calculation of wave field, even after calibration process (Haghshenas et al., 2018). On the other hand, the events B and C in coastal CSI-09 station are under-predicted might be attributed to larger calibrated whitecapping steepness coefficient, which takes more energy out of the system.
The majority of wave research studies employ typical statistical parameters to quantify the performance of wave models (Alves et al., 2002; Janssen, 2008). In this study, the following parameters are taken into account:

Scoring Index (SI):

$$SI = \frac{1}{n} \sum_{i=1}^{N} \left( \frac{X_{mi} - x_{oi}}{x_{oi}} \right)^2$$

(3)
Relative bias:

\[ RBias = \frac{\sum_{i=1}^{N}(X_{mi} - X_{ol})}{\sum_{i=1}^{N}X_{ol}} \]  

Correlation Coefficient of Willmott (1981):

\[ CC = \frac{\sum_{i=1}^{N}(X_{mi} - \bar{X}_{mi})(X_{ol} - \bar{X}_{ol})}{\sqrt{\sum_{i=1}^{N}(X_{mi} - \bar{X}_{mi})^2 \sum_{i=1}^{N}(X_{ol} - \bar{X}_{ol})^2}} \]

Mean absolute error:

\[ MAE = n^{-1} \sum_{i=1}^{N}|X_{mi} - X_{ol}| \]

The index of agreement as given by (Willmott, 1981; Willmott et al., 2012):

\[ IA81 = 1 - \frac{(X_{mi} - X_{ol})^2}{(|X_{mi} - \bar{X}_{mi}| + |X_{ol} - \bar{X}_{ol}|)^2} \]

\[ IA12 = \begin{cases} 
1 - \frac{\sum_{i=1}^{N}|X_{mi} - X_{ol}|}{2 \sum_{i=1}^{N}|X_{ol} - \bar{X}_{ol}|} & \text{when } \sum_{i=1}^{N}|X_{mi} - X_{ol}| \leq 2 \sum_{i=1}^{N}|X_{ol} - \bar{X}_{ol}| \\
2 \sum_{i=1}^{N}|X_{ol} - \bar{X}_{ol}| - 1 & \text{when } \sum_{i=1}^{N}|X_{mi} - X_{ol}| > 2 \sum_{i=1}^{N}|X_{ol} - \bar{X}_{ol}| 
\end{cases} \]

where \( X_{mi} \) and \( X_{ol} \) denote model and observed data, respectively, and overbars indicate the mean values. It is noted that Willmott et al. (2012) recommended the use of absolute-based model-performance-indices over those based on squared differences. Therefore, here MAE is selected instead of root-mean-squared error (RMSE). In SI calculation, the \( H_s \) values less than 0.3 m are removed from analysis to avoid low signal-to-noise ratio of the measured data in fair-weather condition (Siadatmousavi et al., 2012b). Regarding index of agreement (IA), two indices are available: one the original formula from Willmott (1981) (IA81) and the refined formulation based on Willmott et al. (2012) (IA12). The IA81 is bounded between 0 (no agreement) and 1 (complete agreement). The IA12 version avoids including the variability of \( X_{mi} \) within basis of comparison in the denomination, improving the overall performance and flexibility of this index (Willmott et al., 2012). IA12 is bounded by −1.0 and 1.0. Both of IA parameters are included in
as much as IA81 is more easy to interpret as its upper and lower bound is also used by other skill parameters, while IA12 gives more distinction in some of the analysis due to its wider range.

Statistical errors between observational data and numerical model for Hs and Tp are summarized in Table 3.1. In general, the statistical performance of WO and WC is very similar for the NDBC stations indicating small influence of ocean current on wave parameters. The scores for CC and IA81 for significant wave height in CSI-09 station are superior in WO case compared to WC case that we don’t have a clear explanation for. Such a difference is not observed for peak wave period. The relative bias for NDBC 42035 and CSI-09 for $H_s$ is negative (under estimation), which could be because of large energy extraction due to breaking process in the surfzone. Additionally, the CC score for these two stations are slightly less than other three stations, which is attributed to more dynamic interactions of waves with bathymetry at surfzone. Nevertheless, the RBias score for peak wave period is markedly better for these two stations compared with the other three that are further offshore. The IA and CC scores for $H_s$ parameter are much better than $T_p$ due to sensitivity in measurement of peak wave period. The IA12 scores are smaller than IA81 that is because the range of the former index being double as larger as the one for latter. The refined IA12 formulation does not show a difference among the stations for significant wave height. However, a vivid distinction is seen for this index for peak wave period, providing more agreement in coastal stations compared to the offshore ones. Among the offshore stations, the IA and CR value for peak wave period pertaining NDBC 42887 is very poor. The main reason for such poor evaluation is large scatter in observational data particularly in second half of simulation time as perceived in Fig. 3.3.
3.5 Model results and discussion

3.5.1 Wave field inside the Barataria Basin

Here the results of the wave simulation for WC case for the whole three-month period from April to June 2010 as well as two wave events during this time interval are presented and discussed.

In addition to overall wave field within a three-month time span of simulation, two distinct wave regimes are also considered. One regime is the cold front passage (CF), a typical example occurred from 4/23/2010 to 5/03/2010 (Fig. 3.6a1) characterized by clockwise rotation of wind direction as previously discussed in section 3.5.1. The other regime is a persistent wind blowing from the south to southeast (SE) direction which happened from 6/02/2010 to 6/14/2010. (Fig. 3.6a1)

3.5.1.1 General wave statistics

The results of the numerical model show a rather mild wave regime inside Barataria Basin during present summer-season simulation time. Among the lakes and bays inside the Barataria Basin, six lakes can be distinguished based on their size, depth, connection to navigation channels and inclusion of hydraulic structures such as river diversions. These water bodies are Caminada Bay, Barataria Bay, Little Lake, Lake Salvador, Lake Cataouatche and Lac des Allemands as portrayed in Fig. 3.2.

| Model | Station | Significant Wave Height |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
Fig. 3.4a illustrates the temporal average of significant wave height for each of the major lakes during the whole three month, as well as during the CF and SE events. The model predicts larger waves in Barataria Bay compared to other five lakes owing to its larger size, ample depth and connection to the Gulf of Mexico. In general, significant wave height reduces as we move from south to north of the basin as observed in Fig. 3.4a (top panel) and the spatial-temporal average of $H_s$ that is presented in Fig. 3.5. However, the overall depth and area of the water bodies play an important role as well. In Lake Salvador, owing to its area and total depth and prevalent wind direction (Fig. 3.2), wave heights larger than Lake Cataouatche and Lac des Allemands are developed. In Caminada Bay on the opposite, and in spite of being connected to two major inlets, the average wave height is smaller than the one in its counterparts in south of GIWW due to its shallower depth and shorter accessible fetch (Fig. 3.4a and Fig. 3.5). Even though Little Lake, per contra, is smaller and on average shallower than Lake Salvador, nevertheless the orientation of its main axis is in line with most frequent wind direction. Ergo, its average significant wave height is as large as the one predicted in Lake Salvador.

The temporally averaged peak wave period also follows the pattern of significant wave height with Barataria Bay having the greatest $T_p$ values (Fig. 3.4b). Inside the basin it is mainly less than two seconds. It is also observed that the average peak wave period in the Barataria Pass is much larger than the one in the interior of the basin, pointing to the swells coming from Gulf of Mexico. This fact is further confirmed by examining Fig. 3.4c, where the maximum values of peak wave period is illustrated. The model predicts that waves with large periods penetrate through Barataria Pass, Pass Abel and Quatre Bayou Pass and penetrate ~ 5 km into Barataria Bay. Moreover, some swells from continental shelf can enter Caminada Bay through Barataria Pass.
Fig. 3.4. Pseudocolor plot for: (a) temporally-averaged significant wave height, (b) temporally-averaged mean peak wave period, and (c) maximum peak wave period for major water bodies inside Barataria Basin during three month simulation time (upper panel), CF event (mid-panel) and SE event (lower panel). Wind rose corresponding each simulation time is also presented for each subplot.
During April-June 2010, waves are frequented from southeast sector (Fig. 3.1c). Therefore, in lieu of excessive variability in wind direction, a point in the middle of each of the six major lakes can be considered with sufficient depth and wind fetch to exam the temporal change of wave field in that water body. These representative stations are named as BB-1 to BB-6 corresponding Caminada Bay, Barataria Bay, Little Lake, Lake, Lake Cataouatche and Lac des Allemands, respectively (Fig. 3.2). Their respective depth is 1.21, 2.44, 2.44, 2.74, 2.13 and 1.52 m. Time-series plots of wind vector, vertically averaged ocean current, water surface elevation, significant wave height and peak wave period for Barataria Bay station in south, and Lake Cataouatche station in north of GIWW are presented in Fig. 3.6.

Several cold front events occurred during simulation time as the clockwise rotation of wind direction is perceived in the wind vector plot (Fig. 3.6a1 and Fig. 3.6a2). The passage of extratropical storms initiates large winds conducive to generation of large wind-waves in the basin. Four of such wind events labeled as A, B, C and D in Fig. 3.3 can also be detected in Fig. 3.6. The extratropical storms mainly happened during April 2010. The maximum wind speed was found to be 15.7 m/s at the post-frontal stage with winds coming from southeast direction.
addition to cold fronts, the wind stick plot shows persistent southeasterly wind event as appears in June 2010.

Fig. 3.6. Numerical model timeseries results for hydrodynamic and wave parameters for points BB-2 and BB-5: (a) wind stick plots (b) current stick plots (c) significant wave height stick plots in which magnitude of the sticks represent magnitude of significant wave height and direction of the sticks shows mean wave direction (black) and water surface elevation (red) (d) significant wave height (e) peak wave period.
The diurnal oscillation pattern in current, as well as in water level elevation, is clear at Barataria Bay station (Fig. 3.6b1 and Fig. 3.6c1). Maximum vertically averaged tidal current exceeds 0.1 m/s (Fig. 3.6b1). However, such a pattern is not evident at Lake Cataouatche station due to shallow water depth and large frictional dissipation (Fig. 3.6b2). The current magnitude is almost one order of magnitude smaller at Lake Cataouatche station (BB-5) and its direction is mostly from NW to SE presumably because of the almost constant 280 m$^3$/s discharge from Davis Pond Diversion from 20 April to 15 July 2010. Thus, current effects on wave field are anticipated to be minimal in the northern water bodies.

Stick plots of significant wave height are aligned with that of the wind vector, showing wind-wave regime in both of the stations (Fig. 3.6a1 and Fig. 3.6c1). Low-energy waves are prevalent throughout the basin during simulation time with average magnitude from 0.1 to 0.2 m, though the maximum can even reach 0.4 m, depending on water depth and effective fetch.

As depicted in Fig. 3.6e1 and Fig. 3.6e2, the range of peak wave period in both Barataria Bay and Lake Cataouatche stations is between 0.5 to 2.5 s, which is much less than typical range of wind wave in the continental shelf (around 6 s). Such a small wave period is also an indicative of waves that are generated independent from influence of continental shelf.

The mean and maximum value of $H_s$ and $T_p$, for representative stations BB-1 to BB-6, as well as spatially-averaged for the respective lake are tabulated in Table 3.2. The average values of $H_s$ and $T_p$ for the lakes are close enough to the same value corresponding representative stations. The range of peak wave period in all of the water bodies justifies the usage of larger maximum (3 Hz) frequency in such shallow water applications.

A comparison of the maximum $H_s$ and $T_p$ value shows a decreasing trend from south to north in BB-1 to BB-6 stations (Table 3.2). However, looking at the same maximum wave
parameters for each water body, the one corresponding Caminada Bay and Barataria Bay are distinctly larger. Such larger numbers occurred near the Caminada Pass, Barataria Pass and Pass Abel that points to the swells penetrating from the Gulf of Mexico. It is noteworthy that the maximum peak wave period in Lake Cataouatche is about twice as large as the one that is typically observed in mid and northern Barataria Basin. Such large value is observed in a single point in the vicinity of Davis Pond Diversion and as a spike in time-series for that respective node. Thus, it can be ignored as a numerical error in the results.

Table 3.2. Summary of significant wave height and peak wave period for the points inside Barataria Basin.

<table>
<thead>
<tr>
<th>Station</th>
<th>$H_s$ (m)</th>
<th>$T_p$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>max</td>
</tr>
<tr>
<td>BB-1</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td>Average of</td>
<td>0.08</td>
<td>0.97</td>
</tr>
<tr>
<td>Caminada Bay</td>
<td>BB-2</td>
<td>0.14</td>
</tr>
<tr>
<td>Average of</td>
<td>0.13</td>
<td>0.96</td>
</tr>
<tr>
<td>Barataria Bay</td>
<td>BB-3</td>
<td>0.12</td>
</tr>
<tr>
<td>Little Lake</td>
<td>0.10</td>
<td>0.39</td>
</tr>
<tr>
<td>BB-4</td>
<td>0.12</td>
<td>0.32</td>
</tr>
<tr>
<td>Lake Salvador</td>
<td>0.10</td>
<td>0.38</td>
</tr>
<tr>
<td>BB-5</td>
<td>0.09</td>
<td>0.25</td>
</tr>
<tr>
<td>Lake Cataouatche</td>
<td>0.08</td>
<td>0.31</td>
</tr>
<tr>
<td>BB-6</td>
<td>0.08</td>
<td>0.21</td>
</tr>
<tr>
<td>Lac des Allemands</td>
<td>0.07</td>
<td>0.27</td>
</tr>
</tbody>
</table>
3.5.1.2 Relationship between wind- and mean-wave-direction

The statistical analysis between wind- and mean-wave-direction for various stations inside the Barataria Basin clearly shows a strong linear relationship between wind and wave direction, confirming locally generated waves inside all of the water bodies (Fig. 3.7). Correlation coefficients for all stations inside Barataria Basin for the three-month period are about or larger than 0.7 and the index of agreement is mostly greater than 0.8. Scores for BB-1, BB-4 and BB-5 are slightly better than the other stations. A relevantly small CC, IA81 and IA12 score in Point BB-2 (Barataria Bay) might be because this water body is larger and deeper compared with other water bodies in the basin and is open to the Quatre Bayou Pass, Pass Abel and specially deep and wide Barataria Pass with the depth of up to 40 m in the shipping channel, which allows waves from Gulf of Mexico to enter the Barataria Bay and affect the wave field in the Barataria Bay. The reason for smaller CC value in Little Lake and Lac des Allemands is not clear but is possibly due to geometry and relevantly shallower depth in these water bodies.

The same analysis applied for larger waves as presented in Fig. 3.7b demonstrates that larger waves follow the wind direction more closely than weaker waves. In order to evaluate the behavior of larger waves in Barataria Basin and to avoid the model-calculated noise-to-signal ratio prevalent in most estuaries, a threshold of 0.1 m is applied to the computed significant wave heights. The relationship between wind and wave is more linear by showing a sheer enhancement in CC, IA81 and I21. Moreover, a reduction in MAE and SI values in Fig. 3.7b compared to Fig. 3.7a denote less scattered for larger waves around wind direction.

An analysis on wave- and wind-direction is also performed with a time lag of one or two hours between the two. Statistical analysis of the model output reveals that the best scores pertain to the case in which there is no time lag between wind and wave direction. Thus, wave within
Barataria Basin very rapidly adjust itself to wind direction. This is in agreement with the conclusion Lin et al. (2002) drawn for the Chesapeake Bay.

Fig. 3.7. Statistical analysis of wind vs. wave direction for stations BB-1 to BB-6 during April-June 2010: (a) Including all the values of significant wave height (b) Considering wave heights greater than 0.1 m as large significant wave heights.
3.5.1.3 Relationship between wind speed and significant wave height

Regarding relationship between wind-speed vs. $H_s$ for the stations inside Barataria Basin, the same linear relation is established, as provided in Fig. 3.8. Similar to the analysis of wind and wave directions, the somewhat smaller correlation coefficient belongs to Barataria Bay presumably due to the effect of waves from continental shelf entering through major passes.

![Fig. 3.8. Scatter plot of wind speed vs. significant wave height (dots) and linear curve fitted to these two parameters (solid line). The Willmott (1981) correlation coefficient (CC) and Pearson's correlation (R) is calculated for each station.](image)

On a contrary, the statistical parameters corresponding larger waves show an opposite trend compared to the case of wind vs. wave direction. Both CC and R values diminish for the case of the waves larger than 0.1 m. The CC score for large waves for BB-1 to BB-6 stations is 0.75, 0.72, 0.77, 0.81, 0.87 and 0.70, respectively. The Pearson’s coefficient(=R) for these stations is calculated as 0.56, 0.52, 0.59, 0.66, 0.76 and 0.50, respectively. Both of these scores are smaller than the one presented in Fig. 3.8. The reason for diminution in correlation
coefficient for stronger waves is that such waves can travel a longer distance compared to the weaker waves that attenuate faster. Therefore, weaker waves are likely to be generated by winds at the same location, adjusting themselves with local variation of wind field, while larger waves can be introduced from a location further apart with less correlation with instantaneous wind speed. The analysis of one- and two-hour time-lag between wind magnitude and $H_s$ proves that the best correlation coefficient belongs to ‘no time lag’ condition which is similar to the result for wind- and wave direction analysis.

3.5.2 Dynamics of wave and current in the tidal inlets

The dynamics of wave and vertically-averaged current in the major inlets connecting Barataria Basin and the continental shelf is treated by incorporating four stations at Caminada Pass, Barataria Pass, Pass Abel and Quatre Bayou Pass from east to west as displayed in Fig. 3.2 as I-1 to I-4 stations. The water depth at these inlet stations is 0.78, 13.62, 0.63 and 0.4 m, respectively. Fig. 3.9 presents time-series plots of wind vector, vertically averaged current, sea level elevation, significant wave height, and peak wave period for I-2 and I-4 stations, corresponding to the deepest (Barataria Pass) and the shallowest (Quatre Bayou Pass) passes.
Fig. 3.9. Numerical model timeseries results for hydrodynamic and wave parameters for points I-2 and I-5: (a) wind stick plots (b) current stick plots (c) significant wave height stick plots (grey) and water surface elevation (black) (d) significant wave height (e) peak wave period.
Vertically-averaged current in all of the passes followed diurnal tidal cycle prevalent in the Louisiana Coastal of Gulf of Mexico. The magnitude of current could even exceed 1 m/s in deeper Barataria Pass (Fig. 3.9b), which is one order of magnitude greater than the one inside Barataria Basin due to geometric constriction.

As observed in Fig. 3.9d (upper panel) vs. Fig. 3.6d1, wave magnitude is larger in the Barataria Pass compared with the stations inside the Barataria Bay, which is presumably due to exposure of inlets to swells propagating from the continental shelf and beyond. The maximum and mean value of significant wave height in Barataria Pass is 0.58 and 0.24 m, which are about 45% and 65% larger than that of BB-2 station (Fig. 3.6d1 vs. Fig. 3.9d). Peak wave period in the inlets can reach as high as 10 s, another evidence of the waves coming from the deep Gulf of Mexico (Fig. 3.9e).

Analysis of the wind- and mean-wave-direction in the pass stations signifies the presence of both swells from Gulf of Mexico and local wind-sea. As presented in Fig. 3.10 (left column), when winds are from south sector (0° to 180°), (wind and wave direction is to, zero is due east, counterclockwise), waves are mostly propagating to 150°, 120°, 110°, and 90°, approximately aligning with the inward axis of each inlet. The independence of mean wave direction from the wind direction implies that the waves in the inlets are not locally generated but rather depend on large scale wind and wave in the deep Gulf of Mexico. Based on wave theory, as these waves approach coastline, their wave-front bends to align with isobaths due to refraction phenomenon. When winds are from north sector (180° to 360°), i.e. relatively rare northerly wind during this period, waves have two components: one being linearly correlated with and directly generated by local winds, and the other with quite constant direction indicative of waves from the deep gulf.
Comparing four inlets, the wave pattern in Quatre Bayou Pass is more similar to the stations inside the Barataria Basin with stronger direct relation between wind and wave direction. Unlike other inlets, the scatter of points along a constant wave direction is not strong at this pass, which indicates that relatively fewer swells from Gulf of Mexico enter the Barataria Basin.
through this inlet. This is probably due to its shallow depth. Moreover, this pass is in further east compared to other passes and could be more influenced by dynamics of Louisiana Bight due to Mississippi plume.

Considering the analysis of the wind magnitude vs wave height \( (H_s) \), it is seen that results at inlet stations are more scattered with worse correlation coefficients compared to stations inside the basin. This result is due to dominance of non-locally generated waves (Fig. 3.10, right column).

Examining the larger waves (figure not shown), it is found that the locally-generated component of waves disappear for Caminada Pass and Pass Abel. Waves greater than 0.2 m at these two passes are all swells. However, there still remain a few larger wind-seas in Barataria Pass due to its more depth.

3.5.3 Wave characteristics under cold-front and persistent southeasterly-wind events

3.5.3.1 Wave characteristics during cold-front (CF) event

Cold front event signifies a more energetic wave event compared with the ensemble of three-month simulation (Fig. 3.4a, and Fig. 3.5). The magnitude of significant wave height for this event can exceed 0.2 m in Barataria Bay, Little Lake and Lake Salvador. Furthermore, the spatial-temporal average of \( H_s \) shows about 40% of increase in comparison to a three-month simulation (Fig. 3.5). This increase is largest for Lake Cataouache (47%) and smallest for Caminada Bay (23%).

Infiltration of large-period waves diminish in CF event and is mainly confined to vicinity of the passes attesting more dominance of wind-seas during extratropical storms (Fig. 3.4c, mid-panel). The maximum peak wave period in the rest of the water bodies are less than two seconds indicating locally generated waves.
The snapshots of wave field under unsteady wind force during this event reveal that wave quickly adjusts itself to wind direction as presented (Fig. 3.11). The magnitude of wave height would depend on the intensity of local wind, overall depth of the water body and the available fetch in wind direction. In Lake Salvador for instance, during Time I, east-west orientation of the lake provides sufficient fetch for wave height of more than 0.25 m to develop in the eastern shore. However, at Time II, the available fetch in northwest-southeast direction is about ten kilometers, which is approximately half the one for Time I. Therefore, a smaller significant wave height is generated. On the other hand, at Time III though the orientation of wind is about the same as it is in Time II, yet more intense wind (7.53 m/s in Time III vs. 6.4 m/s in Time II) as well as persistency of wind direction generates waves as large as 0.3 m in the northern shores of Lake Salvador.

Fig. 3.11 also illustrates that when general wind direction is from southeast to southwest sectors, swell from Gulf of Mexico with wave height of at least 0.3 m can penetrate the Barataria Bay (Time III and Time IV). Contrastingly, at Time II, when frontal wind blows towards continental shelf, the wave magnitude along the barrier islands is decreased to about 0.15 m. In addition, the arrows indicate that some waves from inside Barataria Bay can enter the coastal zone. Moreover, when the wetland connecting the water bodies become inundated and sufficient wind speed and fetch is available, some large waves can penetrate from one water body to the next. This pattern is observed in Time IV between Lake Salvador and Lake Cataouatche, though the penetration might not be over large distance caused by dissipation of wave in very shallow environment.
Fig. 3.11. (Color) snapshots of modeled wave field driven by unsteady wind. Top panel: wind stick plots for BB-2 station with wind at four selected times in red. Bottom panels: spatial distribution of significant wave height and mean wave direction (arrows). The representative wind speed and direction is plotted for three locations in thick black arrows.
Statistical benchmarks for representative stations demonstrate that locally generated wind seas inside Barataria Basin are more pronounced during cold front event. The results of the statistical analysis for BB-1 to BB-6 and I-1 to I-4 stations during this event are summarized in Table 3.3. Comparing Fig. 3.7 with Table 3.3, the scores of wind- vs mean wave-direction are strongly enhanced. Both CC and IA12 are higher in Table 3.3 than in Fig. 3.7, especially for BB-3 station in Little Lake. MAE value is also reduced to about half of the one for three-month simulation. Further, unlike the case of three-month simulation, incorporation of 10-cm threshold does not improve the statistical measure significantly (Table 3.3). It is because of the rapid change of wind direction during CF event and quick adjustment of waves regardless of their magnitude. Therefore, it can be inferred that both strong and weak waves are governed by wind during CF event. Only in representative station in Lac des Allemands, the CC value is notably larger than the one for the whole waves. Here the assigned threshold eliminated the small waves that were more scattered in this relevantly shallower lake and consequently, the correlation coefficient is boosted.

Table 3.3. Statistical errors for stations inside Barataria Basin and major inlets during CF event. Large waves are the one with $H_s \geq 0.1 \text{ m}$.

<table>
<thead>
<tr>
<th>Station</th>
<th>Wind vs. Wave Direction</th>
<th>Wind Speed vs. $H_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Waves</td>
<td>Large Waves</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>MAE</td>
</tr>
<tr>
<td>BB-1</td>
<td>0.93</td>
<td>10.36</td>
</tr>
<tr>
<td>BB-2</td>
<td>0.79</td>
<td>16.82</td>
</tr>
<tr>
<td>BB-3</td>
<td>0.93</td>
<td>11.19</td>
</tr>
<tr>
<td>BB-4</td>
<td>0.93</td>
<td>11.68</td>
</tr>
<tr>
<td>BB-5</td>
<td>0.92</td>
<td>11.12</td>
</tr>
<tr>
<td>BB-6</td>
<td>0.79</td>
<td>14.92</td>
</tr>
<tr>
<td>I-1</td>
<td>0.63</td>
<td>32.33</td>
</tr>
<tr>
<td>I-2</td>
<td>0.82</td>
<td>22.99</td>
</tr>
<tr>
<td>I-3</td>
<td>0.62</td>
<td>33.44</td>
</tr>
<tr>
<td>I-4</td>
<td>0.83</td>
<td>27.07</td>
</tr>
</tbody>
</table>
As for the inlet stations, the results of the statistical analysis in Table 3.3 demonstrates more correlation between wind- and wave-direction, though IA12 and CC is still less than the stations inside the basin. Thus, contribution of wind-waves in pass stations is increased during cold front event, which confirms what was previously discussed for Fig. 3.4c. The reason for such an improvement is primarily attributed to stronger winds during CF event. The spatially-averaged wind speed for I-1 to I-4 stations during this event is about 7.2 m/s, which is approximately 25% higher than the three-month average value at these points. On the other hand, rotational pattern of wind speed over the whole continental shelf and Louisiana Bight and stronger plume of Mississippi River alter the wave dynamics in coast and deviate the swells to effectively reach the coastline. Therefore, wave becomes more affected by local winds.

The correlation between wind speed and significant wave height did not change much for the stations inside Barataria Basin (Table 3.3 vs. Fig. 3.8). Only in BB-2 station in Barataria Bay, the CC score is somewhat reduced. Since Barataria Bay is a vast water body stretching in all directions, sufficient fetch is available in all directions and large wave heights can be formed during extratropical storm that can travel further distance before dissipation. Therefore, the CC value is reduced compared to a three-month simulation. The wind speed and $H_s$ for inlet stations are also poorly correlated and slightly reduced compared with the one in Fig. 3.10 due to more energetic wave environment during CF event.

Spectral analysis of the stations on the continental shelf, Barataria Basin, and major inlets demonstrate momentous reduction in wave energy from continental shelf to the estuarine system, which is attributed to depth-induced wave breaking and shallow water frictional dissipation. Further, wave energy diminishes as we move from South to North in the Barataria Basin.
Regarding tidal inlets, the most energetic one is Barataria Pass and Quatre Bayou Pass has the lowest overall wave energy. The time series of variance density spectra during CF is depicted in Fig. 3.12 for CSI-09 station on open coast, two stations inside Barataria Basin and two stations at inlet locations. Additionally, three time instances are designated, for which energy spectra are plotted for each selected station. In general, from spectral analysis of all of the stations, three categories of $T_p$ intervals can be distinguished: $T_{p1} = 8-10$ s, $T_{p2} = 3-5$ s and $T_{p3} = 1.5-2.5$ s, which are shaded in grey, green and blue, respectively. The pattern of wave spectra in the inlet-and basin-stations is mostly a single- or double-peak one, with peak periods falling into the above-introduced categories.

During CF event, peak period for the stations inside the basin is far less than the one at continental shelf, attesting locally generated wind seas within Barataria Basin (Fig. 3.12). The shape of spectrum for open coast stations is mainly single-peaked with peak wave period at 8-10 s ($T_{p1}$), though double-peak shape of $T_{p1}$ and $T_{p2}$ is rarely observed towards end of the event (Fig. 3.12a, instance C). For the basin-stations however, the wave energy spectra still has a single peak but with a peak at $T_{p3}$ (Fig. 3.12b and Fig. 3.12c). Concerning the maximum spectral density, this value inside the Barataria Bay is two orders of magnitude smaller than the one pertaining CSI-09 station, which is due to less potential for generation of waves in this much shallower, fetch-limited environment. Comparing BB-2 station at south and BB-5 station at north of Barataria Basin, the wave energy diminishes from south to north because of relevantly larger and deeper water body at Barataria Bay capable of forming comparatively larger waves.
Fig. 3.12. Left Panel: Time series of variance density spectra for (a) CSI-09, (b) BB-2, (c) BB-5, (d) I-2 and (e) I-4 stations during CF event. Three time instances are selected as A, B, and C. Right Panel: Variance Density Spectra for Transects A, B, and C. Shaded areas pertain to $T_{p1} = 8-11$ s (grey), $T_{p2} = 3-5$ s (light green), and $T_{p3} = 1.5-2.5$ s (light blue).
In inlet stations, both influences of waves from continental shelf as well as locally generated waves are witnessed, as presented in Fig. 3.12d and Fig. 3.12e. This result is in agreement with the wind- vs. wave-direction plots as depicted in Fig. 3.10. The wave spectra in these stations are double-peaked for about 50% of the time during CF event. The prevalent peaks are $T_{p1}$ and $T_{p3}$ with $T_{p1}$ as the main period, which points to the dominance of the waves coming from deep Gulf of Mexico. Occasionally, single or triple peaks are seen in the density spectra (e.g. Fig. 3.12b, time B).

Despite the main frequency being the same as CSI-09, yet the magnitude of the spectral density in inlet stations is dwindled, which is caused by significant energy dissipation at the passes (e.g. compare spectral density at peak corresponding $T_{p1}$ in Fig. 3.12a and Fig. 3.12d). The spectral density pertaining $T_{p1}$ (swell from continental shelf) and $T_{p3}$ (locally generated) in three selected time instances is in the same order of magnitude for I-2 station at Barataria Pass indicating comparable contribution of swells and wind seas in this inlet. One a contrary, the peak spectral density in the same instances for I-4 station belongs to $T_{p1}$ category (Fig. 3.12e). Fig. 3.12e conveys that although the behavior of Quatre Bayou Pass more resembles the basin-stations, yet some energetic swells can still propagate through this inlet. Also, the peak of energy spectra at I-2 (Barataria Pass) is more than twice as large as the one at I-4 (Quatre Bayou Pass), marking superiority of the former pass in terms of wave energy.

### 3.5.3.2 Wave characteristics during persistent South-East (SE) event

In general, the average wave parameters during SE event are similar to the one for three-month simulation (Fig. 3.4 and Fig. 3.5). Nonetheless, Fig. 3.13 evinces that wave as large as 0.3 m can form in northern shores of major interior lakes provided that adequate fetch would be available. For instance, since there exists a long-enough fetch in southwest-northwest direction,
large waves grow at northern shores of Barataria Bay and Lake Salvador. Conversely, even though the average water depth is more than 2.3 m, lack of fetch prevents the generation of large waves in Little Lake, while such waves were seen in this lake during CF event (e.g. see Fig. 3.11, Time III).

Further, some instances can be marked when waves from Gulf of Mexico enter the Barataria Basin during SE wind event. Three time instances at which wave enter Barataria Bay are illustrated in Fig. 3.13. In all three cases, such an event corresponds to about four hours after maximum water level and during the slack time. Entering wave from continental shelf is specifically noticeable at time I and II compared with Time III. The wind speed in the offshore location (thick arrow plotted inside Louisiana Bight) is 25% smaller in Time III compared to other two times. Therefore, amplitude of generated wave from Gulf of Mexico entering through Barataria Pass is smaller on that particular time. The overall intensity of significant wave height in Barataria Bay in Time III is also less than other two times that could also be due to somewhat milder wind on that time.

During the SE event, the peak of spectral density at open coast is an order of magnitude smaller than the one in CF event, signifying relevantly less energetic event (Fig. 3.14). The wind speed, averaged over three time instances A, B and C during SE event is calculated as 6.22, 6.82, 6.10, 6.16 and 6.21 m/s for stations CSI-09, BB-1, BB-2, I-2 and I-4, respectively. The average wind speed for time instances of A, B and C (Fig. 3.12) for the same stations during CF event is 20%, 26%, 38%, 48% and 47% greater than those in SE event. Additionally, though the shape of the spectrum is still single peaked at CSI09, yet the peak wave period corresponding the maximum energy is shifted from $T_{p1}$ to $T_{p2}$ (Fig. 3.12a vs. Fig. 3.14a). Regarding the magnitude
of maximum spectral density for CSI-09 station vs. other stations, the difference is one order of magnitude due to nearshore dissipation processes.

The shape of variance density spectra for BB-2 and BB-5 stations also demonstrate locally-generated waves during SE event, with a single-peak spectrum at $T_p$. Nevertheless, the range of variance density is smaller than CF event due to weaker winds in such a wind-sea environment.

![Wind Speed and direction at Station BB-2](image)

Fig. 3.13. (a) Wind stick plots during SE wind event for BB-2 station with wind at three selected times in red; (b) water surface elevation during SE event with wind at three selected times in red; (c) Vertically-averaged current during SE event with wind at three selected times in red; (d) (color) snapshots of modeled wave field driven by unsteady wind for Time I, II and III introduced in panel (a). The wind speed and direction is plotted for three locations, two inside Barataria Basin and one at continental shelf. Small arrows represent mean wave direction.
Fig. 3.14. Left Panel: Time series of variance density spectra for (a) CSI-09, (b) BB-2, (c) BB-5, (d) I-2 and (e) I-4 stations during SE event. Three transects are selected as A, B, and C. Right Panel: Variance Density Spectra for Transects A, B, and C. Shaded areas pertain to $T_{p1} = 8-11$ s (grey), $T_{p2} = 3-5$ s (light green), and $T_{p3} = 1.5-2.5$ s (light blue).
Dual contribution of swells and waves already perceived in statistical analysis in inlet stations can be detected from spectral analysis as well (Fig. 3.14d and Fig. 3.14e). The spectrum at passes usually has two peaks at $T_{p2}$ and $T_{p3}$ with $T_{p2}$ as the one with higher spectral density. The magnitude of peak spectral density in the I-2 station is in the same order of magnitude compared to BB-2 and BB-5 stations. However, the magnitude of peak spectral energy is one order of magnitude smaller in I-4 station. This is because Quatre Bayou Pass, being in the further east, is located in the shade of bird-foot delta of Mississippi River during for the winds coming from South to South-East sector.

3.5.4 Wave exposure (Wexp) along the shores of major lake inside Barataria Basin

Calculation of wave exposure for six main water bodies of Barataria Basin is performed based on a threshold of 0.1 m. This threshold value for $H_s$ is 50% smaller than the study by Seibt et al. (2013) as such waves was found to be capable to initiate sediment motion and cause marsh erosion on the edges in Barataria Basin (Booth et al., 2000). For each boundary cell, closest node to the shoreline in which water depth is larger than the depth specified by breaking criteria is selected. Wave exposure in a certain edge-node is considered as the percentage of time, when the significant wave height in respective non-breaking boundary node exceeds 0.1 m. Therefore, it can be interpreted as the fraction of time when at least 0.1 m reach shoreline before breaking.

The wave exposure pertinent to the whole three month period and each type of wave event is provided in Fig. 3.15. In the three-month simulation period, the average wave exposure for Caminada Bay, Barataria Bay, Little Lake, Lake Salvador, Lake Cataouatche and Lac des Allemands is 33.6%, 49.6%, 36.4%, 32.3%, 28.0% and 18.9%, respectively. Henceforth, the exposure of the shores of Barataria Bay to large waves is at least 36% greater than the other water bodies, making it comparatively more vulnerable to marsh erosion (Fig. 3.15d). At shores
with onshore wind direction, wave exposure increased in northeast direction (Fig. 3.15a). Thus, as a result of more frequent wind from southeast direction in summer 2010 and wind-driven nature of wave inside Barataria Basin, wave exposure is largest at northern shores but small at southern shores.

During CF event, all shores of major lakes, per contra, are exposed to larger waves (Fig. 3.15b). The average wave exposure during this event is at least 40% greater than three-month simulation time. In Lake Cataouatche and Lac des Allemands, mean $W_{exp}$ is increased by 87% and 98%, respectively (Fig. 3.15d). Therefore, it can be inferred that bed erosion inside the Barataria Basin is more pronounced during extratropical storms. Particularly in Barataria Bay, abundance of fetch makes the wind from all directions to be important to boost wave exposure such that wave exposure of shores all around this lake is similar and large in magnitude (Fig. 3.15b).

The pattern of wave exposure during SE event is similar to three-month period, though the model predicts larger wave exposure for Barataria Bay during this event. During this event, opposite shores of the interior water bodies can experience different wave exposures. For instance, northern shores of Barataria Bay, Little Lake and Lake Salvador are exposed to waves whereas the wave exposure at southern shores is relevantly small. The ratio of average wave exposure in CF event is about 76% larger than the one in SE event (Fig. 3.15d). However, the same ratio calculated for maximum value of wave exposure and averaged for all water bodies reduce to 21%. As an extreme case, the maximum wave exposure for this event in Barataria Bay reaches 100% that is even larger than CF event (Fig. 3.15e). Therefore, SE event, though being a comparatively less energetic event, can impose sporadically large wave exposure percentages.
This could be due to a small portion of shore exposed to main wind direction or persistence of swell from continental shelf at the bay iterance (e.g. in Barataria Bay).

Fig. 3.15. Wave exposure of major lakes inside Barataria Basin for (a) three-month simulation period, (b) CF wave event and (c) SE wave event. The colors indicate fraction of 1 hr time intervals per specific time period during which significant wave height was larger than 0.1 m. Wind roses in each panel represent relative frequency of direction and magnitude of wind speed for its respective time interval. (d) Wave exposure averaged over the edge of each interior lake. (e) Maximum value of wave exposure for each lake.
3.5.5 Comparison of wave-only (WO) vs. wave-current (WC) coupled simulations

In order to investigate the effect of tidal elevation and vertically-averaged current on the wave field in Barataria Basin and major passes, a wave-only simulation (WO) was also accomplished for the whole three-month time interval.

Overall, results from numerical model shows that contribution of tidal elevation and vertically-averaged current on altering wave field inside Barataria Basin within three-month time span of simulation is not significant. Fig. 3.16 (left panel) depicts time series results from 06/02 to 06/14/2010 for BB-2 station in Barataria Bay. It is observed that WO and WC have very minor differences in $H_s$, $T_p$ and mean wave direction (Fig. 3.16c1 and Fig. 3.16e1). The significant wave height from WC is occasionally slightly higher than the one from WO, which could be both from the effect of current and more water depth due to additional water surface elevation allowing higher waves to form. In BB-2 station, the magnitude of depth-averaged velocity and water surface elevation are mostly less than 0.1 m/s and 0.5m, respectively (Fig. 3.16b1). From Fig. 3.16, it is observed that significant wave height from WO and WC start to depart from each other where average velocity exceeds 0.1 m/s, and surface elevation is greater than or close to 0.5 m. Further, the statistical analysis of neither wind- vs. wave-direction nor wind speed vs. significant wave height lead to a noticeable change between WO and WC cases. Therefore, the range of velocity and water surface elevation inside Barataria Bay is not large enough to make a palpable difference in wave field.

Investigating the wave field in station BB-5 (Lake Cataouatche) exposed to Davis Pond River Diversion, the results from both WO and WC models were very similar (not shown here). This proves that the current introduced as a result of the discharge from Davis Pond River Diversion is too low to influence the wave field in this lake.
Fig. 3.16. Numerical model timeseries results and statistical analysis for points BB-2 and I-2: (a) wind stick plots, (b) Ocean surface current magnitude (solid black) and water surface elevation (solid grey), (c) significant wave height, (d) mean wave direction, (e) peak wave period, (f) wind vs. wave direction, (g) normalized wind speed vs. normalized significant wave height.

A more notable difference between wave parameters in WC and WO cases is observed for inlet stations, mainly because water level and ebb/flood velocities in these stations are one order of magnitude greater than the one inside the Barataria Basin (Fig. 3.16b2). In general, the significant wave height in the WO case is smoother compared to WC case. Reduction in magnitude of significant wave height is mainly seen where current magnitude exceeds 1 m/s, signifying the effect of large velocity to suppress waves or change its direction (Fig. 3.16c2 and Fig. 3.16d2). Large ocean surface current could alter the mean wave direction in WC case up to 45° as observed in Fig. 3.16d2.

Statistical analysis performed on inlet stations for WO case does not show a significant difference compared to the one for WC case either. The only exception was in I-4 station, where correlation coefficient of wind- vs. wave-direction in WO significantly improved for larger waves (from 0.49 to 0.74) while it was not changes in WC simulation. This demonstrates that if
only wave forcing to be considered, the larger waves from the continental shelf does not influence this inlet and Quatre Bayou Pass tends to behave akin to the points inside the basin. However, the presence of hydrodynamic forcing and most probably long-shore current in Louisiana Bight distorts the linear wind-wave correlation.

A distinct behavior for Quatre Bayou Pass in WO vs. WC simulations was also observed in the analysis of wind-speed vs. $H_s$. The correlation coefficient for WO simulation is found to be quite large (≈ 0.78) whereas no correlation is observed in WC simulation (≈ 0.31). This shows that in absence of hydrodynamic forcing, a linear relation between wind speed and significant wave height is established, but such relation is diminished due to presence of long-shore current, which is attributed to geographical location of this inlet.

3.6 Summary and conclusion

This study investigates the wave field during spring-summer time inside Barataria Basin as well as at four major inlets connecting this water body to the Gulf of Mexico, using numerical modeling. The three-month period from April to June 2010 is selected for this coupled hydrodynamic-wave modeling because both common wind regimes in Gulf of Mexico, i.e. extratropical storms and persistent winds from south to southeast sector, are observed at this time interval.

The wave simulation inside Barataria Basin demonstrated strong locally-generated wind-seas. Wind direction and mean wave direction were highly correlated. Such a linear correlation between wind and wave direction was less pronounced at water bodies with larger average depth or the ones directly connected to LATEX Continental Shelf via inlets. On the other hand, moving towards northern water bodies such as Lake Salvador and Lake Cataouatche, such relation is
enhanced. In addition, a linear regression is established between wind speed and significant wave height indicating locally-generated waves.

The barrier islands effectively block the propagation of swells into the Barataria Basin. Therefore, large waves inside the basin are mostly wind seas. This fact is supported by both statistical and wave-spectral analysis. The statistical scores for wind- vs. wave direction applied to larger waves are substantially improved. By the same token, moving from open coast to inside the basin, the peak frequency in wave spectra decreases and the magnitude of maximum spectral density dwindles by at least one order of magnitude attesting locally-generated waves inside Barataria Basin.

Unlike in the case of directions, statistical benchmarks between wind speed and significant wave height worsen for large waves.

The statistical analysis is also performed introducing time lag of zero, one and two hours between wind and wave that led to zero-time-lag as the best candidate. This result shows almost instantaneous response of wave field to change in wind field.

In the northern Barataria Basin, the statistical analysis for Lac des Allemands did not provide as promising results as Lake Cataouatche or Lake Salvador, which might be due to lake of sufficient bathymetry resolution in this shallow lake.

In the tidal inlets connecting Barataria Basin and Gulf of Mexico, the numerical model predicts larger waves compared to inside of the basin, which is due to swells from Gulf of Mexico. Even though there is no linear relation between wind- and mean wave-direction, part of the wave can still be locally generated. However, they contribute to $H_s$ less than swells. The dual influence of wind-seas and swells is also detected by examining wave-energy density spectrum highlighted with a double-peak pattern in inlet stations.
During cold front event (CF), the wave field inside the basin and at the inlets is governed by wind-waves. The statistical measures between wind- and wave direction are greatly enhanced and are even insensitive to applying a threshold on wave height. Contrarily, during normal condition characterized by a persistent wind blowing from south to southeast direction (SE event), the correlation coefficient values fall, which is attributed to the more marked influence from swells, entering the inlets and the basin from continental shelf. Moreover, although the scale of maximum wave spectral density in the coastal zone is greater during cold front by an order of magnitude, yet at inside the bay and at the inlets, this parameter is in the same order of magnitude during both CF and SE events.

During SE event, swells can occasionally penetrate into Barataria Bay through the passes and travel up to five kilometers into this lake. Such time instances are mainly seen during slack time and when wind comes from southwest direction.

In general, wind exposure follows the pattern of wind-rose for three-month simulation time as well as CF and SE events. Two aforementioned events differ not only in magnitude of wave exposure but also in spatial variation of the shores exposed to large waves (greater than 0.1m). During normal condition, northern shores of the interior lakes are mainly exposed to waves whereas wave exposure is large for almost all shores during extratropical storm. Wave exposure increases by at least 40% in major water bodies during cold front event. Therefore, such an event plays a major role in shoreline erosion inside the basin. Among the six major lakes within Barataria Basin, Barataria Bay is more exposed to waves larger than 0.1 m, owing to its sufficient fetch in all direction and depth.

The spectral analysis also proves that the maximum wave spectral energy correspond to the same range of peak period in both continental shelf and at the inlet stations. However, the
same parameter inside Barataria Basin corresponds to a smaller peak period between 1.5 to 2.5 s. Besides, the intensity of spectral density is comparable in inlet stations and in the interior Barataria Basin.

Among the four inlets examined in this study, Barataria Pass is found to be the most energetic one, while the Quatre Bayou Pass in the further east is the least energetic one with similar behavior as basin stations. The Barataria Pass is wider and much deeper compared with other passes that merits more in-depth investigation.

As for the influence of tidal elevation and current on wave field inside Barataria Basin and at the inlets, a wave-only case is modeled and the results are compared with the one from coupled model. The analysis of both simulations conveys minimal difference, which is due to rather insignificant effect of surface elevation and velocity in this time period. The only clear change from these two models is seen in Quatre Bayou Pass. A more in depth study of influence of dynamics of Louisiana Bight on the inlets is recommended to shed light into the change in this pass and other inlets.

Finally, in lieu of wave measurement inside Barataria Basin, present model is calibrated and validated against experimental data on the open coast and offshore. A rigorous campaign to obtain experimental data would undoubtedly improve this research and further enrich the understanding of wave action in this estuarine system.
CHAPTER 4. COUPLED HYDRODYNAMIC-WAVE-SEDIMENT SIMULATION AND DYNAMICS IN THE MISSISSIPPI RIVER BIRDFOOT DELTA AND THE BARATARIA PASS

4.1 Introduction

The fluvial sediments brought by the rivers are the main source of the global nutrient and carbon cycle (Hedges and Keil, 1995; Mayer et al., 1998). The Mississippi River, the seventh largest river in the world in terms of discharge and suspended load (Milliman and Meade, 1983; Meade, 1996), drains 47% of the conterminous U.S. and carries 66% of the suspended matter from the continental U.S. to the Gulf of Mexico, amassing 210 million tons per year (Meade, 1996; Allison et al., 2012). However, anthropogenic interference on the Mississippi River, such as damming, building of levees and other river control systems and land use change, has reduced the sediment load to half over the past century (Corbett et al., 2004; Blum and Roberts, 2009). The reduction of sediment supply from the Mississippi River, as well as a decrease in overbank fluvial sediment supply due to the construction of levees along the banks of the river, is considered one of the prime reasons for dire wetland loss in coastal Louisiana (Barras et al., 2003; Barras, 2006). Therefore, proper management of available sediment resource from the Mississippi River, beginning with an accurate estimation of water and sediment budgets from various Mississippi Delta passes, is indispensable to make a strategic restoration plan to mitigate the chronic Louisiana coastal and wetland loss.

Allison et al. (2012) conducted an experimental study to estimate the water and sediment budget for the lower Mississippi system and the Mississippi birdfoot outlets utilizing monitoring station data and a rating curve method for the flood years of 2008–2010. However, collecting simultaneous data from various exits of the Mississippi birdfoot is costly and logistically challenging. Therefore, a numerical model, with accurate hydrodynamics and high fidelity to
real world bathymetry, can provide an alternative way to calculate the sediment and water budget through various passes. This study aims to present a numerical model that can achieve this very purpose.

Although the accumulation of fluvial sediment from the Mississippi River into the Gulf of Mexico is found to be localized around the birdfoot delta (Allison et al., 2007; Xu et al., 2011), it varies among various outlets of the Mississippi birdfoot delta. The dispersion of sediment from the Mississippi River is mainly governed by a buoyancy-driven flow modulated by local winds (Munchow and Garvine, 1983; Walker, 1996; Walker et al., 2005). The major outlet responsible for the Mississippi River plume is the Southwest Pass that carries between 45% (Etter et al., 2004) to 67% (Li et al., 2011) of the freshwater and 23% of total suspended sediment load (Allison et al., 2012: average over three years 2008–2010). The wind in the northern Gulf of Mexico is predominantly from the east to southeast in the summer time (May to September) and from northern sector from October through March or April (Rhodes et al., 1985).

The occurrence of northerly winds in the winter and early spring is due to the formation of mid-latitude atmospheric circulation systems called cold fronts (also known as extratropical storms). They occur every 3–10 days in winter and spring season (Moeller et al., 1993; Stone and Wang, 1999) and are characterized by a rotary wind field. During the prefrontal stage of the extratropical storms, wind prevails from southern sectors and larger available fetch from these sectors leads to the formation of larger wind waves. The frontal passage is a short-lived event during which barometric pressure drops sharply and wind direction suddenly changes from southerly to northerly. During the post-frontal stage, cold, dry, high-pressure continental air intrudes southward leading to set-down of coastal water level, increase in barometric pressure and a sudden drop in air temperature (Huh et al., 1984; Roberts et al., 2015).
The dispersion and accumulation of sediment from the Mississippi plume have been the subject of a number of previous studies. Some of the studies employed field observations and radiochemical analysis to quantify the deposition of fluvial sediment (e.g. Corbett et al., 2004; Corbett et al., 2006; Allison et al., 2007). Some used measurements from satellite images to detect and map the ocean surface sediment over the continental shelf and relate the dispersion of sediment to environmental forcing such as river discharge and wind stress (e.g. Walker et al., 1996; Walker et al., 2005). Other studies investigated this subject through numerical simulation. Keen et al. (2004) employed a three-dimensional hydrodynamic model to simulate sediment transport near the birdfoot delta. Xu et al. (2011) used a three-dimensional ROMS model to calculate the dispersion of the Mississippi and Atchafalaya sediment under normal and storm condition. Nonetheless, none of the aforementioned numerical models have a proper resolution at the Mississippi birdfoot to capture the detail of the sediment plume from Southwest Pass and other outlets. This study aims to develop a three-dimensional high-resolution baroclinic numerical modeling system to quantify the dispersion and accumulation of riverine sediment around the the Mississippi Delta.

This study also aims to study the mechanism for the shelf-estuary sediment exchange at Barataria Pass during normal and cold front passage conditions. The Barataria Bay is connected to the open coast through a chain of tidal inlets. The net water transport from the Barataria Bay is estimated as 280 m$^3$/s (Marmer, 1948) and 200 m$^3$/s (Swenson and Swarzenski, 1995). The major pass that conveys the greatest exchange between the bay and the shelf is the Barataria Pass. The amount of water going through this inlet is estimated to be about 66% of the total estuarine-shelf exchange of the Barataria Bay (Marmer, 1948). The tidal regime in the Barataria Pass is diurnal with a range of approximately 0.35 m (Das et al., 2012). A 23-year analysis
(1995-2017) of the wave parameters at NDBC Station 42040 (coordinates: 29.208°N 88.226°W) resulted in an average significant wave height and peak wave period of ~ 1 m and ~ 5.64 s, respectively (Sorourian et al., 2018). However, the significant wave height can reach 2–3 m during cold front events (Dingler et al., 1993).

Despite numerous studies on the transport of water through the Barataria Pass using observational (e.g. Swenson and Swarzenski, 1995; Li et al., 2011) and numerical (e.g. Inoue and Wiseman, 2000; Inoue et al., 2008) means, the mechanism of sediment transport through the Barataria Pass, especially under cold front condition is yet to be studied. Liu (2016) investigated the shelf-bay exchange at this pass but the focus of his study was under hurricane conditions. The objective of this study is to address the main forcing of sediment and water exchange through the Barataria Pass during April-June 2010, a period comprising both wind regimes, i.e., rotational wind during cold front passage (April–May 2010) and persistent southerly winds (June 2010). It should be pointed out that the cold front passages in the springtime are weaker in intensity and duration compared to the ones that occur during the winter season.

Our numerical simulation results indicate that the exchange of sediment between the Louisiana Bight and the Barataria Bay through the Barataria Pass during April-June 2010 is mainly governed by tidal forcing. The morphological features at the inlet are one erosion area that is mainly on the shelf-side of the inlet and two deposition areas at shelf- and bay-side of the inlet. The 3-month net suspended sediment flux through the center of the Barataria Pass is positive (bayward).

This paper is organized as follows. In section 4.2, the study area is introduced, as well as the model system and initial and boundary sediment configuration. In section 4.3, the numerical model simulation is validated. In section 4.4, the results for sediment dispersal in the continental
shelf, the budgeting calculations, and shelf-bay sediment exchange mechanism are presented. Section 4.5 includes a discussion on the results. Finally, in section 4.6, the results are summarized.

### 4.2 Study area and methods

#### 4.2.1 Study area

Our focus in the present investigation is on two locations: one being the outlets of the Mississippi birdfoot delta (Fig. 4.1b) and the other the Barataria Pass (Fig. 4.1c). The Mississippi birdfoot is a river-dominated delta formed as a result of high fluvial sediment from the Mississippi River compared to less significant wave action and tidal forcing in the Louisiana coast. The resultant progradational delta leads to a steep shelf with a width of less than 20 km and a gradient of ~ 0.4° south of the delta (Xu et al., 2011). The Mississippi River exports ~ 530 km³/yr fresh water into the continental shelf (Rong et al., 2014) through several outlets. The main exit among these outlets is the Southwest Pass. Etter et al. (2004) stated that this outlet carries 45% of the total Mississippi flow. Li et al. (2011) reported that the discharge from this pass was about 67% of the total discharge of the Mississippi River based on a high-resolution survey on 5 May 2010. The narrow width of Southwest Pass (~ 700 m) and the jetties constructed along the mouth of this exit (that are also resolved in our numerical grid) develop a strong outflow with a velocity greater than 2 m/s that advects the riverine sediment further offshore. Moreover, previous studies reported the generation of a clockwise gyre from the Mississippi buoyant plume that extends into the Louisiana Bight (Rouse and Coleman, 1976; Wiseman et al., 1976; Walker et al., 1996; Walker et al., 2005). Fig. 4.1c shows the location of the Barataria Pass. Width, length and a maximum depth of this inlet is about 800 m, 430 m and 40 m, respectively.
The numerical domain for the present investigation extends about 700 km in the northern Gulf of Mexico from Dolphin Island, Alabama to Galveston Bay, Texas. It also extends offshore to about 27°N. The unstructured numerical grid is composed of 143546 nodes and 278399 cells with a resolution of ~ 10 km in the southern offshore boundary to ~ 10 m in shallow estuarine channels (Fig. 4.2a). The approximately 700-m width of the Southwest Pass is resolved by 10 triangles. The grid resolution at the South Pass, Pass a Loutre, Main Pass, Locket Pass and Grand Pass is about 100 m, 150 m, 150 m, 50 m and 50 m, respectively (Fig. 4.2b). Eighteen triangles with varying width of 46 m to 274 m resolve the cross-section at the Barataria Pass (Fig. 4.2c). To resolve the variable bathymetry and complex geometry of the coastline, tidal channel and islands on the shelf- and bay-side of the Barataria Pass, the grid resolution of approximately 50 to 500 m with variable grid orientation is incorporated into the numerical model (Fig. 4.2c). In the vertical the numerical model has 19 uniformly distributed sigma layers, which is ~ 0.1 m over the shoal and ~ 1 m in the main channel of the Barataria Pass.
Fig. 4.1. (a) The numerical model domain. Contour lines represent the water depth and the gray shaded regions represent shallow area subjected to wetting and drying. The thick line shows the boundary for the numerical model. (b) An area zoomed to the Mississippi birdfoot delta. The green dots show the locations of cross-sections at the major exits. The red dots are the locations of transects introduced by Allison et al. (2012) for evaluation of sediment budgeting. Two magenta transects are almost perpendicular to the Mississippi plume ~ 5 and 10 km offshore of the outlet at the Southwest Pass. The blue transect represents the along-plume transect from the Southwest Pass to offshore. (c) The area zoomed to the Barataria Pass. The dotted points are representative locations in the study area used for the analysis of the results in sections 4.4.4 and 4.5.1.
4.2.2 The coupled hydrodynamic-wave-sediment transport model

The modeling suite employed in this study is the Finite-Volume Community Ocean Model (FVCOM) for hydrodynamic, FVCOM-SWAVE model for wave simulation, and FVCOM-SED for sediment simulation. FVCOM is an open-source, 3D, unstructured-grid finite
volume ocean model (Chen et al., 2006b, 2013) that is capable of accurately following complex
costlines and bathymetry. The FVCOM-SWAVE model is a third-generation, phase-averaged
wave model that solves wave-action-density over geographic (using the same unstructured-grid
as FVCOM) and spectral domains. It incorporates processes such as wave refraction and
shoaling, wave-current interaction, wave growth, nonlinear triad and quadruplet interaction, and
the wave dissipation due to whitecapping, depth-induced wave breaking and bottom friction (Qi
et al., 2009). More description on FVCOM-SWAVE can be found in the previous chapters.

The FVCOM-SED model is based on the Community Sediment Transport Model System
formulations (Warner et al., 2008), but with the same unstructured-gird finite-volume numerics
as the FVCOM and FVCOM-SWAVE. FVCOM-SED has been successfully applied to the
coastal zone and lakes in a number of studies (e.g. Ralston et al., 2013; Ge et al., 2015; Morales-
Marin et al. 2017; Yellen et al. 2017, Niu et al., 2018). This model allows for multiple user-
defined sediment classes of cohesive and non-cohesive sediment types. For each sediment class,
parameters of median grain diameter, density, settling velocity, critical shear stress for erosion
and deposition, sediment erosion rate and porosity are specified.

The suspended model is represented by 3D advection-diffusion equation:

\[
\frac{\partial c_i}{\partial t} + \nabla \cdot (\vec{U} c_i) + \frac{\partial (W - W_i) c_i}{\partial z} = \frac{\partial}{\partial x} \left( A_h \frac{\partial c_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_h \frac{\partial c_i}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_h \frac{\partial c_i}{\partial z} \right)
\]  

(1)

where \(x, y, \) and \(z\) are the Cartesian coordinates; \(\nabla_H\) is the horizontal derivative; \(\vec{U}\) is the
horizontal water velocity vector; \(W\) is the vertical water velocity; \(W_i\) and \(C_i\) the settling velocity
and concentratin of sediment class \(i\), respectively; and \(A_h\) and \(K_h\) are the horizontal and vertical
eddy diffusivities, respectively.

The boundary condition at the water surface and bed, respectively, are as follows:

\[K_h \frac{\partial c_i}{\partial z} = 0\]  

(2)
\[ K_h \frac{\partial c_i}{\partial z} = E_i - D_i \quad (3) \]

where \( E_i \) and \( D_i \) are erosional and depositional fluxes for sediment class \( i \), respectively.

The erosional flux is parametrized using Ariathurai and Arulanandan (1978) as:

\[ E_i = M_i \left( \max \left\{ \frac{\tau_b - \tau_{ce,i}}{\tau_{ce,i}}, 0 \right\} \right) (1 - \varphi) \quad (4) \]

where \( M_i \) is bed erosion rate, \( \tau_b \) is total skin friction bottom shear stress, \( \tau_{ce,i} \) is critical shear stress for erosion, and \( \varphi \) is the porosity of the top bed layer.

The bed layer is represented as a three-dimensional, user-defined multiple layers below each model cell, in which information of sediment fraction, sediment age and porosity for each sediment type is initialized. The evolution of bed is based on the concept of the active layer, calculated at each time step using the formulation of Harris and Wiberg (1997).

The coupling of the hydrodynamic, wave and sediment components of the model is achieved by (1) online coupling of wave and hydrodynamic model that is elaborated in detail in Chapters 2 and 3, and (2) introducing hourly wave parameters from step (1) into FVCOM-SED model (offline coupling). In step (1) incorporating the radiation stresses from FVCOM-SWAVE, the circulation model calculates water surface elevation and velocity fields and. In step (2) these informain are passed over to the sediment model to solve the sediment advection-diffusion equation. Then, the results are sent to bottom-boundary layer (BBL) model determining the bottom shear stress. The computed bottom shear stress derives the stress exerted on the flow by the bottom in the momentum equation and the resuspension rate of sediment.
4.2.3 Sediment sediment classes and initial conditions

4.2.3.1 Treatment of sediment classes

The model employs 10 sediment classes: three for the Mississippi River representing sand, silt and clay-type sediments (hereafter, referred to as M_sand, M_silt, and M_clay, respectively), three for seabed (non-erodible, BED_sand and BED_mud), three for sediment from Davis Pond River Diversion representing sand, silt and clay-type sediments (D_sand, D_silt, and D_clay, respectively), and one for the fine sediment from the Atchafalaya River. Sediment from the Atchafalaya River and the Davis Pond Diversion did not reach the study area during the present modeling time and thus will not be further elaborated. The attributes for sediment from the Atchafalaya River are selected based on Xu et al. (2011). So long as the sediment from the Atchafalaya River was confined to the inside of the Atchafalaya Bay, no further refinement on sediment types from this source was required. All of the sediment classes are considered as non-cohesive sediment types. Sediment erosion parameters are based on similar studies in the inlets and in the Gulf of Mexico (Warner et al., 2008; Xu et al., 2011, Gatto et al., 2017) and are summarized in Table 2.1 excluding non-erodible sediment type. The attributes of non-erodible sediment are similar to BED_sand, except for values of settling velocity and critical shear stress for erosion that is artificially enlarged to 100 mm/s and 200 Pa to ensure no sediment movement for this sediment class.

4.2.3.2 Spatially non-uniform initial bed

The initial sediment distribution is approximated using the 50-year archived geologic sedimentary data from the usSEABED project (Buczkowski et al., 2006). The data comprises more than 50,000 grain size records for sand, silt and clay sediment fractions. The silt and clay sediment types are combined as BED_mud sediment type in this study. The data is then
interpolated over the modeling domain to generate spatially non-uniform initial BED_mud and BED_sand distributions. The interpolated BED_sand fraction for the whole domain, as well as the Mississippi birdfoot delta and Barataria Pass, is illustrated in Fig. 4.3. The area deeper than 300 m on the continental shelf is comprised of consolidated mud in Xu et al. (2011). In this study, to simplify the calculation and avoid unrealistically high erosion rate, the depth of 300-500 m is represented as 100% BED_sand. The area deeper than 500 m is considered as non-erodible bed as the bed change in that area is not of interest. Moreover, the areas inside the Mississippi River channel and in the mouths of the outlets were subject to large velocity (constantly exceeding 2 m/s) that caused unrealistically high erosion rates and eventually made numerical computation unstable. Therefore, these areas were also treated as artificially non-erodible sediment type. Except for the areas comprised of non-erodible sediment type, the sum of BED_sand and BED_mud add up to 100%. In the locations in which bed is considered as non-erodible, no sediment type other than non-erodible sediment type is specified.

4.2.3.3 Fluvial sediment discharge from the Mississippi river

The sediment discharge at the Mississippi River boundary is taken from Allison et al. (2012) that is based on the measurements at the Belle Chasse station. This station is maintained by U.S. Geological Survey (USGS 07374525) and is located on the west bank of the Mississippi River channel at latitude 29°51'25" and longitude -89°58'40". Sediment was sampled based on USGS boat surveys conducted along a cross-section at the site, 12-15 times per year (Allison et al., 2012). The daily sediment loads at this station were quantified from separate rating curves for total sediment load and sand load from the data that is available during April-June 2010 (Allison et al., 2012). The fraction of fine sediments (M_silt and M_clay) is taken by subtraction of sand
load from total load. 75% and 25% of fine sediment discharge are allocated for $M_{\text{clay}}$ and $M_{\text{silt}}$ based on the suggestion in Allison et al. (2012).

Fig. 4.3. (a) Interpolated sand fraction from usSEABED data as non-uniform initial bed composition. The area between 300-500 m depth (red band) is considered as sand to avoid unrealistic large erosion. The blue area in the southern model boundary, the area inside the Mississippi channel, and in front of the Mississippi River passes are modeled as a non-erodible bed to stabilize the model and minimize southern boundary effects. (b) Same as (a) but zoomed to birdfoot area. (c) Same as (a) but zoomed to Barataria Pass.
Sediment discharge for the Atchafalaya River was taken from Allison et al. (2012) that is collected for USGS 07381495 station at Melville, Louisiana. Since there is only one type of sediment assigned to this boundary (fine sediment type), the sand load from Allison et al. (2012) is subtracted from total load (from the same data source) and applied to the model.

No sediment discharge is considered from open boundaries. The reason is because the Mississippi birdfoot delta extends across the Louisiana continental shelf that blocks the alongshore flow from east to west (Wiseman and Dinnel, 1988). Therefore, no sediment from eastern boundary reaches our study area. Further, since the alongshore flow on the west side of the Mississippi birdfoot is a primarily westward one, no sediment is transported in from the western boundary either.

Table 4.1. Input parameters for the sediment model

<table>
<thead>
<tr>
<th></th>
<th>BED_sand</th>
<th>BED_mud</th>
<th>M_sand</th>
<th>M_silt</th>
<th>M_clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean diameter (mm)</td>
<td>0.125</td>
<td>0.063</td>
<td>0.125</td>
<td>0.063</td>
<td>0.015</td>
</tr>
<tr>
<td>Density (kg m$^{-3}$)</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>Settling velocity (mm s$^{-1}$)</td>
<td>13.5</td>
<td>3.43</td>
<td>6.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Erosion rate (kg m$^{-2}$ s$^{-1}$)</td>
<td>1×10$^{-5}$</td>
<td>1×10$^{-5}$</td>
<td>5×10$^{-4}$</td>
<td>5×10$^{-4}$</td>
<td>5×10$^{-4}$</td>
</tr>
<tr>
<td>Critical shear stress for erosion (Pa)</td>
<td>0.25</td>
<td>0.20</td>
<td>0.25</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>Critical shear stress for Deposition (Pa)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.50</td>
<td>0.60</td>
<td>0.50</td>
<td>0.60</td>
<td>0.70</td>
</tr>
</tbody>
</table>

4.3 Model validation

The radioactive tracer elements that were absorbed by settling particles are widely used to assess the transport and fate of sediments. Profiles of $^{137}$Cs and $^{210}$Pb are mostly used to estimate long-term deposition while those of $^{234}$Th and $^7$Be are more suitable for short-term deposition. Since the simulation time covers a time span of three months, $^{234}$Th ($t_{1/2} = 24.1$ days) and $^7$Be ($t_{1/2} = 53.1$ days) better represent the accumulation rate of sediment in this time-
scale. No radionuclides data were found for April-June 2010. Therefore, the validation for the numerical model is done against field measurement (MiRIR I: Mississippi River Interdisciplinary Research I) from Corbett et al. (2004) performed in early April 2000. The spatial distribution of the $^{234}$Th and $^7$Be inventories from Corbett et al. (2004) are depicted in Fig. 4.4 and Fig. 4.5. The total deposition of Mississippi fluvial sediments after three months modeling period is shown in Fig. 4.6. FVCOM-SWAVE-SED can qualitatively reproduce the depositional pattern in front of the Southwest Pass and the Louisiana Bight. Corbett et al. (2004) provided a measurement of sediment accumulation at two shelf locations: near river and open shelf environments. They reported a deposition of 5 and 9 cm for near-river station based on $^{234}$Th and $^7$Be inventories, respectively. The accumulation rate from our model is about 3.2 cm at the river mouth (Fig. 4.6). However, the calculated deposition in open coast is at least one order of magnitude smaller than that reported by Corbett et al. (2004). This could be because part of the riverine sediments is deposited inside the Mississippi River channel and the three-month simulation period is not sufficient for reworking of those sediments to reach the continental shelf. This fact will be further discussed in Section 4.4.2.
Fig. 4.4. Excess $^{234}$Th inventories during MiRIR I and MiRIR II projects from Corbett et al. (2004).
Fig. 4.5. Spatial distribution of $^7$Be from Corbett et al. (2004).
Fig. 4.6. Total riverine sediment deposition after three months of simulation (April-June 2010) in front of the Mississippi birdfoot and in the Louisiana Bight.

The result from the numerical model is also compared with the true-color satellite images during the three-month simulation. A comparison of the model results and the satellite image obtained from Aqua-1 MODIS true color image with 250-m resolution for two time instances between April-June 2010 is presented in Fig. 4.7 and Fig. 4.8. The numerical modeling result and the satellite images quantitatively agree with each other. In the image of 1 May 2010 07:51 PM, the wind is in a pre-frontal phase of the extratropical storm with dominant southeasterly wind. The Mississippi River plume bends northward into the Louisiana Bight as is also reproduced by the model. On the other hand the wind on 26 April 2010 07:32 PM is an upwelling favorable one diverting the plume to the mid-shelf and towards the east as can be seen in both satellite image and numerical model result. It is noted that quantification of suspended sediment concentration from the satellite images is not straightforward. Therefore, it is hard to make more quantitatively
comparison between the numerical model and satellite-based data. Moreover, The Mississippi birdfoot consists of many small outlets that are not resolved in our numerical model. Therefore, concentration of suspended sediment in some areas around the birdfoot is unrealistically low due to incorrect initial condition.

Fig. 4.7. (Left) The true-color satellite image for 1 May 2010 07:51 PM. (Right) The total (sum of M_silt, M_clay, BED_mud and BED_sand) surface suspended sediment concentration from the numerical model at 1 May 2010 08:00 PM.

Fig. 4.8. (Left) The true-color satellite image for 26 April 2010 07:32 PM. (Right) The total (sum of M_silt, M_clay, BED_mud and BED_sand) surface suspended sediment concentration from the numerical model at 26 April 2010 07:00 PM.
4.4 Results

4.4.1 Water and fluvial sediment budgeting from Belle Chasse to major outlets

The model simulated water and sediment flux at major Mississippi River outlets during April-June 2010, along with observational data, are shown in Fig. 4.9 to Fig. 4.11. The observed water discharges are based on individual rating curves for each outlet that were developed mainly from boat-based ADCP measurements taken between 2008-2011 (six to fourteen measurements between 2008 and 2011) (Allison et al., 2012). Some data for calculation of rating curves were also taken from USACE New Orleans district discharge measurements (Allison et al., 2012).

The numerical model predicts 14.7% of water loss below Belle Chasse and above Head of Passes through three resolved passes (Baptiste Collette, Culbit’s Gap and Grand Pass), which is about half of the estimation of the measured water loss through these passes (Fig. 4.9). The result of the numerical model indicates larger water discharge through tri-furcation channels below the Head of Passes (Southwest Pass, South Pass and Pass a Loutre). In particular, the computed water discharge through the Southwest Pass is 64% of the total discharge from Belle Chasse and 78% of the total water discharge below Head of Passes (Fig. 4.9). The calculated discharge from the numerical model at Southwest Pass is almost twice as large as that observed. The difference could be attributed to the challenges in flux measurement in the channels that requires simultaneous measurement at all the exits of the Mississippi birdfoot. The ADCP measurement has a common error due to side lobe interference that fails to provide an accurate estimation of the velocity in the upper 6-12% of the water column and close to bed (Mueller and Wanger, 2009). Except for the Southwest Pass where the maximum depth reaches 15 m, the depth in other passes does not exceed ~ 10 m. Therefore, considerable information on the current
at surface and close to bed is lost during the measurement process. Other errors such as the effect of sediment on backscattered acoustic energy, the rating curve method itself, and user-specific configuration of the instrument are also among the shortcomings of ADCP method and could add to uncertainly of measurements (Mueller and Wanger, 2009). On the other hand, there is a notable discrepancy between the existing observational data of Allison et al. (2012) and Li et al. (2011). Our prediction of the discharge from the Southwest Pass is closer to the measurement of Li et al. (2011) that was carried out in the same simulation period (67%).

The sum of FVCOM-calculated water discharge exiting from all the outlets is 97% of the discharge introduced through the Belle Chasse boundary (Fig. 4.9). The total observed water flow from all exits is 78.5% of the flow at Belle Chasse. Considering the water discharge from other exists such as Bohemia, Ostrica, Ft St. Philip, West Bay and Small Cuts (Allison et al., 2012), this percentage adds up to 94.2% that is close to the prediction by the numerical model.

The percentage of fine sediment deposition (M_silt and M_clay) below Belle Chasse and above Head of Passes calculated by the model is 52.5%, of which 43.1% was deposited in the main channel and the rest exited through Baptiste Collette, Culbit’s Gap, and Grand Pass (Fig. 4.10 and Fig. 4.11). Similar to the water discharge, the majority of the suspended sediment exits from the Southwest Pass that amounts to 38.9% of the sediment entered into the system through Belle Chasse.

Predicted suspended sediment flux at the Southwest Pass is 17% more than the measured data (Fig. 4.10 and Fig. 4.11). Contrarily, the sediment flux from the numerical model is smaller in South Pass and Pass a Loutre compared to the observed data. The difference in sediment flux at these three passes is due to the method of estimation of sediment in passes used by Allison et al. (2012). The estimated sediment load at tri-furcation channels below Head of Passes was based
on daily-averaged measurements at RM2.6 above Head of Passes and subsequent fractioning of sediments at each channel using its individual water discharge over total water discharge for three passes (Allison et al., 2012). Therefore, if we consider the summation of the sediment discharge at Southwest Pass, South Pass and Pass a Loutre, the difference between the calculated and observed suspended sediment is very small (~ 1%) (Fig. 4.10 and Fig. 4.11).

It is noteworthy that the width of the passes are on the same order of magnitude (Fig. 4.13 and Fig. 4.14). However, Southwest Pass is deeper than other passes at least by an order of magnitude. During the Mississippi flood season that typically starts at October and continues to a flood peak in March or April (Roberts et al., 2015), an increase of river discharge results in larger percentage of depth change in shallow passes. Therefore, it is estimated that the percentage of water and sediment flux at the outlets other than Southwest Pass would increase at flood time. Contrarily, during dry season in the summer time, the ratio of water and fluvial sediment through Southwest Pass becomes larger.
depicted in Fig. 4.1. The black values are the calculated one from the numerical model and the red values are from observations of Allison et al. (2012). The percentages compared to the value at Belle Chasse are given in parenthesis.

Fig. 4.10. Integrated suspended sediment discharge for M_silt sediment type (in $10^6$ tons/3-months) for April-June 2010 for major water exits from the Mississippi River below Belle Chasse, Louisiana. The black values are the calculated one from the numerical model and the red values are from observations of Allison et al. (2012). The percentages compared to the value at Belle Chasse are given in parenthesis.

Fig. 4.11. Same as Fig. 4.10 except for M_clay sediment type.
4.4.2 Sediment dispersal pattern near birdfoot delta

The deposition patterns of M_silt and M_clay sediment for the three-month simulation period are depicted in Fig. 4.12. The M_sand sediment is deposited within the first five kilometers from the upstream Belle Chasse boundary (figure not shown). Back-of-envelope calculation indicates that with a settling velocity of 6.1 mm/s, a mean depth of 27 m in the river channel near Belle Chasse, and a depth-averaged current magnitude of 0.83 m/s, the M_sand sediment exported from the Mississippi River would only travel ~ 3.67 km before initial deposition. Therefore, M_sand does not reach the continental shelf within the three-month simulation period.

M_silt sediment from the Mississippi River mostly deposits inside the river channel (red contour line of 1 cm deposition in Fig. 4.12a). The model predicts a radial deposition of 1 mm with a radius of ~ 5-10 km around the Baptiste Collette, Grand Pass and Pass a Loutre. Due to the existence of a jetty on the east side of the South Pass, M_silt is accumulated mostly at the west side of this outlet (Fig. 4.12a). The strongest river outflow exists in front of the Southwest Pass. The jet-like current transports majority of M_silt as suspended load and less M_silt is deposited near the pass. However, the 0.1 mm deposition line encompasses an area of ~ 500 km², indicating a high energy and low deposition situation near this pass.

Because the same settling velocity is assumed for M_clay and M_silt, the deposition pattern of M_clay is similar to that of M_silt. However, M_clay has a smaller critical shear stress for erosion and is, thus, more easily resuspended and transported onto the continental shelf. Moreover, the ratio of M_clay concentration and M_silt concentration is 3:1. Therefore, a deposition on the order of a few centimeters is observed in front of the outlets for M_clay (Fig.
4.12b). A large part of the fluvial M_clay sediment from Southwest Pass is deposited within a radius of 5 km near this pass.

Fig. 4.12. Deposition of (a) M_silt and (b) M_clay sediment around the outlets of birdfoot delta and in the Louisiana Bight for April-June, 2010.
The three-month-averaged cross-sectional suspended sediment concentration (SSC) distributions for M_clay and M_silt sediment are presented in Fig. 4.13 and Fig. 4.14. The average along-channel velocity at the transects of the Southwest Pass, South Pass, Pass a Loutre, Main Pass, Locket Pass and Grand Pass is 1.17, 1.55, 0.85, 0.62, 1.12 and 0.36 m/s, respectively. The cross-sectional area and geometry vary considerably among the passes. Southwest Pass is the deepest (~ 15 m) while some other passes such as Main Pass are very shallow (average depth ~ 0.18 m). The larger cross-sectional area at Southwest Pass results in overall dominant water and sediment discharge as presented in section 4.4.1.

Although the SSC at the passes show some vertical or lateral variation (Fig. 4.13 and Fig. 4.14), the scale of the color plots conveys that the SSC of both sediment types is almost horizontally and vertically uniform through the cross-section at each of the exits. The SSC concentration of M_clay is larger than that of M_silt probably because of the specified proportion at the upstream boundary (75% vs 25%). There is not a significant difference in the concentration of suspended sediments among various inlets, though the value in the South Pass and Main Pass is smaller than other exits.

Fig. 4.15 and Fig. 4.16 present the SSC distributions for along-plume and cross-plume transects at 5 and 10 km offshore of the Southwest Pass for M_silt and M_clay, respectively. The sediment concentration of $10^{-2}$ kg/m$^3$ is limited to upper four meters of the water column, where the current is larger than 0.5 m/s. This region of higher concentration extends the entire 8 km of transect at 5 km away from the Southwest Pass (Fig. 4.15a and Fig. 4.16a). The width of the high-concentration region is reduced at 10 km away from the Southwest Pass (Fig. 4.15b and Fig. 4.16b vs. Fig. 4.15 and Fig. 4.16a). Fig. 4.15c affirms that the average current magnitude of 1 m/s is sustained over more than eight kilometers away from the outlet during the present
simulation period. It is noted that the Mississippi River plume is dynamic and the velocity and SSC in Fig. 4.15 and Fig. 4.16 is an approximate representation of these variables along the plume.

Fig. 4.13. Three-month averaged suspended sediment concentration for M_clay sediment (color, kg/m$^3$ on a logarithmic scale) and along-channel current (white contour, m/s, interval being 0.25 m/s) at each of the major Mississippi birdfoot outlets. The location of the cross-sections is shown in Fig. 4.1.
Fig. 4.14. Same as Fig. 4.13 except for M_silt sediment.
Fig. 4.15. (a) Three-month averaged suspended sediment concentration for M_silt sediment (color, kg/m$^3$ on a logarithmic scale) and along-plume current (black contour, m/s) at 5 km offshore of the Southwest Pass. (b) Same as (a) but at 10 km offshore of the Southwest Pass. (c) Three-month averaged suspended sediment concentration for M_silt sediment (color, kg/m$^3$ on a logarithmic scale) and parallel-to-transect current (black contour, m/s) at longitudinal transect from the Southwest Pass to 10 km offshore.
4.4.3 The response of surface sediment to different wind events

The circulation in the Louisiana Bight is governed by the confluence of buoyancy-driven flow from the Mississippi River, wind and wave forcing (Zhang et al., 2014, Rong et al., 2016). Given that riverine sediment from the Mississippi River is mainly suspended in the water column, it is highly affected by the circulation pattern over the continental shelf. During April-
June 2010, both upwelling and downwelling favorable winds occur that enable us to assess the influence of wind on sediment dispersal over the shelf.

The surface SSC for M\textsubscript{silt}, M\textsubscript{clay}, BED\textsubscript{mud} and total sediment (i.e., summation of M\textsubscript{silt}, M\textsubscript{clay}, BED\textsubscript{mud} and BED\textsubscript{sand}) for various wind directions are depicted in Fig. 4.17 to Fig. 4.23. Since the surface SSC for BED\textsubscript{sand} is negligible compared with other sediment types, the individual plot for this type of sediment is not included in the aforementioned plots. However, the concentration for this sediment type is included in total sediment concentration in panel (d) of these plots.

The northerly winds mainly occur in the post-frontal stage of the extratropical storm events. When the wind is from the NE (Fig. 4.17), the direction of the wind is aligned with the direction of the Mississippi plume exiting the Southwest Pass. Therefore, the jet of suspended sediment from this pass is extended further offshore. Fig. 4.17 shows that the threshold concentration of $10^{-3}$ kg/m$^3$ in the surface for M\textsubscript{silt} and M\textsubscript{clay} sediment types is retained for ~50 and 80 kilometers away from the Southwest Pass outlet, respectively. Elongation of Mississippi plume is observed during other downwelling favorable winds from E and SE directions in which the Mississippi plume tends to hug the coastline and move downcoast (Fig. 4.19 and Fig. 4.20).

The winds from NW and W directions are observed during the post-frontal period. These winds push the plume towards mid-shelf and east (Fig. 4.18 and Fig. 4.23). A similar movement of the Mississippi plume is also observed for the plume structure during SW wind, though this wind pushes part of the plume to bend into the Louisiana Bight close to the Grand Pass (Fig. 4.22). The plume structure corresponding to a S wind has a more radial shape (Fig. 4.21).
The dispersion of suspended riverine sediment from the passes other than the Southwest Pass is also affected by wind direction. However, the change of SSC and the direction of plume from those passes are not significant compared to the one from the Southwest Pass. The concentration of $10^{-3}$ kg/m$^3$ from those passes is mostly spread around the passes.

The surface SSC of BED_mud sediment is mostly seen during the wind from easterly and southerly sectors during which longer fetch is available to develop stronger waves at the coastline. On the other hand, since there is little fetch for the wind-waves during the northerly winds, the wave-induced sediment resuspension is minimal and surface concentration for BED_mud is mainly confined to the area close to inlets, where current-induced sediment is large (Fig. 4.17c and Fig. 4.18c).
Fig. 4.17. Surface suspended sediment concentration (kg/m³, on a logarithmic scale) for a typical NE wind for (a) M_clay, (b) M_silt, (c) BED_mud, (d) total sediment (i.e., sum of M_clay, M_silt, BED_sand and BED_mud). The red arrow indicates the magnitude and direction of the wind. The blue, black and red contour lines represent concentrations of $10^{-2}$, $10^{-3}$ and $10^{-4}$ kg/m³, respectively.
Fig. 4.18. Same as Fig. 4.17, except for a typical NW wind.
Fig. 4.19. Same as Fig. 4.17, except for a typical E wind.
Fig. 4.20. Same as Fig. 4.17, except for a typical SE wind.
Fig. 4.21. Same as Fig. 4.17, except for a typical S wind.
Fig. 4.22. Same as Fig. 4.17, except for a typical SW wind.
Fig. 4.23. Same as Fig. 4.17, except for a typical W wind.
4.4.4 Hydrodynamic forcing in the Barataria Pass

Sediment erosion, transport, and deposition in the Barataria Pass are mainly controlled by tidal current, wind-driven subtidal current (especially during the cold front event), and wave-induced sediment resuspension. April-June 2010 is a transition period of the year during which winter cold front passage events are still seen (April 21 – May 5, 2010), while weaker summer wind from southern sectors is persistent in June 2010. Fig. 4.24 presents the wind vector plot for a typical point on the shelf side of the Barataria Pass highlighting two cold front passages events in late April and early May, 2010.

![Wind stick plot near the Barataria Pass between April-Jun 2010. Two cold front passage events (CF-1: April 21 – April 28 and CF-2: April 28 – May 3) are shaded.](image)

The time series of water level and velocity are separated into four frequency bands (low frequency: $T>20$ days; subtidal frequency: $40$ hours $<T<20$ days; tidal frequency: $4$ hours $<T<40$ hours, high frequency: $T<4$ hours), and the band-pass filtered signals on the continental shelf (i.e., CSI-09), at the Barataria Pass, and at points in its shelf- and bay-side, and at a point inside the Barataria Bay (Fig. 4.1a and points B1-B3 and BB in Fig. 4.1c) are depicted in Fig. 4.25 to Fig. 4.29. At the offshore station, the subtidal and long-term signals dominate the velocity field (Fig. 4.25), while tidal signal dominates the velocity field at the inlet stations with the relative
signal variance of more than 90% (Fig. 4.26 to Fig. 4.28). The tidal frequency is still the most important band inside the Barataria Bay (Fig. 4.29), though its influence is reduced compared to the one at inlet locations. The band-pass filtering of water level reveals that contribution from the tidal signal on water level reduces as we move from offshore to inlet and further inside the Barataria Bay. The percentage of tidal signal for points BB, B1, B2, B3 (Fig. 4.1c) and CSI-09 are about 33, 43, 48, 55 and 67% (Fig. 4.25 to Fig. 4.29). Conversely, the percentage of low-frequency band increases from the continental shelf to inside the estuary and becomes the major component inside the Barataria Bay (~ 42% in Fig. 4.29). At inlet locations, the effects of subtidal and low-frequency signals are on par with the tidal signal to determine water level variation.
Fig. 4.25. Band-pass filtered velocity (a) and water level (b) for CSI-09 station (Fig. 4.1a). Long-term frequency: $T > 20$ days, subtidal frequency: $40$ hours $< T < 20$ days, tidal frequency: $4$ hours $< T < 40$ hours, high frequency: $T < 4$ hours.
Fig. 4.26. Same as Fig. 4.25 except for a typical point B3 (Fig. 4.1c) at the shelf side of the Barataria Pass.
Fig. 4.27. Same as Fig. 4.25 except for a typical point B2 (Fig. 4.1c) at the Barataria Pass.
Fig. 4.28. Same as Fig. 4.25 except for a typical point B1 (Fig. 4.1c) at the bay side of the Barataria Pass.
Fig. 4.29. Same as Fig. 4.25 except for a typical point BB (Fig. 4.1c) in the Barataria Bay.
Fig. 4.30. Velocity and sediment fluxes through the Barataria Pass: (a) velocity flux, (b) \text{BED\textunderscore sand} sediment flux, and (c) \text{BED\textunderscore mud} sediment flux. The shaded area represents the cold front period.

4.4.5 The pattern of erosion and deposition near the Barataria Pass

Given that the Barataria Pass is an ebb-dominated tidal inlet due to freshwater outflow from the Davis Pond Diversion, the three-month averaged velocity flux in this inlet is negative (towards continental shelf) (Fig. 4.30a). The flux estimation is made in a cross-section at the entrance of the Barataria Pass (Fig. 4.2c, red line). However, the sediment flux for \text{Bed\textunderscore sand} and \text{Bed\textunderscore mud} are both positive indicating net bayward sediment flux (Fig. 4.30b and Fig. 4.30c). The flux for sand type sediment is negligible compared with mud type sediment. It is noted that the
SSC for M_clay and M_silt at this pass is negligible and is not shown. The reason for the different direction of net flux for water and suspended sediments are elaborated in Section 4.5.

Fig. 4.31 presents the net bed change along the barrier islands of the Barataria Bay for the whole April-June 2010 period. The predominant pattern near the Barataria Pass is one erosion area (maximum and averaged erosion rate of 2.87 and 0.58 cm, respectively, in three month) saddled with two deposition regions (deposition rate at shelf side: max = 0.51 cm, mean = 0.074 cm; deposition rate at bay side: max = 0.42 cm, mean = 0.035 cm per three months).

The morphological evolution of bed in front of the Barataria Pass during a cold front passage event resembles the one after three months of simulation, though the deposition/erosion thickness is an order of magnitude smaller for the former (Fig. 4.32). The decomposition of the bed evolution during pre- and post-frontal phase for CF-1 event is illustrated in Fig. 4.33. The pre-frontal stage was associated with southerly winds that lasted for 106 hours for that event (21 April 3:00:00 AM to 25 April 1:00:00 PM). The duration of post-frontal stage through which the wind blew from northern sector was 63 hours for CF-1 event (25 April 2:00:00 PM to 28 April 5:00:00 AM). The average (maximum) wind speed during pre- and post-frontal stages were 6.86 (11.57) and 5.68 (8.76) m/s, respectively. Fig. 4.33 reveals that the bed change in pre-frontal phase is more akin to the bed change in the whole cold-front event. The net morphological change during post-frontal phase shows more distinct ebb tidal delta (Fig. 4.34). The deposition in the post-frontal stage is clearly less than the one during the pre-frontal stage for this CF-1 case.
Fig. 4.31. (a) Net bed change along the barrier islands of the Barataria Bay during April-June 2010. (b) zoomed in around the Barataria Pass. The thick dashed polygons represent one erosion (green) and two deposition areas (black) on the shelf- and bay-side of the Barataria Pass.
Fig. 4.32. Same as Fig. 4.31 except for net bed change during CF-1 cold front passage event. The solid contour lines illustrate the deposition of $10^{-4}$ m (black), $10^{-5}$ m (red) and erosion of $10^{-4}$ m (green).
Fig. 4.33. Same as Fig. 4.32 except for net bed change during the pre-frontal phase of CF-1 cold front passage event.
Fig. 4.34. Same as Fig. 4.32 except for net bed change during the post-frontal phase of CF-1 cold front passage event.
The net volume of water transported during both phases of the extratropical storm for CF-1 and CF-2 events are towards continental shelf (Table 4.2). In spite of shorter post-frontal period for both extratropical storms (CF-1 event: 106 vs. 63 hours for duration of pre- and post-frontal phase; CF-2 event: 128 vs. 33 hours for duration of pre- and post-frontal phase, respectively), the water drained during the post-frontal stage is larger than that during the pre-frontal stage (Table 4.2). The negative direction of sediment mass for both bed-type sediments at post-frontal stage affirms the seaward flux of sediment. However, due to the larger bayward movement of sediment during the pre-frontal stage, the net transported sediment mass at both CF-1 and CF-2 events are positive (towards the Barataria Bay).

Table 4.2. Water/sediment volume/mass transfer during CF-1 and CF-2 and their pre- and post-frontal stages. The negative/positive sign indicates flux towards the ocean/estuary.

<table>
<thead>
<tr>
<th></th>
<th>CF-1 Event</th>
<th>CF-2 Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-front</td>
<td>Post-front</td>
</tr>
<tr>
<td>Water (m$^3$)</td>
<td>-1.23E+8</td>
<td>-1.88E+8</td>
</tr>
<tr>
<td>BED_sand (kg)</td>
<td>3.62E+2</td>
<td>-3.62E+2</td>
</tr>
<tr>
<td>BED_mud (kg)</td>
<td>2.87E+5</td>
<td>-1.18E+5</td>
</tr>
</tbody>
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4.5 Discussion

4.5.1 The bed shear stress in the study area during the three-month simulation period and the cold front passage events

Fig. 4.35a displays the combined wave-current bed shear stress averaged over three month simulation time. The red (blue) contour lines in this figure distinguish the area in which large bed shear stress (i.e. $\tau_{wc} > 0.2$ Pa) occurs for 50% (80%) of the three month simulation period. It is seen that the 50% contour line in Fig. 4.35a is in conformity with distinct erosion/deposition regions presented in Fig. 4.31. The area of large current-induced bed shear
stress (50% exceedance threshold) starts from ~ 1 km on the bay-side of the inlet and extends to ~ 2 km on the shelf-side (Fig. 4.35c). The wave-induced bed shear stress is insignificant compared with the current-induced one in front of the pass on shelf-side (Fig. 4.35b), though it is larger than current-induced bed shear stress away from the inlet just along the barrier islands. The patterns of bed shear stress averaged over CF-1 and CF-2 events, respectively, are alike the three-month-average one, though bed shear stress is notably larger in CF-2 event (Fig. 4.35d to Fig. 4.35i). This explains the larger Bed_mud and Bed_sand fluxes during the CF-2 event than that during the CF-1 event shown in Fig. 4.30b and Fig. 4.30c.

Wave-induced bed shear stress is much larger during the pre-frontal phase along the barrier islands (Fig. 4.36b and Fig. 4.36h), as stronger southerly wind with longer fetch dominates the coastline. During the post-frontal phase (Fig. 4.36e and Fig. 4.36k), the associated northerly winds are weaker (Fig. 4.24) and waves are fetch-limited along the coastline. Thus, wave-induced bed shear stress is smaller than the current-induced shear stress by an order of magnitude. Along the axis of the Barataria Pass, current-induced bed shear stress always dominates the wave-induced one. During the pre-frontal phase of the CF-2 events, combined shear stress at erosional area is greater than the bed resistance in 80% of the time (Fig. 4.36g). Most of this shear stress at the entrance of the inlet and up to 2 km offshore is contributed by the current component (Fig. 4.36i), though the wave component also helps resuspend sediments up to 4 km offshore. It is noted that the comparison of excess shear stress in Fig. 4.35 and Fig. 4.36 is to provide insights into the resuspension process, though the bed change depends not only on excess bed shear stress but also on settling velocity and erosion rate.

The calculated shear stress for representative points (see Fig. 4.1c for locations B1 to B4) shows that current-induced shear stress dominates in the area near the Barataria Pass (Fig. 4.37).
The maximum value of $\tau_c$ can reach 3.80, 6.47, 4.16 and 1.88 Pa at points B1 to B4, respectively. $\tau_w$ is two orders of magnitude smaller than $\tau_c$ on the bay side and inlet location (Fig. 4.37c and Fig. 4.37d). The wave-induced bed shear stress in bayside and inlet location is always less than 0.035 Pa that is insufficient to resuspend sediments at these two locations ($\tau_{ce} = 0.2$ Pa). Although the value of $\tau_w$ at point B3 occasionally reaches the threshold to resuspend the sediments (maximum $\tau_w = 0.34$ Pa), it is still an order of magnitude less than the current-induced shear stress. The wave-induced shear stress can exceed the current-induced one for certain period of time at point B4 and the maximum $\tau_w$ amounts 1.34 Pa that is on par with the maximum $\tau_c$ (1.88 Pa).

4.5.2 The bed shear stress in the study area during a tidal cycle

In order to determine the contribution from different frequency bands to sediment deposition/erosion areas, a band-pass filtering analysis is applied to points B1 and B3 (Fig. 4.1c) and the result is shown in Fig. 4.38. It is observed that the major contribution to the variance of combined wave-current bed shear stress is from the tidal signal. The mean value of $\tau_{wc}$ at points B1 and B3 is 0.50 and 0.58 Pa, respectively (Fig. 4.38). The variance in combined wave-current shear stress caused by tidal signal can exceed 2.0 Pa that is four times larger than the mean value (Fig. 4.38). Thus, tidal forcing has the major effect in the erosion of sediment at inlet location. In addition to tidal component, the sub-tidal signal also has a noticeable effect on the variation of bed shear stress ($\sim 20\%$) (Fig. 4.38). The maximum combined wave-current bed shear stress due to sub-tidal signal at points B1 and B3 is 0.76 and 0.61 Pa, respectively that is slightly greater than the mean value.
Fig. 4.35. (a), (b) and (c): Color map plots for bed shear stress (Pa, on a logarithmic scale) calculated for three month simulation period for combines wave-current stress ($\tau_{wc}$), wave-induced bed shear stress ($\tau_w$) and current-induced bed shear stress ($\tau_c$), respectively. (d) to (f): identical to (a) to (c) but for the CF-1 event. (g) to (i): identical to (a) to (c) but for the CF-2 event. The red, blue and black contour lines represent the area in which bed shear stress exceeds the critical shear stress for erosion for BED_mud sediment type (0.2 Pa) by 50, 80 and 100 percent, respectively. The dotted points are representative locations in the study area.
Fig. 4.36. (a), (b) and (c): Color map plots for bed shear stress (Pa, on a logarithmic scale) calculated for the pre-frontal stage of the CF-1 event for combines wave-current stress ($\tau_{wc}$), wave-induced bed shear stress ($\tau_w$) and current-induced bed shear stress ($\tau_c$), respectively. (d) to (f): identical to (a) to (c) but for the post-frontal stage of the CF-1 event. (g) to (i): identical to (a) to (c) but for the pre-frontal stage of the CF-2 event. (j) to (l): identical to (a) to (c) but for the post-frontal stage of the CF-2 event. The red, blue and black contour lines represent the area in which bed shear stress exceeds the critical shear stress for erosion for BED_mud sediment type (0.2 Pa) by 50, 80 and 100 percent, respectively.
The low-pass filtering analysis of net bed change for a typical point in erosion area and two points in depositional areas at the shelf- and bay-side of the inlet are depicted in Fig. 4.39 and Fig. 4.40. It is observed that tidal variation dominate the net bed change in both erosion and deposition areas. The maximum contribution of sub-tidal signal pertains to the point in deposition area on the bayside of the Barataria Pass, which is close to half of the tidal influence (Fig. 4.40b).
A snapshot of BED_mud SSC and horizontal current velocity for an along-inlet cross section of the Barataria Pass during a tidal cycle at the pre-frontal stage (2010-4-30 20:00:00 to 2010-5-1 20:10:00) is illustrated in Fig. 4.41 and Fig. 4.42. Although the water flux transported during the ebb time is ~ 58% of the positive flux transported towards bay during the flood time (Fig. 4.41e) and despite the fact that current-induced bed shear stress at the location of the erosion area in ebb time is about twice as large as the one during flood time ($\tau_{c,shelf}$ in Fig. 4.41c), the amount of sediment that is transported into the bay is 16.4 times greater than the one transported from out of the bay from the inlet transect (-1.88 KTon vs. 30.86 KTon in Fig. 4.41d). This could be explained considering the location of the erosional area (Fig. 4.31) and the transect location in the Barataria Pass (Fig. 4.2). The majority of the erosional area lies on the shelf-side of the inlet transect. Therefore, most of the sediment that is eroded from this area due to ebb current does not pass through cross-section at the Barataria Pass. As a result, the effect of negative sediment flux at the cross section of this pass is not dominant. During flood flow, sediments that are resuspended from the erosional area are carried into the bay and radially deposited with a radius of approximately 4 km inside the bay (Fig. 4.42f, Fig. 4.43). This creates a positive sediment flux at the cross-section of the inlet. The location of the erosion area for resuspension of sediment as well as the location of cross-section of the Barataria Pass makes the bayward sediment flux larger than seaward sediment flux. Therefore, the net sediment flux at this pass is positive (towards the bay).
Fig. 4.38. Band-pass filtered bed shear stress for (a) a typical point on the shelf-side and (b) on the bayside of the Barataria Pass. Long-term frequency: $T > 20$ days, subtidal frequency: $40$ hours $< T < 20$ days, tidal frequency: $4$ hours $< T < 40$ hours, high frequency: $T < 4$ hours.
Fig. 4.39. Band-pass filtered net bed change for a typical point in the erosional area on the shelf side of the Barataria Pass. Long-term frequency: $T > 20$ days, subtidal frequency: $40$ hours $< T < 20$ days, tidal frequency: $4$ hours $< T < 40$ hours, high frequency: $T < 4$ hours.
Fig. 4.40. Band-pass filtered net bed change for a typical point on the (a) shelf-side and (b) the bayside of the Barataria Pass. Long-term frequency: $T > 20$ days, subtidal frequency: 40 hours $< T < 20$ days, tidal frequency: 4 hours $< T < 40$ hours, high frequency: $T < 4$ hours.
Fig. 4.41. Numerical model results for sediment flux along the Barataria Pass at a time instance during ebb flow in a pre-frontal phase. (a) Significant wave height (color, m), surface current (white arrows, m/s), and representative wind speed (black arrow, m/s). The thick black line shows the location for the along-channel transect. The magenta line represents the transect for cross-channel transect at the inlet (Fig. 4.2c) and two magenta dots represent two typical locations at the bay side and shelf side of the pass (points B1 and B3 in Fig. 4.1c). (b) Depth-averaged stick-plot current at the intersection of along-channel and cross-channel transects. The thick red line represents the current speed (m/s) and direction at this particular moment. (c) current- and wave-induced bed shear stress at the representative shelf- and bay-side points presented in (a). The thick red line represents this particular time instance. (d) Water flux at the cross-channel transect presented in (a). The thick red line represents this particular time instance. (e) Sediment flux for BED_mud sediment at the cross-channel transect presented in (a). The thick red line represents this particular time instance. (f) Suspended sediment concentration (color, kg/m$^3$ on a logarithmic scale) and horizontal current (arrows, m/s) at the along-channel transect depicted in (a). The black and magenta dash lines show the location of cross-channel transect and two representative points presented in (a).
Fig. 4.42. Same as Fig. 4.41 except for a time instance during flood flow in a pre-frontal phase.
Fig. 4.43. (a) Net bed change on coastal Barataria Basin and inside the Barataria Bay during a tidal cycle in post-frontal stage. (b) Same as (a) but zoomed around the Barataria Pass. The thick dashed polygons represent one erosion (green) and two deposition areas (black) on the shelf- and bay-side of the Barataria Pass. The solid contour lines illustrate the deposition of $10^{-4}$ m (black), $10^{-5}$ m (red) and erosion of $10^{-4}$ m (green).
During a tidal cycle in a post-frontal stage (2010-4-27 05:10:00 to 2010-4-28 04:40:00), the depth-averaged velocity and the current-induced shear stress at flood time is weak, especially on the bay side (Fig. 4.44a and Fig. 4.44b). The value of $\tau_c$ exceeds the critical bed shear stress for representative points at shelf and bay side of the inlet at 61% and 15% of the time, respectively (Fig. 4.44c). Thus, relatively less amount of sediment is resuspended during flood time in post-frontal phase of cold front. Besides, as the direction of the wind is opposite to that of the flow at flood time, the water flux is also smaller in the flood period compared to the ebb period. Total volume of water during flood period is 35.8% percent of the one during the ebb period (Fig. 4.44e). Therefore, positive flux of sediment through the Barataria Pass is insignificant (Fig. 4.44d).

During the ebb flow at post-frontal, although the sediment that is eroded from the erosional area on the shelf side of the cross-channel transect is still transported offshore, some sediments are resuspended from the bay-side and transported out of the inlet (Fig. 4.45f). This is due to large current-induced shear stress on the bay-side (Fig. 4.45c). Therefore, the net sediment transport during this tidal cycle is seaward (0.22 KTon during flood time and 2.53 during the ebb time) (Fig. 4.45d). Nonetheless, the net amount of sediment that came in during the pre-frontal phase tidal cycle is an order of magnitude larger than the one that came out of the inlet during post-frontal phase tidal cycle (+28.90 KTon vs. -2.31 KTon).

The net bed change after the tidal cycle in the post-frontal stage is characterized by two distinct radially deposited sediments (Fig. 4.46). The radius of deposition on the shelf side is estimated as about 2 km away from the erosional area. It is noteworthy that the present three-month simulation includes weaker and shorter post frontal stages compared with the extratropical events in the winter season. During winter season with stronger waves and, maybe, stronger
subtidal currents, the export of sediment flux from the bay to the shelf might be more pronounced and merits further investigation.

Fig. 4.44. Same as Fig. 4.41 except for a time instance during flood flow in a post-frontal phase.
Fig. 4.45. Same as Fig. 4.41 except for a time instance during ebb flow in a post-frontal phase.
Fig. 4.46. (a) Net bed change on coastal Barataria Basin and inside the Barataria Bay during a tidal cycle in the post-frontal stage. (b) Same as (a) but zoomed around the Barataria Pass. The thick dashed polygons represent one erosion (green) and two deposition areas (black) on the shelf- and bay-side of the Barataria Pass. The solid contour lines illustrate the deposition of $10^{-4}$ m (black), $10^{-5}$ m (red) and erosion of $10^{-4}$ m (green).
The pattern of sediment transport in a tidal cycle during SE event is similar to the one during the pre-frontal phase of the cold front passage (Fig. 4.47), because during both times wind magnitude and direction are similar. The magnitude of current-induced bed shear stress in the ebb time is close to the one during a tidal cycle in the pre-frontal phase (Fig. 4.47c vs. Fig. 4.41c). However, the \( \tau_c \) in the flood period is about one-fourth of the one in Fig. 4.42c. The volume of water exchanged during the ebb and flood period is -3.55 (seaward) and +2.55 km\(^3\) (bayward), respectively (Fig. 4.47e). The mass of sediment transported into and out of the bay during the flood and ebb period are in the same order of magnitude (0.815 and -1.15 KTon, respectively, Fig. 4.47d). Hence, considering the net sediment flux at three aforementioned tidal cycles, it can be inferred that the net positive sediment flux at the Barataria Pass is mainly caused at the pre-frontal phase of the cold front passage.

The net bed change in a tidal cycle during SE event is depicted in Fig. 4.48. A distinguished depositional lobe at the shelf side similar to Fig. 4.46 is also formed. Comparing Fig. 4.43 with Fig. 4.46 and Fig. 4.48 and considering the bed shear stress distribution during pre- and post-frontal stages (Fig. 4.36) it can be construed that in absence of strong wave forcing, the radial deposition of sediment at shelf-side of the Barataria Pass is more pronounced. In moments of strong wave action (i.e. in pre-frontal cold front phase), this pattern is disturbed.
Fig. 4.47. Same as Fig. 4.41 except for a time instance during ebb flow in the SE event.
Fig. 4.48. (a) Net bed change on coastal Barataria Basin and inside the Barataria Bay during a tidal cycle in SE event. (b) Same as (a) but zoomed around the Barataria Pass. The thick dashed polygons represent one erosion (green) and two deposition areas (black) on the shelf- and bay-side of the Barataria Pass. The solid contour lines illustrate the deposition of $10^{-4}$ m (black), $10^{-5}$ m (red) and erosion of $10^{-4}$ m (green).
4.5.3 Sediment budget around the inlet and the alongshore sediment transport effect

The sediment budget in the study area around the Barataria Pass is illustrated in Fig. 4.49. In total, 23.01 KTon of sediment (both BED_mud and BED_sand) is eroded from the erosional area in front of the inlet during the three-month simulation period. Total deposition on the shelf- and bay-side of the inlet is estimated as 10.00 and 11.85 KTon, respectively. The net alongshore sediment flux on both upcoast and downcoast of the study area is negative (i.e. westward) and is computed as 2.14 and 5.76 KTon, respectively (Fig. 4.49a and b). The net sediment flux in the offshore boundary of the study area is seaward in amount of 3.67 KTon (Fig. 4.49c). Except for the times associated with pre-frontal stage of cold fronts (Fig. 4.24), the alongshore sediment transport is insignificant (Fig. 4.49 and Fig. 4.30). Overall, the calculation shows 6.13 KTon of sediment deficit that could be eroded from both marginal flood channels and other small erosional spots in the study area.
Fig. 4.49. Total alongshore bed sediment flux (a) upcoast and (b) downcoast of the study area (negative indicates westward movement). (c) Total bed sediment flux offshore of the study area. (d) Schematic representation of the erosion area (green), shelf- and bay-side depositional areas (yellow), alongshore sediment flux from upcoast (green arrow), downcoast (black arrow) and offshore to the study area (red arrow). Numbers are in KTon per three months of simulation time.
4.6 Conclusion

In this study the water and sediment budget from six major outlets of the Mississippi birdfoot delta, dispersal pattern of the fine sediment from these exits on the Louisiana continental shelf, and mechanism for morphological change near the Barataria Pass, the major tidal inlet between the Barataria Bay and adjacent continental shelf are investigated. Using the coupled FVCOM-SWAVE-SED numerical model for a three-month simulation period of April-June 2010 comprising both cold front events and persistent southeasterly wind condition, the following conclusions can be drawn:

1. The major outlet among the exits of the Mississippi birdfoot delta is Southwest Pass, through which ~ 64%/39% of the water/sediment exits. South Pass has the least water and sediment flux among the tri-furcation channels below the Head of Passes. Water and sediment fluxes for the Baptiste Collette, Culbit’s Gap and Grand Pass are also evaluated. The water flux from the numerical model at the Southwest Pass agrees well with the observation of Li et al. (2011).

2. Due to the more energetic outlet at Southwest Pass, the dispersion/deposition pattern at this pass is more elongated compared to other outlets. The high sediment concentration (SSC = 10^{-2} kg/m^3) of the Mississippi River plume exiting from the Southwest Pass is maintained in the upper four meters of the water column for more than eight kilometers. The average width of the Mississippi River plume with this concentration at five kilometers away from the Southwest Pass is ~ 8 km.
3. The pattern of the Mississippi River plume varies with wind direction and the buoyant plume bends towards the coast/mid-shelf due to downwelling/upwelling favorable wind.

4. While the water flux passing through a transect at the Barataria Pass during April-June 2010 is towards the coastal ocean, the net sediment flux is in opposite direction. This is because (1) there exists an erosional area, most of whose area resides on the shelf side of the cross-section at the Barataria Pass; and (2) tidal forcing determines the bed change at this study area. Therefore, the contribution of the ebb current, though being stronger, to the bayward sediment flux is smaller than the effect of flood current that brings the suspended sediment into the Barataria Bay.

5. The tidal cycles at the pre-frontal phase of the extratropical storms cause the largest bayward sediment flux in present three month simulation period. During post-frontal period, the sediment flux was negative (seaward) though the magnitude of the flux during this period is less than pre-frontal phase by an order of magnitude.
CHAPTER 5. SUMMARY AND CONCLUSIONS

In this dissertation, the wave dynamics inside the major water bodies of the Barataria Basin and at major tidal inlets connecting this estuarine system and the Louisiana Bight are examined during a three-month period in 2010 comprising both wind regimes in the Gulf of Mexico, i.e., rotational wind during cold front passage (April–May 2010) and persistent southerly or southeasterly winds (June 2010). This dissertation also tackles the budgeting of water and suspended sediment flux among main outlets of the Mississippi birdfoot delta, dispersion and deposition of sediment around those exits, response of the Mississippi River plume to various wind directions, and the mechanism for sediment exchange between the Barataria Bay and the coastal ocean through the Barataria Pass.

In chapter 2, the wave dynamics and wave-current interaction for six major inlets connecting the Barataria Bay with the Gulf of Mexico are investigated with the three-dimensional, wave-current coupled FVCOM and FVCOM-SWAVE models. The validated models are used to address the causality of waves at each inlet and their shelf and bay sides. Model simulation results indicate that waves on the shelf side of the inlets are mainly wind seas and swells from the Gulf of Mexico that are modified by ocean currents in the Louisiana Bight. These currents include the Mississippi River plume, the buoyancy- and wind-driven alongshore current, as well as the tidal jet in the Barataria Pass. The bay sides of the inlets, similar to the interior of the Barataria Basin, are dominated by locally generated waves. In the middle of the inlets, both wind seas and swells are presented, though different inlets behave differently in terms of contribution from each component. The wind seas enhance during cold front passage. Contrastingly, the influence of swells from the continental shelf is more pronounced during persistent southeast wind event. FVCOM-SWAVE predicts a decrease in significant wave height
inside the Louisiana Bight due to current-induced refraction and wave stretching effect caused by the clockwise gyre from the Mississippi plume. The modulation of significant wave height at the Barataria Pass due to partial wave blocking by the opposing current, and wave stretching by the following current can be up to 20%. The effect of depth-induced breaking and bottom friction overshadows the one from wave-current interaction at other shallower inlets.

The causality between wind and wave and relative contribution of seas and swells inside the Barataria Basin are investigated for major water bodies inside the Barataria Basin in Chapter 3. They are also compared to the characteristics at the four major tidal inlets of the Barataria Bay. The numerical simulation result, using the same fully-coupled three-dimensional FVCOM and FVCOM-SWAVE as employed in Chapter 2, indicates that the locally generated wind-seas are the main source of wave field inside the basin. The numerical model results demonstrates the dominance of wind-seas during cold front events as well as for waves greater than 0.1 m. Moreover, the model predicts almost instantaneous response of the wave field to the change in the wind direction. An analysis of wave exposure, i.e. frequency of occurrence of wind waves with significant wave height greater than 0.1m, reveals the significant impact of extratropical storms on shoreline erosion along the edge of the basin. Among the six major water bodies inside the Barataria Basin, the Barataria Bay is more exposed to waves probably due to its sheer size and consequent larger fetch. Further, the analysis of the results indicates a linear relation between wind speed and significant wave height. The contribution of hydrodynamic forces are assessed and found to be more important in the inlets rather than in the interior of the basin.

Chapter 4 focuses on the application of the coupled FVCOM-SWAVE-SED model to accurately calculate water and sediment fluxes at six main outlets of the Mississippi birdfoot delta during the same time span as in chapter 2 and 3. The numerical model predicts that ~ 64%
(39%) of the water (sediment) from the Belle Chasse transect exits through the Southwest Pass. The summation of the suspended sediment concentration passing through the tri-furcation channels below the Head of Passes vary from the that of measured data in the same three-month period (Allison et al., 2012) only by 1%. It is also shown that the dispersion/deposition pattern at the Southwest Pass is more elongated compared to other outlets. The high sediment concentration (SSC = 10^{-2} \text{ kg/m}^3) of the Mississippi River plume exiting from the Southwest Pass is maintained in the upper four meters of the water column for more than eight kilometers. The exchange of sediment between the Louisiana Bight and the Barataria Bay through Barataria Pass during April-June 2010 is mainly governed by tidal forcing. The morphological features at the inlet are one erosion area that is mainly on the shelf-side of the inlet and two deposition areas at shelf- and bay-side of the inlet. The 3-month net suspended sediment flux through the center of the Barataria Pass is bayward.

The more rigorous campaign to measure wave parameters inside the Barataria Basin and at various tidal inlets would contribute towards refinement of the wave study in chapter 2 and 3. It would also be an worthwhile endeavor to incorporate vortex force formalism (McWilliams et al., 2004) to enhance the calculation of wave effects on circulation and simulation processes such as rip current, surface onshore flow and bottom undertow.

Conducting more observational studies of sediment flux through tidal inlets of the Barataria estuary, as well as detailed measurement of bed composition at those passes, would contribute to refinement of the sediment model and more accurate calculation of morphological evolution at the inlet locations. Since stronger cold front passages occur during the winter season, investigating the wave regime in the Barataria Basin in the winter time is recommended to gain further insight into wave dynamics in estuaries during cold front events. Moreover,
application of sediment model at Barataria Pass in winter time would expand the understanding of the mechanism of bed change during extratropical storms.

Finally, the water discharge from the Mississippi River varied from 12,000 to 26,000 $\text{m}^3\text{s}^{-1}$ during the current simulation period. However, this value typically changes from less than 1,000 to more than 35,000 $\text{m}^3\text{s}^{-1}$ each year. Investigating the budgeting of flux and sediment under various discharge regimes from the Mississippi River would improve and broaden the scope of the estimation of the partitioning of water and fluvial sediments.
REFERENCES


GoMRI: Gulf of Mexico Research Initiative, 2019. GoMRI History. Available at: http://gulfresearchinitiative.org/about-gomri/gri-history/


Swenson, E. M., and C. M. Swarzenski (1995), Water levels and salinity in the Barataria-Terrebonne Estuarine system, in Status and Trends of Hydrologic Modification,


APPENDIX: PERMISSION LETTER

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VITA

Soroush Sorourian was born in Hamadan, the capital city of Hamadan Province of Iran. He graduated from the Baha’i Institute for Higher Education with a bachelor’s degree in Civil Engineering in September, 2002. Following graduation, Soroush worked for two years as an inspector and expediter for steel structures and as a structural engineer. He then entered University of Ottawa, Canada to further his studies in Civil Engineering (Water Resources). He returned to Iran and worked for six years as a coastal engineer and modeler and maritime structure designer. In 2013, Soroush came to the Department of Oceanography and Coastal Sciences at Louisiana State University to pursue a PhD degree. At the same time, he accomplished a minor in Civil Engineering from Department of Civil & Environmental Engineering at Louisiana State University. His primary area of research involves numerical modeling of wave dynamics and sediment transport in the nearshore and in eastuaries. He has active interest in coupled hydrodynamic-wave-sediment modeling using ocean community models, riverine and marine sediment transport, cohesive sediment transport, wave mechanics, and turbulence modeling.