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Quantifying cold front induced water transport of a bay with *in situ* observations using manned and unmanned boats

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Abstract

The generation of high-resolution data is increasingly important in understanding the complexities of coastal ocean and developing sound management strategies, especially in view of the long-term impact of severe weather systems. The impact of severe weather systems, when integrated over time, can be significant when compared with tidal oscillations. This paper presents a study of water transport out of Vermilion Bay in response to a short, intense event associated with a passing atmospheric cold front, and reports the application of an Acoustic Doppler Current Profiler (ADCP) mounted on an Automated Surface Craft (ASC), known as the auto-boat or unmanned boat, developed in our lab at the Louisiana State University, to generate high resolution data accurately at a fraction of the cost of a manned boat. In our study, we used a manned boat and an unmanned boat, each for over 24 h to cover an entire diurnal tidal cycle, to measure flow velocity profiles to calculate the total transport. A stationary ADCP was deployed in the Southwest Pass of the Vermilion Bay from May 2009 to April 2012, providing data almost continuously (with only one major gap), with a 717-day record of water transport between the northern Gulf of Mexico and Vermilion Bay, and demonstrates the importance of the pass in water transport.

Key words: cold fronts, unmanned boat, Vermillion Bay, Acoustic Doppler Current Profiler, surveys, regression on transport

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1 Introduction

Containing 40% of US coastal and estuarine wetlands (Stone et al., 1997; Penland et al., 1990), the Louisiana coastal zone is the subject of extensive interest and study of fluxes of water and land-derived materials running from the rivers and tributaries and associated geomorphological impact under various forcing conditions of the tide and weather (Coleman, 1976; Feng and Li, 2010; Huh et al., 1991; Moeller et al., 1993; Pepper and Stone, 2004; Perret and Caillouet, 1974; Roberts et al., 1980, 1987, 2015; Rouse et al., 1978; Walker, 2001; Walker and Hammack, 2000; Li et al., 2011, 2017, 2018; Lin et al., 2016). In view of sea-level rise, subsidence, river discharge, navigation, flood control, habitat loss, commercial fisheries, carbon sinks, sediment transport and deposition, and nutrient cycling, to mention just a few concerns, this dynamic system is of national and international, and economic, social and environmental importance. Understanding the environmental processes that impact this sensitive and important environment is essential in developing sound environmental management practices.

Louisiana coast has micro-tides. The major forcing for bay oscillations and circulation in estuaries and the coast is wind as demonstrated by many studies (e.g., Chuang and Wiseman, 1983; Cochrane and Kelly, 1986; Wiseman et al., 1997; Rego, 2006; Feng et al., 2012). More specifically, tropical storms and cold front passages significantly impact this area (Georgiou et al., 2005; Reed, 1989). A cold front is the leading edge of a cooler, drier air mass, moving to replace a lighter, warmer, damper air mass (Hsu, 1988; Li et al., 2011). Cold fronts are typically associated with a significant shear in wind velocity, change in wind direction in the northern hemisphere from southern quadrants to northern quadrants, and a rapid drop in air temperature and pressure. The atmospheric event leads to a drop in water level in coastal bays of the northern Gulf of Mexico as water is pushed offshore by the northerly winds. The associated flushing of inshore bays affects sediment re-suspension and transport, nutrient exchange, water temperature and salinity (Li et al., 2011; Feng and Li, 2010; Kineke et al., 2006; Roberts et al., 1987; Turner, 2006). The impacts of storm events are dependent on the characteristics of the storm (intensity, duration, direction) in relation to the local geomorphology and environmental conditions.

Despite the studies of the impact of cold fronts on the coastal bays and estuaries in Louisiana area, all previous studies lack in situ measurements of the water transport calibrated to cover the entire cross section of a tidal channel through which the flushing occurs. For example, the measurements of flow velocities of Li et al. (2011) were done at a fixed location outside of the Wax Lake

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Delta. The study of Feng and Li (2010) mainly used water level data. In a recent study (Huang and Li, 2017), several cold front events were observed and studied with numerical experiments for a large estuarine lake—Lake Pontchartrain. Remote and local wind effects before, during, and after the cold front passages were discussed. In Li et al. (2018), 76 cold front events were studied with an unmanned boat and a long-term deployment at Port Fourchon between 2006 and 2008. Cold front event is common in many places other than Louisiana (e.g., Li, 2013; Li and Chen, 2014).

In this paper, we report a complete coverage of transport through the Southwest Pass of Vermilion Bay of Louisiana during a strong cold front. The transport was calibrated by running an unmanned automated boat (Li and Weeks, 2009; Weeks et al., 2011) across the channel over an entire tidal cycle prior to the cold front. The passage of this cold front occurred on 30 October 2009 and had a considerable impact on water transport in Vermilion Bay. Despite the connectivity of Vermilion Bay to the Atchafalaya Bay system to the east, a large portion of the water transport occurred through the deep Southwest Pass (~40 m in the channel, vs. just a couple of meter shallow shoals between the Vermilion and Atchafalaya Bays). Data collected from this study correlate wind direction and intensity with water transport, and provide high resolution data characterizing the dynamic processes associated with flushing in an open system.

2 Study area

The Vermilion Bay (Fig. 1) is the western most bay in a series of five interconnected bays in the Atchafalaya Bay system in coastal Louisiana. Under fair weather conditions, diurnal tides dominate water level and transport in the coastal zone where the tidal range is usually smaller than 0.6 m, and water depths in the bay ranges from 1 to 4 m (Marmer, 1954; Walker, 2001). A small amount of fresh river water enters through Weeks Bay and Little Vermilion Bay via the Gulf Intracoastal Waterway (Walker, 2001). Vermilion Bay is separated from the Gulf of Mexico by Marsh Island to the south and the Atchafalaya Bay to the east. Southwest pass, a deep narrow channel (40 m maximum depth, 27 m average depth) to the west of Marsh Island, connects the bay to the gulf. Along the predominantly east-west Louisiana coastline, a cold front is often preceded by strong winds from the southern quadrants that produce high waves and a setup inshore (Feng and Li, 2010; Li et al., 2011). Given the fact that the Vermilion Bay is semi-enclosed and its only opening into the Gulf of Mexico is deep (~40 m) and narrow (~1 km scale) (Fig. 1), exchange through the channel is expected to be significant under strong wind event. The reason that the narrow channel is deep is because of the strong turbulent flows causing significant erosions. The exchange of water and suspended sediments through these narrow channels are important to the ocean-land interaction and the coastal environment. The study of such exchange processes is however lacking despite the fact that the northern Gulf of Mexico coastline has many similar semi-enclosed bays and estuaries with narrow openings. This study site is selected because of logistic convenience and our previous studies of eddies using an unmanned automated boat (Li and Weeks, 2009).

3 Methods

On 25 May 2009, an RDI Channel Master side looking ADCP was installed in southwest pass to record water velocity (cm/s) through the channel (Fig. 2). The instrument was set to record data at ~2 m depth over a 100 m cross section of the 380 m wide channel. Water velocity and water level data collected by the 600 kHz ADCP are automatically averaged to two minute intervals and transmitted 21 km via a Digi International 900 MHz radio modem to a hub at Cypremort Point that can be remotely ac-

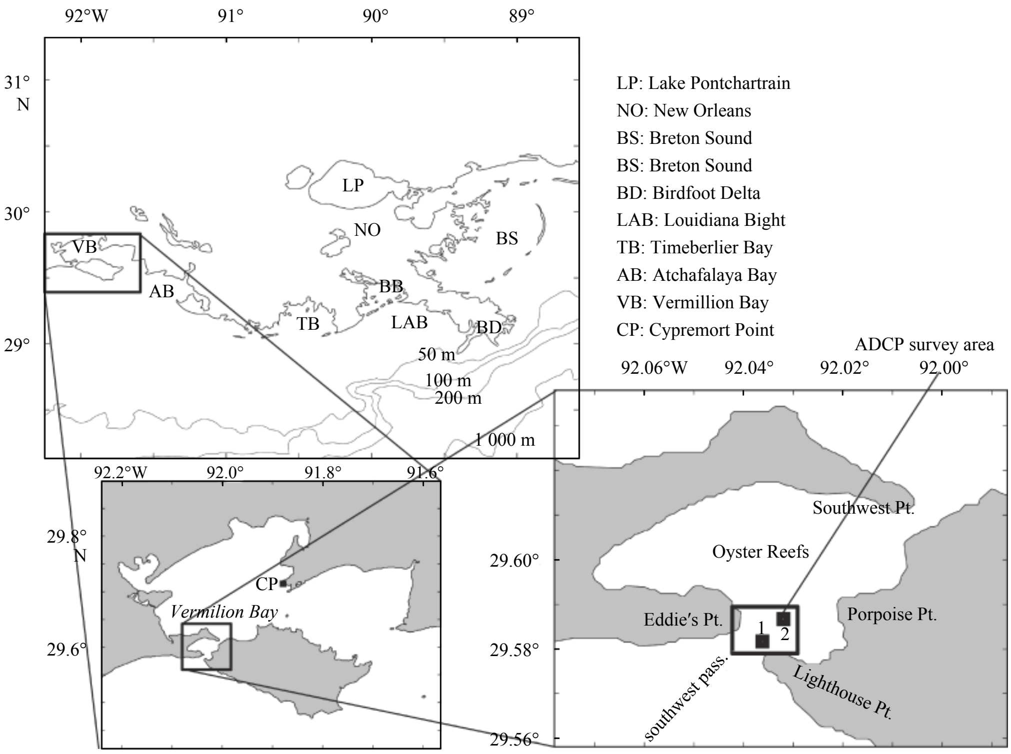

Fig. 1. Study area. Shown in the left rectangle are the locations of deployments marked by 1 and 2, corresponding to the first and second deployments, respectively.

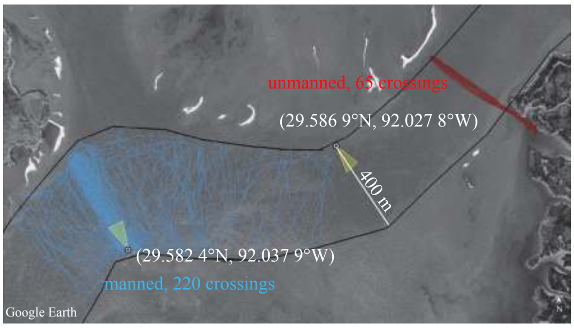

Fig. 2. Locations of deployments, manned boat survey tracks with 220 crossings (light blue lines) and unmanned boat survey tracks with 65 crossings (red lines). The triangles show the orientation of the horizontal ADCP.

cessed. Damage to the ADCP mount resulted in the abandonment of the study site on 1 December 2009, providing data covering close to 173 consecutive days. On 22 September 2010, this system was relocated on another channel marker and collected close to an additional 545 days of data, making the total time series of horizontal velocity at 2-min intervals for ~717 days, covering ~25% of the channel. Figure 2 shows the locations and beam directions marked in yellow.

Velocity measurements from the stationary ADCP were correlated to volume transport measurements calculated from 24-hour surveys using a vessel mounted RDI 1 200 kHz ADCP. Volume transport measurements were calculated by using the velocity profiles measured acoustically along the water column. Two 24-hour surveys were undertaken, one with a manned small boat and the other an unmanned automated boat. More specifically, the first 24-hour survey was completed using a 26 foot, twin diesel charter boat with a three-person crew. Transport was measured 227 times over the 24-hour period. The second 24-hour survey was conducted after the repositioning of the side looking ADCP, this time using the auto-boat, a 14 foot canoe, propelled by two 12-V DC trolling motors powered by two 100-A/h, 12-V, deep cycle batteries in parallel and a small 1 000 Watt gasoline generator. Two people monitored the survey from a moored vessel in the nearby marsh, with minimal user input during the survey. It was determined beforehand that ~50 crossings were enough for a good regression and 62 were done.

The boat mounted ADCP measured velocity data were first calibrated for misalignment and scaling (Joyce, 1989). Each time the boat went across the channel, the velocity was integrated across the channel, with a linear extrapolation from 1.21 m below the surface to the surface and a replacement of the near bottom couple of data points by a linear interpolation to a bottom velocity of zero (to exclude errors caused by the sidelobe effect near bottom). The edge of the route was already very close to shore with shallow water (Weeks et al., 2011). A linear extrapolation was made to include values near the side boundaries in the integration for the total cross channel transport. The standard error of velocity measurements for manned boat is about a few centimeters per second for flows ~1 m/s (e.g., Li et al., 2006). The standard error of velocity for the unmanned boat is much improved (about only 1/3 of that from the manned boat). This is mainly because the unmanned boat can repeat the planned route much more accurately (Weeks et al., 2011).

Figure 3 shows an example of the vertical profile and depth averaged flow velocity vectors along the transect in one crossing. As a result, the auto-boat would survey across the channel twice then put into position hold mode for some time before the next round trip for more data. This same auto-boat has completed well over a thousand crossings in the past and could have done ~300 crossings if left to run nonstop at 1.5 m/s. This would create a lot of extra data processing with little to no increase in accuracy of the regression. The auto-boat was also required to run at a slower speed to help with the bottom tracking of the onboard ADCP. Only an auto-boat or autopilot can maintain such a strait track with currents over 50% of boat speed. Weeks et al. (2011) provides a detailed description of the design and hardware of the auto-boat and the benefits of using the unmanned vessel in regards to energy efficiency, ease of operation, endurance, and superior accuracy in following a course.

Figures 4 and 5 show the regression between transport calcu-

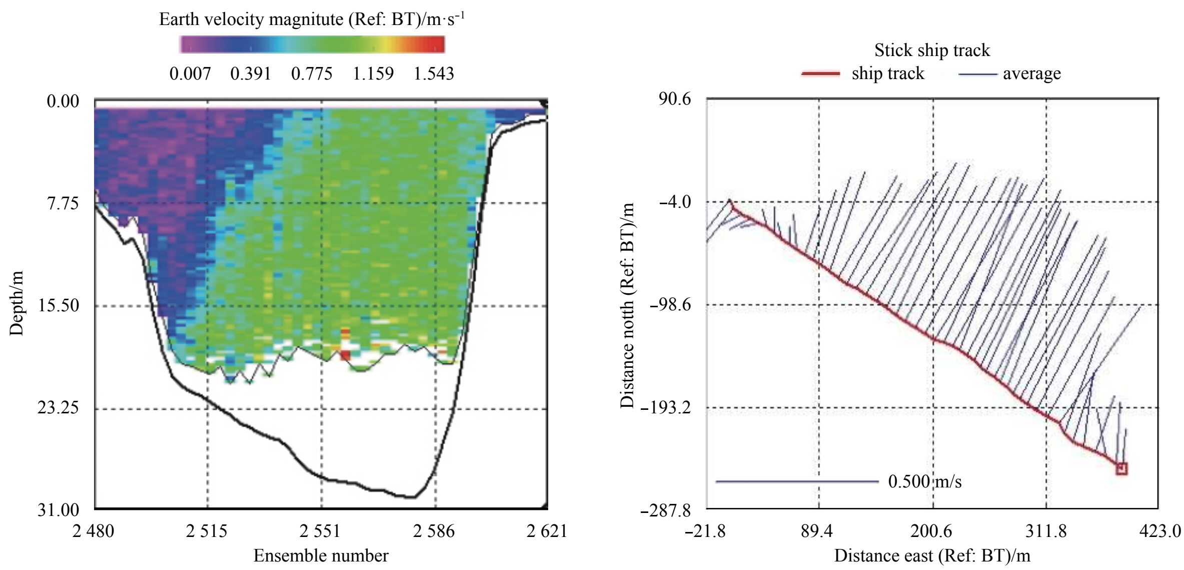

Fig. 3. Example of cross sectional view of the flow velocity profiles (left panel) and depth averaged velocity vector along the transect for the unmanned boat (right panel). BT: bottom tracking.

lations from the vessel mounted ADCPs and velocity measurements taken concurrently from the stationary ADCP. The two 24-hour surveys show similar results, proving the value of the autoboat, and confirming a strong correlation to the side looking ADCP velocity measurements (R^2=0.94) and (R^2=0.96), allowing a time series of volume transport to be confidently calculated for the 717 days when the side looking ADCP was deployed. Repositioning of the side looking ADCP to the other side of the channel, had the effect of reversing the beam *x* coordinate relative to water flowing into the bay from the gulf. Both regressions use the beam *x* velocities, thus one regression is positive while the other is negative. The manned 24-hour regression is in error at the time the tide was coming in. The 24-hour survey shows the currents move north on the far side of the channel first and the side looking ADCP misses this movement until the currents pickup speed and start flowing across the whole channel (Fig. 4).

The velocity data measured from the ADCP are averaged to 20 minute intervals and calculated as volume measurements to provide a high resolution history of water transport into and out of Vermilion Bay through southwest pass. Weather data were collected from a 10 m pole-mounted weather station in the Vermilion Bay, 0.5 km from the Cypremort Point coastline. Water level data were collated from USGS instruments under the weather station (USGS 07387040). Water velocity, volume transport and wind data are shown to describe the weather event in the context of standard variability.

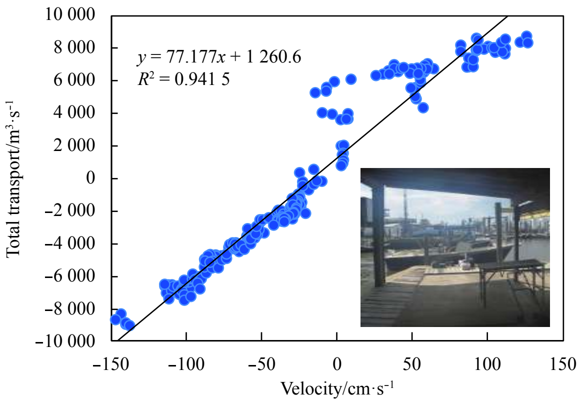

Fig. 4. Regression between the horizontal ADCP measured mean velocity (the component that is perpendicular to the transect line) and the total transport measured from the manned boat.

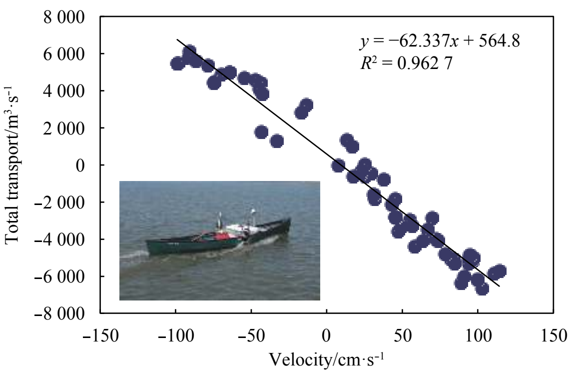

Fig. 5. Regression between the horizontal ADCP measured mean velocity (the component that is perpendicular to the transect line) and the total transport measured from the unmanned boat.

4 Results and discussion

On 30 October 2009, a fast moving atmospheric low pressure system characterized by a cold front, associated with a strong upper-level low over Kansas, combined with warm moist air from the Gulf of Mexico contributing to the formation of a line of thunder storms that rapidly moved across the study area (Fig. 3), with dramatic change in wind speed, wind direction, water level and water transport in the Vermilion Bay. Water level in the bay was below maximum with the tide predicted to rise for a further two hours in the tidal cycle when the event began.

The weather event incorporated a drastic shift in wind direction from southeast to northwest that included sustained winds exceeding 15 m/s for over 3 h (Fig. 6). During this event the water level in Southwest Pass dropped 0.88 m over 4 h. The event lasted 15 h before the northwest wind dropped below 10 m/s. Water level in Vermillion Bay also began falling sharply with the onset of the event and continued to fall for 12 h before rebound and the tidal cycle began to raise water level, overpowering the subsiding northwest winds.

The response of the current in Southwest Pass was dramatic. The average current speed over the 717 day deployment was 0.63 m/s, with a diurnal tidal cycle dominating water transport through the pass (Fig. 7). Prior to the weather event, aided by a strong southeast wind, the current velocity was recorded as 1.01 m/s flowing northward into the bay, contributing to slightly elevated water levels. The cold front brought a wind shift that caused a switch in current speed and direction, with a reversal in current direction to outflow into the gulf at a velocity of 2.60 m/s through southwest pass.

The volume transport values immediately before and after the event onset, correspond to a change in volume flow from an inflowing volume of 7 484 m^3/s to an outflow of –18 193 m^3/s (Fig. 7). By comparison, for the five tidal cycles prior to the event, it had an average inflow of 5 486 m^3/s and an outflow of –6 011 m^3/s per tidal cycle. In a wider perspective, the long term average Mississippi River discharge is –13 308 m^3/s (www.lacoast.gov). At three times of the average volume outflow and over four times of the average flow velocity, the storm event had a striking impact on the hydrodynamics of the bay.

Even though the Vermilion Bay is an open system with a large passage through Atchafalaya Bay into the gulf to the east, for this event, the data the record water almost exclusively exiting the Vermilion Bay through southwest pass. A total of 259×10^6 m^3 of water moved out of the Vermilion Bay through southwest pass during the 6 h after the wind shift. Given that the area of the bay is 497×10^6 m^2, the transport of this volume of water out of the bay would account for a water level drop of 0.52 m. The actual water level drop recorded mid-bay at Cypremort Point was 0.54 m. The calculated drop in water level based on the volume of water leaving through the pass accounts for 96% of the total water level drop for the first 6 h. After 13 h, when the water started to return to the bay, a total of -396×10^6 m^3 was removed through the pass. This volume accounts for 40% of the total volume given an average depth of 2 m (Fig. 7).

The next step was to determine, how often an event like this happens. Is this an unusually strong event? It was certainly the strongest while the ADCP was installed but that was only 717 days. Data from the USGS water level station, located mid bay was examine on the same 6-hour time scale for 10 years. The results were surprising. This event ranked 47th in terms of lowering

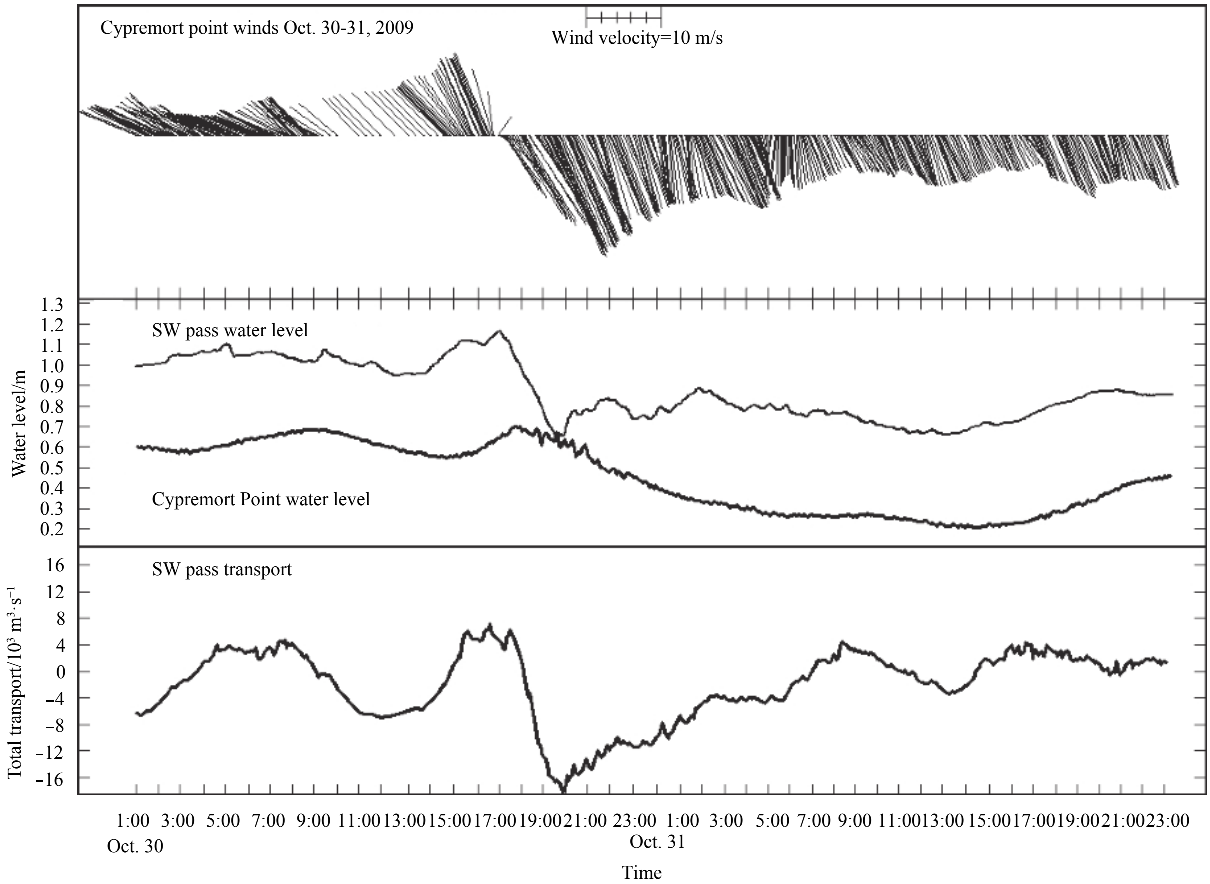

Fig. 6. Zoomed-in time series of wind from Cypremort Point (upper panel), water level at the southwest pass of the Vermillion Bay at the NOAA station (middle panel), and the total transport from our results (lower panel).

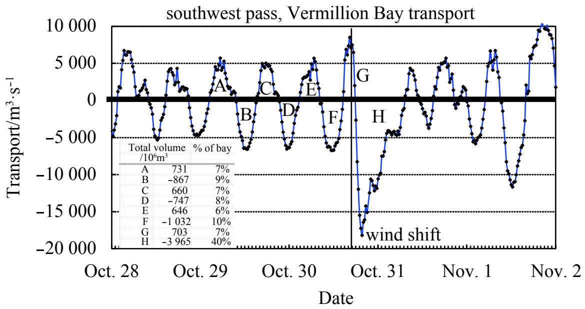

Fig. 7. Time series of the transport from the regression.

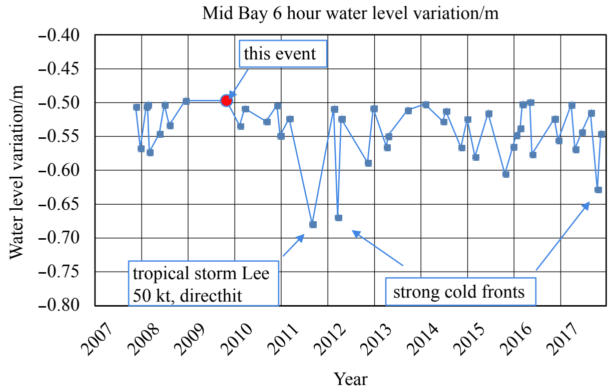

Fig. 8. Historic data of extreme values in subtidal water level variations from NOAA data for the last 10 years.

the water level over 6 h. Figure 8 shows the strongest cold front over this 10 year period, lowered the water level 1.0 m over 8 hours and 0.67 m over 6 h. The southerly winds had setup the water level 0.7 m above average and the event ended with water being 0.3 m below average.

Walker (2001) discussed circulation, sediment mobilization and salinity in the Atchafalaya Bay system in relation to hurricane and tropical storm events. Salinity patterns in the five bays are distinct. High salinity in the bays to the east may not be reflected in Vermilion Bay (Walker, 2001). Typical salinity values in Vermilion Bay are around 4–7. A salinity gradient within Vermilion Bay is related to tidal flushing, freshwater river inputs and water transport during weather events (Walker, 2001). Extreme weather events can result in a wider range of salinity values, with freshwater dominating the signal and providing values of 1–2, and inflow of gulf water increasing salinity to greater than 15.

Salinity is largely dependent on water transport, which is influenced by a number of factors, such as tide and weather. Therefore, the flushing of the bay and the changes in salinity can vary depending upon the specific conditions. During tropical storm Frances in 1998, water transport contributing to coastal set-up occurred mostly through the Atchafalaya Bay (Walker, 2001; Walker and Hammack, 2000). However, low water level in Vermilion Bay after a storm event can be followed by strong inflow of saline Gulf water through southwest pass (Walker, 2001; Walker and Hammack, 2000). Walker (2001) suggested processes that may contribute to higher salinity in the Atchafalaya Bay System associated with southwest pass, including wind driven impacts on upwelling, vertical and horizontal mixing, and transport of freshwater plumes around the inner shelf, seaward of the pass. Flooding of marshes with saline water can severely stress vegetation, with subsequent impacts on erosion and sediment mobilization.

Vermilion Bay is home to an array of aquatic life, including commercial species of fish, crab and shrimp (Perret and Caillouet, 1974). A study of fish in the Vermilion Bay (Perret and Caillouet, 1974) documented 43 species, representing 24 families, in the bay. Species populations were unevenly distributed across the bay, with the greatest number of species in Southwest Pass (Perret and Caillouet, 1974). Fish and other aquatic life, are sensitive to their environment and can be greatly impacted by changes to salinity, temperature, suspended sediment and current, affecting population presence, migration, distribution and recovery.

In a complex coast that includes prograding, retreating and transitional environments, understanding sediment transport is important (Kemp, 1986; Kineke et al., 2006; Roberts et al., 1987, 1997). Increased turbidity, as a result of wind and a drop in water level, increases suspended solids in the water column (Walker, 2001). Roberts et al. (1987) discussed sediment distribution along the Louisiana coast characterizing cold fronts as "agents of coastal change", with intensity, speed, duration, and orientation of the front controlling physical processes. Although the Gulf coast is subject to the impacts of tropical storms and hurricanes, the lower energy, but higher frequency of cold fronts (20–30 per season) is a greater cumulative driving force behind coastal processes and physical change (Reed, 1989; Roberts et al., 1987).

5 Conclusions

This study provided high resolution data for water transport in the Vermilion Bay. The study utilized the application of an ADCP mounted to the auto-boat in a 24-hour study to correlate water volume transport with water velocity measurements from a stationary side looking ADCP deployed in the channel of Southwest Pass. While Weeks et al. (2011) documented the benefits of the auto-boat in comparison to traditional manned vessels in terms of labor, cost and accuracy, this study provided a comparison between the two methods in data collection using a vessel mounted ADCP. A simple regression confirms the strong correlation between the vessel mounted water transport measurements and the side looking water velocity measurements (R^2=0.94–0.96), and demonstrates the applicability of the auto-boat in data collection.

Although the Vermilion Bay is part of the larger Atchafalaya Bay system, the sheer volume of water transport out of the bay through Southwest Pass during the weather event, especially when considered relative to the mean Mississippi River discharge, highlights the importance of understanding the hydrodynamics within small scale systems. Flushing effects can be considerable in such an extreme event and understanding water transport is essential for planning and management of the environment, especially in regards to sediment mobilization and movement, and nutrient cycling, with significant potential impacts to the local and wider environment.

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