Sub-Tidal Hydrodynamics of the Multi-Inlet Lake Pontchartrain Estuary Influenced by Mississippi River Diversion and Wind Associated with Atmospheric Fronts

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SUB-TIDAL HYDRODYNAMICS OF THE MULTI-INLET LAKE PONTCHARTRAIN ESTUARY INFLUENCED BY MISSISSIPPI RIVER DIVERSION AND WIND ASSOCIATED WITH ATMOSPHERIC FRONTS

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 Science

by

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ABSTRACT

In-situ observations and a Finite Volume Community Ocean Model (FVCOM) are used to investigate the cold front induced sub-tidal hydrodynamics of Lake Pontchartrain, a semi-enclosed low-salinity estuary with multiple inlets connecting to the open ocean. Observations show that the sub-tidal hydrodynamic responses are highly correlated with the meteorological parameters during cold front events. Model results indicate that, under barotropic conditions, the remote wind effect has the greatest contribution to the overall water level variation, while the local wind stress during cold front events determines the slope for the water level inside the estuary. An examination of a quasi-steady state force balance shows that the water level slope in the north-south direction inside the estuary is determined by the north-south wind stress, explaining ~ 83% of the variability but less so in the east-west direction (~ 43%), a lower value mainly caused by the eastern open boundary at the Rigolets.

Furthermore, under baroclinic conditions, circulation patterns of the lake are examined by numerical experiments. In general, circulation in the low-salinity estuary with restricted openings to the ocean is mainly driven by wind and to a lesser extent by water level fluctuations at the open boundaries. Local wind effect tends to produce downwind flows in coastal, shallow water regions and on the surface, but upwind flows near the bottom, a result consistent with barotropic wind-driven circulations; while the remote wind effect is important mostly near the open boundary. Remote wind effect decreases into the interior due to bottom friction. The quasi-steady state balance is more accurate in the cross-estuary direction than that in the along-estuary direction ($R^2 \sim 0.94$ vs. 0.60) under baroclinic conditions. This difference in the accuracy of the quasi-steady state balance between the cross- and along-estuary directions is caused by the open boundary - a tidally-induced mean slope exists. Furthermore, even if the tidal effect is removed,
the accuracy still decreases toward the open end for slopes in both directions. Remote wind
effect and residual flow through the eastern open boundary tends to introduce a departure from
the quasi-steady state balance in both along- and cross-estuary directions. In addition, there is
another reason for the quasi-steady state balance being more (less) accurate in the along- (cross)
estuary direction before cold front passages - the relatively higher (lower) occurrence of the wind
in that direction.

Results from numerical modeling by FVCOM show that northerly and southerly winds
tend to stretch the plume in east-west directions, while easterly and westerly winds constrain the
plume to expand in north-south directions. Sensitivity experiments to wind magnitude are
conducted. Increasing wind magnitude tends to increase the salt content of the lake except under
the westerly wind during which salt content decreases if the wind speed is less than 6 m/s.
Increasing wind magnitude can enhance both surface downwind flow and bottom upwind flow
and lower the no-motion layer between the two opposite flows. Leaked water before the opening
of the spillway has significant influence on the vertical structure of flows and salinity: mixing is
facilitated by the large amount of freshwater leaked into the lake; gyres are diminished; the
Average Potential Energy Demand (APED) is reduced to very low values; quasi-steady state
balance tends to be affected; about 1,500,000 kg of salt content is reduced. The Lake
Pontchartrain estuary is completely dominated by the freshwater from the river diversion within
25 days, replacing a total water volume of $9.77 \times 10^9$ m$^3$, indicating that salinity drops to
minimum value after 25 days.
CHAPTER 1. GENERAL INTRODUCTION

1.1. Background

Southern Louisiana is situated in the central region along the Northern Gulf of Mexico (NGOM) coastline. It has a series of estuaries. Some of these estuaries, e.g. Lake Pontchartrain, have very limited connections with the coastal ocean except through narrow inlets. These are different from inland freshwater lakes or general coastal plain estuaries connected to the coastal ocean through multiple inlets. This is particularly true for Lake Pontchartrain which is almost enclosed. It has connections to the coastal ocean mainly through three channels (The Rigolets, Chef Menteur, and Industrial Canal) with a width of 90 m to a few hundreds of meters. Compared to the size of the Lake (~ 66 km east west), the channels are very narrow. Synoptic weather systems and hurricanes can produce responses in these water bodies affecting the water exchange, which is important to the ecosystem (Chuang and Wiseman, 1983; Siadatmousavi and Jose, 2015; Walker and Hammack, 2000; White et al, 2009). However, there is a lack of in-depth analysis of weather conditions characterizing different weather patterns and the impact to hydrodynamics. Li et al. (2008b) studied wind straining induced bottom saltwater intrusion into Lake Pontchartrain during cold front events. Li et al. (2010) analyzed the water flux of Lake Pontchartrain induced by Hurricanes Gustav and Ike through three inlets in 2008. The characteristics of winter storms are very different from hurricanes whether in terms of temporal and spatial scales or their physical structures and processes. Keen (2002) used numerical models to predict waves and currents during cold fronts for the Mississippi Bight. Keen and Stavn (2012) later used observations and numerical models with interaction of atmospheric forcing and hydrodynamics to investigate the optical environment at Santa Rosa Island, Florida during two cold front passages. Water exchange and circulations under meso-scale weather systems like
winter storms and cold fronts can impact not only the water exchange in the coastal regions, but also sediment transport (Warn et al., 2008; Li et al., 2017). Studies related to sediment transport and concentration in the shallow shelf of Gulf of Mexico and the coastal estuaries under the influence of cold front passages in winter time were investigated by Perez et al. (2000), Walker and Hammack (2000), and Kineke et al. (2006). Siadatmousavi et al. (2012) studied the wave energy during a cold front and examined the thickness, density, kinematic viscosity of the mud layer. All the studies above show that cold fronts have significant impact on the hydrodynamics of the coastal water bodies along the Louisiana coast in the NGOM.

In estuaries, wind has a considerable effect on hydrodynamics and is one of the major contributors to subtidal exchanges between estuaries and the adjacent coastal oceans (Chuang and Swenson, 1981; Walker and Hammack, 2000; Sanay and Valle-Levinson, 2005; Feng and Li, 2010; Schoen, 2014; Herrling and Winter, 2015). Subtidal motion of Lake Pontchartrain is found to be the most important factor in controlling lake surface variations, and water level is found to be highly correlated with wind of which the repeating period is ~3.3 day (Swenson and Chuang, 1983). Therefore, subtidal water exchange in this kind of estuaries is mainly governed by wind (Swenson and Chuang, 1983; Wong, 1987; Buijsman and Ridderinkhof, 2007; Ralston et al., 2008; Wong et al, 2009; Dzonkowski et al., 2014). Weisberg (1976) and Weisberg and Sturges (1976) found that wind was the main forcing dominating the low-frequency circulation in the Providence River and the west passage of Narrangansett Bay. Wind effect on estuarine circulation has been explored by many studies. For example, Elliott (1978) and Wang and Elliott (1978) observed wind-driven pulses in currents of an estuary. Wind induced and hurricane induced exchange and circulations in coastal waters in Indian River Bay, Delaware and the adjacent continental shelf were investigated by Wong (2002). The results showed that coastal sea
winter storms and cold fronts can impact not only the water exchange in the coastal regions, but also sediment transport (Warner et al., 2008; Li et al., 2017). Studies related to sediment transport and concentration in the shallow shelf of Gulf of Mexico and the coastal estuaries under the influence of cold front passages in winter time were investigated by Perez et al. (2000), Walker and Hammack (2000), and Kineke et al. (2006). Siadatmousavi et al. (2012) studied the wave energy during a cold front and examined the thickness, density, kinematic viscosity of the mud layer. All the studies above show that cold fronts have significant impact on the hydrodynamics of the coastal water bodies along the Louisiana coast in the NGOM.

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level fluctuations were coherent with winds over 2-10 days. Their study also showed that subtidal exchanges were mainly accomplished by remote wind effects. A study of a semi-enclosed homogeneous, rotating basin by Sanay and Valle-Levinson (2005), demonstrated the wind effect on hydrodynamics. Subtidal flows in estuaries and subtropical lagoons have been examined with acoustic Doppler current profiler (ADCP) data in many studies (e.g. Henrie and Valle-Levinson, 2014; Li et al., 2008a; Murphy et al., 2009; Speulveda et al., 2004).

1.2. Motivation

Lake Pontchartrain (Fig. 1.1) is located in southeastern Louisiana in the United States. It has an area of about 1,600 km² and has an average depth of about 4m (Penland et al., 2002). Lake Pontchartrain and the adjacent bays make up one of the largest estuarine ecosystems on the coast of the Gulf of Mexico and encompasses 16 parishes in southeast Louisiana (Penland et al., 2002). It is located in the center of the Lake Pontchartrain Basin. This area has the largest population center in Louisiana, New Orleans, with more than 423,000 people. Lake Pontchartrain is an almost closed water body but is a low-salinity estuary as it is connected to the coastal ocean and has measurable salinity gradients with an average surface salinity of about 4 PSU but the bottom salinity can reach at least 12 PSU at times (Li et al., 2008b). The lake is connected to the Gulf of Mexico mainly through three narrow channels: the Industrial Canal, Chef Menteur Pass, and The Rigolets. Its drainage area comprises more than 125,000 ha of wetland, including bottomland hardwoods and cypress swamps along with a complex mixture of herbaceous wetlands including fresh, intermediate and brackish marsh (Keddy, et al., 2007). The distance of its axis from north to south is about 40 km, and that from east to west is about 66 km, containing a total water volume of 9.77×10⁹ m³ (Li et al., 2008b).
Figure 1.1. Study sites and measurement locations. Numbers 1, 2, 3, 4 are the locations where the pressure sensors (HOBO) are deployed in 2016 in the east, west, north, and south sides of Lake Pontchartrain. ADCPs deployed in 2008 were located at the Rigolets (RIG), Chef Menteur (CM), and Industrial Canal (IC).

Freshwater plumes have been observed in the Lake Pontchartrain estuary during flood season when an artificial diversion structure, Bonnet Carré Spillway (BCS), is opened to lower the water level of Mississippi River, hence, preventing flood risk to the city of New Orleans, LA. On average historically, the spillway is opened every 10 years. However, in the past decade, flood risk to the city of New Orleans has necessitated the opening in 2008, 2011, 2016, 2018, and twice in 2019. The plume of freshwater diverted into the estuary is unique in that it is within an enclosed, oligohaline estuary with mean salinity of only ~ 4 PSU. About 9.1 million tons of
sand was deposited on the Mississippi River Channel adjacent to the BCS (Allison et al., 2013) during the opening event in 2011. Georgiou et al. (2009) investigated the salinity distributions with freshwater input from adjacent rivers and BCS under tidal forcing, which indicates that a significant salinity reduction occurs in Lake Pontchartrain. The low salinity and low turbidity environment are favorable for the formation of algal blooms in the Lake Pontchartrain estuary (McCorquodale et al., 2009, Bargu et al., 2011). Nutrient and sediment input through the Bonnet Carré Spillway can result in significant changes in dissolved inorganic nitrogen concentrations (Lane, et al., 2001; White et al., 2009). Increased nutrient levels can potentially trigger enhanced primary production, phytoplankton community shifts, and algal bloom formation (White et al., 2009). Recent studies have shown that the Lake Pontchartrain estuary experiences high interannual variability in nutrients and phytoplankton community dynamics, mainly due to the effects of seasonal and episodic rainfall on hydrology and the Mississippi River diversion management that causes variability in the timing and magnitude of the freshwater discharge to the estuary (White, et al., 2009; Bargu, et al, 2011; Roy, et al., 2013). Under a changing climate, increasing water temperatures over decades favor cyanobacterial growth in the estuary, leading to a greater frequency of potentially harmful algal blooms capable of adversely affecting water resources, especially when diverting a nutrient load by the freshwater plume (McCorquodale et al., 2009, Bargu et al. 2011). Chao et al. (2013, 2016) revealed that a large amount of sediment is discharged into Lake Pontchartrain, moving eastward and expanding northward after the opening of the BCS in 2011. Li et al. (2008b) illustrated that northerly winds can promote counter water flow at depth in a narrow inlet resulting in a bottom plume of higher salinity. Retana (2008) conducted a series of sensitivity experiments using FVCOM on a simulation of hydrodynamics during an opening of BCS. However, the fit between observed and modeled salinity distribution
is marginal. Georgiou (2002) simulated the saltwater intrusion near the Industrial Canal (also called Inner Harbor Navigation Canal) using the Princeton Ocean Model (POM) model. The result shows that wind is responsible for the redistribution of density plume. Chilmakuri (2002) suggested that a spatially variable counter-clockwise wind in the middle of the lake is able to turn the plume from the BCS eastward during the opening period in 1997.

Investigating the hydrodynamic responses of the water in Lake Pontchartrain under both barotropic and baroclinic conditions can enhance physical background knowledge for a better understanding of the fisheries, ecosystems, and water exchanges between the coastal estuary and the open ocean.

1.3 Objectives

1) Use observational data obtained from the three major tidal channels of Lake Pontchartrain estuary and meteorological data to investigate the flows induced by cold front events.

2) Use a Finite Volume Community Ocean Model (FVCOM) to study the hydrodynamic response to cold front events under both barotropic and baroclinic conditions, and compare the circulations under local wind, remote wind, and both local and remote winds.

3) Quantify the response of the velocity field to different wind conditions in different parts of the estuary.

4) Further examine the quasi-steady state balance in more detail under both barotropic and baroclinic conditions and different wind conditions associated with cold front events.

5) Use FVCOM to simulate the freshwater diversion from the Bonnet Carré Spillway to a), examine the impact of wind from cold fronts on the evolution of the freshwater plume
from the BCS, b) analyze the sensitivity of salt mass, vertical structure of salinity and
current to the magnitudes and directions of wind, c) illustrate the effect of the minor
leakage event from the BCS on salinity, circulation pattern, potential energy, and quasi-
steady state balance, and d) discuss the influence time of the fresh water diversion and
compare it with that from Lagrangian particle tracking.

1.4. General Methodology

Observational data from ADCP and HOBOs are used to analyze the sub-tidal current
velocity and water level variations in Lake Pontchartrain and their responses to atmospheric front
events. Validated numerical experiments by FVCOM are conducted to simulate the
hydrodynamics in Lake Pontchartrain under both barotropic and baroclinic conditions.
Sensitivity experiments using FVCOM are done for examining how salinity, current, and
potential energy change with different wind magnitudes. Highly simplified linear theoretical
equation is introduced to check the quasi-steady state balance between wind stress and pressure
gradient. Potential energy equation is cited to investigate the stability of the water column in
Lake Pontchartrain during the opening of the BCS.

1.5. Organization of Dissertation

Chapter 1 provides the background introduction, motivation, and objectives of this study.
Chapter 2 analyzes the hydrodynamic responses in the inlets of Lake Pontchartrain to cold fronts
using observations and investigates the remote/local wind effect using a FVCOM model. Chapter
3 investigates the cold front induced circulations under local/remote/combined effect using the
FVCOM under both barotropic and baroclinic conditions, and explains the asymmetry of quasi-
steady state balance in along- and cross- estuarine directions. Chapter 4 studies the freshwater
plume from BCS, the evolution of the plume and the vertical structures of velocity and salinity with the effects of freshwater diversion and minor leakage prior to the diversion. Chapter 5 summarizes all results presented in previous chapters and discusses possible future work.
CHAPTER 2. COLD FRONT DRIVEN FLOWS THROUGH MULTIPLE INLETS OF LAKE PONTCHARTRAIN ESTUARY

2.1. Introduction

Winds in the mid-latitudes are often controlled by weather systems such as cold fronts. From October to the following April every year, the northern Gulf of Mexico (NGOM) experiences intensified cold fronts, sometimes with severe storms (Roberts, 1987). These weather systems affect the coastal NGOM significantly (e.g. Walker and Hammack, 2000; Feng and Li, 2010; Li et al., 2011; Siadatmousavi et al., 2012; Siadatmousavi and Jose, 2015; Lin et al., 2016; Li et al., 2017), as well as other areas (e.g. Li and Chen, 2014). The cold front passages can result in wind regime shifts across the area. The wind direction switches from the southern quadrants to northern quadrants, which can result in oscillations of bay water level and associated flushing of the bays (Feng and Li, 2010). A weather system in the cold season (October to April) is often characterized by the existence of an eastward-, southward, or southeastward-propagating mid-latitude cyclone that extends deep into the subtropics (Ferreira et al., 2013). The coastal area of north-central Gulf of Mexico has micro tides (average tidal range is about 0.35m). Wind forcing during storm events can cause much greater water level changes than tides (Murray, 1976; Wax et al., 1978). For example, Kemp et al. (1980) recorded meteorologically induced water level variations of 1.2 m during winter associated with frequent frontal passages, nearly double the maximum astronomical tidal range. In Barataria Bay, Louisiana, Kjerfve (1973) indicated that water levels and circulation were controlled by winds on a scale of a few days and diurnal tides on a daily scale. This kind of weather conditions can induce significant sub-tidal oscillations, and as a result, cause sub-tidal water exchange (Feng and Li, 2010) which can have impact to ecosystems and fisheries. Water quality can be affected by the wind induced water level oscillations. For instance, oyster farms can be polluted by
wastewater from sewage treatment plants at low water under the influence of northerly winds (Li et al., 2011). For better monitoring the ecosystem health and coastal management for estuaries such as Lake Pontchartrain estuary, it is important to study the corresponding hydrodynamic response to cold front events that occur in this area.

The goals of this chapter are to (1) quantify the exchange flow through three inlets (the Rigolets, Chef Menteur, and Industrial Canal), (2) determine the relationship between the variations in water level and current velocities in the three inlets and the patterns of cold front systems, and to categorize the hydrodynamic response of the multi-inlets during cold front events, and (3) determine the characteristics of the remote and local wind effects in such a system, where remote wind effects are defined as a collective effect of wind stress, Earth rotation (e.g. Ekman pumping), air pressure forcing, etc. that are included in the low-pass filtered water level change at the open boundary, and local wind effect is only referred to that induced by wind in the local region of Lake Pontchartrain.

2.2. Methodology

2.2.1. Study Site and Measurement

As introduced in Chapter 1, Lake Pontchartrain (Fig. 2.1) is located in southeastern Louisiana in the United States. It has an area of about 1,600 km² and has an average depth of about 4m (Penland et al., 2002). Lake Pontchartrain and the adjacent bays make up one of the largest estuarine ecosystems on the coast of the Gulf of Mexico and encompasses 16 parishes in southeast Louisiana (Penland et al., 2002). It is located in the center of Lake Pontchartrain Basin. This area has the largest population center in Louisiana, New Orleans, with more than 1.5 million people (Penland et al., 2002). Lake Pontchartrain was connected to the Gulf of Mexico mainly through three narrow channels prior to June 2012: the Industrial
Canal, Chef Menteur Pass, and Rigolets. Lake Pontchartrain is roughly oval in shape with its major axis from east to west being about 66 km and the minor axis from north to south about 40 km, containing a total water volume of $9.77 \times 10^9$ m$^3$ (Li et al., 2008b).

There are two kinds of observations in this study. One is velocity data from ADCPs and the other one is water level data from water pressure sensors (Onset HOBO data loggers). The water velocity profile data were obtained using 1200 KHz Teledyne RDI ADCPs deployed in the three channels (black triangles in Fig. 2.1) in 2008. Water level data were recorded by the pressure sensors on the ADCPs. The ADCP deployed in the Rigolets was located at $(30°10´15.67´´N, 89°40´27.84´´W)$. This is a location in a channel constriction at the east end of Lake Pontchartrain and the channel is oriented at 30° clockwise from the east. It is connected to the Gulf of Mexico through Lake Borgne with a width of ~ 600 – 800 m. The deployment in Chef Menteur was at $30°05´03.96´´$ N and $89°47´28.89´´$ W where the channel is oriented northeast-southwest with an angle of 26° clockwise from the north. Water exchanges between Lake Pontchartrain and Lake Borgne are mainly through this ~300 m wide channel. Lake Borgne is connected to Gulf of Mexico. The deployment in the Industrial Canal was at $(30°0´18.26´´N, 90°1´31.86´´W)$. Water goes through this ~90-220 m wide elongated channel and all the way to Chandeleur Sound through the Mississippi River Gulf Outlet (MRGO) and Lake Borgne (MRGO has been closed since 2016 but was open during the time of data collection). The corresponding meteorological data (wind data and air pressure data) are obtained from NOAA’s National Ocean Service Station NWCL1 (8761927), which is located at $(30°1´37´´, 90°6´46´´W)$ (middle south shore of Lake Pontchartrain, Fig. 2.1).

Several HOBO water level data loggers (U20) were deployed in the south, north, east, and west edges of Lake Pontchartrain from Jan 28th to March 24th, 2016 (dark dots in Fig. 2.1).
The GPS readings of these sites are (30°9´19´´N, 89°51´21´´W), (30°6´28´´N, 90°25´20´´W), (30.3535°21´13´´N, 90°4´14´´W), and (30°1´14´´N, 90°9´31´´W) for the east (Site 1), west (Site 2), north (Site 3), and south stations (Site 4), respectively. Data were recorded every 30 minutes. An extra HOBO was deployed in the air near site 2 to monitor the air pressure and to correct the water level variations at all stations.

In this study, current velocity data obtained from the Industrial Canal are not used due to an improper selection of the deployment site: it was near a piling of a bridge, measuring the flow field affected by the structure. However, the water level data are used as they were not affected by the piling on the scales of our interest.

**Figure 2.1.** Study sites and measurement locations. Numbers 1, 2, 3, 4 are the locations where the Hobos are deployed in 2016 in the east, west, north, and south sides of Lake Pontchartrain. ADCPs deployed in 2008 are located at the Rigolets (RIG), Chef Menteur (CM), and Industrial Canal (IC).
2.2.2. Data Processing

Since we have two kinds of observational data with two time segments, we pre-process the two segments of data separately. One is the ADCP data deployment in 2008. The ADCPs collected water level and current velocity data at 5-minute intervals. Each ADCP was installed on a Sea-spider (a mounting frame), looking upward, and deployed at bottom with the transducers at a height about 1m from the bottom. The first bin of valid data along the vertical was at about 0.62m from the transducers, making the first data point at 1.62 m above the bottom. The bin size was set to be 0.25 m. Outliers of the time series are removed. The velocity data were then vertically interpolated at 0.25m and temporally interpolated at 5-minute intervals. The other observation was the water pressure data obtained by HOBO pressure sensor in 2016. We calculated and corrected the water level obtained from HOBOs for the influence of air pressure using the equation below:

\[ h = \frac{(p_{total} - p_{air})}{(\rho \cdot g)} \]  

(2.1)

Where \( h \) is the actual water depth, \( p_{total} \) is the pressure in the water, and \( p_{air} \) is the pressure in the air. Water density \( \rho \) is 1007 kg/m\(^3\), gravitational acceleration \( g \) is 9.8 m/s\(^2\). These HOBO data were used to validate the water level difference for the modeled result.

To extract the response under the influence of winter storms, a 6\(^{th}\) order Butterworth low-pass filter with a cutoff frequency of 0.6 cycles per day was then applied. Wind data were interpolated at 6-minute intervals after removing outliers. The current velocity data were recorded in the Earth Coordinate with north, east, and vertical components. For convenience in analyzing transport of water, we rotated the coordinate system to obtain the along and cross channel components of the velocity. Positive/negative along channel velocity was defined as the current flowing into/out of the lake. The along channel component was found to be much larger in magnitude than the cross-channel component. The cross-channel velocity component was
omitted in the discussion as our interest was the along channel flows which determined the transport.

2.3. Results and Discussion

2.3.1. Meteorological Background

There were five cold fronts passed through Lake Pontchartrain from Oct 09 to Nov 18, 2008 (Table 2.1) during the deployment of the three ADCPs. The start and end times for a cold front event are determined by the time when the cold front reached the northwest most point of Louisiana and when it left the southwest point of Louisiana. Fig. 2.2 shows the surface weather analysis with air pressure contours, and fronts for each of the five events. The 1\textsuperscript{st}, 3\textsuperscript{rd}, and 5\textsuperscript{th} cold fronts were associated with high-latitude cyclones which were centered at Quebec, Canada. The elongated fronts at the trough of these cyclones swept through almost the entire continental US and moved eastward as the centers of the lows moved. The 2\textsuperscript{nd} and 4\textsuperscript{th} events were originated from fully developed mid-latitude cyclones located near Nebraska. High pressure centers following the cyclones, pushing the cold fronts eastward. The isobars for the first cold front event were relatively sparse, while isobars for 3\textsuperscript{rd}, 4\textsuperscript{th}, and 5\textsuperscript{th} cold front events were denser, with faster moving speed of these cold fronts than the first two. The moving speed of the 2\textsuperscript{nd} cold front was affected by a high pressure center located in its east, unlike the other four cold front systems. On the other hand, the moving direction was from west to east for the 2\textsuperscript{nd} cold front system, but was from NW to SE for the other four cold front systems. The durations of the cold front systems occupying the study area for the 1\textsuperscript{st} and 2\textsuperscript{nd} cold front events were longer than the other events, consistent with their slow speed.
Figure 2.2. Surface meteorological analysis for five cold front event of Oct 16th to 17th (a), Oct 23rd to 24th (b), Oct 26th to 27th (c), Nov 07th to 08th (d), Nov 18th to 19th (e) in 2008. Each picture shows the moment when cold front is passing by Lake Pontchartrain. Weather map obtained from the NOAA’s website: http://www.wpc.ncep.noaa.gov/dailywxmap/. It includes height contours (solid lines), temperatures (dashed lines), fronts, and precipitation area (shaded).
Table 2.1. Time period of each cold front events and the corresponding response for sub-tidal hydrodynamics.

<table>
<thead>
<tr>
<th>Cold front events</th>
<th>Time begun (UTC)</th>
<th>Time ended (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold front 1</td>
<td>03:00 10/17/2008</td>
<td>03:00 10/19/2008</td>
</tr>
<tr>
<td>Cold front 2</td>
<td>12:00 10/23/2008</td>
<td>12:00 10/25/2008</td>
</tr>
<tr>
<td>Cold front 3</td>
<td>06:00 10/27/2008</td>
<td>06:00 10/28/2008</td>
</tr>
<tr>
<td>Cold front 4</td>
<td>12:00 11/07/2008</td>
<td>12:00 11/08/2008</td>
</tr>
<tr>
<td>Cold front 5</td>
<td>03:00 11/15/2008</td>
<td>03:00 11/16/2008</td>
</tr>
</tbody>
</table>

2.3.2. Observed Flows through Multiple Inlets under Different Cold Front Events

During the first cold front, which was a weak event, variation of air pressure was not obvious in the first few hours and then increased from 00:00 Oct 18 in the next two days after the passage of the front. Wind direction changed from southeast to northwest with a maximum magnitude of 10.3 m/s. The low-pass filtered water level (Fig. 2.3a) decreased 12.2 cm in Chef Menteur for the first day and then increased about 9.4 cm in the second day. The along-channel low-pass filtered current velocity (Fig. 2.4b) was in the direction of SW-NE and outward of Lake Pontchartrain. In the Rigolets, the low-pass filtered along channel velocity was negative, i.e. water was flowing to the east and moving outside of the lake, in the same direction of the westerly wind. The low-pass filtered water level dropped by 19.7 cm on Oct 17 and then increased slightly (7.1 cm) on Oct 18. In the Industrial Canal, water was flowing out of the lake. Water level raised by 17.0 cm during the first day and dropped around 6.5 cm for the second day during this cold front event. Note that even though the low-pass filtered water level had only small changes during this event, the flow through the inlet was significant because the lake was large and the inlets were narrow.
Figure 2.3. a. Air pressure change from NOAA NOS station NWCL1 and water depth in three inlets of Lake Pontchartrain. Air pressure is in thin black line, water depth in the Rigolets (RIG), Chef Menteur (CM), and Industrial Canal (IC) are in the color of black, dark gray, and light gray respectively. b. Wind vector observed by NOAA NOS station NWCL1 in the corresponding time period. Vertical lines showing the beginning date of each cold front event.

For the second cold front on Oct 24, 2008, the air pressure at station NWCL1 dropped nearly 10 millibars within 2 days and remained at the minimum pressure of 1016 millibars for nearly the whole period of this event. Wind direction changed from east to north and its magnitude increased with time. The wind was from the east for 35-hr before changing to the north. The low-pass filtered water level in Chef Menteur increased about 40.2 cm within one day during easterly wind and dropped by about the same amount after the passage of the front during northerly wind. This was a much stronger event. The water flowed into the lake during the
second event, with an increase before the front and a decrease after (Fig. 2.4b). The low-pass filtered water level in the Rigolets during the second cold front increased 44.7 cm within the first day and then decreased 30.6 cm on the following day. The sub-tidal flow was into (positive) Lake Pontchartrain. For the Industrial Canal, water level increased 42.3 cm. For all three stations, the water level decreased dramatically after Oct 24 and continued to decrease until the passage of 3rd cold front. This is because these two cold fronts were very close. After the 2nd cold front passage, the low-pass filtered water level dropped by 45.2 cm in about two days.

![Figure 2.4](image.png)

**Figure 2.4.** Vertical structure of along channel current for two inlets of the (a) Rigolets and (b) Chef Menteur. Positive along channel velocity indicates the water flow is moving into the Lake Pontchartrain. Vertical black lines indicate the beginning date of each cold front passage. Fluctuating black lines represent water level variation in the two inlets.

The third cold front occurred on Oct 27 with the front passing Lake Pontchartrain after 12 UTC, Oct 27. The cold front system was moving at 56.2 km/hr along the NW-SE direction. Wind direction changed from southwest to north with a maximum of 15.5 m/s. The maximum change of the air pressure was 8.8 millibars during the event. At Chef Menteur, sub-tidal water level decreased by only 19.5 cm within 24 hours. The flow was out of the lake for more than one day. The low-pass filtered water level in the Rigolets during the third cold front event (Fig. 2.3a)
decreased by 22.4 cm. Water level stayed low for a few days and increased slightly until the next cold front event. Current velocity remained eastward. At the Industrial Canal, low-pass filtered water level dropped for about 15.8 cm within one day after the passage of the 3rd cold front system.

The fourth cold front begun to influence the area at 12:00 UTC on Nov 7, and left the region around 12:00 UTC, Nov 8. It came through Lake Pontchartrain at 15:00 UTC on Nov. 7th, when the wind direction changed from southwest to northwest. Air pressure increased by only 3.6 millibars during this event. Maximum wind was 9.85 m/s. The average moving speed of cold front system was about 35.6 km/h in the NW-SE direction. The water level at Chef Menteur (Fig. 2.3a) decreased about 11.8 cm during this event. Water was flowing out of Lake Pontchartrain. The water level in the Rigolets decreased for about 13.6 cm during this event. The current velocity reversed its direction from westward to eastward as the cold front crossed the Lake Pontchartrain. In the Industrial Canal, water level decreased by 12.6 cm. This apparently represents another very weak cold front.

During the last event, the cold front system came from the northwest moving to the southeast with an average moving frontal speed of about 83 km/h. Its duration was shorter – only about 24 hours after 3:00 UTC on Nov 15 due to its fast moving speed. Maximum wind speed reached 12.7 m/s in the NW-SE direction. Air pressure increased by 14.5 millibar. Water level decreased 8.2 cm within 24 hours in Chef Menteur. The along channel current was out of Lake Pontchartrain. At the Rigolets, the water level dropped 25.3 cm during this event. Current velocity showed a negative value indicating an eastward along channel flow moving out of Lake Pontchartrain. At the Industrial Canal, the water level decreased 12.4 cm in 24 hours.

Generally speaking, air pressure drops before cold front passage, and increases after.
Except the second cold front, wind direction changed from southeast or south to northeast. Correspondingly, water level decreased and flowed out of Lake Pontchartrain. The maximum water level difference before and after a cold front event was 25.3 cm. For the second cold front, the air pressure stayed relatively low for more than two days. Wind direction changed from southeast to east. After the cold front passage, east wind dominated for more than 24 hours. As a result, water level increased about 42.3 cm and flowed into the lake.

2.3.3. Water Level Difference

From the above discussion of the results, even though some general characteristics can be seen regarding how water levels would respond to a cold front system, it is however difficult to evaluate how much of the water level change is due to local wind effect and how much is due to remote wind effect. To clarify this issue, we need to evaluate the water level gradients. Indeed, even though the water levels in the three channels had similar variations for the whole time period, there were differences (gradients) of the zonal and meridional water levels in the lake. To examine the water level slopes, we use the 2016 water level data obtained from the south and north stations and those from the east and west stations. Water level difference in zonal direction is calculated by subtracting the low pass filtered water level in the west site from that in the east site. Water level difference in meridional direction is calculated by subtracting the low pass filtered water level at the south site from that at the north site. What is left is only the water level variations due to wind. After the de-meaned water level differences are calculated, we compare them with the northerly and easterly wind components. Fig. 2.5 shows the time series of water level differences in S-N and E-W directions and their corresponding wind components. Fig. 2.5a reveals that when northerly wind velocity component is positive, i.e. the wind is from the south, the water level difference is almost always negative: water level has a south-north slope (higher in the north) as anticipated. Likewise, when the wind is from the north, water level is higher on
the south side of Lake Pontchartrain. Similarly, when wind is from the west, water level is higher in the east (Fig. 2.5b), and vice versa. These local wind stress induced water level changes are about 10% of the total water level variations. A hypothesis of this difference is that the water level gradients within Lake Pontchartrain are a result of local wind stress while the remote wind effect produces the overall set up and set down of the whole Lake. In section 2.3.5, this will be further discussed with the numerical model results.

Figure 2.5. Water level difference in 2016 between north side and south side, and between west side and east side of Lake Pontchartrain, and their relationship with south wind and west wind. Black line in 5a represents the water level difference between south side and north side, black line in 5b shows the water level difference between west side and east side. Dashed lines represent the wind in N-S direction and that in E-W direction. When wind speed is larger than zero, wind direction is in south for the south wind and is in west for the west wind.
2.3.4. Correlation between Hydrologic Elements and Meteorological Factors

As discussed above, the low-pass filtered water level and current velocity in the three channels are apparently related to the cold fronts. To quantify the relations, we calculated the correlations between atmospheric and oceanic parameters. The correlations are shown in Table 2.2. There are six kinds of correlation coefficients: those between air pressure and water level (Pres-D), air pressure and along channel current velocity (Pres-U), northerly wind and along channel current velocity (Wn-U), easterly wind and along channel current velocity (We-U), northerly wind and water level (Wn-D), and easterly wind and water level (We-D), respectively. The column of Delayed time in Table 2.2 indicates the time lag of the hydrodynamic responses.

It can be seen that for all the three inlets, air pressure is inversely correlated with water levels with lag of 0 days, and is positively correlated with along channel velocity with 2.5 days lag, which means that water level responds to the air pressure instantly, but the response of the along channel velocity has a lag of 2.5 days to air pressure. North wind is positively correlated with water level and along channel velocity, indicating that during north wind, water level is increasing in the three inlets, along channel velocity has the same sign with the north wind, namely flowing into the Lake Pontchartrain. Furthermore, water level responses to the north wind with a lag of 0.2 days, which is shorter than the lag of 1.2 days for along channel velocity to response to north wind. East wind is reversely correlated to both water level and along channel velocity. Since the sign of east wind is negative during east winds, water level is increasing, along channel velocity is positive, meaning water flows into the lake. Hydrodynamics’ responses have the same lags to east wind component, 1.2 days for water level, and 0.2 days for along channel velocity, indicating that water level responses slower than along channel velocity about 1 days under winds’ impact.

The maximum absolute correlation coefficients among that between air pressure and
water level and that between air pressure and along channel velocity are 0.41 and 0.32, respectively. The maximum absolute correlation coefficients among that between north wind component and water level and that between north wind component and along channel velocity are 0.44 and 0.31, respectively. The maximum absolute correlation coefficients among that between east wind component and water level and that between the east wind component and along channel velocity are 0.78 and 0.80, respectively. That comparison of correlation coefficients between different atmospheric parameters and hydrodynamics indicating that the east wind contributes the most to both water level variations and along channel velocities.

Table 2.2. Correlation between air pressure and water level, and correlation between north wind speed and along-channel current velocity.

<table>
<thead>
<tr>
<th></th>
<th>Correlation</th>
<th>Delayed (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The Rigolets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pres-D</td>
<td>-0.41</td>
<td>0</td>
</tr>
<tr>
<td>Pres-U</td>
<td>0.32</td>
<td>2.5</td>
</tr>
<tr>
<td>Wn-U</td>
<td>0.44</td>
<td>0.2</td>
</tr>
<tr>
<td>We-U</td>
<td>-0.73</td>
<td>0.2</td>
</tr>
<tr>
<td>Wn-D</td>
<td>0.28</td>
<td>1.2</td>
</tr>
<tr>
<td>We-D</td>
<td>-0.80</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Industrial Canal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pres-D</td>
<td>-0.34</td>
<td>0</td>
</tr>
<tr>
<td>Wn-D</td>
<td>0.27</td>
<td>1.2</td>
</tr>
<tr>
<td>We-D</td>
<td>-0.78</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Chef Menteur</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pres-D</td>
<td>-0.23</td>
<td>0</td>
</tr>
<tr>
<td>Pres-U</td>
<td>0.27</td>
<td>2.5</td>
</tr>
<tr>
<td>Wn-U</td>
<td>0.31</td>
<td>0.2</td>
</tr>
<tr>
<td>We-U</td>
<td>-0.77</td>
<td>0.2</td>
</tr>
<tr>
<td>Wn-D</td>
<td>0.24</td>
<td>1.2</td>
</tr>
<tr>
<td>We-D</td>
<td>-0.65</td>
<td>1.2</td>
</tr>
</tbody>
</table>

2.3.5. **Numerical Modelling Using FVCOM**

In the above discussion, we analyzed how water level and currents responded to wind and air pressure during cold fronts. However, those wind induced effects are constrained to only
within Lake Pontchartrain. To further discuss the local and remote wind effects, we conducted several numerical experiments. We can also use the model results to investigate the circulation during cold front passages.

Water level and water currents for 2008 and 2016 are simulated using FVCOM. The model domain (Fig. 2.6) covers Lake Pontchartrain, with two open boundaries in the east and south connecting to the Gulf of Mexico. The finest resolution is less than 150 m in the narrow southern canals. The model has 10159 triangles covering the entire domain with a total of 5809 node points (Fig. 2.6). There are 10 vertical layers using the sigma coordinate. The time step for the external (barotropic) mode is set to be 1 second, and the ratio of time steps between external and internal modes is 1:10 so that the total number of time steps for the simulation of year 2008 is 388800 (10/05/2008 to 11/18/2008, total 1080 hours) and 362880 for the year of 2016 (02/12/2016 to 03/24/2016, total 1008 hours).

Figure 2.6. Model mesh for the FVCOM modeling for the Lake Pontchartrain Basin.

Two types of open boundary forcing are used. One only used tidal elevation at the open
boundary, and the other used observed water elevation which included tide and wind effect.

Tidal elevation and observed water level for the southern boundary nodes are obtained from NOAA’s tide predictions in Shell Beach, LA (Station ID: 8761305, 29° 52.1’ N, 89° 40.4’ W). Tidal elevation and observed water level for the eastern boundary nodes are represented using NOAA’s tide prediction in Bay Waveland Yacht, MS (Station ID: 8747437, 30° 19.5’ N, 89° 19.5’ W). The time interval of the input water level data is 1-hour. Our main purpose is to investigate the wind effect during cold fronts, so the meteorological forcing only includes wind. The input wind data with interval of 1 hour is obtained from the NDBC New Canal Station north of New Orleans, LA (NWCL).

Table 2.3. Model design for two groups of numerical modeling.

<table>
<thead>
<tr>
<th>Group1</th>
<th>10/05/2008-11/19/2008</th>
<th>Group2</th>
<th>02/12/2016-03/24/2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atmospheric forcing</td>
<td>Input on open boundary</td>
<td>Atmospheric forcing</td>
</tr>
<tr>
<td>1</td>
<td>No wind</td>
<td>Tidal elevation</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Spatially uniform wind</td>
<td>Tidal elevation</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>No wind</td>
<td>Observed water level</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Spatially uniform wind</td>
<td>Observed water level</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Spatially non-uniform wind</td>
<td>Observed water level</td>
<td></td>
</tr>
</tbody>
</table>

Seven experiments are conducted and divided into two groups (Table 2.3). Group one (Experiments 1-5) includes the simulations for the time period from Oct. 5 to Nov. 19 in 2008, and group two is for the time period from Feb. 12 to Mar. 24 in 2016. Observations in 2008 are used to validate the model. Skill assessment of the model is done (Appendix A). As shown in Fig. 2.7, modeled water levels (black lines) are in good agreement with the observations with excellent skill score [Allen et al., 2007; Liu et al., 2009; Murphy, 1988; Ralston et al., 2010]. The simulation of along channel velocity in the Rigolets and Chef Menteur are excellent (Fig. 2.8).
However, the accuracy of the modeled cross channel velocity is relatively low. Since our main interest is the dominant flux in and out of the lake, we omitted the discussion on the small cross-channel flow component that does not contribute to the along channel transport. Water pressure obtained from 2016 is used to validate the wind induced water level difference in zonal and meridional directions. Thin grey lines in Fig. 2.9 show the surface slope between east and west and that between north and south calculated using the observational water pressure data. Modeled results of local wind induced water difference (solid black line in Fig. 2.9a to 2.9b) under tide forcing at the open boundary and the spatially uniform wind forcing are consistent with the observation, while the remote wind induced water level difference (solid black line in Fig. 2.9c to 2.9d) doesn’t match the observed water level difference, especially that remote wind can barely induced no essential surface slope in north-south direction, indicating that local wind induced water level oscillation contributes the most for the variation of the lake surface slope.

**Figure 2.7.** Water level validation of Experiment 4 for The Rigolets (a), Chef Menteur (b), and Industrial Canal (c). Dotted line represents the observed water level, and black line represents the simulated water level by Experiment 4. CC is the correlation coefficient, RMSE is the root mean square error, and SS is the skill score.
**Figure 2.8.** Validation of flow velocity in The Rigolets and Chef Menteur. (a) is the along channel velocity (flowing into the lake) in The Rigolets, (b) is the cross channel velocity in The Rigolets, (c) is the along channel velocity (flowing into the lake) in Chef Menteur, and (d) is the cross channel velocity in Chef Menteur. Dotted line represents the observed water surface velocity, and black solid line represents the modeled water surface velocity. CC is the correlation coefficient, RMSE is the root mean square error, and SS is the skill score.
**Figure 2.9.** Water level difference for 2016. (a) and (b) are the water level difference induced by local wind, (c) and (d) are that induced by remote wind. (a) and (c) are water level difference in the east-west direction, while (b) and (d) are the water difference in the north-south direction. Thin grey lines are the water level difference calculated using the observations in 2016, solid lines are resulted from the numerical experiments.

Experiment 1 (Group 1) was forced by tidal elevation at the open boundary without any wind forcing. Lake circulation within Lake Pontchartrain for these two experiments only includes tidal processes. Experiments 2 and 6 are simulated by using the tidal elevation at the open boundary plus a spatially uniform wind forcing at every mesh node. Wind forcing is only covered by the model grid for the local region of Lake Pontchartrain, therefore local wind effect can be deduced by subtracting results of Experiment 1 from results of Experiment 2.

Experiment 3 and 7 apply the observed water level from NOAA as the water elevation forcing at the open boundary. Wind forcing is turned off for these experiments. Since the observed water level at the open boundary not only includes tidal effect, but also is affected by the remote wind effect (Garvine, 1985). The results of Experiment 3 and 7 can be used to deduce
the remote wind effect by excluding the tidal effect by subtracting the results from Experiment 1.

Experiments 4 uses spatially uniform wind at each mesh node. These experiments should produce the most reliable hydrodynamics, because it contains both remote wind effect from the observed water level at the open boundary and the local wind effect. The difference between remote wind effect and local wind effect can be compared using the results of Experiment 3 and those from Experiments 4.

To examine the effect of non-uniform wind, another simulation using spatially variable wind field is also conducted (Experiment 5). The difference between the water level under uniform wind (dashed dark gray line in Fig. 2.10) and under spatially non-uniform wind (solid light gray line in Fig. 2.10) is negligible, indicating that the non-uniform wind field does not induce any major difference in the modeled water level under the uniform wind field. This is apparently because of the small spatial scale of Lake Pontchartrain compared to the synoptic weather scale. For that reason, it is sufficient that we only use spatially uniform wind for this study.

Figure 2.10. Modeled water level under different wind condition and with different input water elevation at the open boundary. Line with marker “.” represents the observation of water level. Black dashed line represents modeled water level from Experiment 3, black solid line represents that from Experiment 4, and gray solid line represents modeled water level from Experiment 5. Dark gray dashed line represents that from Experiment 1, and solid dark gray line represents that from Experiment 2.
2.3.6. Local and Remote Wind Effect

Local Wind Effect

Local wind effect is produced by subtracting results of Experiment 1 from that of Experiment 2. Dashed and solid dark gray line in Fig. 2.10 show the results of Experiments 1 and 2, respectively, for one week from 10/22/2008 to 10/29/2008, revealing no significant difference between the two, which indicates that local wind effect has little impact on low frequency variation of the total water level. The local wind induced water level variation can also be seen from the dark gray line in Fig 2.11. Compared with the observed low-pass filtered water level (dashed line in Fig. 2.11), the water level resulted from the local wind is negligible.

Results of Experiment 6 illustrate the importance of local wind effect on water level gradient oscillation in the lake. Though local wind contributes little to the total water level variation, it cannot be neglected in terms of the lake’s surface slope. Fig. 2.9a and Fig. 2.9b show that the local wind induced water level difference (solid black line) has bigger magnitude than that induced by remote wind (black lines in Fig. 2.9c and 2.9d).

![Figure 2.11](image.png)

**Figure 2.11.** Wind induced water level in Chef Menteur from Oct 09 to Nov 18 in 2008. Vertical black lines represent the beginning time of cold front passages in Lake Pontchartrain.

Remote Wind Effect

Remote wind effect on water level can be obtained from Experiments 7. The Model results of Experiments 6 (solid black lines) and 7 (dark grey lines) (Fig. 2.12a to 2.12d) show the water...
levels at the east, west, south, and north sites around Lake Pontchartrain from the model simulation for 2016. Black lines in Fig. 2.12a to 2.12d from Experiment 7 indicate that the remote wind contributes the most to the water level change. Therefore, the subtidal change of water level is mainly caused by the remote wind.

**Figure 2.12.** Water level time series from the model output for the four stations around Lake Pontchartrain from the (a) E, (b) W, (c) S, and (d) N stations, respectively.

Total subtidal water level change is calculated by subtracting the tidal elevation from the observed water level, which reveals the total wind effect on water level. Fig. 2.13 shows the contrasts between the total wind induced water level change and the local wind induced lake surface water level difference in north-south (solid black line) and east-west (dotted line) directions. The peaks of water level difference corresponded to wind associated with the cold fronts. This is also true for the peaks of water level induced by the water level forcing at the open boundary (Thin black line in Fig. 2.13). However, the magnitude of the total subtidal water level change is larger than local wind induced lake surface water level difference in both direction
especially for the second cold front event, in which the total wind induced water level peak (about 0.7 m) is 14 times of the local wind induced peak lake surface water difference (about 0.05m). This may be related to the unique feature of the second cold front, which has a deeper high air pressure center occupying a larger region with a stronger and longer east wind.

![Figure 2.13](image)

Figure 2.13. Water level difference in 2008 calculated by model result on the direction of W-E (dotted line) and S-N (thick black line), and that calculated by using real water level from NOAA minus predicted tide from NOAA (thin black line). Vertical black lines represent the beginning time of cold front passages in Lake Pontchartrain.

### 2.3.7. Wind Induced Volume Flux through Multiple Inlets

Water velocity simulated by Experiments 4 is used to calculate water volume flux through the three inlets. Water volume passed through a transect perpendicular to the along channel direction is defined as the water volume flux and calculated by the following equations (Lin et al., 2016):

\[
WV(t)|_{\Gamma} = \int_{-H}^{C} \left( \int_{0}^{L} V_n(x, y, z, t) \right)_{\Gamma} d\xi \right) dz \tag{2.2}
\]

in which \(WV\) is the water volume flux in cubic meters per time second. \(\Gamma\) is the transect perpendicular to the along channel direction, \(H\) is the water depth, \(\zeta\) is the surface elevation. \(V_n(x, y, z, t)\) is the along channel velocity in different water depth. Positive sign means water us transported into the Lake Pontchartrain. The sixth-order Butterworth filter with a cutoff
frequency of 0.6 CPD (i.e. 40 hours) is used to calculate the low-pass filtered water volume flux.

The modeled water volume flux from Experiment 4 (Fig. 2.14a) reveals a diurnal periodicity. Water volume flux through Chef Menteur is larger than those through the other two inlets, and it is significantly smaller through the Industrial Canal. During spring tide, water volume flux through Chef Menteur can reach $2.8 \times 10^3$ m$^3$/s, and only $5.6 \times 10^2$ m$^3$/s through Industrial Canal (Fig. 2.14a). To check the wind induced water exchange through the three inlets, low-pass-filtered water volume flux is compared (Fig. 2.14b). As a cold front passing by, water volume flux increases in the next 1-2 days. Except for the second cold front, water is moving out of Lake Pontchartrain under the north wind. Water volume flux is into the lake for the second cold front when the easterly wind dominated. The magnitude of low-pass-filtered water volume flux is nearly half of the total water volume flux.

![Figure 2.14](image)

**Figure 2.14.** Water transport through three inlets from model results. (a) is the water volume flux simulated by the model. (b) is the low pass filtered water volume flux. Black line represents the water volume flux through the Rigolets, dark gray line represents that through Chef Menteur, and light gray line Industrial Canal.
2.3.8. Mechanism Discussion

To further illustrate the impact of local wind stress, we now use a quasi-steady state force balance between wind stress and surface slope (Garvine, 1985) to calculate the local wind induced water level difference in east-west direction using the east wind component, and that in north-south direction using north wind component. The following equation is applicable under these assumptions: 1) quasi-steady state, 2) bottom friction can be ignored, 3) the flow is barotropic so that the density gradient can be omitted, which simplified the Equation (2.3) as the following:

\[ 0 = -g \frac{\partial \zeta}{\partial x} + \frac{\tau_a}{\rho h} \]  \hspace{1cm} (2.3)

where \( \partial \zeta \) (or \( \Delta \zeta \)) is the water level difference in east-west and south-north direction, \( \partial x \) (or \( \Delta x \)) is the length of the lake in east-west and south-north direction, \( \Delta x \) is 40 km in north-south direction, and is 66 km in east-west direction, \( g \) is the gravitational acceleration, \( \rho \) is the water density which is 1020 kg/m\(^3\) in the Lake Pontchartrain, \( h \) is the average water depth of 4.0 m. \( \tau_a \) is the wind stress calculated using equation (2.4) (Garvine, 1985):

\[ \tau_a = \rho_a C_d W^2 \]  \hspace{1cm} (2.4)

where \( \rho_a \) is the air density (1.29 kg/m\(^3\)), \( C_d \) is the drag coefficient of \( 1.24 \times 10^{-3} \) (Feng and Li, 2010), \( W \) is the wind velocity. The results are showing in Fig. 2.15. The upper panel Fig. 2.15(a) shows the north wind component induced water level difference. Water level difference resulted from the steady hydrodynamic equation (thin grey line) is almost identical to the model results from the Experiment 2 (solid line), which is induced by local wind. The lower panel Fig. 2.15(b) shows water level difference in north-south direction calculated by steady hydrodynamic equation and by Experiment 2. Water level differences in the north-south direction calculated from the two different methods are very similar with an \( R^2 \) value of 0.83, while an \( R^2 \) value of
only 0.43.

**Figure 2.15.** Wind induced water level difference in east-west and north-south direction under steady state equation (thin grey line) and that calculated by Experiment 2 (black solid line). Vertical lines marks at the beginning time for each cold front.

To contrast the effect of direct wind stress applied to the estuarine surface (the local wind effect) and effect caused by the open boundary water level change (which here we termed it the “remote wind effect” for convenience), we also make a comparison between the water level difference from Experiment 3, and results from the steady state equation (Fig. 2.16). The open boundary effect or remote wind effect induced water level difference is very different from that calculated using Equation 2.3 in either the north-south direction (Fig. 2.16a) or east-west direction (Fig. 2.16b). This result makes several interesting points: first, even though the model is time dependent, the local wind stress induced water slope is almost identical to the simple quasi-steady state force balance between the wind stress and surface slope in the north-south direction, in which no friction or nonlinearity is involved; second, this simple quasi-steady state
balance is partially broken in the east-west direction, which is anticipated as the relatively wide Rigolets channel provides a passage for significant water exchange with Gulf of Mexico, thereby modifying the surface slope that would have been established if there were no open boundary; third, the open boundary water level controls the overall water level variation inside the estuary and does not provide significant addition to the water level slope across the water body in either directions. The selective preference of response to wind stress is possible because the estuary is almost enclosed except at the three inlets with narrow passages connecting to the coastal ocean.

![Wind induced water level difference in east-west and north-south direction under steady state equation (thin grey line) and that calculated by Experiment 3 (black solid line). Vertical lines mark at the beginning time for each cold front.](image)

**Figure 2.16.** Wind induced water level difference in east-west and north-south direction under steady state equation (thin grey line) and that calculated by Experiment 3 (black solid line). Vertical lines mark at the beginning time for each cold front.

### 2.4. Conclusions

Analysis of observation by ADCP reveals that the hydrodynamics is highly correlated to wind vector and air pressure. Except the 1st and 4th cold front events, the water level is inversely correlated with the air pressure. The sub-tidal flows oscillated in and out of Lake Pontchartrain. Wind direction changes with the cold front passages after which the northerly wind lasts for at
least 2-3 days. The along channel flow in the Rigolets was generally out of Lake Pontchartrain for two days after the frontal passage. However, after the 2\textsuperscript{nd} cold front event, water was flowing into Lake Pontchartrain. At Chef Menteur, the along channel flow was out of Lake Pontchartrain after the cold front passages except for the 2\textsuperscript{nd} cold front event. For the 2\textsuperscript{nd} cold front passage, water was moving into Lake Pontchartrain. The direction of subtidal flow is controlled by the wind direction.

The FVCOM provides a reliable tool for the simulations of hydrodynamics and helps put the observations into useful perspective for Lake Pontchartrain. Model results are essentially the same whether the spatial variability of wind is included or not. The model simulation confirms that wind variations associated with cold front systems have a great influence on the exchange flows. The northerly winds after the cold front passage can push the water out of the lake, while the easterly winds into the lake.

The numerical experiment shows that local wind vector has a very small impact on the overall water level variation, but it impacts the lake surface slope, particularly in the north-south direction. The results also show that the remote wind effect mainly controls the overall water level change. The remote wind induced water level change reached maximum after each cold front passage. In addition, the maximum water level change induced by the open boundary or remote wind effect is about 14 times larger than the peak of lake surface difference induced by the local wind effect.

Water volume flux is the greatest in Chef Menteur but roughly the same as in the Rigolets, and smallest in the Industrial Canal, consistent with Li et al. (2010) -8-12\% through Industrial Canal, and split half-half between the other two inlets. The direction of water volume exchange with Gulf of Mexico is all the same through the three inlets.
CHAPTER 3. SPATIAL VARIATION OF WIND-DRIVEN CIRCULATION AND QUASI-STEADY STATE BALANCE IN LAKE PONTCHARTRAIN ESTUARY

3.1. Introduction

Wind can significantly impact hydrodynamics in estuaries and coastal waters including water transports (Wong, 1987; Buijsman and Ridderinkhof, 2007; Wong et al, 2009); subtidal water level variations (Dzwonkowski et al., 2014); circulations (Sanay and Valle-Levinson, 2005; Schoen, 2014; Herrling and Winter, 2015); salinity distributions (Ralston et al., 2008); mixing (Scully, et al., 2005); sediment transport (Roberts et al., 2015; Roberts et al, 1989; Kemp et al., 1980; Crout and Hamiter, 1981; Bloesch, 1995); and larval distribution (Scheffer, 2004). Winds affect estuarine circulation and water level through different mechanisms. Under barotropic conditions, the wind induced surface flow tends to be in the direction of wind, particularly in shallow waters, while on the other hand, the flow in deeper water or bottom layer tends to be against the wind (Engelund, 1973; Csanady, 1973; Falconer et al., 1991; Gibbs et al., 2016).

To illustrate, wind can induce two-layered circulation as shown in the East River (Filadelfo, et al., 1991), which is also uncovered in Delaware Bay region and is attributed to the geomorphology effect and mass balance requirement (Garvine, 1991). Winds can produce seiches (Csanady, 1968b), alter thermocline slopes, and induce strong currents in coastal zones by raising or depressing the thermocline (Csanady, 1968a). Both uniform wind varying with time and steady wind can produce a strong boundary current (Csanady, 1968b).

Previous studies have revealed that wind induced water volume exchanges and water level variations in the Gulf of Mexico can be comparable to, if not greater than, tidal exchanges (Feng and Li, 2010). In the northern Gulf of Mexico, where tidal amplitudes are small, wind
plays an important role in controlling the water exchanges. Winds associated with winter cold fronts provide major forcing for the water exchanges between the bay and coastal water in the Gulf of Mexico (Smith, 1977). For example, strong northerly winds during winter storms are responsible for more than 1 m of water level variations and rapid flushing from the Atchafalaya Bay (Walker and Hammack, 2000). Furthermore, the post-frontal winds facilitate the offshore transport of plume water out of the Atchafalaya Bay (Cobb et al., 2008). In addition, hydrodynamic response to 76 atmospheric front events in a tidal channel in the southern Louisiana (Li et al., 2018a) is found to be highly correlated with the atmospheric forcing: cold (warm) fronts can produce outward (inward) transports (Weeks et al., 2018). East wind can drive saltwater intrusion through the remote wind effect (Lin et al., 2016). In short, winds, especially cold front induced winds are significant in controlling hydrodynamics of coastal water bodies.

Wang and Elliott (1978) separate the local and non-local wind effects, and conclude that the alongshore non-local wind is responsible for setting up the up-bay propagation of coastal sea level fluctuations. Such non-local effect also exists at the mouth of Chesapeake Bay (Wong and Garvine, 1984). Garvine (1985) presents a barotropic analytical model showing that remote wind is responsible for the overall water level variations inside the estuary, which is confirmed by additional studies, e.g. by Wong (2002), Wong and Valle-Levinson (2002), Snedden et al. (2007), and Casares-Salazar and Mariño-Tapia (2016). Here the remote wind effect is defined as the water level variations at the mouth of an estuary due to weather forcing away from the estuary, which depends on the large-scale atmospheric conditions and ocean dynamics. The remote wind effect is a result of complex hydrodynamic response to nonlocal weather forcing. In contrast, the local wind effect is defined as the direct impact of surface wind stress to the hydrodynamics inside the estuary. In reality, an estuary is under both remote and local wind effects.
forcing, which we call the *combined effect.*

Even though the water level variations are determined by remote wind, local wind is responsible for the sub-tidal current (Wong and Moses, 1998). Specifically, under local winds, flows in shallow (deep) waters are downwind (upwind) (Wong, 1994). Local wind produces surface slope variations (Guo and Valle-Levinson, 2008; Huang and Li, 2017), while remote wind generates the overall water level variations in the estuary. In addition, local wind leads to a quasi-steady state balance between the 40-hr low-pass filtered wind stress and the surface slope induced pressure gradient force (Huang and Li, 2017), which is quite accurate even when the wind changes with time. This balance is also satisfied in Barataria Bay (Li et al., 2019b) and an Arctic lagoon (Li et al., 2019a). Furthermore, any changing wind can produce a seiche that dissipates within 2-3 cycles or a few hours in Lake Pontchartrain (Li et al, 2018b). However, the effects of local and remote winds on the circulation inside an estuarine lake with limited connection to the ocean under baroclinic conditions have not been adequately examined.

In this chapter, how remote and local winds impact the circulation in the low-salinity Lake Pontchartrain is examined. Several numerical experiments are designed to accomplish these goals: 1) examine the circulations of local wind, remote wind, and both local and remote winds with baroclinicity included; 2) quantify the response of the velocity field to different wind conditions in different parts of the estuary; and 3) further examine the quasi-steady state balance in more detail under baroclinic conditions and different wind conditions associated with 16 cold front events.

### 3.2. Study Site and Previous Studies

Lake Pontchartrain (Fig. 3.1a) is located in the southeastern Louisiana, USA, covering an area of about 1,600 km² with an average depth of about 4 m. The lake is in the center of the
12,173 km² Pontchartrain drainage basin (Keddy, et al., 2007) encompassing 16 parishes in southeast Louisiana (Penland et al., 2002). Lake Pontchartrain is about 40 km along the north-south direction, and about 60 km along the east-west direction, with a total water volume of 9.77×10⁹ m³ (Li et al., 2008). Lake Pontchartrain was connected to Gulf of Mexico mainly through three narrow channels prior to the year 2012 (Fig. 3.1): the Industrial Canal (30°0´18.26´´N, 90°1´31.86´´W), the Chef Menteur Pass (30°05´03.96´´N and 89°47´28.89´´W), and the Rigolets (30°10´15.67´´N and 89°40´27.84´´W). The average depth of the Rigolets and Chef Mentuer are ~12 m, and ~9 m for Industrial Canal (Fig. 3.1b).

**Figure 3.1.** Study site, mesh (a), and bathymetry of Lake Pontchartrain (b) for numerical model. Star represents the station of wind data. Black dots are the four sites used to calculate the surface slopes.
The physical processes of water exchange of this almost-enclosed estuary with the coastal ocean determine the transport of water, salt, nutrients, pollutants, fish larvae, and sediment (Bianchi and Argyrou, 1997; Georgiou et al., 2009; Li et al., 2008; McCorquodale, et al., 2009; O'Connell, et al., 2014; Roy, et al., 2012; Signell and List, 1997; White, et al., 2009). The hydrodynamic responses of Lake Pontchartrain to weather, including hurricanes and winter storms, and the subtidal water exchanges with the coastal ocean have been investigated using observations, analytical solutions, and numerical simulations. About 8-12% of the water flux was through the Industrial Canal. The remaining flux is roughly equally partitioned between the Rigolets and Chef Menteur (Li, et al., 2010).

The water level fluctuations are correlated with the wind (Chuang and Swenson, 1981). For instance, subtidal water volume exchanges through the tidal passes are on the same order of the magnitude of the tidal oscillation of volume flux (Swenson and Chuang, 1983). Furthermore, when wind speed exceeds 3.0 m/s, wind dominates the circulation; when wind speed is less than 2.0 m/s, tidal effects dominate the circulation (Haralampides, 2000). The depth-averaged wind-driven circulation in the system (Georgiou, 2002; Georgiou et al., 2009) has higher amplitude in the region adjacent to the open boundary in the east. In addition, Chao et al. (2012) demonstrate a two-gyre circulation pattern during southeast wind and a return flow in the middle of the lake.

The subtidal water level gradient is a result of a quasi-steady state balance with wind, particularly during atmospheric cold fronts (Huang and Li, 2017; Li et al., 2019a, b). The scaling analysis of the wind-driven subtidal flow shows that subtidal pressure gradient term is two orders of magnitude larger than the local rate of change of the subtidal flow components (Li et al., 2019a), leading to a quasi-steady state balance. The mechanism of this quasi-steady state balance is also studied from another point of view by Li et al. (2018b) with numerical experiments for the
adjustment processes under stepwise constant wind varying its direction at 15-day intervals. Results suggest that a change in wind produces a seiche that dissipates within 2-3 cycles that last for a few hours, which is much shorter than the diurnal tidal time scales (~24 hr). These studies, however, use only barotropic models and the potential effect of stratification has not been examined yet. This research will extend the work by including stratification and examine the effect of local vs. remote wind effects.

3.3. Model Description and Validation

3.3.1. FVCOM Model Description

A 3-D Finite Volume Community Ocean Model (FVCOM) is applied to simulate the hydrodynamics of Lake Pontchartrain with observed wind and with stratification. The focus is on the analysis of the response of circulation and surface slopes in the along- and cross-estuary directions to different wind conditions. Since Lake Pontchartrain is east-west (E-W) oriented, we define the E-W direction as the along-estuary direction, and the north-south (N-S) direction as the cross-estuary direction.

The bathymetry (Fig. 3.1b) used in the numerical model combines the bathymetry from previous models (Li et al., 2008; Huang and Li, 2017; Li et al., 2018b) and the water depth measured from vessel-based surveys (Li et al., 2009, 2010; Li and Zheng, 2016). Lake Pontchartrain has the average surface salinity of about 4 PSU, but the bottom salinity can reach 12 PSU at times (Li et al., 2008).

FVCOM model has been widely used for studying coastal ocean hydrodynamics (Chen et al., 2003; Huang et al., 2008; Liu, et al., 2015), especially for regions with complicated topography (e.g. Huang et al., 2011). The governing equations are (Chen et al., 2003):

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - f v = - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} (K_m \frac{\partial u}{\partial z}) + F_u
\]  

(3.1)
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \left( K_m \frac{\partial v}{\partial z} \right) + F_v \tag{3.2}
\]

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho_0} \frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left( K_m \frac{\partial w}{\partial z} \right) + F_w - g \tag{3.3}
\]

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3.4}
\]

\[
\frac{\partial t}{\partial t} + u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} + w \frac{\partial t}{\partial z} = \frac{\partial}{\partial z} \left( K_h \frac{\partial t}{\partial z} \right) + F_T \tag{3.5}
\]

\[
\frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x} + v \frac{\partial S}{\partial y} + w \frac{\partial S}{\partial z} = \frac{\partial}{\partial z} \left( K_h \frac{\partial S}{\partial z} \right) + F_S \tag{3.6}
\]

\[
\rho = \rho(T, S, p) \tag{3.7}
\]

where \( x, y, z \) are the three axes in the east, north, and vertical direction, respectively; \( u, v, w \) are the \( x, y, z \) velocities, respectively, \( \rho_0 \) is density; \( P \) the total pressure of air and water; \( f \) the Coriolis parameter; \( g \) the gravitational acceleration; \( K_h \) the horizontal eddy diffusion coefficient, \( K_m \) the vertical eddy diffusion coefficient, determined by the Mellor and Yamada (1982) level-2.5 (MY-2.5) turbulent closure scheme modified by Galperin et al. (1988); \( T \) the temperature, \( S \) the salinity, \( F_w \) the diffusion term of the vertical momentum, and \( F_u, F_v, F_T, \) and \( F_S \) are the diffusion terms for the horizontal momentums, thermal, and salt, respectively.

The surface and bottom boundary conditions are:

\[
K_m \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \frac{1}{\rho_0} \left( \tau_{sx}, \tau_{sy} \right), w = \frac{\partial \zeta}{\partial t} + \frac{\partial \zeta}{\partial x} + \frac{\partial \zeta}{\partial y}, \text{at } z = \zeta(x, y, t) \tag{3.8}
\]

\[
K_m \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \frac{1}{\rho_0} \left( \tau_{sx}, \tau_{sy} \right), w = -u \frac{\partial H}{\partial x} - v \frac{\partial H}{\partial y}, \text{at } z = -H(x, y) \tag{3.9}
\]

where \( (\tau_{sx}, \tau_{sy}) \) and \( (\tau_{bx}, \tau_{by}) \) are surface wind stress and bottom stress vectors, respectively. \( H \) is the water depth and \( \zeta \) is the surface elevation. \( (\tau_{bx}, \tau_{by}) \) is the bottom stress calculated by

\[C_d \sqrt{u^2 + v^2}(u, v)\]

where \( C_d \) is the drag coefficient and is determined by the following equation:
\[ C_d = \max \left( \frac{k^2}{\ln \left( \frac{z_{ab}}{z_0} \right)}, 0.0025 \right) \] (3.10)

where \( k \) is the von Karman constant (0.4); \( z_0 \) is the bottom roughness parameter, and \( z_{ab} \) is the height above the bottom.

3.3.2. The computational mesh and model setup

The computational mesh for the model (Fig. 3.1a) contains 6053 nodes and 10580 triangular cells. There are a total of 20 vertical sigma layers with a finest horizontal resolution of approximately 50 m. The time step for the external mode is 1 second. The time interval for output is 30 minutes. The water elevation prescribed at the open boundary is either predicted tidal elevation or observed water level (both obtained from NOAA). The wind is spatially uniform for the entire domain but varies in time. The boundary temperature and salinity conditions are provided by the USGS observations. Initial temperature and salinity are set to be constants, which are 29.7 °C and 1.7 PSU. The model is run with “cold start” from Jul. 01, 2010 to Jan. 1, 2011 to match the time of observations. The first three months run is for spin up for salinity and temperature fields.

The remote and local wind effects are calculated by using different combinations of open boundary conditions and atmospheric forcing (Table 3.1). The combined effect is simulated by using observed water level imposed at the open boundary with a spatially uniform wind time series (Experiment 1), which is the case with measured wind driving the model and the measured water level as the open boundary condition. The local wind effect is calculated by specifying tidal elevation at the open boundary plus a spatially uniform wind (Experiment 2). The remote wind effect is simulated by imposing the observed water elevation at the open boundary and excluding local wind forcing (Experiment 3). Since the non-tidal change of the observed water level elevation is from a remote region, the sub-tidal variation inside the basin, obtained by a
low-pass filtering of the model results, is mainly driven by wind and the remote wind effect.

Although the low-pass filtering removes the tidal oscillations, a tidally induced constant water level is remained. For comparison with Experiment 3, Experiment 4 is driven only by local wind, in which the water level at the open boundary is set to be 0 while allowing free water exchange with the outside, so that the tidally induced mean value is excluded.

**Table 3.1.** Design of numerical experiment with different open boundary condition and atmospheric forcing.

<table>
<thead>
<tr>
<th>Open boundary condition</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
<th>Experiment 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed water level</td>
<td>Tide</td>
<td>Observed water level</td>
<td>Water level is 0 at all the time</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3.3. Data and forcing

Water level and weather data used here are from NOAA’s National Ocean Service Station NWCL1 (8761927), which is located at 30°1′37″N, 90°6′46″W (middle south shore of Lake Pontchartrain) (red star in Fig. 3.1). The salinity data are from the USGS station, Rigolets at Hwy 90 near Slidell (USGS 20100110894442600, 30°10′01″N and 89°44′26″W), from Oct. 1, 2010 to Jan. 1, 2011. Current velocity data used for the model validation were measured by an Acoustic Doppler Current Profiler (ADCP) deployed between Oct. 9 and Nov. 18, 2008 in Chef Menteur (Fig. 3.1). The ADCP was deployed at the bottom of the inlets, looking upward with vertical bins of 0.25 m (Li, et al., 2010). The coordinate system at the inlet is rotated so the axes are aligned in the along-channel and cross-channel directions, respectively. The cross-channel velocity is ignored here as we are only interested in the flows in and out of the estuary. Positive along channel velocity means a flow into the lake.

The model is forced by weather, river discharge, and water level variations at the open boundary. The weather forcing includes the surface air pressure, and wind stress using the wind
data scaled at 10m above the mean sea level for the period between Jul. 1, 2010 and Jan. 1, 2011. Daily river discharge data for the model input are obtained from the USGS stations of Pearl River (USGS 02490500), East Pearl River (USGS 02492110), Amite River (USGS 07380120), Tangi River (USGS 07375500), Tchefuncte River (USGS 07375000), and Tickfaw River (USGS 07376000) for Jul. 1, 2010 to Jan. 1, 2011. The daily salinity and temperature data used for forcing the open boundaries are obtained from USGS stations at Mississippi Sound (ID: 300722089150100) and Black Bay (ID: 07374526) from Jul. 1, 2010 to Jan. 1, 2011.

3.3.4. Validation

The skill scores of the FVCOM computed water level (Fig. 3.2a) and salinity (Fig. 3.2b) from Oct. 1, 2010 to Jan. 1, 2011 are excellent (0.9), and very good (0.58), respectively, using the definition of Allen et al. (2007) and Wu et al. (2011). During this time period, there are no data for velocity. The velocity is validated for a different time period with measurements of velocity profiles using an ADCP deployed at the Chef Menteur Pass from Oct. 8, to Nov. 18, 2008. The simulated surface and bottom current velocity (Figs. 3.2c and 3.2d) are consistent with the observed data with skill scores of 0.61 and 0.62, which can be categorized as very good (Wu et al., 2011).
Figure 3.2. Validation of water level (a) and salinity (b) for simulation from Oct. 1, 2010 to Jan. 1, 2011. Validation of along channel velocity in 2008 for Chef Menteur. (c) and (d) are surface and bottom along-channel velocity at this site.
3.4. Results

3.4.1. The overall circulation pattern of Lake Pontchartrain

We first discuss the circulation under the easterly, westerly, northerly, and southerly to illustrate the surface and bottom circulation patterns and salinity distribution induced by the combined effect (combined current, CC), remote wind effect (remote current, RC), and local wind effect (local current, LC). Winds in the four directions are chosen during the period of cold front passages: northerly wind on Nov. 27, southerly wind on Dec. 26, easterly wind on Nov. 29, and westerly wind on Nov. 16.

Under southerly (northerly) wind, the surface CC (Fig. 3.3a and Fig. 3.4a) tends to be downwind toward the northern (southern) shore in most of the interior. Near the open boundary in the east, when the water level increases at the open boundary, the CC is into the estuary through the Rigolets and Chef Menteur; when the water level is dropping, the CC is out of the estuary. The bottom CC (Fig. 3.3b and Fig. 3.4b) is upwind in the western interior, but downwind along the western shore where water is shallower. The bottom CC along the western coast turns along the northern (southern) shore to the east after reaching the northern (southern) shore under the southerly (northerly) wind, and then joins the return flow in the deeper water area in the center, forming a clockwise (counter-clockwise) circulation in the western region of the estuary. In the eastern region, because of the water level variations at the open boundary, flows alternate in and out of the estuary and are intensified by the narrow channel of the Rigolets and Chef Menteur, thus the CC in the eastern region is essentially in the west-east directions.
Figure 3.3. Circulation pattern and salinity distribution under southerly wind (08:00 UTC on Dec, 16, 2010). Left column shows the surface circulation (a, combined effect, c, local wind, and e, remote wind effect). Right column represents bottom circulation (b, combined effect, d, local wind, and f, remote wind effect). Color bar represents salinity (PSU).
Figure 3.4. Circulation pattern and salinity distribution under northerly wind (00:00 UTC on Nov, 27, 2010). Left column shows the surface circulation (a, combined effect, c, local wind, and e, remote wind effect). Right column represents bottom circulation (b, combined effect, d, local wind, and f, remote wind effect). Color bar represents salinity (PSU).

Under easterly (westerly) wind, the surface CC (Fig. 3.5a and Fig. 3.6a) over most of the lake is downwind. For the central lake, surface CC is weaker than that in the coastal area. The bottom CC (Figs. 3.5b and 3.6b) in the shallower shore region is downwind. A return flow is established from west (east) to east (west) in the interior in the western region. When this return
flow meets with the inflow from the two inlets in the east, it bifurcates into two branches to the south and north, respectively.

Salinity is higher (>9 PSU) in the eastern region. Saltwater is transported into the lake through the Rigolets. In the central of the lake, salinity is around 4 PSU, in the coastal zone along the lake shore, the salinity is lower than 2 PSU. When water is flowing into the lake (Figs. 3.3a, b and Figs. 3.5a, b), salinity in the western central lake is relatively high. When water is flowing out of the lake (Figs. 3.4a, b, and Figs. 3.6a, b), salinity in the western central lake is relatively low.
Figure 3.5. Circulation pattern and salinity distribution under easterly wind (00:00 UTC on Nov, 29, 2010). Left column shows the surface circulation (a, combined effect, c, local wind, and e, remote wind effect). Right column represents bottom circulation (b, combined effect, d, local wind, and f, remote wind effect). Color bar represents salinity (PSU).
3.4.2. Circulation pattern under local and remote wind effect

Local wind induced circulation

Under southerly (northerly) wind, the surface LC (Fig. 3.3c and Fig. 3.4c) for the entire estuary tends to be downwind in general. The inward or outward flows through the Rigolets are...
not as strong as those under the combined effect, indicating that the local wind does not contribute significantly to the inward/outward flows through the restricted open boundary. There is a broad return flow in the bottom layer (Fig. 3.3d and Fig. 3.4d) in the central lake, which is upwind, with almost the same magnitude as the total return flow (Fig. 3.3b and Fig. 3.4b). The return flow bifurcates into two branches of coastal currents in opposite directions after arriving the northern (southern) coast, forming a clockwise (counter-clockwise) circulation in the western lake.

When the easterly (westerly) wind dominates, the surface LC (Fig. 3.5c and Fig. 3.6c) for the coastal region has almost the same pattern inside the estuary with a magnitude comparable to that of the combined effect (Fig. 3.5a and Fig. 3.6a), flowing in the downwind direction. There is no obvious inflow or outflow from the two inlets. For the eastern region close to the restricted open boundary, the surface LC is downwind but has a different pattern compared to the CC flows. The bottom upwind return flow is more evident (Fig. 3.5d and Fig. 3.6d), resulting in a counter-clockwise (clockwise) circulation.

Salinity distribution inside the lake is similar to that of the combined effect. The obvious difference is that high salinity under local wind is mainly located at the Chef Mentuer (Fig. 3.3c, d). During southerly wind, salinity is higher at the Industrial Canal (Figs. 3.3c, d). In other cases, local winds are only responsible to distribute the salinity through Chef Menteur.

**Remote wind induced circulation**

For the remote wind effect, when water is flooding into the lake (Fig. 3.3e and Fig. 3.5e), the surface RC in the eastern side is consistent with the inflow from the open boundary. Since most of the water volume is transported through the eastern inlets (Li et al., 2008), surface RC is strong along the northeastern shore. The surface RC turns to southern shore on the western side.
After the surface RC flows back to the eastern side along the southern shore after reaching the southern shore, forming a counter-clockwise circulation on the surface. The bottom RC (Fig. 3.3f and Fig. 3.5f) is in the direction of the inflow from the open boundary, and bifurcates to the south and north while flowing toward the western shore.

When water is ebbing out of the lake (Fig. 3.4e and Fig. 3.6e), the surface RC is in the direction of the outflow for most of the lake. RC at the northeastern side is toward the south. For the bottom RC (Fig. 3.4f and Fig. 3.6f), there is a return flow in the central lake. The return flow diverges into two branches as it moves toward the west.

Salinity distribution under remote wind effect is similar to that under combined effect. High salinity water is at the eastern side and is transported into the lake through the Rigolets channel. Salinity in the Chef Menteur inlet is lower under remote wind effect than that under local wind effect. The salinity distribution in the central lake is determined by the water exchange with the open ocean, because when the water level increases, salinity inside the lake is higher, when water level decreases, salinity inside the lake is lower.

3.4.3. Spatial distribution of velocity magnitude under local/remote wind effect.

Distribution of velocity magnitude (Figs. 3.7-4.9) under different wind conditions is examined as follows. Under southerly wind (Figs. 3.7a,c,e), the local winds mainly influence the flows along the coast and in the western central interior, while the remote winds mainly affect the flows in the eastern and northeastern areas. The current velocity near the bottom exhibits the same features as that of the surface layer (Figs. 3.7b,d,f). The remote winds have the most influence in the eastern and northeastern regions and near the open boundary, while on the other hand the local winds determine flows in the coastal regions and the shallow western interior. Remote wind effect is dissipated by the bottom friction away from the eastern open boundary.
Under easterly and westerly winds, the remote wind effects dominate the flows near the open boundary region; however, in parts of the interior, especially in the southwestern region, the remote wind effect (Fig. 3.8e) has almost completely disappeared due to friction; but in the
central and northeastern region, remote winds still exhibit considerable influences. For the coastal region, local wind effect is again the main contributor to circulations. These features also appear in the bottom flows (Figs. 3.8b,d,f).

**Figure 3.8.** Magnitude of current velocity under easterly wind. Figs. (a), (c), (e) are the velocity magnitudes in surface layer of combined effect, local wind effect, and remote wind effect, respectively. Figs. (b), (d), (f) are the velocity magnitudes in bottom layer of combined effect, local wind effect, and remote wind effect, respectively.
To further examine and quantify the spatial distribution of remote and local wind effects, we have calculated the difference of the velocity magnitude between the combined effect and remote wind effect and that between the combined effect and local wind effect. The smaller the difference is, the closer the remote (local) wind effect is to the combined effect, therefore, more important than the local (remote) wind effect. The larger difference between the combined effect and remote wind effect (Figs. 3.9 c, d) is mainly located in the region along the shore zones; and the larger difference between the combined effect and local wind effect reaches the maximum in the eastern region close to the open boundary (Figs. 3.9a), which is consistent with the previous finding that the remote wind effect is dominant in the eastern region close to the open boundary, whereas local wind effect controls the velocity along coastal regions and part of the central region. There is a region around 30.2ºN and 92.1ºW where both local and remote wind effects are evident.
Figure 3.9. Difference of magnitude between combined effect and local/remote wind effect under southerly wind. Magnitude of current velocity under southerly wind. Figs. (a) and (b) are the difference of velocity magnitudes between the velocity magnitude of the combined effect and that of local wind effect in surface and bottom layers. Figs. (c) and (d) are the difference of velocity magnitudes between the velocity magnitude of combined effect and that of remote wind effect in surface and bottom layers.

The bottom layer circulations are shown in Figs. 3.9b and 3.9d. Indeed, the difference between the LC and CC in the bottom layer reaches the maximum near the open boundary (Fig. 3.9b) i.e. the remote wind is dominant. In the western and southwestern shore area, differences are larger (Fig. 3.9d), indicating that the local wind effect dominates.

To further quantify the relative importance of the local and remote wind effects, we calculate the ratio of total flows normalized by the combined effect with the following equations:

$$E_{LC} = \frac{\text{sum}(u_{LC})}{\text{sum}(u_{CC})}$$  \hspace{1cm} (3.11)
\[ E_{RC} = \frac{\text{sum}(U_{RC})}{\text{sum}(U_{CC})} \]  

(3.12)

in which \( E_{LC} \) and \( E_{RC} \) represent the ratios between the local and remote wind effects and the combined effect in each of the three lake regions (the eastern, coastal, and central regions), \( 
\text{sum}(U_{LC}), \text{sum}(U_{RC}), \text{and } \text{sum}(U_{CC}) \) are the summations of the velocity magnitude of each region under local wind only, remote wind only, and both local and remote winds, respectively. \( E_{LC} \) and \( E_{RC} \) represent the relative importance of local and remote wind effect compared with the combined effect. Note that we are not comparing with the velocity vectors at each point, and \( (E_{LC}+E_{RC}) \) does not necessarily equal to 1 because the combined effect is not a simple superposition of remote and local wind effects and the problem is not linear. The results show that in the coastal region, the ratio (Table 3.2) between local wind effect and the combined effect (\( E_{LC} \)) is about 0.87, larger than \( E_{RC} \) (0.79), which means that the local wind effect contributes more in the regions with shallower water along the coastal zones. For the central lake region, \( E_{LC} \) is 0.6, smaller than \( E_{RC} \) which is 0.88, indicates the more important role the remote wind effect plays in this region. For the eastern region near the open boundary, the remote wind effect is dominant with a ratio of 1.01, compared with the local wind effect of 0.5.

Table 3.2. Ratio of local/remote wind effect comparing with the combined effect in terms of integrated velocity magnitude in three different lake regions.

<table>
<thead>
<tr>
<th></th>
<th>Open boundary region</th>
<th>Coastal region</th>
<th>Central lake region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local effect/combined effect</td>
<td>0.50</td>
<td>0.87</td>
<td>0.60</td>
</tr>
<tr>
<td>Remote effect/combined effect</td>
<td>1.01</td>
<td>0.79</td>
<td>0.88</td>
</tr>
</tbody>
</table>

3.5. Discussion

3.5.1. Quasi-steady state balance in cross- and along-estuary directions

The above discussion clearly reveals that local wind effect controls the circulations for part of the interior, particularly in shallow waters, on the surface, and most of the coastal regions.
Furthermore, local wind is also the main driver of the lake surface slope in the along- and cross-
estuary directions, and can be well approximated by a quasi-steady state force balance, which is an extension of results of Huang and Li (2017), Li et al. (2019a, b), and Li et al. (2018a, b) in which no stratification was considered. This quasi-steady state balance is:

$$0 = -g \frac{\partial \zeta}{\partial x} + \frac{\tau_{ax}}{\rho h}$$

(3.13)

where $\partial \zeta$ is the subtidal surface level difference in two directions, $\partial x$ is the cross- and along-
estuary distance (37 or 52 km, respectively). Four points from N, S, W, and E sites around the lake are selected. In equation 3.13, $\rho$ is the water density (1024 kg/m$^3$), $h$ is the average water depth of 4.0 m. $\tau_{ax}$ is the wind stress in the cross or along-estuary direction (Garvine, 1985):

$$\tau_{ax} = \rho_a C_d |W| W_x$$

(3.14)

where $\rho_a$ is the air density (1.29 kg/m$^3$), $C_d$ is the drag coefficient of $1.24 \times 10^{-3}$, $W_x$ is the wind velocity component in the cross- or along-estuary direction with a total wind speed of $W$ obtained from the NOAA’s NDBC station NWCL1 (Fig. 3.1).

The study of Li et al. (2018) indicates that the quasi-steady state is a result of a quick adjustment process under variable winds. This adjustment is a forced damped seiche oscillation. The periods of the damped oscillations are accurately verified by a numerical experiment in Lake Pontchartrain based on the seiche oscillation period determined by

$$T = \frac{2L}{\sqrt{gh}}$$

(3.15)

in which $T$, $L$, $g$, and $h$ are the period of seiche oscillation, the distance between two points on opposite coasts, gravitational acceleration, and mean water depth along the line, respectively (Proudman, 1953; deBoer and Maas, 2011).

The R$^2$ values for the approximation in the cross- and along-estuary directions in Huang
and Li (2017) are 0.83 and 0.43, respectively, indicating a different quasi-steady state balance in cross- and along-estuary directions. Here we examine the quasi-steady state balance between wind-induced pressure gradient and wind-stress when stratification is present. Results (Figs. 3.10a, c) show that the cross-estuary surface slopes between Oct. 1, 2010 and Jan. 1, 2011 estimated by the quasi-steady state equation (gray dashed line) from both Experiment 2 and Experiment 4 are in an almost perfect agreement with that calculated from the model results (black solid line). However, in the along-estuary direction, surface slope resulted from Experiment 2 (black solid line in Fig. 3.10b) is lower than that produced by the quasi-steady state balance (gray dashed line in Fig. 3.10b), leading to a lower $R^2$ (0.65) under this experimental condition. To further examine the relationships, we also subtract the mean surface slopes and calculate the $R^2$ value between the quasi-steady balance induced surface slopes and the demeaned surface slopes from the numerical experiments. The $R^2$ value (Table 3.3) for Experiment 1 (combined effect) in the along-estuary and cross-estuary directions are the lowest (0.60 and 0.94). After subtracting the mean slope from the simulated surface slopes, the $R^2$ value in the along-estuary direction is significantly increased to 0.96. $R^2$ values for Experiment 2 (0.95 and 0.65) are slightly higher than that for Experiment 1 (0.94 and 0.60). The demeaned $R^2$ values for Experiment 2 are increased to 0.98 in the along-estuary direction. $R^2$ values for Experiment 4 in both directions are high and comparable (> 0.95). These results show that either subtracting the mean slope or remove the tidal input at the open boundary can increase the $R^2$ between the quasi-steady state balance and the FVCOM results in the along-estuary direction.
Figure 3.10. Comparison between quasi-steady state balance induced surface slopes (dashed grey lines) and that calculated by the FVCOM model (solid black lines) in cross estuary (N-S) and along estuary directions (E-W). Figures a) and b) are under local wind conditions with tide at the open boundary (Experiment 2), c) and d) are under local wind conditions but without tidal forcing at the open boundary (Experiment 4).

The reason of the difference of $R^2$ values in the two directions is because of the open boundary being in the east. Tide is input from the east. The shallow water of the lake leads to a relatively high nonlinearity due to tidal oscillation (~ 4 m mean depth), which is the strongest at the eastern open end. The bottom friction and nonlinear tide will produce a mean slope into the
lake toward the west (the subtidal or mean water level on the west being slightly higher than the east) as shown in Li and O’Donnell (1997), adding a net negative slope due to tide (see the lower curve from FVCOM results and the higher curve from the quasi-steady state balance in Fig. 3.10b). When the open end is closed, the tidal effect disappears and the two R² values become very close (Figs. 3.10c,d). Note also that even though the two directions have very different R² values, the trends are very much the same. As a result, the correlation coefficients are all high (CC~0.98-0.99, Fig. 3.10). Since the tidally induced mean slope does not change with wind and it has much smaller variations. Consequently, the correlation coefficients between the FVCOM model results and the quasi-steady state balance equation are all high in the two directions (Fig. 3.10). If we subtract the mean slope or exclude tidal input at the open boundary, the R² value in the east-west direction will increase to ~ 95% (Table 3.3), the same value to that in the north-south direction. In other words, if the tidal effect is taken away by removing the mean, the two directions appear to be the same. Alternatively, defining zero amplitude for tide at the open end will also increase the R² to about 95%.

**Table 3.3.** R square value (R²) and root mean squared error (RMSE) for the approximation of surface slope in cross- and along-estuary directions under combined effect, local wind effect, pure local wind effect, and remote wind effect.

<table>
<thead>
<tr>
<th></th>
<th>Combined effect (Experiment 1)</th>
<th>Local wind effect 1 (Experiment 2)</th>
<th>Local wind effect 2 (Experiment 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²</td>
<td>RMSE</td>
<td>R²</td>
</tr>
<tr>
<td>Cross-estuary</td>
<td>0.94</td>
<td>0.0036</td>
<td>0.95</td>
</tr>
<tr>
<td>Cross-estuary (demeaned)</td>
<td>0.95</td>
<td>0.0036</td>
<td>0.95</td>
</tr>
<tr>
<td>Along-estuary</td>
<td>0.60</td>
<td>0.0089</td>
<td>0.65</td>
</tr>
<tr>
<td>Along-estuary (demeaned)</td>
<td>0.96</td>
<td>0.0029</td>
<td>0.98</td>
</tr>
</tbody>
</table>

To reinforce this argument, we have analyzed 4 more transect lines in the E-W and N-S directions, respectively, to examine the open boundary effects on the quasi-steady state.

First, 4 transects (figure 3.11a) are selected to calculate the total water level difference in
both E-W and N-S directions. As shown in Fig. 3.12, the N-S water level differences for lines 1-4 and the E-W water level differences for lines 5-8 are calculated using the quasi-steady state equation and FVCOM results, respectively. The data are low-pass filtered and demeaned, meaning that the tidal effect and a constant mean value added by non-linear tidal effect have been completely excluded. Results show that the $R^2$ values of the E-W water level differences from north to south (Figs. 3.12a-3.12d) are all higher than 0.9, however, $R^2$ values of the N-S water level differences from east to north (Figs. 3.12e-3.12h) are increasing with the lowest $R^2$ only 0.66 for the east-most transect, meaning the existence of eastern open boundary can significantly affect the quasi-steady state balance in the eastern region.
Figure 3.11. a, Lines selected to calculate the water level difference. Lines 1-4 are all in the N-S direction, lines 5-8 are all in the E-W direction. b, Segments along the N-S and E-W transects. Segments 1-4 are between every two adjacent nodes (red dots) along the transect in the N-S direction, segments 5-8 are between every two adjacent nodes (blue dots) along the transect in the E-W direction.
Figure 3.12. Water level differences calculated from the quasi-steady state equation (dashed red lines) and that from FVCOM (solid black lines) for each line in Fig. 3.11a. a-d are the E-W water level differences for lines 1-4 from north to south, and e-h are the N-S water level differences for lines 5-8 from east to west.

Secondly, we select two transects (Fig. 3.11b) to investigate the N-S and E-W water level differences along each transect so that we can check how water level difference changes along the transects. As showing in Fig. 3.13, two transects are selected with 5 nodes on each transect. Calculations of water level differences from the quasi-steady state and FVCOM are done between adjacent nodes or for each segment (Fig. 3.13). The $R^2$ values are increasing from east to west with 0.44 at the east-most segment and 0.94 at the west-most segment (Figs. 3.13a-3.13d), which indicates that the accuracy of quasi-steady state balance decreases towards the eastern open boundary, which confirms our previous conclusion that eastern open boundary effect tends to impact the quasi-steady state balance. For the transect in N-S direction (Figs. 3.13e-3.13h),...
3.13e-3.13h), the $R^2$ values are higher (exceeds 0.9) for the segments near coastal region and lower (0.85 and 0.88) for segments 2 and 3 in central lake region.

![Figure 3.13](image)

Figure 3.13. Water level differences calculated from the quasi-steady state equation (dashed red lines) and that from FVCOM results (solid black lines) for each segment in Fig. 3.11b. a-d are the water level differences for segments 5-8 along transect in the E-W direction, e-h are for the segments 1-4 along transect in the N-S direction.

### 3.5.2. Quasi-steady state during cold fronts

Given that local wind is the main force setting up the surface slope and the change in wind regimes occurs during atmospheric cold front events (Moeller et al., 1993; Cobb et al., 2008; Feng and Li, 2010; Li and Chen, 2014), we now examine the circulations in Lake Pontchartrain from Oct. 1, 2010 to Jan. 1, 2011 during which there are 16 cold frontal passages (Table 3.4) and our FVCOM model run includes this time period with Experiment 2. For convenience, we define the start time of each front as the time when the cold front enters the northwestern Louisiana, and the ending time is when the cold front leaves the area at the southeastern of LA (Table 3.4). Changes of wind regimes associated with cold front passages can
be viewed as three stages: prefrontal, frontal, and postfrontal stages. The frontal passage time is usually very short (~ a few hours). Fig. 3.14 provides the statistics of the wind before and after the 16 cold front passages with the frequency of occurrence. Before the cold front passages (Fig. 3.14a), southerly wind is most frequent (more than 40%), there is also more than 20% of east/west wind, while nearly 60% of the wind after the cold front passages is northerly or northeasterly (Fig. 3.14b).

Table 3.4. Starting time and leaving time of the 16 cold front events affecting Louisiana (LA) State from Oct. 01 to Dec. 31, 2010.

<table>
<thead>
<tr>
<th></th>
<th>Date entered LA</th>
<th>Date left LA</th>
</tr>
</thead>
<tbody>
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<td>2010 10 3 0</td>
<td>2010 10 3 12</td>
</tr>
<tr>
<td>2</td>
<td>2010 10 12 18</td>
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<td>2010 11 15 6</td>
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<td>2010 11 16 21</td>
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<td>9</td>
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<td>2010 11 19 0</td>
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<td>2010 12 12 12</td>
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<tr>
<td>14</td>
<td>2010 12 16 15</td>
<td>2010 12 18 3</td>
</tr>
<tr>
<td>15</td>
<td>2010 12 22 6</td>
<td>2010 12 23 9</td>
</tr>
<tr>
<td>16</td>
<td>2010 12 25 6</td>
<td>2010 12 25 21</td>
</tr>
</tbody>
</table>
Figure 3.14. Probability of occurrence (%) per degree of wind direction and velocity magnitude based on hourly interpolated wind data obtained from NDBC station (NWCL1 NO. 8761927) for the time period before- (a) and after- (b) the 16 cold front passages.

Table 3.5. $R^2$ and standard deviation for the approximation of surface slope in cross-estuary (N-S) and along-estuary (W-E) directions under corresponding wind directions using quasi-steady state equation before and after each cold front passage.

<table>
<thead>
<tr>
<th></th>
<th>Cross-estuary</th>
<th>Along-estuary</th>
<th>Cross-estuary</th>
<th>Along-estuary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.87</td>
<td>0.64</td>
<td>0.95</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>0.94</td>
<td>0.00</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>0.74</td>
<td>0.00</td>
<td>0.71</td>
<td>0.57</td>
</tr>
<tr>
<td>5</td>
<td>0.99</td>
<td>0.81</td>
<td>0.97</td>
<td>0.87</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.99</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>0.97</td>
<td>0.94</td>
<td>0.73</td>
<td>0.77</td>
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<tr>
<td>8</td>
<td>0.00</td>
<td>0.93</td>
<td>0.00</td>
<td>0.83</td>
</tr>
<tr>
<td>9</td>
<td>0.87</td>
<td>0.96</td>
<td>0.31</td>
<td>0.96</td>
</tr>
<tr>
<td>10</td>
<td>0.99</td>
<td>0.71</td>
<td>0.98</td>
<td>0.00</td>
</tr>
<tr>
<td>11</td>
<td>0.51</td>
<td>0.86</td>
<td>0.50</td>
<td>0.88</td>
</tr>
<tr>
<td>12</td>
<td>0.10</td>
<td>0.43</td>
<td>0.54</td>
<td>0.08</td>
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<tr>
<td>13</td>
<td>0.00</td>
<td>0.99</td>
<td>0.28</td>
<td>0.90</td>
</tr>
<tr>
<td>14</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
<td>0.91</td>
</tr>
<tr>
<td>15</td>
<td>0.99</td>
<td>0.53</td>
<td>0.98</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>0.81</td>
<td>0.00</td>
<td>0.64</td>
<td>0.18</td>
</tr>
<tr>
<td>Average $R^2$</td>
<td>0.55</td>
<td>0.67</td>
<td>0.66</td>
<td>0.57</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.46</td>
<td>0.37</td>
<td>0.35</td>
<td>0.39</td>
</tr>
</tbody>
</table>
The quasi-steady state equation is applied to calculate the approximated surface slopes, before and after each of the cold front passages. Comparing with the FVCOM calculated surface slopes from Experiment 2 (local wind with tidal forcing at open boundary), the $R^2$ values are computed. Table 3.5 shows that before the cold front, the average $R^2$ values in the cross- and along-estuary directions are 0.55 and 0.67, respectively. The higher average $R^2$ in the along-estuary direction is apparently caused by the more frequent easterly or westerly winds before the cold fronts. However, the post-front average $R^2$ values in the cross- and along-estuary directions are 0.66 and 0.57, respectively. The higher average $R^2$ in the cross-estuary direction is due to the strong northerly wind after the cold front passages.

3.6. Conclusions

In this chapter, the spatial structures of the velocity field in the Lake Pontchartrain Estuary are studied for local, remote, and combined wind effects. A baroclinic FVCOM has been applied in the study with four sets of numerical experiments for the hydrodynamics of wind-driven circulations under winds from a sequence of 16 cold fronts. The general circulation pattern of remote and local wind effects can be described below. The remote wind effect facilitates the inflow and outflow through the inlets in the eastern side, and has a great influence in the eastern interior or the region close to the open boundary. Currents under local wind tend to be in the downwind direction in shallow coastal region, with a return flow against the wind at near bottom, similar to the barotropic circulation (Li et al., 2019b). Besides, salt transported through the Rigolets is mainly controlled by the remote wind effect, and that transported through Industrial Canal and Chef Menteur is controlled by the local wind.

Circulation patterns and velocity magnitude in the shallow western interior of Lake Pontchartrain and the coastal regions are dominated by local winds. However, remote wind
effect is responsible for the inflow or outflow through the inlets and controls the magnitude of the current velocity in the eastern region close to the open boundary (explaining almost 100% of the total variation). As a result, the further away from the open boundary, the less impact from the remote wind effect. The reason for the difference in remote wind effect in different regions is that the open boundaries are all on the eastern side, making the remote wind effect generally the strongest there, which subsequently dissipates away from the open boundary. Salinity distribution is mostly determined by remote wind effect. This is because salt is transported into the lake by the water exchanges through three inlets which is mainly controlled by the remote wind.

When compared with model results, the surface slopes approximated by the quasi-steady state equation lead to high $R^2$ values (0.95 - 0.97) under local wind when tidal effects are not included at the open boundary. The high $R^2$ values indicate that the subtidal surface slopes are mainly controlled by local winds, consistent with the non-stratified model results. When the tide is included from the open boundary, however, the $R^2$ value in the along-estuary direction is drastically reduced to ~ 0.60. Hence, the tidally induced surface slope (Li and O’Donnell, 1997) adds an extra constant to the quasi-steady state balance in the along-estuary direction. When tidal effect is removed, the open boundary still reduces the accuracy of the quasi-steady state balance to some extent. Consequently, the further away from the open boundary, the smaller the influence and the larger the $R^2$ values.

The results also demonstrate that the frequency of dominant wind direction affects the $R^2$ values of the quasi-steady state balance. When the cross-estuary (north-south directed) wind is dominant, the quasi-steady state balance is more accurate in that direction; same for the along-estuary direction. In addition, the $R^2$ values are higher in the cross-estuary (north-south) direction.
than that in the along-estuary (east-west) direction after the cold front passages when the wind is the strongest and mostly from the northerly quadrants.
CHAPTER 4. NUMERICAL EXPERIMENTS ON FRESHWATER PLUME FROM MISSISSIPPI RIVER DIVERSION

4.1. Introduction

4.1.1. River Plumes

Coastal plumes are common in and out of estuaries. A plume is usually a bulge of buoyant freshwater with a sharp boundary (the front) which spreads horizontally under gravity over heavier and more saline ambient water (Garvine, 1977, 1987; Kourafalou et al., 1996). The plume region is characterized by enhanced static stability, a significant salinity gradient, and convergence at the front (Garvine and Monk, 1974; O’Donnell, et al., 1998, 2008). The plume caused by the discharge of rivers into coastal waters has a significant impact on suspended sediment transport (Dinnel et al., 1990), dispersion of pollutants (Eisma, 1981; DiGiacomo et al., 2004), plankton communities (Chen, et al., 2009; Lehrter et al., 2009), bacterial concentrations (Ackerman and Weisberg, 2003), water quality (Araújo, et al., 2017), geo-chemical characteristics (Nezlin et al., 2008), and even air-sea interactions (Huang et al., 2013).

Freshwater plumes are affected by a variety of factors including coastal currents, tides, bathymetry, river discharge, and earth rotation (Oey, et al., 1993; Ou et al., 2009; Wiseman and Garvine, 1995; Marsaleix et al., 1998; Horner-Devine, et al., 2009; Lee and Valle-Levinson, 2013; Shi and Wang, 2009; Zu and Gan, 2015). For example, Halverson and Pwalowicz (2008) report that the salinity in a plume is a quasi-linear function of river discharge. The study also demonstrates that the salinity of the plume increases during ebb tides. On the other hand, when the estuary width is equal to or larger than the Rossby radius, the Coriolis effect cannot be ignored. The effect of Earth’s rotation will lead to a laterally asymmetric plume and a two-layered circulation (Chao and Boicourt, 1986; Chao, 1988). Furthermore, the Coriolis force sets up a coastal current directing the meandering plume towards the shore (Garvine, 1987).
O’Donnell (1990) studies how along shore currents affect the buoyant plume and he concludes that a smaller along shore velocity will facilitate the expansion of the buoyant layer with a thinner plume but a larger area of the plume would be susceptible to vertical mixing.

Another important factor in controlling the evolution and dynamics of the fresh water plume is wind (Walker, 1996; Horner-Devine, 2009). Zu et al. (2014) point out that tide plays an important role in determining the vertical structure of a fresh water coastal plume by enhancing mixing and influencing the off-shore shape of the plume by changing the near-shore plume structure, wind helps to spread and mix the plume by wind-driven coastal currents. Winds and ambient wind driven current play important roles in transporting the freshwater downstream (Fong and Geyer, 2002; Dong et al., 2004; Gan et al., 2009; Hordoir, et al., 2006). For instance, a study of Merrimack River plume by Kakoulaki et al. (2014) shows that the plumes with scales less than 12 km are sensitive to wind direction when wind speed exceeds 4m/s. Androulidakis et al. (2015) use a numerical model to examine the role of wind-driven circulation on the evolution of Mississippi River plume into the Gulf of Mexico. They demonstrate that the downstream flow over the Louisiana-Texas shelf can be strengthened by the downwelling-favorable winds, thus deepening the plume. The transport of Mississippi River plume water towards the Mississippi-Alabama-Florida shelf however can be enhanced by upwelling-favorable wind as it eliminates or reverses the downstream current. This is similar to findings in the Delaware coastal plume (Jiang, et al., 2009). Hickey et al. (1998) and Berdeal et al. (2002) both confirm that downwelling/upwelling winds would drive the buoyant plume from the Columbia River onshore/offshore. Ekman currents associated with the upwelling favorable winds tend to widen and thin the river plume (Fong and Geyer, 2001; Houghton et al., 2004).

Wind has not only a great impact on the orientation and development of freshwater or
saltwater plumes (van den Heuvel, 2010), but also is a main reason for the variability in both along-shelf flow and cross-shelf structure of the Amazon Plume (Lentz, 1995). Walker (1996) and Walker et al. (1996) study the Mississippi River plume by using satellite images and in situ measurements. They demonstrate that the day-to-day variability in plume size is closely related to the changes in the wind field. Walker et al. (2005) investigate the relationship between the seasonal variation of wind’s direction and the structure of the Mississippi River Plume. The results show that river waters are driven westward by east winds in autumn, winter, and spring, leading to the increased river discharge onto the Louisiana/Texas shelf. In addition, the direction of movement of the plume can be reversed by atmospheric cold fronts (Walker, 1996).

Valle-Levinson et al. (2007) explore the impact of bathymetry and local and remote atmospheric effects on the Chesapeake Bay outflow plume. Both wind speed and wind direction affect the Peal River estuary’s plume front in winter (Zheng et al., 2014). Moderate down-estuary winds enhance estuarine stratification, while strong down-estuary winds and all up-estuary winds reduce stratification (Chen and Sanford, 2009; Xie and Li, 2018). Li and Li (2011 and 2012) study the down-estuary and up-estuary wind effect on the stratification and circulation. Both down-estuary and up-estuary winds decrease the stratification when Coriolis force is not taken into consideration, down-estuary (up-estuary) wind can induce a counterclockwise (clockwise) lateral circulation.

4.1.2. Plume in the Low-Salinity Estuary – Lake Pontchartrain

This study examines the river plume from the Mississippi River water diversion into the low-salinity Lake Pontchartrain Estuary. We will therefore focus on the review of previous work in this estuary in the following.

Plumes have been observed in the Lake Pontchartrain Estuary during spring flood season
when an artificial diversion structure, Bonnet Carré Spillway (BCS), is opened to relieve downstream pressure, hence, reducing flood risk to the city of New Orleans, LA. Historically, the spillway had been opened every 10 years on average. However, in the past decade alone, an apparent increase of winter and spring river flood events has led to four openings (2008, 2011, 2016, 2018, and twice in 2019). The plume of freshwater diverted into the estuary is unique in that it is within an enclosed, oligohaline estuary with mean salinity of only ~ 4 - 5. A total amount of 9.1 million tons of sand was deposited on the Mississippi River Channel adjacent to the BCS (Allison et al., 2013) during the opening event in 2011. Georgiou et al. (2009) investigate the salinity distributions with freshwater input from adjacent rivers and Bonnet Carré Spillway (BCS) under tidal forcing, which indicates a significant reduction in salinity. Furthermore, the low salinity and high turbidity environment are favorable for the formation of algal blooms in the Lake Pontchartrain Estuary (McCorquodale et al., 2009, Bargu et al., 2011). Nutrient and sediment input through Bonnet Carré Spillway can result in significant changes in dissolved inorganic nitrogen concentrations (Lane, et al., 2001; White et al, 2009). Increased nutrient levels can potentially trigger enhanced primary production, phytoplankton community shifts, and algal bloom formation.

Recent studies have shown that the Lake Pontchartrain Estuary experiences high interannual variability in nutrients and phytoplankton community, mainly due to the effects of seasonal and episodic rainfall on hydrology and the Mississippi River diversion management that cause variability in the timing and magnitude of the freshwater discharge to the estuary (White, et al., 2009; Bargu, et al, 2011; Roy, et al., 2013). Under a changing climate, increasing water temperatures over decades favor cyanobacterial growth in the estuary, leading to a greater frequency of potentially harmful algal blooms capable of adversely affecting water resources,
especially when diverting a nutrient load by the freshwater plume can increase the potential for harmful algal bloom (McCorquodale et al., 2009, Bargu et al. 2011). Chao et al. (2013, 2016) reveal that a large amount of sediment is discharged into Lake Pontchartrain, moving eastward and expanding northward after the opening of the Bonnet Carré Spillway. Retana (2008) conducts a series of sensitivity experiments using FVCOM for the hydrodynamic response during an opening of Bonnet Carré Spillway. Chilmakuri (2002) suggests that a spatially variable- counter-clockwise- wind in the middle of the lake is able to turn the plume from the Bonnet Carré Spillway eastward. Iles (2017) studies the Mississippi River Diversion in 2016 using the MODIS satellite image and proposes that wind determines the location of the highest sediment concentration.

Huang and Li (2017) and Li et al. (2018b) investigated the wind-driven circulation in the Lake Pontchartrain Estuary under barotropic conditions. The remote wind controls the overall setup of the water level variation while local wind determines the surface slope (Huang and Li, 2017). A quasi-steady state balance is verified in this system as well as in other coastal water bodies such as Barataria Bay (Li, et al., 2019b) and Elson Lagoon in the Arctic region (Li, et al., 2019a). This quasi-steady balance is reached because any adjustment to wind variation in the form of a seiche would be quick (compared to tidal cycle) in this kind of systems. The wind-driven seiche would be dissipated within 2-3 cycles in several hours (Li, et al., 2018b). Huang and Li (2019) further confirm that the quasi-steady balance is asymmetric in along- and cross-estuary directions: the R² value between the slope from the quasi-steady balance and that from the model result is lower in the east-west direction because of the impact of the eastern open boundary. However, the R² is still very high (>0.9).

In this study, we use a 3-D FVCOM to simulate the freshwater diversion plume from the
Bonnet Carré Spillway (BCS) to 1) examine the impact of wind from cold fronts on the evolution of the freshwater plume from the BCS; 2) analyze the sensitivities of total salt content, vertical structure of salinity and currents to the magnitudes and directions of wind; 3) illustrate the effect of the minor leakage of river water from the BCS before opening of the diversion on the salinity, circulation pattern, stratification, and quasi-steady state balance; and 4) discuss the influence (residence) time of the fresh water inside the estuary and compare it with that from Lagrangian particle tracking.

**Figure 4.1.** Study site and model mesh. BCS is the Bonnet Carré Spillway, NWCL1 is the NDBC station from where the wind and atmospheric data are obtained. Line1 and line 2 are used to show the vertical structures of velocity during the development of the fresh water plume. Line 3 and line 4 are selected to illustrate the vertical structure of the salinity and current distribution in the sensitivity experiments of wind magnitudes.
4.2. Study Area and Data Description

Lake Pontchartrain (Fig. 4.1) is a large (~1600 km$^2$), shallow (~4 m), and almost enclosed estuary connected to the Gulf of Mexico through three narrow inlets: the Rigolets, Chef Menteur, and Industrial Canal. It has an oval shape with the longer axis (~66 km) in the east-west direction and the shorter axis (~40 km) in the north-south direction with a total volume of about 9.77×10$^9$ m$^3$ (Keddy et al., 2007). The average salinity of Lake Pontchartrain Estuary (LPE) is about 4. The bottom salinity can reach as high as 12 (Li et al., 2008). The city of New Orleans is located due south of the LPE. Lake Pontchartrain has been used for river flood diversion to protect New Orleans through a control structure, the Bonnet Carré Spillway (BCS). The spillway is located at the southwestern corner of the estuary connecting the LPE with Mississippi River. The spillway is about 9 km in length and the control structure consists of 350 “bays” each about 2.9 m wide. The structure allows a maximum of ~ 7000 m$^3$s$^{-1}$ of Mississippi River water to be diverted into the estuary (Bargu et al., 2011). The BCS was opened after heavy rains in the Mississippi River and Ohio River valleys increased river stages on May 9, 2011 to prevent the Mississippi River flows at New Orleans from exceeding 35000 m$^3$/s (Allison et al., 2013). The spillway was completely closed again on June 20, 2011. The discharge from BCS can be obtained from the US Army Corps of Engineers website (https://www.mvn.usace.army.mil/) and is shown in Fig. 4.2. According to the US Army Corps of Engineers, there is an amount of fresh water from Mississippi River that leaks into the Lake Pontchartrain estuary through the small spaces between the wooden timbers that hold back the water in each bay. This leakage is referred to as a minor diversion and occurs a few weeks in the spring or early summer when river stage exceeds the elevation of the spillway. The amount of the leakage is usually less than 300 m$^3$/s (https://www.mvn.usace.army.mil/), but may increase due to flood river stage.
In this study, observations of water level used for model validation are from NOAA’s New Canal Station (ID: 8761927: 30°1.6´ N and 90°6.8´ W). Salinity data used for model validation is from an USGS station at Hwy 90 near Slidell (USGS 2010011089442600, 30°10´01´´ N, 89°44´26´´ W, Fig. 5.1) from Jan. 01, 2011 to Sep. 30, 2011. The daily salinity and temperature data used for the open boundaries are from USGS stations at Mississippi Sound (ID: 300722089150100) and Black Bay (ID: 07374526) from Jul. 01, 2010 to Sep. 30, 2011. Wind and air pressure data at 6-minute intervals are the NDBC meteorological observation at the NWCL1 station. Daily river discharge data for the model input are from USGS stations of Pearl River (USGS 02490500), East Pearl River (USGS 02492110), Amite River (USGS 07380120), Tangi River (USGS 07375500), Tchefuncte River (USGS 07375000), and Tickfaw River (USGS 07376000) between Jul. 01, 2010 and Sep. 30, 2011. Water elevation and tide prescribed at the open boundary are the hourly data from NOAA’s stations: Bay Waveland Yacht Club, MS (Station ID: 8747437, 30°19.5´ N, 89°19.5´ W) for the eastern open boundary and Shell Beach, LA (Station ID: 8761306, 29°52.1´ N, 89°40.4´ W) for the southeastern open boundary.

Figure 4.2. Freshwater discharge from BCS and the leakage added in the model.
4.3. Model Description

FVCOM has been widely used for studying coastal ocean hydrodynamics (Chen et al., 2003; Huang et al., 2008), especially for regions with complicated topography (e.g. Huang et al., 2011). The governing equations and parameters are the same with that described in Chapter 3. The model mesh has 6053 nodes and 10580 cells (Fig. 4.1). The two open boundaries are located at the east of Lake Borgne and the south end of Mississippi River Gulf Outlet (MRGO), respectively. The simulation time period is from 2010/07/01 to 2011/09/30. The water level forcing at the open boundaries were hourly observed water level from NOAA’s stations. Spatially uniform and temporally changing wind and air pressure are added for the atmospheric forcing. River discharges from seven rivers (Pearl River, East Pearl River, Amite River, Tangipahoa River, Tchefuncte River, and Tickfaw River) are included. During the opening of the BCS, discharge is included as a river from the spillway from May 09, 2011 to Jun. 19, 2011. All salinities for these rivers are set to be 0. Temperatures for these rivers are given the same function as the observed temperature of a USGS station at Rigolets at Hwy 90 near Slidell. The initial salinity and temperature are set to be constant 1.7 and 28.7 °C for all nodes. In simulating the freshwater diversion, it is reasonable to add an amount of freshwater discharge due to the minor leakage. Since there is no measurement of leakage, we can only test our model by adding a small amount of leakage by trial and error. Results show that when the leakage is set to be 100 m$^3$/s from Jul, 2010 to Mar, 2011, 500 m$^3$/s from Mar, 2011 to May, 09, 2011, and 200 m$^3$/s from Jun, 2011 to the end of simulation (Fig. 4.2), the skill score of the simulation of salinity is increased from 0.58 to 0.64, indicating that the leakage added in our numerical experiments is reasonable.

To examine the wind effect and the influence of the opening of the BCS, three
experiments are conducted (Table 4.1). Experiment 1 simulates the real case using observed water level as forcing at the open boundaries and wind forcing for all nodes of the study area. Experiment 2 excludes wind effect by only applying tidal forcing at the open boundaries. The comparison between experiment 1 and 2 can reveal the influence of wind. Experiment 3 excludes the influence of diversion by closing the BCS. Experiment 4 is used to discuss the impact of freshwater leakage, which is exactly the same as Experiment 1 except that no freshwater leakage is added in the river discharge. Experiment 5 is a series of simulation during the spillway opening period with the wind magnitude increases from 2 m/s to 14 m/s under four directions (north, south, east, and west). These experiments are used to examine the sensitivity of circulations and salinity to wind direction and wind magnitude.

Table 4.1. Model design for two groups of numerical modeling.

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As shown in Fig. 4.3, performance of FVCOM in simulating the water level can be categorized as excellent with a skill score of 0.9 according to Allen et al. (2007). The simulated salinity near the Rigolets exhibits very good performance (Skill score is 0.64) when compared with the observations (Fig. 4.3). Surface salinity contour plots are consistent with the satellite images (Fig. 4.4).

![Figure 4.3. Validation of water level at New Canal (a) and salinity at the USGS station near the Rigolets (b). Solid black lines represent the model results, dashed grey lines represent the observations.](image-url)
4.4. Results

4.4.1. Evolution of Freshwater Plume

With the opening of BCS from May 9, 2011, fresh water was diverted into Lake Pontchartrain. Salt content is calculated using the following equation:

\[
Mass_{salt}(t) = \sum_{i=1}^{ncell} \int_{-h}^{\zeta} S(i,z,t) \times A(i) dz
\]

where \(Mass_{salt}(t)\) is the total mass of salt for the whole study area at time \(t\); \(ncell\) is the total number of cells of the mesh and equals 10580 in our model; \(h\) and \(\zeta\) represent water depth and free surface elevation, respectively; \(S(i,z,t)\) is salinity for the \(i^{th}\) cell at a given water depth \(z\) at time \(t\); \(A(i)\) is the area for the \(i^{th}\) cell; and \(z\) is the vertical position. Fig. 4.5 shows the time series of salt content from the three experiments. Solid black line in Fig. 4.5 shows the time series of salt content variation during the opening of the spillway. It is found that salt content was decreasing during the first 10 days of the opening, and maintained a relatively low value after May. The shape of the fresh water plume on May 16 was shown by satellite image and model results in Figs. 4.4a,b, the plume with more suspended sediment from the Mississippi river was
diverted into Lake Pontchartrain. The edge of the front of the plume was asymmetric, the southeastern edge of the plume and the southern shoreline form an acute angle pointing to the east (rectangle 1 in Fig. 4.4b), while the western edge and the western shoreline form an obtuse angle which is pointing to the south (rectangle 2 in Fig. 4.4b). As the fresh water being continuously diverted into the lake, the area of the plume expanded into the whole lake after June 5, 2011. Since wind determines the flow pattern inside the lake (Li et al., 2018b), current flows in the direction with wind along the near shore area and against the direction of the wind in central interior of the lake (Huang and Li, 2017; Li, et al., 2018b).

![Figure 4.5. Salt content from Experiment 1 (solid black line), Experiment 2 (solid grey line), and Experiment 3 (dashed line).](image)

Figure 4.6 shows how the shape of the plume is affected by wind. The plumes with or without wind are compared. Figures 4.6a, c, e, and g are real case simulations (Experiment 1) under southerly, northerly, easterly, and westerly winds, respectively. Figures. 4.6b, d, f, and h are results with only tidal forcing (Experiment 2). During southerly wind (Figs. 4.6a and 4.6b), the western edge of the plume resulted from Experiment 1 was extended further to the northern area compared with that of Experiment 2, while the southeastern edge of the plume from Experiment 1 was constrained further to the west compared with that from Experiment 2.
Northerly wind tends to limit the expansion of the fresh water plume. During northerly wind, the area of the plume from Experiment 1 (Fig. 4.6c) is apparently smaller than that from Experiment 2 (Fig. 4.6d) which is simulated without wind.

Easterly wind facilitates the inward flow from the eastern open boundary, compressing the plume and keeping it from expanding to the northern and eastern areas (Experiment 1) (Fig. 4.6e); so that the edge of the plume is more restricted to the southern area than that from Experiment 2 (Fig. 4.6f). Westerly wind pushes the plume from Experiment 1 (Fig. 4.6g) to eastern area than that from Experiment 2 (Fig. 4.6h), making the shape of the plume from Experiment 1 more elongated in the east-west direction than that from Experiment 2.

Above all, the southwestern edge of the freshwater plume can be extended to the east by the westerly along shore flows induced by the west wind, while easterly and northerly winds tend to compress the plume from extending to the northern area, and southerly wind facilitates the plume’s expansion to the northern area. Wind is responsible for the asymmetric shape of the plume compared with that only under tidal effect.
Figure 4.6. Salinity and velocity vector during four different wind directions from experiments 1 and 2. Figures 6a, 6c, 6e, and 6g are real case simulation (Experiment 1) under southerly (12:00 UTC, May 13\textsuperscript{th}), northerly (12:00 UTC, May 15\textsuperscript{th}), easterly (16:00 UTC, May 18\textsuperscript{th}), and westerly (00:00 UTC, May 18\textsuperscript{th}) winds. Figures 6b, 6d, 6f, and 6h are the cases simulated only under tidal effect and the wind effect was excluded (Experiment 2). Leakage was included. Arrows are current vectors.
4.4.2. Impact of Wind on Salinity Distribution

Winds during atmospheric frontal passages have significant impact on the hydrodynamics of coastal water bodies. For example, hydrodynamic response to 76 atmospheric front events in a tidal channel in the southern Louisiana is found to be highly correlated with the atmospheric forcing: cold (warm) fronts can produce outward (inward) transports (Li et al., 2018a; Weeks et al., 2019). In addition, southerly winds prior to a cold front event can drive saltwater intrusion (Li et al., 2011; Lin et al., 2016). There were three atmospheric fronts affecting the study area during the opening of the BCS (vertical lines in Fig. 4.7) on 06:00 UTC, May 14, 06:00 UTC, May 18, and 18:00 UTC, May 27, respectively. The first cold front was denoted by the change of wind direction from south to northwest (Fig. 4.7). Winds for the second cold front changed its direction from north to southeast. The third cold front was represented by the transient wind direction from northeast to southwest. The common feature of the three cold fronts is that there is a relatively long period (more than 18 hours) during which southerly wind dominated.

![Wind vector from May 09 to Jun 06. Vertical black lines represent the dates of three cold front event during this time period.](image)

**Figure 4.7.** Wind vector from May 09 to Jun 06. Vertical black lines represent the dates of three cold front event during this time period.
To illustrate the vertical structure of salinity and current, nodes along 2 lines are selected (Fig. 4.1). Line 1 is along the southern coast in east-west direction, line 2 has a 45° inclination from the east-west direction and is along the orientation of the BCS. Velocities are all rotated to be along and cross the lines. Only the along-line components are plotted in Fig. 4.8. On May 14th, the currents along both lines 1 and 2 exhibit two-layer structures (Fig. 4.8a and 4.8d). Wind on May 14 is overwhelmingly from the southern quadrants (Fig. 4.7). The water column along both lines 1 and 2 is almost well mixed, but with vertical shears of horizontal velocity as demonstrated by the top layer water flowing away from BCS, and bottom water flowing back towards BCS at lower layer (Fig. 4.8a and Fig. 4.8b). The circulation patterns are consistent with Li et al. (2018b), i.e., surface current and the coastal current flow downwind, while bottom current in the lake flows against the wind. This is the case for May 18th (Figs. 4.8 d, e) and May 28th (Figs. 4.8 c, f) when southeasterly wind and southwesterly wind were dominating.
Figure 4.8. Vertical structure of salinity and along-line velocity for nodes along line 1 (a, b, c) and line 2 (d, e, f) on different dates. Results are from Experiment 1. Dates represents the time for three cold front passages during the fresh water diversion period. Arrows are along-line current vectors.
4.4.3. Sensitivity Experiments of Magnitude of Wind

Sensitivity of Salt Content

Responses of salt content to increasing wind magnitude under 4 wind directions is shown in Fig. 4.9. The salt content is increasing as the magnitude of wind increases except for westerly wind. Under westerly wind, when wind magnitude is lower than 6 m/s, salt content is decreasing, when wind is larger than 6 m/s, salt content is increasing. This is because westerly wind tends to blow more freshwater to the lake when wind is less than 6 m/s, when wind increases to larger than 6 m/s, salt water from eastern open boundary is transported into the lake with a rate higher than that of the freshwater input from the BCS.

Figure 4.9. Sensitivity of salt content to increasing wind magnitude. Results are from Experiment 5.
Figure 4.10. Vertical structure of along-line3 velocity and salinity under easterly (a,b,c) and westerly winds (d,e,f). Unit of salinity is psu. Results are from Experiment 5. Arrows are along-line current vectors.
Figure 4.11. Vertical structure of along-line velocity and salinity under northerly (a,b,c) and southerly winds (d,e,f). Unit of salinity is psu. Results are from Experiment 5. Arrows are along-line current vectors.
Sensitivity of Vertical Structure of Salinity and Currents

Two lines are selected to illustrate the vertical structure of the salinity distribution and the current in east-west (line 3 in Fig. 4.1) and north-south (line 4 in Fig. 4.1) directions. During easterly wind and westerly wind, when the wind magnitude changes from 4 m/s to 12 m/s (Fig. 4.10), the surface flow along line 3 is downwind, while the bottom flow upwind. Both surface and bottom flows become stronger when the wind magnitude increases. There is a no-motion surface between the two-layer flows (white lines in Fig. 4.10). As the magnitude of the wind increases, the no-motion surface migrates downward to a lower layer. In terms of the salinity distribution under easterly wind, high salinity zone is located near the eastern side of the line. As east wind increases in magnitude, more salt water is transported into the lake through the eastern open boundary. As a result, higher salinity zone expands to a larger area inside the lake. However, when wind from the west, salt water tends to be transported out of the lake through the eastern open boundary, leading to a smaller salt water zone as the magnitude of the wind increases.

During northerly and southerly wind, when the magnitude of wind changes from 4 m/s to 12 m/s (Fig. 4.11), the surface flow along line 3 is downwind, and the bottom flow is upwind. Similarly, under easterly and westerly wind conditions, the surface and bottom flows become stronger when wind magnitude increases. Again, there is a no-motion surface between the two-layer flows (white lines in Fig. 4.11), migrating to a deeper layer as the magnitude of wind increases. Since line 4 is from north to south with its southern side near the Industrial Canal, salinity in this line is affected more by the salt water transported through the Industrial Canal at the southern end of the line. During northerly wind, bottom flow is increasing, so that more fresh
water is transported to the south end, leading to a fresher water zone located in the south side.

During southerly wind, salt water is transported through Industrial Canal, resulting in a high salinity zone at the south end of line 4.

4.4.4. Leakage Effect on the Hydrodynamics of the Lake

Leakage Effect on Salt Content

An amount of fresh water leaks to Lake Pontchartrain through the BCS is added into the simulation. This amount of freshwater, though small compared with the diversion during the opening of the BCS, has great impact on the salt content of Lake Pontchartrain. To illustrate the effect of the leakage on the salt content, we compare the results with or without the leakage (Fig. 4.12). After adding the freshwater leakage, salt content in the lake is only 500000 kg at the beginning of the opening of Spillway. The difference between the two experiments reaches 1500000 kg, which means that the leaked freshwater decreases the salt content in the lake by 3 times.

![Figure 4.12. Comparison between the salt mass flux with (black line) and without (grey line) leakage effect. Results are from Experiment 1 (with leakage) and Experiment 4 (without leakage).](image)
Figure 4.13. Salinity and velocity vector during four different wind directions from experiments 4 and 6. Figures a, c, e, and g are without leakage effect from Experiment 4 under southerly, northerly, easterly, and westerly winds. Figures b, d, f, and h are the cases simulated only under tidal effect and the wind and leakage effect were excluded (Experiment 6). Arrows are current vectors.
Leakage Effect on Circulation Pattern

The influence of freshwater leakage from the Mississippi River can be illustrated by removing the leakage at the BCS. Circulation and the salinity distribution without the leakage effect for the whole lake is shown in Fig. 4.13. The frontal zone of the river plume is much closer to the BCS than that with the leakage (Fig. 4.6). Salinity for the water near the eastern open boundary without leakage (Fig. 4.13) is about 4-5 higher than that in Fig. 4.6. For the circulation, flows along the southern shore (Fig. 4.13) is weaker than that with the leakage (Fig. 4.6), indicating that the leakage can enhance the flow along the southern shore. Under northerly and southerly winds, the surface flows in the central lake is mainly against the wind (Fig. 4.13a and 4.13c), however, this kind of return flows is not shown in Fig. 4.6 when there is leakage. Under easterly or westerly wind (Fig. 4.13e and 4.13g), there are clockwise and counter-clockwise gyres in the northern central lake, however these patterns are not seen in Fig. 4.6.

Leakage Effect on APED

The Average Potential Energy Demand (APED) for the whole lake is calculated using the following equation (Simpson et al., 1990; Li et al., 2009) to determine the water column gravitational stability:

\[
\Phi = \frac{1}{h} \int_{-h}^{\zeta} (\bar{\rho} - \rho)gz \, dz
\]

(4.2)

where \( h \) and \( \zeta \) represent water depth and free surface elevation, \( \bar{\rho} \) and \( \rho \) represent the averaged density and in situ density, \( g \) is the gravity acceleration, and \( z \) is the vertical position. The larger the APED is, the more energy it needs to reach the vertically-well mixed conditions, or the stratified the water column is. The results show that APED decreases no matter what the wind direction is, namely the water column is more mixed as wind magnitude increases.
Figure 4.14. APED contour plot during three cold front events. Figs. a, c, and e are resulted from Experiment 4, Figs. b, d, and f are calculated using Experiment 6.

APED for a water column of each nodes is shown in Fig. 4.14. It is found that high APED region under real condition (Figs. 4.14a, 4.14c, and 4.14e) appears in a band, which is consistent with location of the edge of the fresh water plume from BCS. As the plume moved to the northeast, the peak values of APED decreases. When wind is excluded (Figs. 4.14b, 4.14d, and 4.14f), the band with high APED disappears. High APED area only shows in the eastern side, which may be the result of salt water intrusion from the open boundary. This indicates that wind has a straining effect on the stratification of salinity along the edges of the fresh water plume when no leakage is added. When leakage of freshwater is added, there is no obvious larger
APED values for the whole lake (Fig. 4.15) because the entire lake is essentially all freshwater from the river.

Figure 4.15. APED contour plot during three cold front events. Figs. a, c, and e are resulted from Experiment 1, Figs. b, d, and f are calculated using Experiment 2.
Figure 4.16. Vertical structure of salinity and along-line velocity for nodes along line 1 (a, b, c) and line 2 (d, e, f) on different dates.
Leakage Effect on Salinity and Velocity

To illustrate the leakage effect on the vertical structure of the circulation and salinity distribution, Fig. 4.8 is compared with Fig. 4.16 in which the leakage has not been added to the model. From Fig. 4.16, one can see that on May 14th, the velocity along both lines 1 and 2 exhibits two-layer structures. A weak vertical variation in the water column of line 1 is seen at about 16 km away from the BCS, where the surface velocity reaches its maximum with freshwater on top of the slightly saltier water in the bottom layers. On line 2, water at 10 to 24 km away from the BCS shows slight vertical change in salinity. A strong return flow in the bottom layers can be seen. The vertical structure of salinity on May 18th and May 28th are similar to that on May 14th. A sign of slight stratification can be seen at the front between the river water from the BCS and the surrounding water. Generally, the plume from the BCS in the southwestern corner spread to the northeastern part of the lake.

Compared with the salinity distribution shown in Fig. 4.8, salinity in Fig. 4.16 is higher by 4 PSU, the horizontal salinity difference (4) is also much larger than that shown in Fig. 4.8 (0.5). The saltier zone is more extended into the interior, for example, on May, 16, the water becomes saltier at 10 km away from the BCS (Fig. 4.16a). However, it is saltier at 23 km away from the BCS (Fig. 4.8a). In terms of the vertical structure of the horizontal velocity along the transect, the return flow in the lower layer on both lines 1 and 2 is stronger when leakage is excluded. This indicates that with the influence of the leakage, water in the Lake Pontchartrain tends to be well mixed and fresher. The leakage makes the salinity to drop dramatically, leading to a very small density gradient in the horizontal.

Diversion and Leakage Effect on Quasi-Steady State Balance

Previous studies have shown that local wind is the main driver of the lake surface slope in
the along- and cross-estuary directions, and can be well approximated by a quasi-steady state force balance (Huang and Li, 2017; Li et al., 2019a, b; and Li et al., 2018a,b) in which no stratification was considered. This quasi-steady state balance is:

\[ 0 = -g \frac{\partial \zeta}{\partial x} + \frac{\tau_{ax}}{\rho h} \]  

(4.3)

where \( \partial \zeta \) is the subtidal surface level difference in two directions, \( \partial x \) is the cross- and along-estuary distance (37 or 52 km, respectively). Four points from N, S, W, and E sites around the lake are selected. In Equation 4.3, \( \rho \) is the water density (1024 kg/m\(^3\)), \( h \) is the average water depth of 4.0 m. \( \tau_{ax} \) is the wind stress in the cross or along-estuary direction (Garvine, 1985):

\[ \tau_{ax} = \rho_a C_d |W| W_x \]  

(4.4)

where \( \rho_a \) is the air density (1.29 kg/m\(^3\)), \( C_d \) is the drag coefficient of 1.24 \( \times \) \( 10^{-3} \), \( W \) is the wind velocity component in the cross- or along-estuary direction with a total wind speed of \( W \) obtained from the NOAA’s NDBC station NWCL1 (Fig. 1). Quasi-steady state balance induced water level difference resulted from Equation 4.3 is shown in Fig. 4.17 (purple lines).

Water level difference in the along- and cross-estuary directions in the three different experiments are calculated: the first one is from Experiment 1 (blue line in Fig. 4.17); the second one is from Experiment 4 (yellow lines in Fig. 4.17); and the third one from Experiment 3 (red lines in Fig. 4.17). \( R^2 \) values between water level differences from equation 13 and that from FVCOM experiments are calculated. \( R^2 \) is the highest when there is no diversion nor leakage (0.96 in N-S direction and 0.92 in E-W direction); on the other hand, the \( R^2 \) drops to 0.94 and 0.85 in N-S and E-W directions, respectively, after adding the diversion and leakage. Fig. 4.17 reveals that from May 8 to May 25, the discrepancy between the quasi-steady state balance induced water level difference and that from FVCOM are the largest. This is the time period
when a large amount of freshwater is diverted into the lake, apparently interrupting the quasi-steady state balance, demonstrated by a lower $R^2$ value especially in east-west direction.

4.5. Discussion: Influence Time of Freshwater Diversion

To quantify the time scale of river diversion effect to reach a given location, we define the influence time of a given node to be the time between the onset of the diversion till the salinity decrease to 0 at that node. This quantity is shown in Fig. 4.18. Obviously, the further away from the diversion, the longer time it takes to be affected by the river water (Fig. 4.18a). However, when there is no wind forcing (Fig. 4.18b), it takes a shorter time for the western and
northern regions to be influenced by the river diversion, and longer for the southeastern region to be influenced. This indicates the important role of wind on the evolution of river plume from BCS. In addition, the time for the whole lake to respond to the river plume is about 25 days, that means that the river water is full of fresh water after 25 days (red color in Fig. 4.18a), which is consistent with Fig. 4.4 which shows that the salt content reached its minimum after Jun 05.

During the diversion, we measured the total discharge at the entrance to the lake using a boat mounted ADCP to be ~ 6000-7000 m$^3$/s. Taking the volume of the lake as 9.77x10$^9$ m$^3$, and a rate of discharge as 7000 m$^3$, it would take about 16-19 days for the entire lake to be filled by freshwater, which is close to the 25 day influencing time for the whole lake.

![Figure 4.18](image_url)  
**Figure 4.18.** Time for each node being influenced by the fresh water diversion. Figure a is the case under real condition (Experiment 1), figure b is that without wind forcing (Experiment 2).

An open-source package, the FVCOM I-state Configuration Model (FISCM, FISCM, 2013) is employed for the Lagrangian particle tracking with 247 freshwater parcels from the BCS. This offline tracking model shows high performance on tracking bay scallops in Buzzards Bay using the results from FVCOM model (Liu, et al., 2015). The advection of each individual particle is determined by:

\[
\frac{d\vec{x}}{dt} \vec{X}(t) = \vec{V}(\vec{X}(t), t)  
\]  
(4.5)
where \( \bar{X}(t) \) is the position of the individual particle at time \( t \), \( \vec{V} \) is the velocity field resulted from FVCOM. Fig. 4.19a shows the positions after 5, 15, and 20 days, and the ending time of individual particles with the initial positions all at the BCS. Within 10 days (sky blue dots and blue dots in Fig. 4.19a), most of the particles are moving in front of the plume so the positions are in line with the edge of the plume as shown in Fig. 4.4. After 15 days of opening of the Spillway (black dots in Fig. 4.19a), a large number of particles reach the northern shore, and a small portion of the particles are outside of the lake already. On Sep 30, 2011, 3 months after the opening (red dots in Fig. 4.19a), the particles are randomly distributed on the eastern side of the lake.

When wind forcing is excluded, the only forcing is tide (Fig. 4.19b), the particles are moving towards the southeastern end of the lake and exit the lake through Industrial Canal and Chef Menteur after 15 days of the opening of the Spillway. This is due to the Coriolis force making the particles to stay on the right-hand side facing their moving direction.
Figure 4.19. Lagrangian tracking with (a) and without (b) effect of wind.
4.6. Conclusions

The fresh water plume resulted from the opening of the BCS from May 09 to Jun 19, 2011 is simulated using FVCOM. FVCOM shows very good performance in simulating the salinity with a skill score of 0.64. The simulated shape of the plume is consistent with that obtained from the satellite images.

The shape of the plume is mainly affected by the location of the BCS where it comes from and the wind forcing. Southerly wind tends to constrain the expansion of the southeastern edge of the plume. Northerly wind tends to prevent the northeastern edge of the plume from expanding. The shape of the plume is more sensitive to easterly and westerly winds, which tend to limit the edge of the plume to extend to the northern shore and facilitate the western edge further to the eastern area.

Increasing wind magnitude tends to increase the salt content under easterly, northerly, and southerly wind directions. Salt content is decreased from 2 m/s to 6 m/s during westerly wind and increases when wind magnitude is larger than 6 m/s, indicating that for winds less than 6 m/s and in the west direction, the rate of the salt water transported into the lake is larger than the upwind bottom flow which contains freshwater from the BCS. When wind continues to increase, the rate of the freshwater transported to the eastern lake exceeds that of the salt water transported into the lake.

When the magnitudes of the winds in four directions increase, both surface downwind flow and bottom upwind flow are increasing. However, bottom upwind flows tend to be stronger than the surface downwind stream. Furthermore, there is a no-motion layer between the two-layer flows, which migrates to a lower layer when wind magnitude increases. Water with higher salinity is constrained to further eastern area under westerly wind, and extend to further interior
under easterly wind. On the other hand, saltier water extends to further northern area under southerly wind.

Leakage through BCS during flooding season has significant impact on hydrodynamics of the water in the Lake Pontchartrain. The leakage of freshwater reduces nearly 1,500,000 kg of salt content all over the lake, leading to a drop of 3 of salinity compared with the condition without the leakage effect. Leakage of freshwater leads to a tendency of diminishing gyers in the lake, but increases the mixing of the water, resulting a very low APED for the whole lake. In addition, together with the influence of diversion, leakage from BCS tends to affect the quasi-steady state balance. Thus, the R² between the water level difference from quasi-steady state balance and that from the FVCOM result with freshwater diversion and leakage effect is the lowest in both east-west and north-south directions.

It takes about 25 days for the whole lake to be influenced by the river diversion from BCS. Salt content drops from $6 \times 10^5$ kg to less than $1 \times 10^5$ kg after 25 days of the opening of the spillway. This conclusion is consistent with the trajectory of the particles calculated by the Lagrangian tracking.
CHAPTER 5. CONCLUSIONS AND FUTURE STUDIES

5.1. Summary of Work Done

Observational data from ADCP deployed at three inlets (the Rigolets, Chef Menteur, and Industrial Canal) are used to analyze the current velocity and water level variations in the narrow channels to examine the impact of atmospheric cold fronts. Numerical models using FVCOM are conducted to simulate the hydrodynamics of Lake Pontchartrain under either barotropic or baroclinic conditions. Water level and current velocity under barotropic conditions are simulated for the time periods of Oct. 5th to Nov. 18th, 2008 and Feb. 12th to Mar. 24th, 2016. These two group of numerical experiments are designed to separate and examine the roles of remote and local wind effects by applying different open boundary conditions and surface forcing. Water level, current velocity, and salinity from Jul. 1st, 2010 to Jan. 1st, 2011 are simulated to investigate the circulation patterns for the lake with shallow water depth and with multiple inlets connecting the coastal ocean under baroclinic conditions. Results from these experiments are also used to investigate the mechanisms of the quasi-steady state balance and its spatial variations in both along- and cross- estuary directions. Freshwater plume resulted from the opening of the BCS from May 9, 2011 to Jun 19, 2011 is simulated using the FVCOM to study the evolution of the freshwater plume, the minor leakage effect, and how the freshwater plume is affected by different wind conditions. A set of sensitivity experiments are conducted to test the responses of hydrodynamics of the lake to wind magnitudes increasing from 2 m/s to 14 m/s in northerly, southerly, easterly, and westerly directions. Results are used to shed light on how increasing wind magnitudes affect the salt content, circulation pattern, and quasi-steady state balance between the wind stress and pressure gradient.
5.2. Conclusions of the Work

By analyzing observational data, atmospheric cold fronts are found to have great impact on the current velocity and water level variation in three inlets of Lake Pontchartrain (the Rigolets, Chef Menteur, and Industrial Canal). The sub-tidal hydrodynamics are highly correlated with atmospheric parameters especially those associated with cold front passages. Easterly and southerly winds before cold front passages tend to push water into the Lake Pontchartrain through the inlets, while westerly and northerly winds are responsible for the maximum outward flow through these inlets. About 40% of the total flux is transported through the Rigolets, 40% through Chef Menteur, and only 20% through the Industrial Canal. Data from the HOBO data loggers deployed around the lake show that water level differences in both east-west and north-south directions satisfy the quasi-steady state balance between wind stress and pressure gradient, which means surface slopes reach a new value almost instantaneously with the changing wind.

The remote and local wind effects are separated and compared by analyzing the output of numerical experiments using different combinations of open boundary conditions and atmospheric forcing. It is found that remote wind contributes the most to the overall rise and fall of the water level. It also controls the flow patterns near the eastern open boundary. It determines the water and salt exchanges with the open ocean, and the magnitude of the current velocity in the eastern region close to the open boundary. The remote wind effect dissipates away from the open boundary due to bottom friction.

On the other hand, the local wind effect is responsible for the surface slope of the lake, though it has little impact on the overall water level variation. Local wind effect determines the circulation pattern inside the lake under both barotropic and baroclinic conditions. Under local
wind, flows are in the downwind direction in the shallow western interior of the lake and in the coastal shore regions. There is a return flow existing in the deeper interior lake which is against the wind.

Quasi-steady state balance is found between the wind stress and pressure gradient. The surface slopes approximated by the quasi-steady state equation have high $R^2$ values (>0.90) under local wind effect (tide is excluded) under either barotropic or baroclinic conditions, which indicates that subtidal surface slopes are mainly controlled by local winds. When the tidally-induced flows are included, the $R^2$ value in the along-estuary direction decreases to ~0.6. This is because the tidally induced surface slope adds an extra constant to the quasi-steady state balance. The more distance away from the open boundary, the smaller the influence and the larger the $R^2$ value.

The $R^2$ value between surface slopes from the model and that predicted by the quasi-steady state equation is also affected by the frequency of the wind. When the cross-estuary (north-south directed) wind is dominant, the quasi-steady state balance is more accurate in that direction; same for the along-estuary direction. As a result, the $R^2$ values are higher in the cross-estuary (north-south) direction than that in the along-estuary (east-west) direction after the cold front passages when the wind is the strongest and mostly from the northerly quadrants.

Freshwater plume resulted from the opening of the BCS from May 9, 2011 to Jun 19, 2011 is simulated using the FVCOM. Results show very good performance in simulating the salinity with a skill score of 0.64 when a minor leakage event is added. Winds have significant influence on the evolution of the freshwater plume. Southerly wind tends to constrain the expansion of the southeastern edge of the plume. Northerly wind tends to prevent the northeastern edge of the plume from expanding. The shape of the plume is more sensitive to
easterly and westerly winds, which tend to limit the edge of the plume to extend to the northern shore and facilitate the western edge further to the eastern area. It takes about 25 days for the whole lake to be influenced by the river diversion from BCS.

Sensitivity experiments are conducted to test how hydrodynamics change with different wind velocities. When wind magnitude is under 6 m/s, salt content decreases only under westerly wind. Except for this condition, salt content increases when wind magnitude increases from 2 m/s to 14 m/s no matter what the wind direction is. Surface downwind flow and bottom upwind flow all increase with the magnitude of wind under northerly, southerly, easterly, and westerly winds. The bottom flow is usually stronger. There is a no-motion plane between the surface and bottom flows, which migrates to a lower layer when wind magnitude increases.

Leakage of freshwater from the BCS during flood season has a great impact on the hydrodynamics of the water in the Lake Pontchartrain. It reduces the salt mass by 1500000 kg in the lake and decreases salinity by 3 psu should there be no leakage. Leakage of freshwater tends to diminish the gyres in the lake and enhance the mixing of the water columns, thus leading to a very low average potential energy demand for the whole lake. The leakage can also lead to a lower $R^2$ value between the surface slope approximated by the quasi-steady state equation and that from the FVCOM model in both along- and cross- estuary directions.

5.3. Discussion of Future Work

Future studies are still needed based on what has been done. As some examples, cold front events can be categorized in terms of the strength and area impacted. The corresponding responses of sub-tidal hydrodynamics to different categories can be examined. The influence of different categories of cold fronts can be quantified and predicted.
Salinity and temperature can be modeled with higher accuracy so that circulation under baroclinic conditions can be further investigated. This will need more measurements of the vertical profiles of salinity and velocity at different locations of Lake Pontchartrain with proper initial and boundary conditions.

The current modeling domain can be nested into a larger domain which cover the whole Gulf of Mexico so that remote wind effect can be examined with more detail. This will need velocity, salinity and temperature with higher resolution as initial conditions and also heating and radiation data for longer period simulations.

Quasi-steady state balance can be tested in more water bodies with shallower water depth and limited connection to the open ocean. The role of topography (water depth and width of the channels or inlets) can be further confirmed and classified. It can also be a good predictor for the subtidal variations of water levels in certain water bodies.
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APPENDIX A. MODEL VALIDATION

The model results for water level and velocity in the three channels were first compared with the observations from 2008. To test the wind effect, we also use the water pressure data from 2016 at the E, W, S, and N sites around the lake to check the water level difference from the model. Correlation coefficient (CC) was used to evaluate the model results against the observed data as [Wu et al., 2011; Qiu and Zhu, 2013]

\[
CC = \frac{\sum_{i=1}^{N} (X_{mod} - \bar{X}_{mod})(X_{obs} - \bar{X}_{obs})}{\left[\sum_{i=1}^{N} (X_{mod} - \bar{X}_{mod})^2 \sum_{i=1}^{N} (X_{obs} - \bar{X}_{obs})^2\right]^{1/2}}
\]  

(1)

where N is the length of time series, \(X_{mod}\) is the model results and \(X_{obs}\) is the observed data. The root-mean-square error (RMSE) was calculated by:

\[
RMSE = \left[\frac{\sum_{i=1}^{N} (X_{mod} - \bar{X}_{mod})^2}{N}\right]^{1/2}
\]

(2)

And the skill score (SS) [Allen et al., 2007; Liu et al., 2009; Murphy, 1988; Ralston et al., 2010]:

\[
SS = 1 - \frac{\sum_{i=1}^{N} (X_{mod} - X_{obs})^2}{\sum_{i=1}^{N} (X_{obs} - \bar{X}_{obs})^2}
\]

(3)

was used to assess the model performance. Model Results with SS > 0.65 was categorized as excellent; 0.65 -0.5 very good; 0.5 -0.2 good; and <0.2 poor [Wu et al., 2011].

The validation of the modeled water level (Fig. 7) and along channel velocity (Fig. 8) in the three inlets indicates that tidal components and low frequency variations were well simulated (due to the ineffectiveness of the velocity data in the Industrial Canal, modeled velocity in this site is not compared with observations). The model performance on the water level for the Rigolets and Industrial Canal is excellent and for Chef Menteur is very good (Fig. 7). The simulation of along channel velocity in the Rigolets and Chef Menteur are excellent (Fig. 8). However, the accuracy of the modeled cross channel velocity is relatively low. Since our main interest is the dominant flux in and out of the lake, we omitted the discussion on the small cross-channel flow component.
that does not contribute to the along channel transport. We also used the HOBOs’ pressure data from 2016 to validate the lake surface slope induced by the wind associated with cold front passages. Dotted lines in Fig. 10 show the surface slope between east and west and that between north and south calculated using the observational water pressure data obtained from HOBOs’ deployment. Modeled results of water difference (solid black line in Fig. 9e and 9f) under real water level forcing at the open boundary and the spatially uniform wind forcing are consistent with the observation, indicating that wind induced water level oscillation for the lake surface was well simulated by the model.
APPENDIX B. DAMPING OF REMOTE WIND EFFECT DUE TO BOTTOM FRICTION

Five extra experiments were conducted to confirm the damping of remote wind effect due to bottom friction using changing bottom coefficients (0.00001, 0.0005, 0.005). Figure B1 shows that the remote wind effect is able to reach the interior of the lake with drag coefficient smaller than normal, e.g. 0.00001 (Figs. B1a and B1b). The bottom friction is the main reason for the reduction of the remote wind effect in the interior of Lake Pontchartrain. The remote wind is almost damped and has very limited effect on the interior when the bottom friction coefficient is large (Figs. B1e and B1f).
Fig. B1. Magnitude of surface and bottom velocity under different drag coefficient values ($C_D = 0.00001$ for a and b, 0.0005 for c and d, 0.005 for e and f) under easterly wind. The left panels are for surface currents. The right panels are for bottom currents.
APPENDIX C. PUBLICATIONS

Papers as First Author or Co-author During Ph.D. at LSU


VITA

Wei Huang entered Nanjing University of Information Science and Technology in September, 2006, and received her Bachelor degree in Marine Science in June, 2010. She continued to her graduate study on Meteorology at Nanjing University of Information Science and Technology in September, 2010 and earned her Master’s degree in June, 2013. Under the supervision of Professor Jianhong Wang, her graduate research was mainly focused on the heavy rain forecasting using numerical modeling and atmospheric Radar for local regions.

She enrolled in the Department of Oceanography and Coastal Science, Louisiana State University since August 6th, 2014 as a Ph. D student under the supervision of Professor Chunyan Li. Her research was supported by Professor Li, aiming at the response of sub-tidal hydrodynamics of estuaries to meso-scale atmospheric systems such as cold and warm fronts using both numerical modeling and in-situ measurements.