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A mobile monitoring system to understand the processes controlling episodic events in Corpus Christi Bay

Mohammad Shahidul Islam · James S. Bonner · Temitope O. Ojo · Cheryl Page

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Abstract Corpus Christi Bay (TX, USA) is a shallow wind-driven bay and thereby, can be characterized as a highly pulsed system. It cycles through various episodic events such as hypoxia, water column stratification, sediment resuspension, flooding, etc. Understanding of the processes that control these events requires an efficient observation system that can measure various hydrodynamic and water quality parameters at the multitude of spatial and temporal scales of interest. As part of our effort to implement an efficient observation system for Corpus Christi Bay, a mobile monitoring system was developed that can acquire and visualize data measured by various submersible sensors on an undulating tow-body deployed behind a research vessel. Along with this system, we have installed a downward-looking Acoustic Doppler Current Profiler to measure the vertical profile of water currents. Real-time display of each measured parameter intensity (measured value relative to a pre-set peak value) guides in selecting the transect route to capture the event of interest. In addition, large synchronized datasets measured by this system provide an opportunity to understand the processes that control various episodic events in the bay. To illustrate the capability of this system, datasets from two research cruises are presented in this paper that help to clarify processes inducing an inverse estuary condition at the mouth of the ship channel and hypoxia at the bottom of the bay. These measured datasets can also be used to drive numerical models to understand various environmental phenomena that control the water quality of the bay.

Keywords Mobile monitoring system · Adaptive sampling · Hypoxia · Stratification · Corpus Christi Bay

M. S. Islam (✉) · J. S. Bonner · T. O. Ojo
Science and Technology, Beacon Institute for Rivers and Estuaries, Beacon, NY 12508, USA
e-mail: sislam@bire.org

C. Page
Texas Engineering Experiment Station, Texas A&M University, College Station, TX 77843, USA

Introduction

Corpus Christi Bay (Texas, USA) is home to the nation's seventh largest port with numerous petrochemical facilities. Considering its impact to the economy, the National Estuary Program designated Corpus Christi (CC) Bay as a National Estuary in 1992 and created the Corpus Christi

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Bay National Estuary Program to protect the health of this bay while supporting its economic growth. This enclosed shallow bay is wind-driven and so can be described as a highly pulsed system (Ojo et al. 2006). It cycles through various episodic events such as sediment resuspension, flooding, water column stratification, and hypoxia. One of the episodic events that draws national attention is the occurrence of hypoxia (dissolved oxygen <2 mg/l) in this shallow bay. Hypoxia was first reported in the southeast part of CC Bay in 1988 (Montagna and Kalke 1992) and has been observed every summer thereafter (Ritter and Montagna 1999). Hypoxic events that occur in this bay can last on the order of hours to days (Ritter and Montagna 2001). Therefore, understanding this phenomenon requires the development of monitoring systems that can capture the stochastic processes controlling water quality in the bay.

Monitoring of water quality parameters and environmental indicators that influence the physical processes of hypoxia poses a challenge due to the spatial extent and dynamics associated with CC Bay. There are various sampling methods available to measure water quality parameters; some methods are ex situ whereas others are in situ. Grab sampling and flow-through sampling have been used for ex situ collection of water samples in routine monitoring where immediate results are not required, and/or analysis must be done through wet chemistry (Volpe and Esser 2002). These sampling types have limitations because of poor spatial and temporal resolution. With recent advances in technology, real-time measurements of water quality parameters are possible through the use of submersible in situ sensors (Agrawal and Pottsmith 2000; Boss et al. 2007; Visbeck and Fischer 1995). The advantage of in situ sensors is that the parameter can be measured in real time, thereby omitting the time gap between sample collection and data analysis. The real-time availability of the measured parameter has made it possible to invoke a paradigm shift in designing sampling strategies for environmental monitoring. Instead of selecting the transect route, sampling frequency, and total number of measurements prior to the start of the monitoring study, it is now possible to implement adaptive/sequential plans that will guide the choice of sampling route where more information about the parameter of interest can be gathered (Thompson and Seber 1996). This adaptive sampling scheme has gained wider acceptance as a valuable tool for the sampling of the abundant but clustered population of data in natural sciences (Fiorelli et al. 2006). In addition to the implementation of an adaptive sampling technique, the proper characterization of the spatial and temporal scale of the event depends on the type of platforms where in situ sensors are installed (e.g., mobile platforms, fixed platforms, bottom tripods, drifters, and floats; Dickey 1991; Dickey et al. 1998). Remote platforms such as satellites, aircraft, and shore-based platforms can also be used to deploy various types of sensors. Each type of platform has its advantages and disadvantages, for example, sensors installed on fixed platforms can collect data at greater temporal resolution but will be limited in spatial resolution. On the other hand, mobile platforms (e.g., autonomous underwater vehicles, remote-operated vehicles, gliders, and towed undulators) can address this limitation by housing in situ sensors and collecting data at greater spatial resolution (Blackwell et al. 2008; Barth and Bogucki 2000). This data, however, will have limited temporal resolution. The advances in remote sensing techniques help to capture physical and biological variabilities of the upper layer of the water column at greater temporal and spatial resolution but have not succeeded yet to capture the chemical species and sub-surface condition of the water column (Glenn et al. 2000a). Therefore, installation of sensors on a single type of platform will not be able to measure all parameters at proper resolution to capture the event of interest.

The advances in sensor systems, platform design, and communication technology in this decade have provided an opportunity to develop an efficient observation system through the integration of the above mentioned platforms to measure water quality, hydrodynamic, and meteorological parameters at a multitude of spatial and temporal scales of interest. The National Oceanographic and Atmospheric Administration (NOAA) is currently operating the Physical Oceanographic Real-Time System (PORTS) that provides real-time data from several waterbodies to improve the safety and efficiency of maritime commerce and coastal resource management. Other observatory systems that have been deployed at various coastal environments are MYSound in Long Island Sound (Tedesco et al. 2003), the COlumbia RIver Environment (CORIE) (Baptista et al. 2005), the Chesapeake Bay Observing System (CBOS) and the Long-term Ecosystem Observatory (LEO-15) (Glenn et al. 2000b). In addition, the National Science Foundation (NSF) has provided funding to establish WATer and Environmental Research Systems (WATERS) network which tests various aspects of observatory design and operation at different test beds sites. This network will make available measured data from various observatories and will help in investigating multi-scale environmental phenomena (Montgomery et al. 2007). CC Bay has been selected as one of the test bed sites of WATERS network. We have developed various monitoring systems to measure meteorological, hydrodynamic, and water quality parameters at high spatial and temporal resolution. Along with an Acoustic Doppler Current Profiler (ADCP) and meteorological sensors, we have installed robotic profiler systems at fixed platforms to measure the vertical variation of hydrodynamic, meteorological, and water quality parameters at high temporal resolution (i.e., on the order of seconds for meteorological and hydrodynamic parameters and on the order of minutes for water quality parameters). The details of this system have been discussed in Islam (2009a). We have also installed a high frequency (HF) radar system on remote platforms to generate hourly surface current maps of CC Bay (Trujillo et al. 2004; Ojo et al. 2007a). The development of a mobile monitoring system that can measure various parameters at high spatial resolution (on the order of centimeters and meters in vertical and horizontal direction, respectively) will complement our observation system.

Various types of mobile monitoring systems such as autonomous underwater vehicles (AUV), solar-powered autonomous underwater vehicles (SAUV) and tethered sensor systems have been developed by various researchers (Wiebe et al. 2002; MacNaughton et al. 2004; Chatila and Laumond 1985). Although AUVs have certain advantages such as autonomous control of the vehicle, operation without the host vessel, and higher operational range, these systems are expensive and need specialized personnel to maintain, program, and deploy. Also these systems are not flexible enough to conduct adaptive sampling and need to be taken out of the water frequently for battery recharging. Dr. Art Sanderson (professor at Rensselaer Polytechnic Institute) has been working on SAUV development in collaboration with D. Richard Blidberg of the Autonomous Undersea Systems Institute in Lee, N.H. (SAUV 2009). This system will be recharged with solar power and will communicate with other AUVs. This system has the similar limitations as described for the AUVs except it does not need to be taken out of water for recharging. Wiebe et al. (2002) has developed BIOMAPPER-II, a tethered sensor system that can measure biological and physical parameters at greater spatial resolution and display the measured data in real time. All of these systems described here have been deployed in the deep water and were not implemented for the measurements of various environmental parameters in shallow water like CC Bay where distinct vertical gradients exist in various water quality parameters (Islam et al. 2008).

The research objective for this paper was to describe the design, construction, test deployment, and evaluation of a mobile monitoring system that could address the limitation of spatial scales of interest in existing monitoring efforts and could be deployed in shallow water. This system was installed on a mobile platform (i.e., our research vessel) and is able to measure various parameters "synchronically" over a highly resolved horizontal and vertical regime. Besides collecting data at high spatial resolution, this system is capable of displaying data in real time and thereby provides guidance on transect route selection during research cruises. This monitoring system was deployed in CC Bay for routine monitoring and for providing aid in understanding phenomena associated with episodic events in the bay. This mobile monitoring system was also integrated with the fixed robotic profiler system and the HF-radar system on remote platforms to develop an adaptive sampling scheme to capture the extent, frequency, and duration of hypoxia and other episodic events in CC Bay. The integration of these real-time monitoring systems is discussed in detail in Islam et al. (2009b). This integrated system also provides myriad datasets that can be used to drive numerical models which will help to understand the processes controlling dissolved oxygen (DO) variation in the bay.

Study area

Corpus Christi Bay, depicted in Fig. 1, is located on the Texas coastline and covers an area of approximately 432.9 km^2 (Flint 1985). This bay is linked with the Gulf of Mexico through a narrow ship channel (15 m depth), which runs from east to west. Recently, Packery Channel, located at the southern reaches of the bay, has been opened and it is another source for water exchange with the Gulf of Mexico. CC Bay is connected with four embayments namely Redfish Bay in the northeast, Nueces Bay in the northwest, Oso Bay in the southwest, and Upper Laguna Madre in the south. Freshwater enters CC Bay via the Nueces River and Nueces Bay, whereas high-saline water enters the bay during summer months from the shallow Upper Laguna Madre and Oso Bay. The Upper Laguna Madre is one of the most hypersaline lagoons in the world (Gunter 1967). Our research facility (Shoreline Environmental Research Facility shown as magenta-colored solid triangle in Fig. 1) located close to the Upper Laguna Madre provides convenient field support for regular monitoring of the bay. This bay is mainly dominated by southeasterly winds although northerly winds occur periodically during the winter months. During some portions of the year, especially summer, the wind subsides and the bay becomes very quiescent. This condition can be altered and results in a well-mixed water column on the order of hours to days if wind conditions change. Hypoxia has been reported to occur at the southeast part of the bay at every

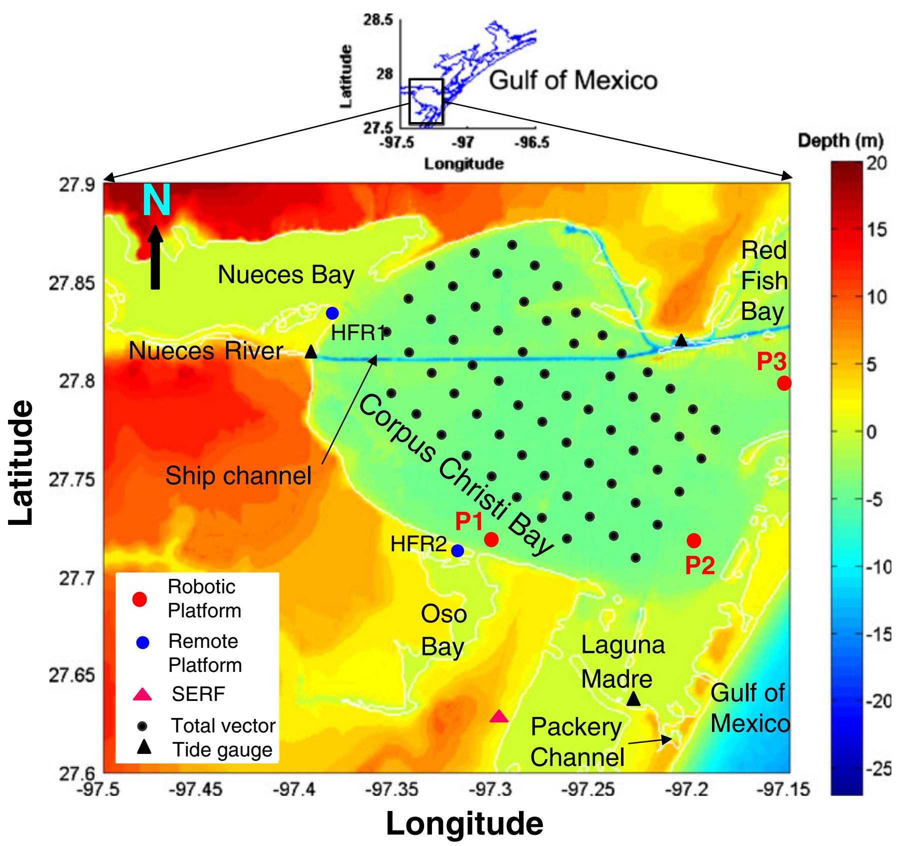

Fig. 1 Features of the study area (Corpus Christi Bay) and platform locations

summer (Ritter and Montagna 1999; Hodges et al. 2008). The three solid red circles denote the strategic locations of our fixed robotic platforms in the bay. As detailed in Islam (2009a), the vertical profile of water quality parameters are measured around these platforms with in situ sensors (i.e., a particle sizer, a DO sensor, a conductivity, temperature, and depth (CTD) sensor, and a fluorometer), installed on the robotic profiler system. Along with these water quality sensors, an upward-looking 1,200 KHz Acoustic Doppler Current Profiler and a meteorological sensor are deployed on each fixed robotic platform to measure hydrodynamic and meteorological parameters, respectively. Platform 'P1' (27°43.531′ N, 97° 18.412′ W) is positioned 100 m from the mouth of Oso Bay to characterize the effects of Oso Bay inflow, which has been reported to trigger hypoxia in that part of the bay. Platform 'P2' (27°43.375′ N, 97°11.403′ W) is positioned in the southeast portion of the bay where hypoxia has been documented since 1988 (Ritter and Montagna 1999). Some of the ship channel effects on CC Bay may be captured through our Platform 'P3' (27°48.560′ N, 97°08.513′ W) in the northeast part of the bay. The solid blue circles represent the location of our remote platforms where HF-radar systems are installed, and the solid black circles depict the locations of surface current mapping vector generated from these HF-radar systems. In addition, water surface level variation due to tidal forces can be collected from several NOAA water level stations (shown as green triangles in the Fig. 1), which are maintained by Texas Coastal Ocean Observation Network (TCOON; Division of Nearshore Research, Conrad Blucher Institute for Surveying and Science, Texas A&M University—Corpus Christi).

Mobile monitoring system

Originally, our research group developed a portable Integrated Data Acquisition, Communication, and Control (IDACC) system that was deployed on our mobile platform (i.e., our research vessel) and could measure variation of water quality parameters 'synchronically' over a highly resolved spatial regime (Ojo et al. 2007b). This system could acquire and visualize data measured by submersible sensors on an undulating tow-body (Acrobat LTV-50HB, by Sea Sciences Inc.) deployed behind the boat. Real-time display of the parameter intensity (measured value relative to a pre-set peak value) provided guidance on transects route selection during each research cruise. However, this prototype system had limited success in capturing vertical gradients of the parameters of interest, especially steep vertical gradients. Data acquisition software of the system did not consider the slow response time of some sensors, and so when the measured data values changed rapidly in vertical direction, the system could not capture the actual variation. As there exists a significant vertical gradient of environmental parameters in CC Bay during the occurrence of hypoxia, this system was not able to characterize the processes that are dominant under this condition (Islam 2009a). Therefore, the IDACC system was significantly modified in this study so that it can successfully capture vertical variations of the parameters and display them in real time. Hardware upgrades to the IDACC system include use of a lightweight ruggedized laptop(s) to replace the previous bulky hardware components for data acquisition and visualization, and use of a single global positioning system (GPS) as opposed the original setup that required two GPS units. Software upgrades to the IDACC system include three-dimensional (i.e., horizontal and vertical) visualization of measured parameters in real time whereas the previous software was only capable of displaying the parameters variation in the horizontal dimensions. Modified hardware and software components are described in the following paragraphs.

Figure 2 shows the schematic diagram of our developed mobile monitoring system. In this system, three ruggedized laptop computers are set up in a local area network: (a) a laptop (computer 1 in Fig. 2) to control the undulation of the tow-body, (b) a laptop (computer 2 in Fig. 2) to acquire and visualize data from the in situ sensor suite on the tow-body, and (c) a laptop (computer 3 in Fig. 2) to determine the water current structure within the water column based on ADCP data. The laptops are situated on computer docking stations inside the boat cabin. A differential GPS

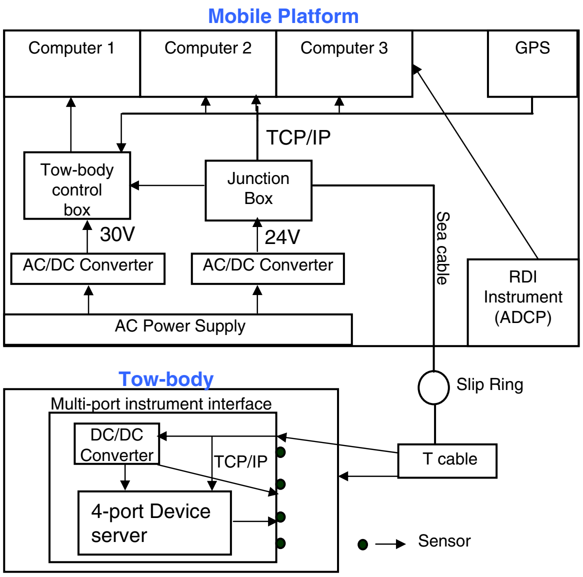

Fig. 2 Schematic diagram of the mobile monitoring system

(DGPS, Garmin, GPSMAP 3210C) is used to geo-reference the observed data and is serially connected with all three computers. Manufacturer software (Sea Sciences, Inc.) is used for the automatic control of the tow-body movement and the display of tow-body location within the water column. It can also be controlled manually through the tow-body control box that acquires 30 V DC through the conversion of the vessel's AC power. A downward-looking bottom-tracking 1,200 KHz Workhorse ADCP is installed on the starboard side of the boat to measure (a) water velocities, (b) bathymetry, (c) acoustic backscatter intensities which are indirectly related to particle concentrations, and (d) shear structure of the water column. The manufacturer software (WINRIVER I by RDI, Inc.) presents the contour plot of real-time variation of these parameters along the transect route. The computer designated to acquire and visualize sensor suite data is connected with different submersible sensors in the Acrobat tow-body cage through a subsurface multi-port sensor interface using transmission control protocol/internet protocol (TCP/IP). The instruments currently included are a particle sizer (LISST 100, by Sequoia Sciences), a DO sensor (Optode, by Aanderaa), a CTD sensor (SBE 49 "FastCat", by Sea-Bird Electronics, Inc.), and a fluorosensor (Eco-FL3, by WETLabs).

The multi-port instrument interface shown on the lower left portion of Fig. 2 serves as a power distribution, data communication unit for the submersible sensor suite. It is comprised of a multiport serial device server and a DC/DC power converter, which acts as a power conditioner, distributing 15 ± 0.07 V DC to as many as four different sensors simultaneously. The interface acquires the power from the AC/DC power converter mounted on the mobile platform that supplies 24 V DC output. The device server is essentially a multiplexed RS232 serial instrument interface which uses the TCP/IP protocol and addressing to implement virtual COM ports between the sensors mounted on the tow-body and a laptop (computer 2 in Fig. 2). The details regarding the development of this submersible interface can be found in Ojo et al. (2007b). The sea cable, made of stranded and twisted pair wires of power and communication lines from tow-body and multi-port instrument interface, is sent through the winch/slip ring assembly to the T-cable. It then diverges one set of power and communication wire to the tow-body whereas the other sets are connected to the submersible multi-port instrument interface. Data telemetry is facilitated through a network interface that connects two on-board laptops (e.g., computer 1 and computer 2 shown in Fig. 2) with the subsurface devices for data acquisition and sending command signals via TCP/IP to the sensors mounted on the tow-body.

Previously, data measured by various submersible sensors were acquired and visualized in real time through the Multi-Parameter Instrument Array and Control System (MPIACS) software developed in our research group (Ojo et al. 2006, 2007b). It displayed horizontal variation of intensities of the measured parameters (measured value relative to a pre-set peak value) along the transect route and thereby aided in selecting the transect route 'on the fly' to capture the horizontal extent of the parameters of interest. For this study, we augmented the MPIACS software to acquire and display the vertical variation of water quality parameters along the transect route as well as the horizontal variation (i.e., upgrade of display from two dimensional to three dimensional). Figure 3 presents a snapshot of the graphical user interface (GUI) generated by the modified MPIACS II software during one of our routine monitoring cruises in CC Bay. The lower left portion of the GUI gives user the option to select the type/number of instruments to be used in each monitoring activity. At present, the system allows a maximum of six instruments to be included for synchronized measurements. The user also has the option to select the area to be monitored. Currently, Corpus Christi Bay and other Texas coastline areas (Matagorda Bay, Galveston Bay, and Galveston Offshore) have been loaded into the software so that user can use them directly as reference boundaries for their monitoring activities. The lower middle panel of the GUI displays the color-coded trace line of the travel route whereas the upper middle panel shows the vertical variation of a water quality parameter along that route. In this snapshot, it shows the relative DO (measured DO with respect to preset peak DO values) variation along the travel route but the user can select other parameters (e.g., temperature, salinity, and total particle concentration) for display. The real-time display capability of the system provides guidance in selecting the monitoring route to capture the event of interest. Along with the graphical displays, the system also presents the numerical values of the synchronized measurements and their location coordinates in the edit boxes at the lower right side of the GUI. The cycle time for each set of synchronized measurements is determined by considering the fastest stable response time of each sensor in the instrument suite. For the sensor suite installed on our mobile monitoring system, it takes approximately 7 s to get a set of synchronized stable readings. The undulation speed of the tow-body is controlled in such a way so that it can collect sufficient amounts of data to capture a significant change in the vertical gradient of the measured parameter (e.g., salinity (S) difference over 2 m depth, ΔS >

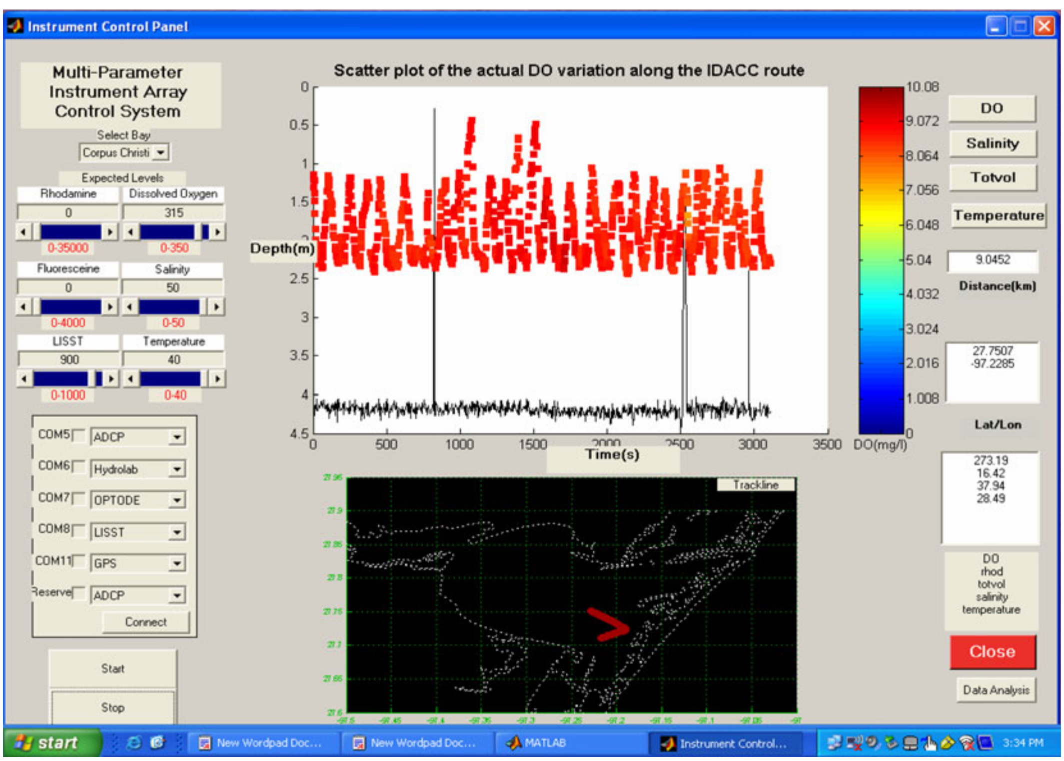

Fig. 3 Snapshot of graphical user interface generated by real-time data acquisition and visualization software (MPIACS-II) during one of our routine monitoring activities of CC Bay

4 psu/2 m). All measured parameters are archived in a text-file format. The post analysis of this measured dataset will help to infer interrelated processes that control various episodic events in the bay.

Results and discussions

Routine monitoring of CC Bay has been performed through periodic deployments of the mobile monitoring system. This system provides synchronized measurements of large hydrodynamic and water quality datasets. To illustrate the capability of the system in capturing various environmental parameters and thereby to help in clarifying the processes controlling various episodic events, measured datasets from two research cruises made on November 29, 2006 and August 07, 2007 are presented here.

November 29, 2006 cruise

On November 29, 2006, the cruise transect began at the mouth of the ship channel where it is connected to the Gulf of Mexico and moved in a westerly fashion along the ship channel. Figure 4 shows the actual transect route for the cruise made on November 29, 2006. The deep ship channel serves as a conduit to exchange materials between the bay and the Gulf of Mexico. Therefore, various parameter measurements at the ship channel can shed light on the contribution of the Gulf of Mexico to the overall condition of the water quality of the bay. From the set of measured parameters, vertical variation of two parameters (salinity and particle concentration) along the transect route are presented here. This information provides evidence of the mobile monitoring system's capability in characterizing the water quality and the particle dynamics of the bay.

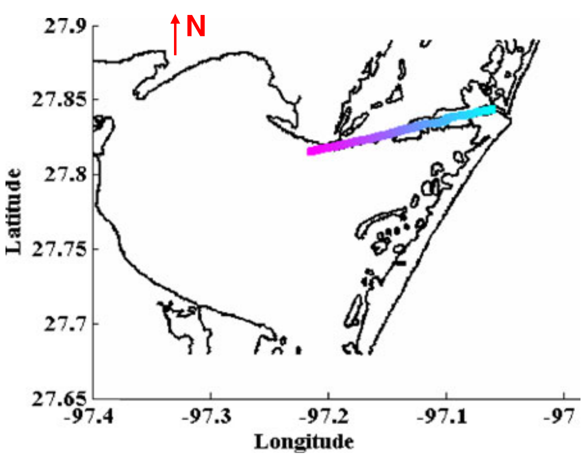

Fig. 4 Transect route of the cruise made on November 29, 2006 (direction of transect was east-to-west)

Figure 5 displays vertical variation of salinity along the transect route of the cruise shown in Fig. 4. The route line is color-coded and correlates with the horizontal color-coding along the top and bottom of Fig. 5. This kind of representation helps to match the observed data with the location of measurements. In addition, the solid black line in the figure represents the seabed profile. This measured vertical salinity profile suggests that the inverse estuary situation existed in the ship channel, i.e., water became more saline and dense as the vessel moved from the mouth of the Gulf of Mexico (GOM) towards the bay interior. The salinity level at the beginning of our cruise (i.e., mouth of ship channel) was around 32 psu but it was expected to be around 35 psu due to its proximity to the GOM. Understanding the hydrodynamic conditions of the bay can provide insight about the reasons for the existence of this salinity pattern. Figure 6 displays vertical variation of the magnitude of water current direction (measured clockwise from North) along the transect route as captured by the ADCP sensor on the mobile platform. From this plot, it is clear that water current was moving from the narrow ship channel toward the GOM (i.e., magnitude of water current direction is around 90° from north), and so the salinity level did change due to the plug of water coming from the bay interior and precipitated water from surrounding watersheds along the ship channel. Therefore, salinity levels at the mouth of the ship channel did not reach to the value of oceanic salinity during the cruise. On the other hand, the higher salinity levels at the later part of the cruise could be explained well through the understanding of circulation patterns in the bay. As this shallow bay is wind-driven, meteorological data may be helpful in clarifying

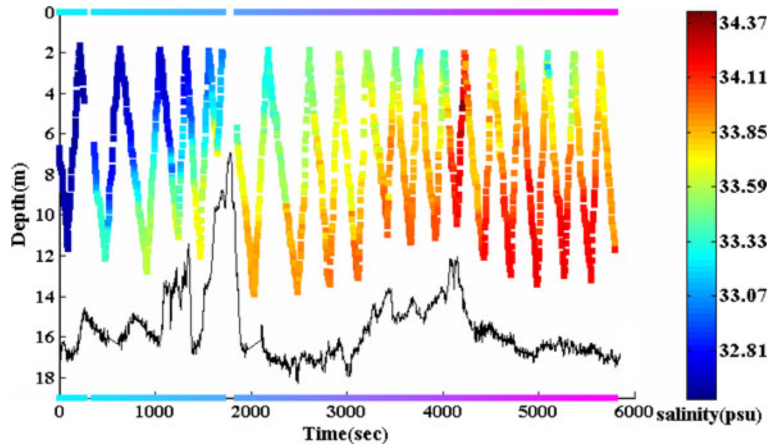

Fig. 5 Vertical profile of salinity variation along the transect route on November 29, 2006 (the *colored horizontal lines* at the *top*/*bottom* of the figure correlate to the transect route as presented in Fig. 4)

the hydrodynamic condition of the bay. Figure 7a, b displays the measured variation of wind speed and direction at one of our fixed robotic platform 'P2' (shown in Fig. 1) during the November 28–29, 2006 time frame, respectively. The wind was consistently from the south–east direction during this time period; this wind may "push" high saline water from the mouth of the upper Laguna Madre and Oso Bay northward towards the ship channel. Low freshwater inflow and the dominance of evaporation over rainfall tend to increase the salinity levels in the shallow upper Laguna Madre and the mouth of the Oso Bay as compared to the rest of the bay (Hodges et al. 2008, manuscript submitted to *Journal of Hydraulic Engineering*, in review). Our research collaborators (Dr. Ben Hodges' research group, The University of Texas at Austin) have been working on the development of a 3D hydrodynamic model of CC Bay. The preliminary results of their model showed a similar circulation pattern. Therefore, the mobile monitoring system is capable of measuring critical datasets that can capture episodic events such as the occurrence of an inverse estuary situation in the bay. In addition, data collected from this system can be integrated with the numerical model for greater understanding of various processes that occur in this dynamic bay.

The characterization of particle dynamics is crucial for assessing the health of coastal ecosystem. Movement of traffic in the ship channel can re-suspend bottom sediment and thereby affect water quality. Particles can transport 'particulate BOD' (biochemical oxygen demand), thus

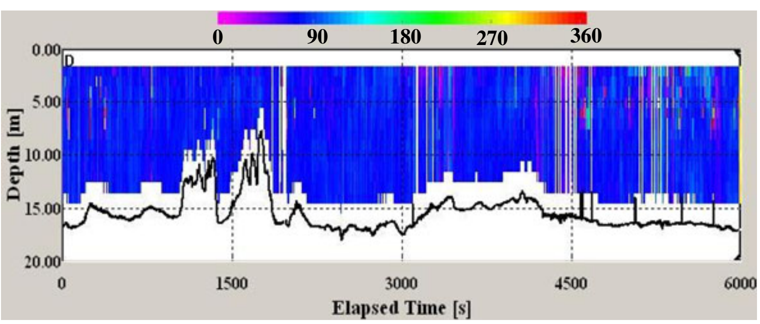

Fig. 6 Contour plot of water current direction along the transect route on November 29, 2006. The current direction is measured clockwise from the north and color changes from pink to red as the current deviates from north (the *solid black line* represents sea-bed)

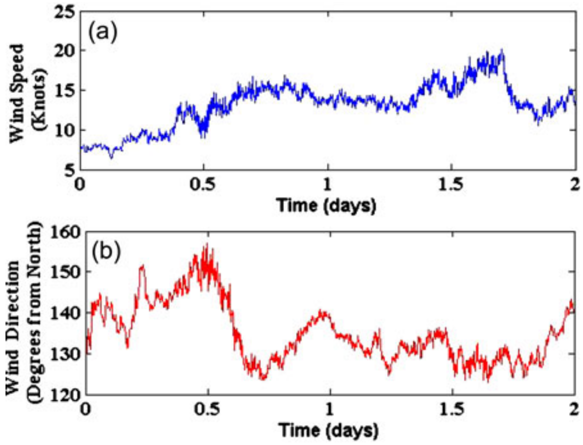

Fig. 7 Variation of wind speed (**a**) and direction (**b**) around the platform "P2" on November 28–29, 2006, respectively

affecting hypoxia. Quantification of the particle influx/outflux to the Gulf of Mexico through the channel may help us to understand the contribution of the ship channel dynamics in affecting hypoxia of the bay. The particle sizer installed on the mobile monitoring system measures particle concentration. The vertical profile of measured particle concentration along the transect route (color-coded route shown in Fig. 4) of the cruise made on November 29 are presented in Fig. 8. During this cruise, we were able to capture bottom sediment re-suspension event due to the movement of large tanker in the ship channel. As we headed from east to west in the narrow ship channel, we saw a large tanker coming from the opposite direction, and so we moved towards the side of the channel for the safe undulation of the instrument suite. The sudden change in the sea-bed depth (T = 1,800 s) in Fig. 8 represents the location where we moved towards the side of the channel. After the tanker passed us, we came back in the main channel and observed high concentration of particles along the trace route of the tanker which is evident from the particle concentration profile at time = 2,600 s. This suggests that the tanker re-suspended the bottom sediment. Also, particle concentrations measured by a particle sizer are well correlated with the acoustic backscatter intensity measured by an ADCP (Thorne and Hanes 2002; Gartner 2002; Hay and Sheng 1992). This kind of relationship is very important because it provides a greater capability to characterize the particle dynamics of the bay. An ADCP can measure a vertical profile of acoustic backscatter intensity whereas a particle sizer measures the particle concentration at a given point. The synchronized measurements of particle concentration and acoustic backscatter intensity at our monitoring mobile platform provide opportunities to investigate this kind of relationship. Figure 9 displays the acoustic backscatter intensity variation along the transect route. Note that Fig. 9 presents only a portion of the transect data for the ADCP (from T = 2,100 s through T = 4,800 s). Comparing Figs. 8 and 9, it is clearly visible that higher particle concentrations (encircled in black, Fig. 8) correspond to the higher acoustic backscatter intensity data

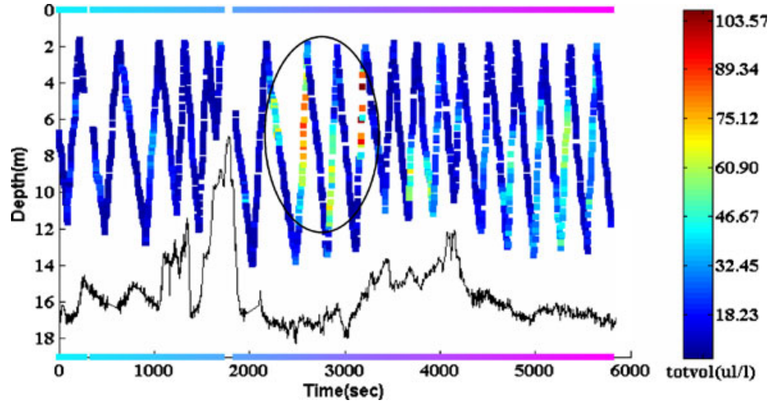

Fig. 8 Particle concentration variation along the November 29, 2006 cruise transect (the *colored horizontal lines* at the *top*/*bottom* of the figure correlate to the transect route as presented in Fig. 4)

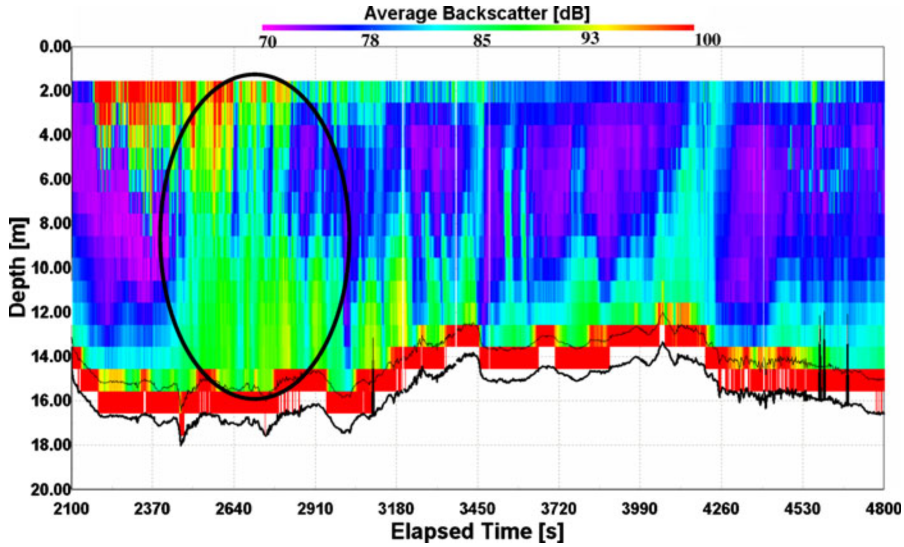

Fig. 9 Average acoustic backscatter intensity variation along the portion of transect route (time = 2,100 ∼ 4,800 s) on November 29, 2006

(encircled in black, Fig. 9). In order to interpret and understand a quantitative relationship between acoustic backscatter intensity with the actual particle concentration, it is necessary to analyze other water quality parameter measurements such as salinity, temperature, and particle type and size distribution in the water column. Future research will provide more insight in clarifying the relationship between acoustic backscatter intensity and particle concentration with other water quality parameters measured with our monitoring mobile platform and therefore, will help to better understand the particle dynamics of CC Bay and other particle-mediated transport processes.

August 07, 2007 cruise

The second dataset was collected from the research cruise made on August 07, 2007. In that cruise, the southeast part of the bay was monitored where hypoxia is observed each summer (Ritter and Montagna 1999). We started the transect from the Upper Laguna Madre and headed toward the Oso Bay. Data collected from this cruise are plotted in Figs. 10, 11, 12, 13, and 14 and the actual cruise route is depicted on the inset plots in each figure. The relative concentrations of each measured parameter are displayed in color-coded points on these figures and thereby

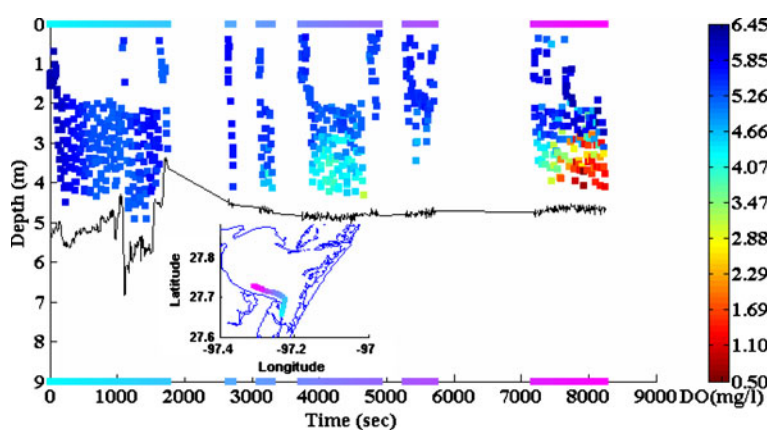

Fig. 10 Scatter plot of actual DO variation along the transect route on August 07, 2007 (*squares* DO data points (mg/l), *line* sea-bed profile)

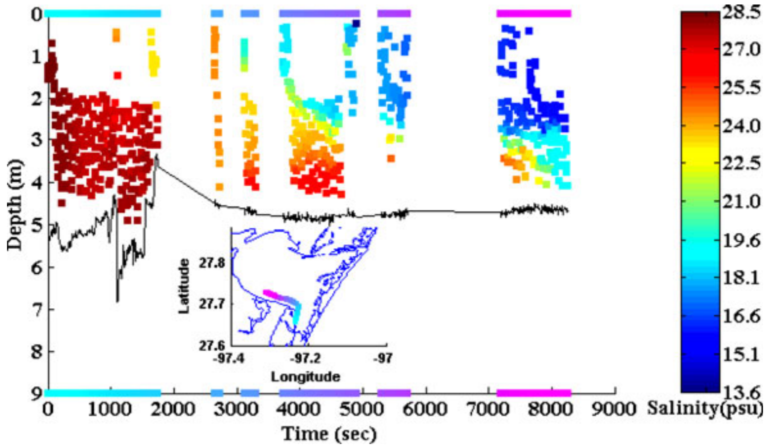

Fig. 11 Scatter plot of actual salinity variation along the transect route on August 07, 2007 (*squares* salinity data points (psu); *line* sea-bed profile)

help to visually comprehend spatial variation of the parameters. It should be noted that at several points during this transect we had to stop collecting data and pull our instrument suite onto the boat deck for inspection after inadvertent seafloor hits. These data gaps are evident in Figs. 10, 11, 12, 13 and 14.

Figure 10 displays the vertical variation of DO along the transect route. DO levels were moderate (~6.5 mg/l) in the Upper Laguna Madre and decreased gradually along the transect route from the Upper Laguna Madre towards Oso Bay. Finally, water was found to be hypoxic at the lower depths of the bay near the junction point of Oso Bay and CC Bay. Real-time display of measured DO concentrations through this mobile monitoring system guided in the transect route selection so that we could fully investigate the hypoxic area. The cruise was terminated at the mouth of Oso Bay. Various factors might induce this hypoxic condition. For example, if the water column is stratified, aerated surface water may not mix with bottom water and thereby, a significant vertical gradient in DO concentration develops (Turner et al. 1987). Also, high sediment oxygen demand, organic matter decomposition, and low

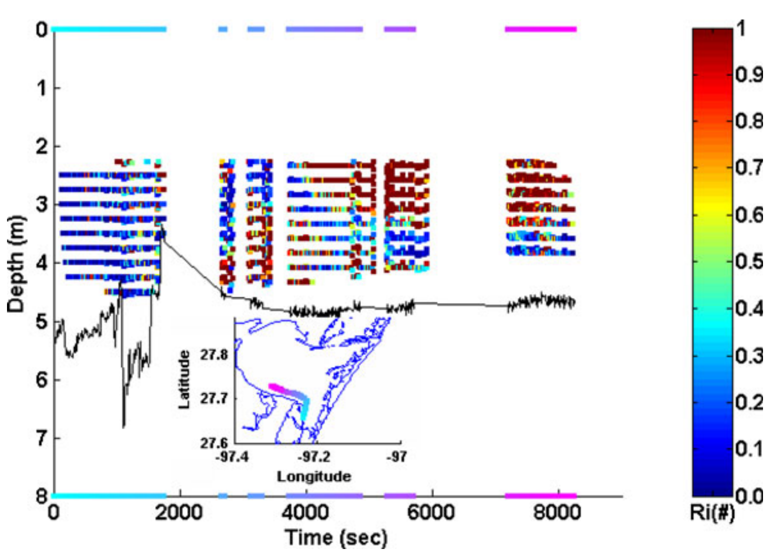

Fig. 12 Vertical variation of Richardson number (Ri) along the transect route on August 07, 2007 (*squares* Ri, *line* sea-bed profile)

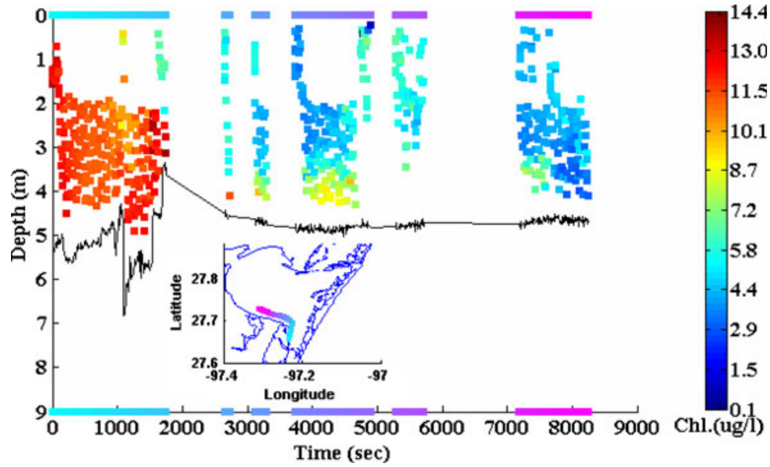

Fig. 13 Chlorophyll-a variation along the transect route on August 07, 2007 (*squares* chlorophyll-a data points (μg/l), *line* sea-bed profile)

rates of photosynthesis may turn bottom water hypoxic. The analysis of other measured parameters will help to test these hypothetical scenarios and will assist in the determination of the processes inducing hypoxia at the bottom of the bay.

The vertical variation of salinity along the same transect route is shown in Fig. 11. The water was highly saline in the Upper Laguna Madre where the research cruise began. As the cruise progressed, a distinct and pronounced vertical salinity gradient was noted. The dominance of fresh water in the gradient became more pronounced at the end of the cruise transect. This trend might be due to the intrusion of high saline water from the Upper Laguna Madre which is one of the most hypersaline lagoons in the world (Gunter 1967). The inflow of freshwater into the Upper Laguna Madre is less than the evaporation rate and the system is also separated from the Gulf of Mexico by a barrier island. This can significantly increase the salinity level in the water column. If fresh water lies above the dense saline water, the water column may remain stratified until the vertical shear structure is strong enough to mix the water column.

The ADCP sensor installed on the mobile monitoring platform measured the vertical current structure of the water column. The examination of water current structure and density profile along the transect route can provide insight into the sta-

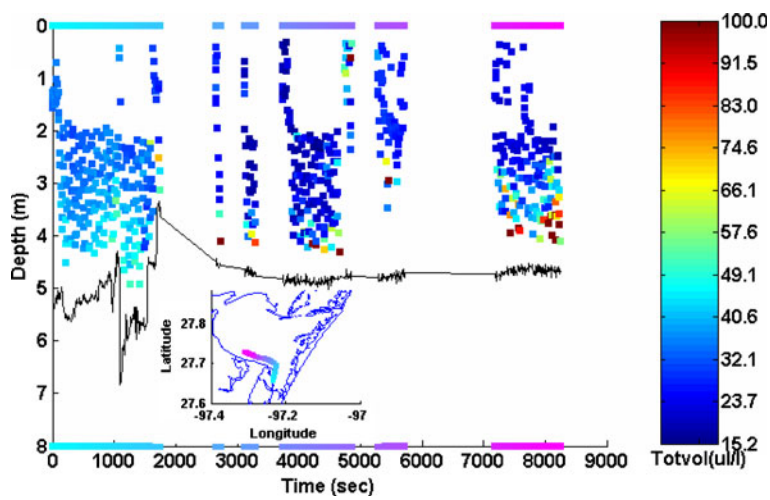

Fig. 14 Scatter plot of actual particle concentration variation along the transect route August 07, 2007 (*squares* total particle concentration (μl/l), *line* sea-bed profile)

bility of the stratified water column. The gradient Richardson number (R_i) is used as an indicator of the stability of the stratified water column. R_i is the ratio of the amount of work required to resist mixing of the stratified water column to the amount of kinetic energy available from the existing shear current structure of the water column. Mathematically, it can be described by the following Eq. 1:

$$R_i = \frac{-\frac{g}{\rho}\frac{d\rho}{dz}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \tag{1}$$

where, ρ is water density, g is gravity acceleration, z is the depth from the water surface, and u and v are the east–west and north–south velocity components, respectively. Water density is calculated from the temperature and salinity profile captured by the CTD sensor on the instrument suite, whereas vertical profile of u and v is measured by the ADCP. The sampling frequency of the CTD sensor is different than that of ADCP. Therefore, a suitable interpolation scheme was developed in this study to synchronize these two different datasets. The ADCP was configured to measure a vertical profile every 2 s from an ensemble of 11 pings. It measured water currents at several vertical bins. Each bin was separated by 25 cm and the first measured "good" bin was at a depth of 2 m after considering the blanking distance from the transducer head and the depth of transducer from the water surface. Since there was no good water current data for the top 2 m of the water column, R_i values were calculated at different points below that level. The vertical profile of measured density was interpolated into the regular grid using a triangle-based linear interpolation algorithm. Both ADCP-measured water currents and density data were interpolated at a regular grid consisting of 25-cm increments in depth and 30-s increments in time. Once both datasets were synchronized in depth and time, the vertical distribution of the Richardson (R_i) number was calculated using Eq. 1. Miles (1961) and Howard (1961) have demonstrated that $R_i >$ 0.25 is sufficient conditions for stability in a shear layer with linearly varying water current and density. When the nonlinear interactions are considered, sufficient conditions for stability in a three-dimensional stratified parallel shear flow becomes $R_i > 1$ (Abarbanel et al. 1984). The color-coded variation of the Richardson number along the transect route is plotted in Fig. 12, assigning the Richardson number greater than unity as red. This representation helps to differentiate the areas between stratified and non-stratified water column. From Fig. 12, it is clear that water column is vertically well-mixed in the Upper Laguna Madre, whereas it remained stratified near Oso Bay (time = ~4,000–8,200 s) and the mouth of Upper Laguna Madre (time = ~2,800–3,600 s). The high DO region is co-located with the well-mixed region in the Upper Laguna Madre. Interestingly, the water was hypoxic in the lower water column near the mouth of Oso Bay (Fig. 10) where the Richardson number was high in the upper water column (Fig. 12) in that area of the bay. This substantiates the hypothesis that highly aerated surface water may not mix with bottom water where the consumption of dissolved oxygen continued through respiration and decomposition of organic matter. Although the water did not become hypoxic at the lower depths where Richardson number was high (time = ~2,800–3,600 s), dissolved oxygen level was somewhat lower as compared to the upper region of the water column. The measured vertical profile of chlorophyll concentrations, total particle concentrations, and current structures along the transect route may further shed light in clarifying the processes controlling dissolved oxygen distribution in the bay, as discussed in the next paragraph.

The measured vertical profile of chlorophyll-a concentrations, an indirect measure of phytoplankton biomass, is shown in Fig. 13. The chlorophyll concentration was significantly higher in the upper Laguna Madre compared to the bay. The vertical profile of total particle concentrations was also higher in the upper Laguna Madre (Fig. 14). This suggests the presence of high amounts of biogenic particles around this region. Biogenic particles such as phytoplankton can produce DO through photosynthetic activities in the day light, and may be the one of the reasons for the presence of higher DO levels in this area. Also, the water column was not stratified around the upper Laguna Madre (Fig. 12) and so aerated surface water may also transfer DO into the lower levels of water column. One interesting point to notice from Figs. 11, 13, and 14 is that a salt wedge might move from the upper Laguna Madre towards the bottom of Oso Bay and carry high amount of particles. As particles traveled from upper Laguna Madre towards Oso Bay, they started to settle and high amount of particles were found in the lower depths around the mouth of the Oso Bay (shown in Fig. 14) where low DO concentrations were also observed. The decomposition of dead biogenic particles may exert oxygen demand in the lower level of water column. Also, a density-stratified water column at the mouth of Oso Bay might prevent high-aerated surface water to mix with low DO water and thereby, induce a hypoxic condition at the bottom of the water column.

The observed vertical current structure along the transect route can shed light on the hydrodynamic condition of the water column which will further assist in greater understanding of the processes causing hypoxia in the bay. Figure 15 displays observed water current vectors along the transect route of the cruise at successive depths

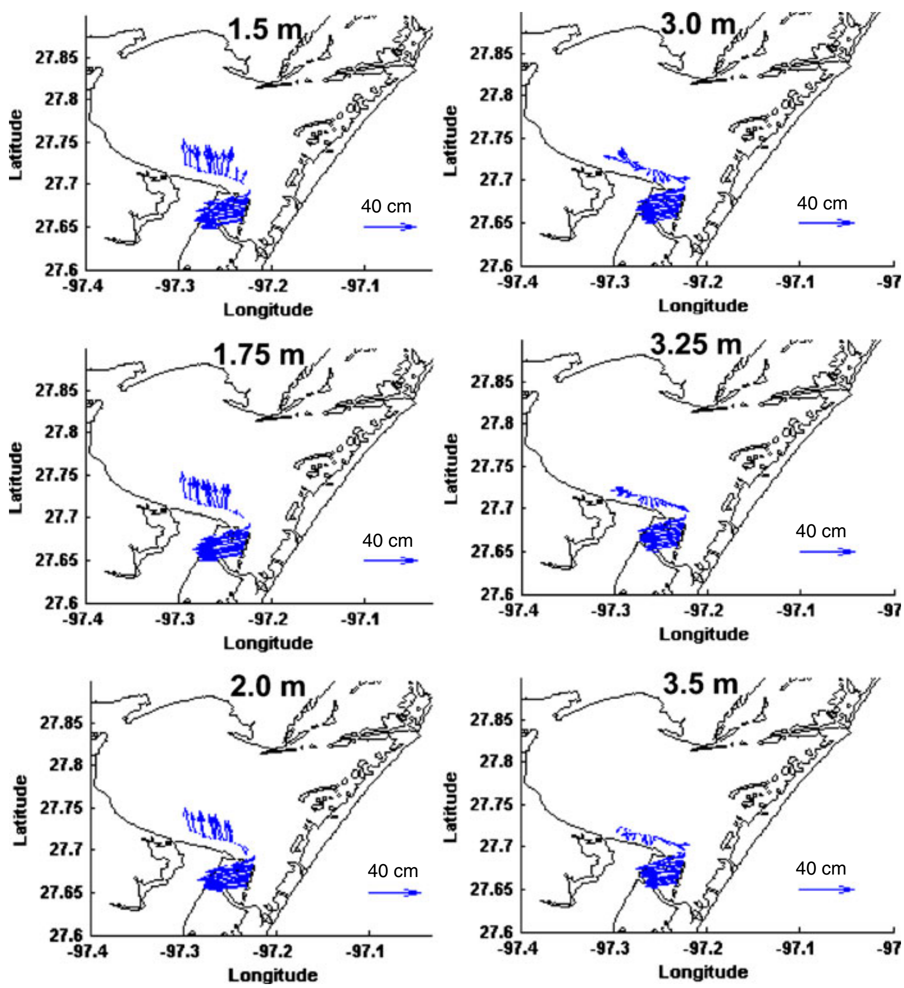

Fig. 15 Water current maps along the transect route of the cruise made on August 07, 2007 at successive depths of 1.5, 1.75, 2.0, 3.0, 3.25 and 3.5 m, respectively (from *top left* to *bottom right*) (*arrows* scaled by current vector magnitude (cm/s))

of 1.5, 1.75, 2.0, 3.0, 3.25, and 3.5 m, respectively (from top left to bottom right). It is evident from this figure that water currents in the Upper Laguna Madre flow at the same direction in different levels of water column, whereas water moves at reverse directions at the top and bottom levels of water column in the bay portion of the transect. Interestingly, comparisons between Figs. 11 and 15 reveal that the water flow is unidirectional when the water column is not salinity-stratified, whereas the water currents travel in opposite directions above and below the level of stratification. This suggests that hydrodynamics of the water column may be controlled by gravity flow, i.e., denser water travel along the bottom of the water column whereas fresher water moves along the surface level. However, the direction of the bottom water current as shown in Fig. 15 does not follow the direction of the longitudinal salinity gradient and so hydrodynamics of the bay are not primarily controlled by the gravity flow. The tidal and wind forces also may significantly influence water current pattern in this shallow bay. The tidal elevation data collected at NOAA's tidal gauge stations (location of stations shown in Fig. 1) suggests that high tidal condition existed during our cruise time period in August 07 (data plot not presented here). This might push dense saline water at the Upper Laguna Madre towards south. However, under low tide conditions, this dense saline water may move from the Upper Laguna Madre towards the bay. This low tide condition in addition with persistent winds from the south–east direction may move dense saline water from the Upper Laguna Madre towards the bay, and contribute to water column stratification at the southeast part of the bay. The assimilation of measured water currents with the hydrodynamic model will assist in greater understanding of the circulation pattern of the bay and thereby, shed more light on the critical processes causing hypoxia in the bay.

The datasets presented here from two cruises provide evidence of the capability of our mobile monitoring system in capturing episodic events such as the occurrence of hypoxia and the inverse estuary condition in the bay. Also, this system measures critical datasets that assist in clarifying the key processes controlling these events.

Conclusions

The mobile monitoring system developed in this study is able to measure hydrodynamic and water quality parameters at high spatial resolution. The real-time display capability of the system provides guidance in transect route selection to capture the event of interest. Data presented in this paper illustrates the capability of this system in measuring various parameters which help to clarify processes inducing an inverse estuary condition at the mouth of the ship channel and hypoxia at the bottom of the southeast part of the bay. The inflow of high dense saline water from the shallow upper Laguna Madre and the movement of water in the ship channel towards the Gulf of Mexico created the inverse estuary situation. On the other hand, water becomes hypoxic due to the stratified water column which prevents vertical mixing and the existence of high amount of biogenic particles that exert oxygen demand on the lower water column during decomposition. This high amount of biogenic particles might travel with the salt wedge, which moves from the upper Laguna Madre towards the mouth of the Oso Bay and settle at the bottom. The data collected from the mobile platform also shed light on the water current profile in the southeast part of bay. Water travels in opposite directions above and below the level of stratification. The assimilation of these measured water currents with the hydrodynamic model will further assist in greater understanding of the circulation pattern of the bay. In addition, the development of quantitative relationships between acoustic backscatter intensity measured by the ADCP and particle concentration measured by the particle sizer using other measured parameters will facilitate better understanding of particle dynamics of the bay that can significantly affect hypoxia through the transport of the particulate BOD in/out of the bay. The development of these kinds of quantitative relationships is the subject of our future research.

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