Environ Monit Assess
DOI 10.1007/s10661-010-1316-8

Integrated real-time monitoring system to investigate the hypoxia in a shallow wind-driven bay

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Received: 6 August 2009 / Accepted: 15 January 2010

Abstract Corpus Christi Bay (Texas, USA) is a shallow wind-driven bay which experiences hypoxia (dissolved oxygen < 2 mg/L) during the summer. Since this bay is a very dynamic system, the processes that control the hypoxia can last on the order of hours to days. Monitoring systems installed on a single type of platform cannot fully capture these processes at the spatial and temporal scales of interest. Therefore, we have integrated monitoring systems installed on three different platform types: (1) fixed robotic, (2) mobile, and (3) remote. On the fixed robotic platform, an automated profiler system vertically moves a suite of water quality measuring sensors within the water column for continuous measurements. An integrated data acquisition, communication and control system has been configured on our mobile platform (research vessel) for synchronized measurements of hydrodynamic and water quality parameters at greater spatial resolution. In addition, a high-frequency radar system has been installed on remote platforms to generate surface current maps for the bay. With our integrated system, we were able to capture evidence of a hypoxic event in summer 2007; moreover, we detected low dissolved oxygen conditions in a part of the bay with no previously reported history of hypoxia.

Keywords Monitoring systems · Sensors · Hypoxia · Stratification · Corpus Christi Bay

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Introduction

Corpus Christi Bay in the state of Texas in the USA harbors the nation's seventh largest port and a large complex of petroleum facilities. In 1992, the National Estuary Program designated Corpus Christi (CC) Bay as a National Estuary and created the Corpus Christi Bay National Estuary Program to protect the health of this bay while supporting its economic growth. This shallow bay has an average depth of 3.6 m (Ward 1997) and is connected to the Gulf of Mexico through two narrow inlets. Therefore, the hydrodynamic conditions of the bay are primarily wind-driven as

Published online: 04 February 2010

opposed to tidally dominated. However, this dynamic bay routinely experiences hypoxia, which can be described as the condition of the water column when dissolved oxygen (DO) levels dip below 2 mg/L. Most aerobic aquatic organisms cannot survive under this condition (Rabalais et al. 1996). Hypoxia was first observed in the southeast portion of CC Bay in summer 1988 (Montagna and Kalke 1992) and has been reported to reoccur every year thereafter (Ritter and Montagna 1999).

Factors such as eutrophication, water column stratification, geomorphology of the bay, meteorology, etc. may contribute to the development of hypoxia (Buzzelli et al. 2002). Ritter et al. (2005) concluded that eutrophication is not the likely cause for hypoxia in CC Bay since over the past 14 years, freshwater inflow rates into the bay have decreased and nutrient levels have not changed significantly. Although water column stratification is a possible cause for hypoxia, CC Bay would not be considered a likely candidate for stratification because it is a shallow wind-driven bay with an expected high level of mixing. However, stratification does occur, and this phenomenon has been observed in other shallow bays such as Mobile Bay in Alabama (Turner et al. 1987) and Pamlico River estuary in North Carolina (Stanley and Nixon 1992) where oxygen-depleted waters were found at the bottom of the bays during low-wind conditions. Ritter and Montagna (2001) observed hypoxic events in CC Bay usually at night or early morning, which typically lasted on the order of hours. The understanding of these transitory hypoxic events in this energetic system requires the development of real-time monitoring systems that can measure water quality and hydrodynamic and meteorological parameters at greater spatial and temporal resolution. This information can then assist in clarifying the key processes that induce hypoxia 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 this bay. With recent advances in technology, real-time measurements of various water quality parameters are possible through the use of submersible in situ sensors (Agrawal and Pottsmith 2000; Boss et al. 2002; Visbeck and Fischer 1995). The advantage of in situ sensors is that the parameter of interest can be measured in real time, thereby omitting the time gap between sample collection and data analysis. This real-time high-resolution data can expedite decision making in the case of emergency responses. The in situ sensors can be installed on fixed platforms for continuous environmental and oceanographic measurements. Although real-time data collected from in situ sensors on fixed platforms provide information at a high temporal resolution, the spatial resolution is limited. 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). These data, however, will have limited temporal resolution. The technical advances in remote sensing help to capture physical and biological variability in the upper layer of the water column at greater temporal and spatial resolution, but have not succeeded yet in capturing the chemical species and subsurface condition of the water column (Glenn et al. 2000). Therefore, it is optimum to deploy monitoring systems on different platform types and develop an integrated sampling scheme to better capture the dynamics of CC Bay.

The advances in communication technology, relational database management system, and World Wide Web applications provide an opportunity to access the data from various systems in real time and thereby help to develop an integrated adaptive sampling scheme for monitoring systems in capturing the events of interest. The research objective for this paper was to develop a cyberinfrastructure which will support real-time data acquisition, storage, visualization, management, and dissemination for the greater understanding of hypoxic events in CC Bay, as well as other episodic events. Once developed, it helps to implement a coordinated sampling scheme for our monitoring systems in capturing an episodic event. We have developed and installed different monitoring systems on three different types of platform. A robotic profiler system installed on a fixed robotic platform can measure vertical variation of various water quality parameters at high temporal resolution. Other sensors installed on the fixed robotic platform are an acoustic Doppler current profiler (ADCP) to measure current structure of the water column and meteorological sensors to determine wind speed and direction, atmospheric pressure, and air temperature. A monitoring system configured on a mobile platform (i.e., research vessel) can measure variation of various water quality parameters "synchronically" over a highly resolved horizontal and vertical regime. Besides collecting data at greater spatial resolution, this system is capable of displaying data in real time and thereby providing guidance on transect route selection during a research cruise. In addition to these two types of in situ monitoring systems, two high-frequency (HF) radar units were installed on remote platforms to generate surface current maps for the bay (Trujillo et al. 2004; Ojo and Bonner 2002; Ojo et al. 2007). The development of the robotic profiler system and the mobile monitoring system are discussed in detail in Islam (2009). These three monitoring platform types (i.e., fixed robotic, mobile, and remote) have been integrated, and the successful implementation of this integrated system to capture the extent and timing of a hypoxic event in CC Bay is described in this paper.

Site description

Corpus Christi Bay is located on the Texas coastline and covers an area of approximately 432.9 km^2 (Flint 1985). It is connected with the Gulf of Mexico through a narrow ship channel (15-m depth) which runs from east to west (Fig. 1). Freshwater enters the 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. 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 mainly dominated by southeasterly winds, although northerly winds occur periodically during the winter months. Figure 1 shows characteristic features of the bay. The three solid red circles denote the strategic locations of our fixed robotic platforms in the bay. 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

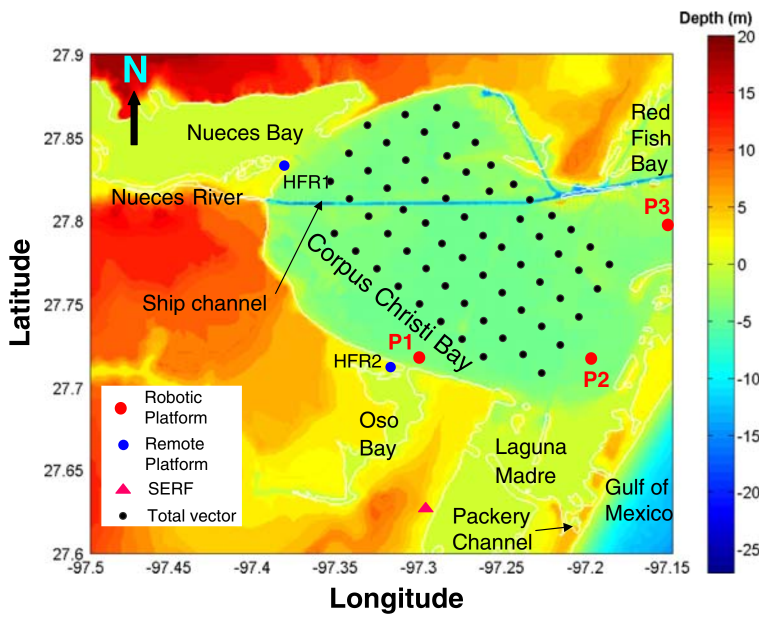


Fig. 1 Features of the study area and platform locations

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 data collected from this platform provide the necessary boundary conditions for simulation of our three-dimensional mechanistic model to predict the DO distribution in the bay (Islam et al. 2008).

Along with the fixed robotic platforms, we have installed HF radar systems on remote platforms which are shown as blue circles in Fig. 1. They are located on the CC Bay shoreline (HFR1, 27°49.92′ N, 97°22.80′ W and HFR2, 27°42.84′ N, 97°19.26′ W). The radial current vectors measured by HF radar system at sites (HFR1 and HFR2) are combined on regular grids (black solid circles in Fig. 1) to generate hourly surface current maps for the bay. Moreover, our research facility (Shoreline Environmental Research Facility, SERF) is located close to the Upper Laguna Madre and provides convenient field support for the regular monitoring of the bay (shown as magenta-colored solid triangle in Fig. 1).

Materials and methods

Monitoring platforms

The robotic profiler system, installed on each fixed robotic platform, moves the sensor suite from mean low-water level to the bottom of the bay over a 2.5-min time period and measures water quality parameters at five equidistant depth levels. The cycle time of profiling is currently set for 1 h, but it can be set to any user-defined interval. Between cycles, it pulls the instrument suite and keeps it in a stationary position above the water column. The instruments currently deployed on this profiler are a particle sizer (LISST 100X, by Sequoia Sciences), a DO sensor (Optode, by Aanderaa), a conductivity, temperature, and depth (CTD) sensor (SBE 37 SIP, by Sea-Bird Electronics, Inc.), and a fluorometer (Eco-FL3, by WETLabs). Along with these water quality sensors, an upward-looking 1,200-KHz acoustic Doppler current profiler (Workhorse Monitor ADCP, by Teledyne RDI) and a meteorological sensor (Wind Monitor-MA 05106 by RM Young Inc.) are installed on each fixed robotic platform. The ADCP is configured to measure a vertical current profile every 5 min where each profile is measured from an ensemble of 45 pings, and the time between pings is 1 s. In addition to water currents, the ADCP can also measure acoustic backscatter intensity, waves, and other hydrographic information.

The mobile monitoring platform contains the similar suite of instruments as those installed on the robotic profiler system. In addition, a global positioning system is used to georeference the synchronized measurements of water quality and hydrodynamic parameters. This system acquires and visualizes data measured by submersible sensors on an undulating tow-body (Acrobat LTV-50HB, Sea Sciences Inc.) deployed behind the research vessel. 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 this sensor suite, 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 amount of data to capture a significant change in vertical gradient of the measured parameters. All instruments are pre- and post-calibrated for each research cruise, and the data collected from the mobile platform are screened to remove outliers before performing any kind of post-data analysis. MATLAB® toolboxes have been used for the post-processing of observed data.

The HF radar system at each remote platform generates radial vectors where the transmitting antenna sends out radio waves which are scattered off from the ocean surface. The return of these sea echo signals has been captured by the receiving antenna and processed to determine the range, bearing, and radial velocity of the ocean surface toward/away from it (Barrick et al. 1977; Barrick and Lipa 1999). All radial vectors are collected and processed at our Corpus Christi base station (SERF, Fig. 1) using manufacturer (CODAR

Ocean Sensors, Inc.) software to generate hourly surface current maps on a regular grid.

Three robotic profiling platforms deployed at CC Bay takes around 4–5 months, which includes the time for engineering design, fabrication, pre-deployment tests, and actual deployment. The major expenses involved for a robotic profiling platform are profiler and communication systems development (approximately 60,000 USD), sensors (approximately 80,000 USD), and labor (approximately 30,000 USD). The operation and maintenance (O&M) costs associated with each robotic profiler platform per year is around 50,000 USD. On the other hand, mobile platform built mostly with off-the-shelf components was tested and deployed in approximately 3 months. This system costs around 30,000 USD for tow body, 85,000 USD for sensors, and approximately 25,000 for labor. The current O&M costs per year for this system are around 40,000 USD without considering the expenses associated with the boat maintenance and operations. We are planning to implement common design features in future versions of our mobile and fixed robotic platform which will help to lower both capital and O&M costs. The capital costs for our pair of remote platforms in CC Bay is approximately 190,000 USD (pair of HF radar systems are around 150,000 USD, supporting infrastructure for two platforms is approximately 25,000 USD, and labor is approximately 15,000 USD), and O&M costs per year is around 30,000 USD. Two of our remote platforms were installed in CC Bay within a month.

All measurements from our monitoring systems are stored in a relational database system (Microsoft Structured Query Language, SQL server 2000) and are retrieved using a MATLAB® database toolbox for post-processing. These data are shown on our web server in real time and are checked daily by a research staff member to ensure data quality. If any anomaly in the dataset is noticed, then those data are analyzed to determine whether it arises from a sensor defect or from a change in the actual bay conditions. Sensor or other technical malfunctions may require a platform service trip, whereas changes in bay conditions may serve as a prompt for a research cruise (e.g., mobile platform deployment) to further investigate the phenomenon. All sensors on each profiler are pre- and post-calibrated before and after deployment.

Description of the developed cyberinfrastructure

Measurements of water quality and meteorological and hydrodynamic parameters through in situ sensors at our fixed robotic platforms and HF radar units at our remote platforms need to be made available to stakeholders (i.e., public, scientific community, resource managers and planners, etc.) in near real time for taking the full advantage of these deployed sensors. We have developed cyberinfrastructure which can be described as a computing and communications technology infrastructure system to acquire and publish those data in real time. Figure 2 presents the schematic diagram of our cyberinfrastructure system. The data flow and various components of this diagram are described as follows.

All water quality sensors on the robotic profiler system are serially connected with the WINCUBE (i.e., PC/104 computer platform standard; customized and ruggedized in our labs) which acquires data from these sensors through the data acquisition software developed in this study. The manufacturer-supplied software for the meteorological sensors and the ADCP has also been installed on the WINCUBE to collect data. The collected data are stored in a temporary folder on the WINCUBE prior to being telemetried to our base station, SERF. A wireless data transceiver (FGR-115RE, Freewave Technologies, Inc.) with directional antenna has been installed at each fixed robotic platform for establishing radio links to the shore-based network. Since wireless (radio) links are subject to distance limitations, intermediate radio relay stations have also been established for the data telemetry to SERF. The wireless data transceiver with omnidirectional antenna at SERF receives data from our fixed robotic platforms. Corpus Christi Bay radar sites (HFR1 and HFR2, Fig. 1) communicate with SERF through DSL and radio relay. Radial vectors collected from HF radar sites are processed in the "total vector processing server" to generate total vectors. The surface current map generated from this server is then imported to the data aggregation

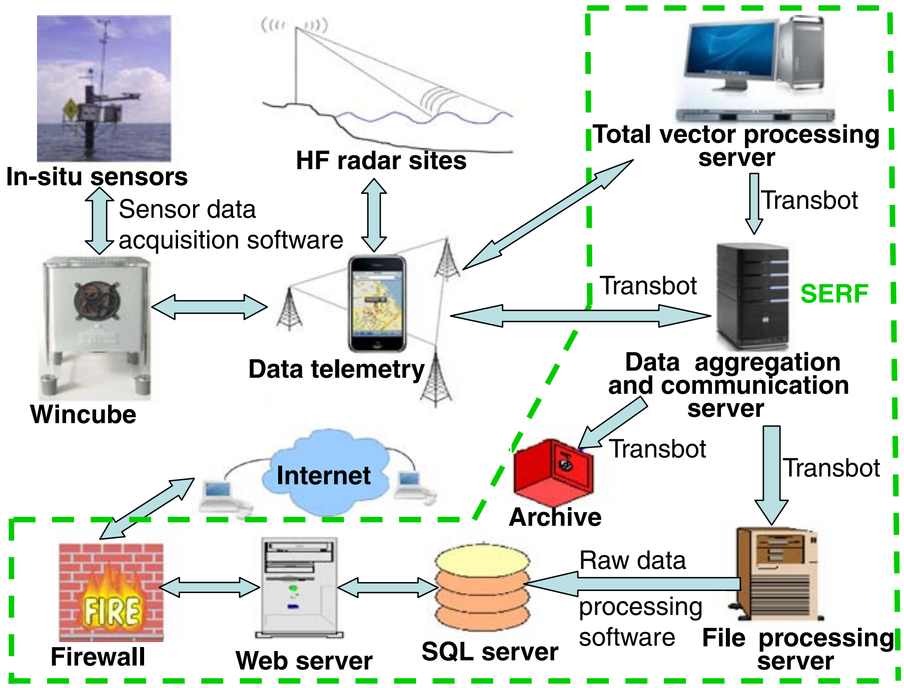


Fig. 2 Schematic diagram of the developed cyberinfrastructure

and communication server. We have developed a program (named "Transbot") which is installed on this server for the scheduled transfer and archival of real-time data from an arbitrary number of remote stations (fixed robotic platforms, total vector processing server) to a file processing server. While originally conceived to gather environmental data from a variety of remote sites, Transbot is transparent and generic, i.e., it is capable of managing any arbitrary data stream. It is configured through plain text configuration files, making administration separate from programming maintenance. Once all data are in the file processing server, they are processed for the conversion into meaningful units and are then standardized for the insertion into the relational database which manages this myriad of water quality and hydrodynamic and meteorological datasets. The web server at SERF hosts the web services through which researchers, educators, policymakers, natural resource managers, and the general public can get data in real time. We have developed and installed the software on our web server through which requested data are queried into our SQL database and then converted into the XML format to facilitate the sharing of structured data on the web.

Results and discussion

The monitoring system on each fixed robotic platform provides continuous measurements of water quality parameters and current structure of the water column at a given spatial location, while the HF radar system on remote platforms continuously measures the surface currents for the bay. In addition, the monitoring system installed on the mobile platform provides a temporal snapshot of the water column condition for the larger spatial portion of the bay. These systems have been integrated in this study to capture the extent and timing of a hypoxic event in CC Bay. Any unusual (i.e., non-baseline) measurements from a fixed robotic platform can alert our research group regarding a potential "critical" condition of the water column and trigger the demand for further investigation. The departure from baseline conditions is first investigated to ensure whether this variation is due to changes in water column conditions or sensor malfunctions. Sensor synergy studies such as comparisons of water temperature measured by three different sensors (particle sizer, DO, and CTD sensors) at the same level of measurements can be performed to detect sensor malfunctions. In addition, data from similar sensors at different platforms can also be used to exploit spatiotemporal correlations inherent in environmental processes which will allow differentiation between a sensor malfunction and a change in environmental conditions (Hill and Minsker 2010). When we conclude that the unusual measurements are not due to sensor malfunctions, we then further investigate/analyze the observed data (e.g., dissolved oxygen level, density gradient, surface current map and current structure of the water column, etc.). If water column conditions appear favorable for hypoxia or have already turned hypoxic, then a mobile platform deployment is warranted for further investigation.

With this integrated real-time monitoring system, we were able to detect and investigate the extent of hypoxia in CC Bay in summer 2007. Our findings included hypoxic conditions in a new region of the bay which had not been reported previously for hypoxia. The following paragraphs illustrate the success of our integrated system in capturing the hypoxic event at greater spatial and temporal resolution.

Investigation of a hypoxic event (July 22–25, 2007)

In situ sensors installed on our three fixed robotic platforms can provide baseline observations for CC Bay throughout the year. The following figures (Figs. 3, 4, 5, 6, 7, 8, 9, and 10) provide examples for some of the water quality and hydrodynamic information available during summer 2007. A snapshot in time (July 22–25) illustrates the capability of our fixed robotic platform monitoring system to alert researchers as to a potentially critical condition of the water column, thus allowing us to potentially capture an episodic event (such as hypoxia). In each of the figures associated with our fixed robotic platforms, the data points are color-coded to indicate the range of the measurements at five water depths. The wavy blue line at the top of these figures represents the actual water surface elevation at the fixed robotic platforms. The temporal variation of several water quality and hydrodynamic parameters is shown starting at 0000 hours on July 22 through 2400 hours on July 25.

In Fig. 3, the color-coded lines indicate the salinity variation at five different depths at platform P3. There existed a significant salinity gradient (salinity difference over 2-m depth, $\Delta S > 4$ psu) between the first and fifth level of measurement on July 22 to mid-day of July 23 (x-axis, 0.00–1.60 days), whereas this gradient is typically low ($\Delta S < 2$ psu) most of the year. This is an example of the type of unusual (non-baseline) measurement which alerts our research group and requires further investigation for a clarification of this anomaly. We then analyze all water quality and hydrodynamic information collected at our fixed robotic platforms and remote platforms. Park et al. (2007) observed significant correlation between hypoxic conditions and the bottom surface salinity gradient. They found that 65–78% of their collected dissolved oxygen data at the bottom of shallow Mobile Bay remained below 2 mg/L when the salinity gradient (over 2.5-m depth) was >4 psu. The observed data from the profiler at platform P3 showed high dissolved oxygen concentrations (~8 mg/L, data plot not presented) at all levels of measurements above 1 m from the seabed, though it is possible that dissolved oxygen levels dropped below 2 mg/L closer to the bottom. Salinity and vertical current

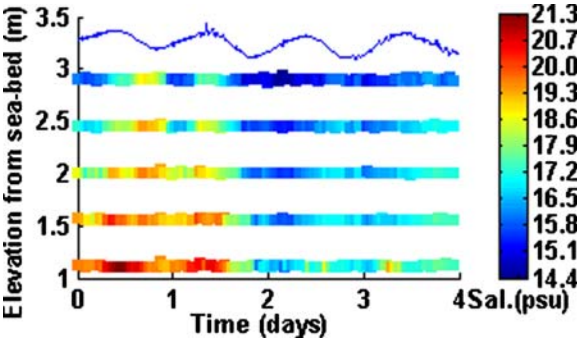


Fig. 3 Vertical variation of salinity at platform P3 during July 22–25, 2007 (*square*, salinity data points; *solid line*, water surface elevation)

profile measured at the fixed robotic platforms together with the surface current maps generated by the HF radar system shed light on the condition of the water column and thereby helped evaluate the status of hypoxia in the bay. The analysis of these measured parameters is discussed in detail in the following paragraphs.

Stratification created by the salinity gradient can suppress the vertical mixing of oxygen-rich surface water with the low-DO bottom waters, whereas the vertical shear produced from the velocity gradient can enhance the mixing. The salinity and water current structure provides the necessary information to determine the relative importance of the mechanisms in controlling the vertical mixing and thereby help to infer the dissolved oxygen condition in the bay. The salinity profile on July 22–25, 2007 at platform P2 is shown in Fig. 4. It should be noted that the profiler mechanism was not operating properly during this time frame; as such, the data measurement collection did not occur at five equidistant depths which is our preferred mode of operations. Nevertheless, the data are insightful for assessing the potential for hypoxia during this time frame. Salinity levels at platform P2 were higher at all measurement depths compared to levels at platform P3 (Fig. 3) during the July 22 to mid-day of July 23 time frame (x-axis, 0.00–1.60 days). This may be due to the inflow of high-saline water from the shallow Oso Bay and the Upper Laguna Madre which is one of

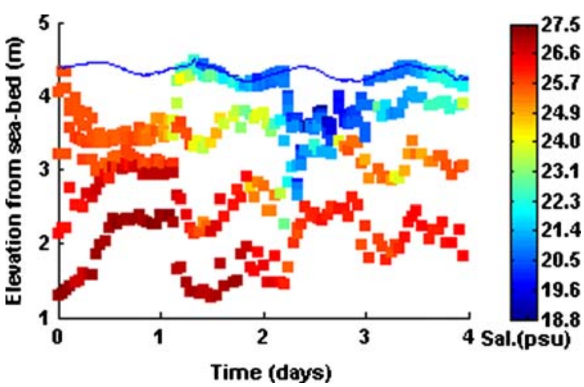


Fig. 4 Vertical salinity variation at platform P2 during July 22–25, 2007 (*square*, salinity data points; *solid line*, water surface elevation)

the most hypersaline lagoons in the world (Gunter 1967). In addition, precipitation data collected from the National Weather Service station at Port Aransas (just north of P3) indicate that significant rainfall occurred during July 17–20 and July 23, 2007, and thereby, it may contribute to lower salinity level around our platform P3. Under this condition, the water circulation pattern may be controlled by gravity flow, i.e., denser saline water moves toward platform P3 through the bottom, whereas fresher water moves along the surface toward platform P2. The vertical salinity profile shown in Fig. 4 supports this hypothesis as there existed a significant salinity gradient ($\Delta S > 8$ psu) at platform P2 on July 24 (x-axis, 2.25–2.75 days), whereas the salinity level was low at all depths at platform P3 during this time.

The HF radar system on our remote platforms can shed more light on the bay's hydrodynamic conditions as it determines surface water current velocities by analyzing the backscattering of radar pulses from the moving ocean surface (Barrick et al. 1977). If the bay is calm, this system is not able to capture this information. The surface current maps generated by the HF radar system are presented in Fig. 5 at successive days from July 21 to July 24. During much of this time frame, the water remained calm as inferred from low values of surface current and data gaps (particularly in the eastern portion of the bay). On July 22, the HF radar system captured the clockwise circulation pattern, i.e., water moved at the surface from platform P3 to platform P2 and this further substantiates our hypothesis of the gravity flow. Our HF radar system generated only one hourly surface current map from 2300 hours on July 22 to 0900 hours on July 23 due to the calm condition of the bay. The same condition occurred from 2200 hours July 23 to 0600 hours July 24. Therefore, the circulation maps at midnight (0000 hours) are missing for July 23 and July 24 from the set of surface current maps presented here. If the less saline water overlays the more saline water and the bay is calm, the water column then may be stratified and the oxygen-rich surface water may not mix with less oxygenated water at the bottom. This may induce hypoxia at the bottom of the bay. The quantitative analysis of measured water current and density will assist in

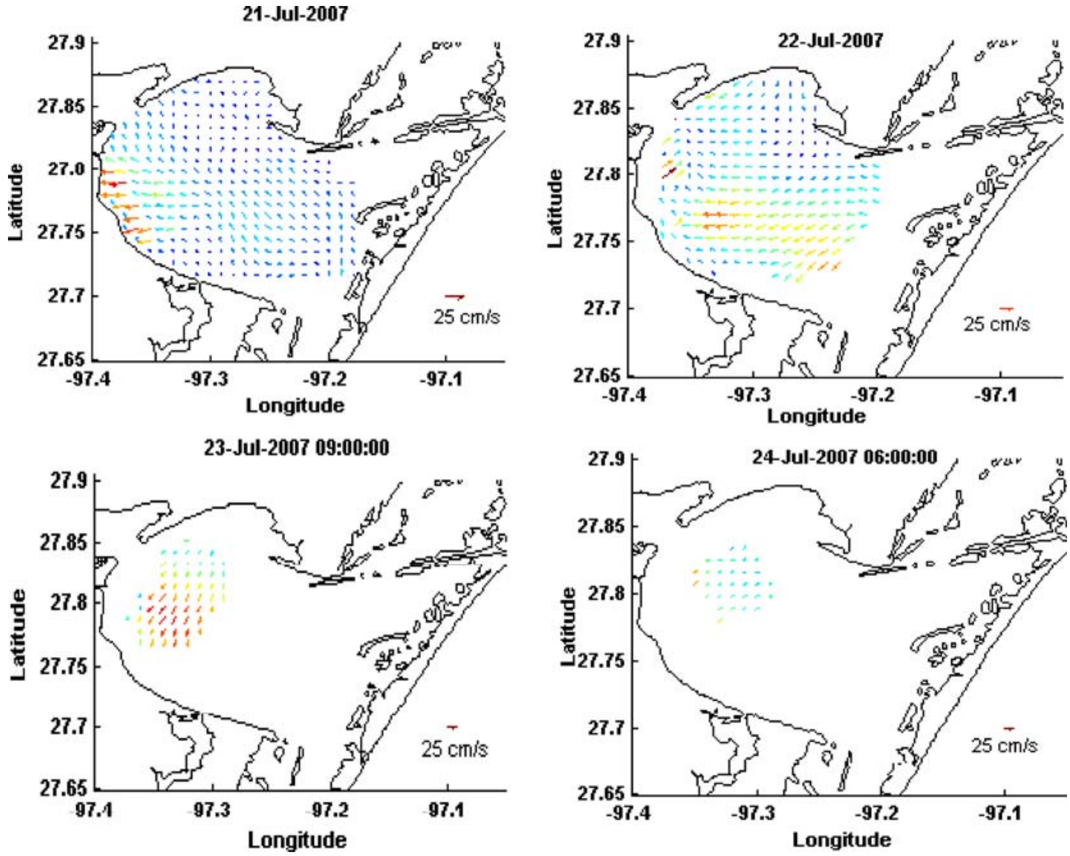


Fig. 5 Surface current maps of CC Bay as captured by our HF radar system at successive days from July 21 to July 24, 2007 (*top left* to *bottom right*). *Colored arrow* is scaled by color magnitude (cm/s): *red–blue* (*large–small*)

understanding the stratification condition of the water column which might create hypoxia at the bottom of the bay.

The kinetic energy generated from the vertical shear structure indicates the mixing potential of the water column. The shear rate (S) can be calculated using Eq. 1:

$$S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 \quad (1)$$

The east–west (u) and north–south (v) velocity components used in this equation are measured by the ADCP at the fixed robotic platforms. This velocity information is post-processed to calculate the shear rate. Figure 6 shows the vertical variation of shear rate at platform P2 on July 22–25. There was not a significant amount of shear to mix the water column except at the later part of the day on July 23, 2007 (x-axis, 1.4–2.0 days). On the other hand, the amount of work required to mix density stratified water column can be determined through the quantification of the buoyancy

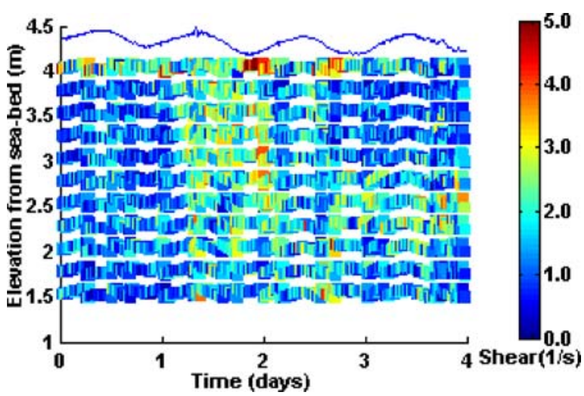


Fig. 6 Vertical variation of shear at platform P2 during July 22–25, 2007 (*square*, shear magnitude (1/s) data points; *solid line*, water surface elevation)

frequency (N) which can be described by the following Eq. 2:

$$N^2 = -\frac{g}{\rho}\frac{d\rho}{dz} \tag{2}$$

where ρ is water density, g is gravity acceleration, and z is the depth from the water surface. The vertical density profile captured by our CTD sensor is post-processed to determine N. Figure 7 displays the vertical variation of buoyancy frequency at platform P2 on July 22–25, 2007. The buoyancy frequency was high from the morning to the end of the day on July 24, 2007 (x-axis, 2.3–3.0 days). Therefore, the amount of work required to mix the water column is high and so the water column may remain stratified if the shear is not high enough to mix this column.

The gradient Richardson number (Ri), the ratio of the above calculated buoyancy frequency and shear rate, is used as an indicator of the stability of the stratified water column. Mathematically, this number can be defined by Eq. 3:

$$Ri = \frac{N^2}{S^2} \tag{3}$$

Miles (1961) and Howard (1961) have demonstrated that $Ri > 0.25$ is a sufficient condition 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 $Ri > 1$ (Abarbanel et al.

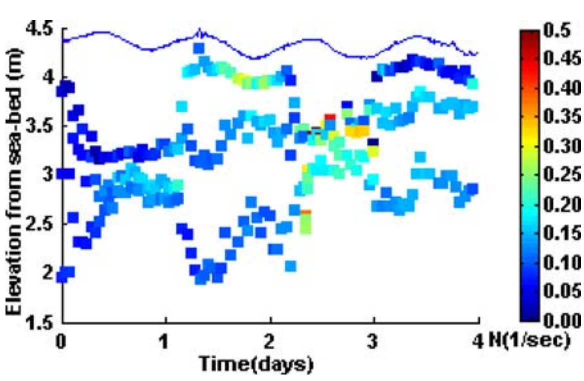


Fig. 7 Vertical variation of buoyancy frequency at platform P2 during July 22–25, 2007 (*square*, buoyancy data points (1/s); *solid line*, water surface elevation)

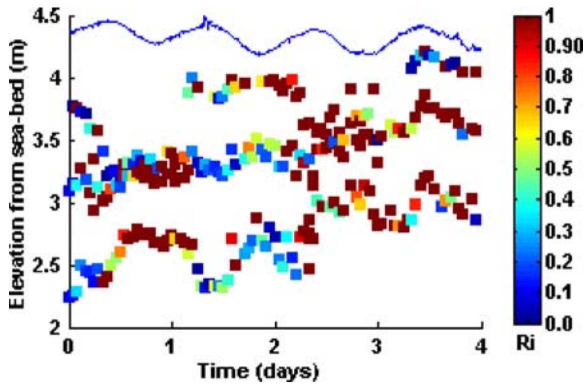


Fig. 8 Vertical Richardson number (Ri) variation at platform P2 during July 22–25, 2007 (*square*, Richardson number; *solid line*, water surface elevation)

1984). The vertical variation of the Richardson number at platform P2 is plotted in color code in Fig. 8, assigning the Richardson number greater than unity as red. It can be seen from this figure that the water column was stratified from midday July 22 to early morning of July 23 (x-axis, 0.6–1.2 days) and became restratified again from the early morning of July 24 (x-axis, ~2.15 days). Therefore, the water column at the bottom of the bay may turn hypoxic if this condition prevails. The observed vertical dissolved oxygen profile at platform P2 (Fig. 9) does not indicate any hypoxic condition above 2 m from the seabed at that time frame. However, the dissolved oxygen level close to the bottom (0–1.0 m) could be hypoxic

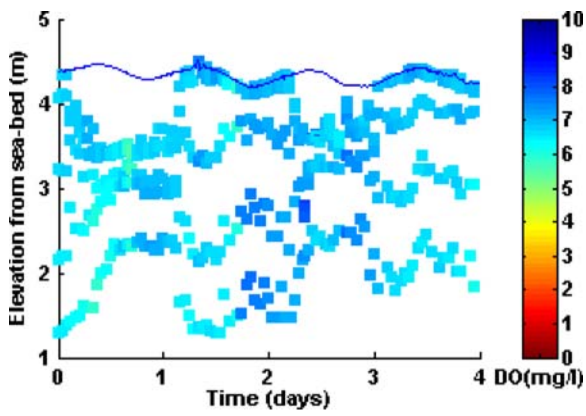


Fig. 9 Vertical dissolved oxygen (DO) variation at platform P2 during July 22–25, 2007 (*square*, DO data points (mg/L); *solid line*, water surface elevation)

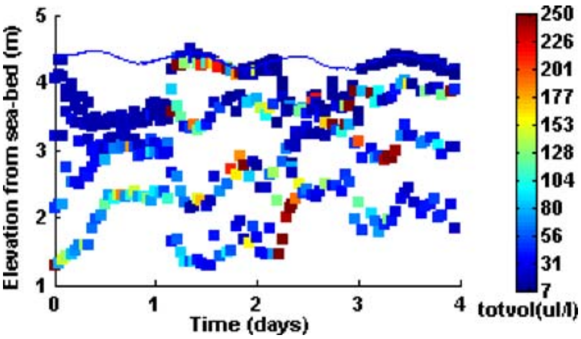


Fig. 10 Vertical variation of particle concentration at platform P2 during July 22–25, 2007 (*square*, total particle concentration (μl/L); *solid line*, water surface elevation)

depending on the duration of the stratified conditions and the presence of the amounts of organic matter at the bottom. The fluorosensor deployed on the profiler determines the chlorophyll concentration which is a measure of phytoplankton biomass available in the water column. This sensor detected insignificant amounts of chlorophyll (Chl. a < 5 μg/L, data plot not presented here) in the water column and so phytoplankton would not produce noticeable changes in the dissolved oxygen condition in the water column through photosynthesis. However, the particle sizer on the robotic profiler system at platform P2 detected a noticeable amount of particles in the water column (Fig. 10). In the figure, "totvol" represents the amount of total particle concentration. These particles include silt, clay, sand and biogenic particles, etc. If the concentration of dead biogenic particles is significant, they may potentially reduce DO levels in the water column through consuming oxygen during decomposition. We collected water samples at several bay locations in the month of July 2007 and found that the biochemical oxygen demand (BOD) was significant (5–7.5 mg/L) in the Upper Laguna Madre and around our platform P2, whereas BOD was undetectable (<2 mg/L) in other portions (e.g., near the mouth of Oso Bay (P1), near platform P3, etc.) of the bay (Islam et al. 2008). This suggests the presence of oxygen consuming particles in the water column near platform P2. Since the fixed robotic platform data (Figs. 3, 4, 5, 6, 7, 8, 9, and 10) suggest the possibility of low DO water at the bay bottom, it was deemed necessary to collect samples at greater spatial resolution (both vertical and horizontal directions) to determine the extent of the DO levels in the hypoxia-prone regions of CC Bay. As such, the mobile platform was deployed.

The mobile platform (research vessel and tow body with sensor suite) was deployed on the morning of July 24, 2007. The real-time display of relative concentration of measured parameters guided the cruise transect direction to capture the extent of hypoxia, if indeed it was occurring. Data results are presented as color-coded scatter points in Figs. 11, 12, 13, 14, 15, 16, and 17, and the

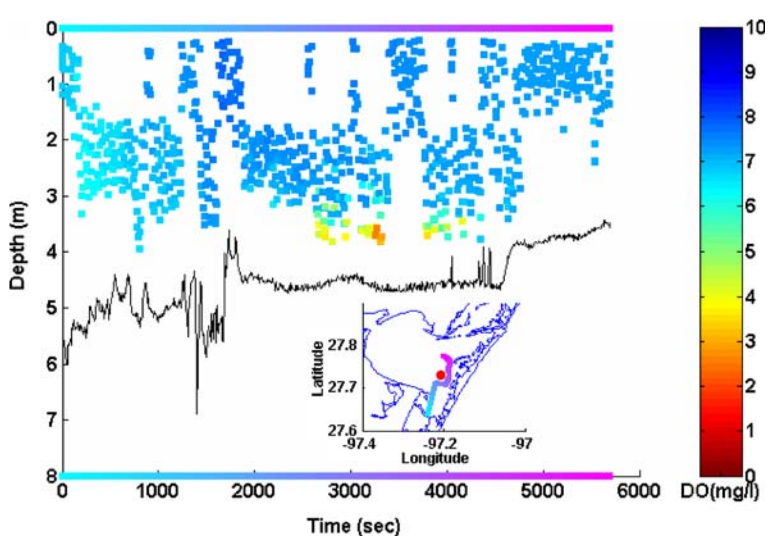


Fig. 11 Scatter plot of actual DO variation along the first transect route on July 24, 2007 (*square*, DO data points (mg/L); *circle*, platform P2 location; *solid line*, seabed profile)

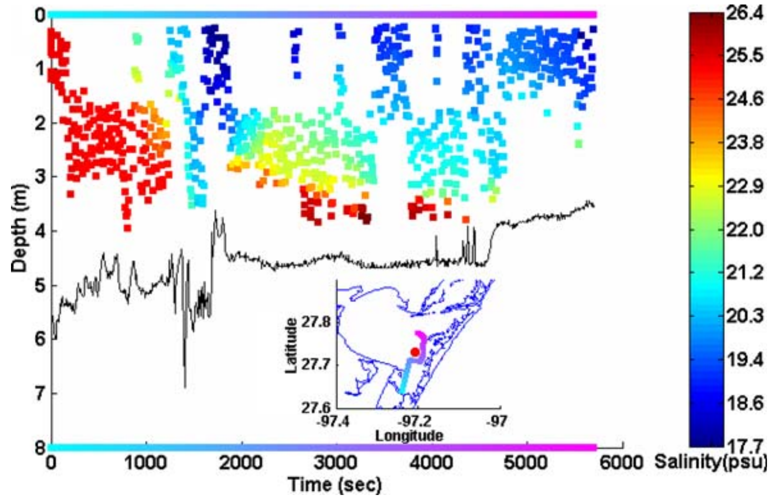


Fig. 12 Scatter plot of actual salinity variation along the first transect route on July 24, 2007 (*square*, salinity data points (psu); *circle*, platform P2 location; *solid line*, seabed profile)

actual cruise route is depicted on the inset plots in each figure. The route line is color-coded and correlates with the horizontal color coding along the top and bottom of each figure, thus matching the observed data with the location of measurements in the bay. The black solid line in each of these figures represents the seabed profile along the transect route. The first transect began in the Upper Laguna Madre and headed north toward platform P2 where a sharp salinity gradient and favorable hypoxic conditions had been detected by our fixed robotic platform systems (Fig. 4).

Figure 11 presents the vertical dissolved oxygen variation during our first transect. The red solid circle on the inset shows the location of platform P2. Unfortunately, there were ongoing field activities by a commercial seismic company in the proximity of our platform, and the crew had posted warning signs requesting no interruption of their activities. Therefore, we towed our instrument array away from our platform in the depth range of 0–2 m (*x*-axis: $t = \sim 3{,}500$–$3{,}800$ s). Once we moved out of the area, we began towing again in the full depth range of the monitoring

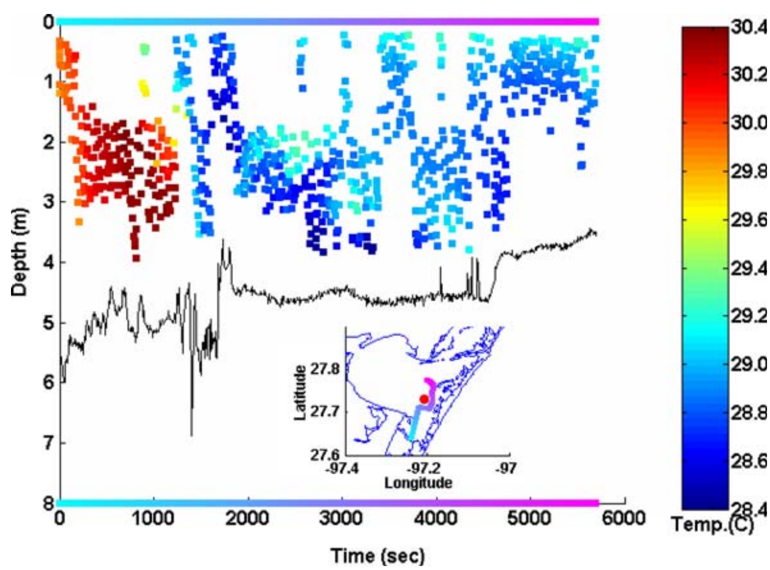


Fig. 13 Scatter plot of actual temperature variation along the first transect route on July 24, 2007 (*square*, temperature data points (°C); *circle*, platform P2 location; *solid line*, seabed profile)

system (near-surface levels to approximately 1 m above the bay bottom to avoid impact). Dissolved oxygen levels at the bottom of the water column around platform P2 were low (x-axis: t = 2,800–4,000 s). Ritter and Montagna (1999) observed hypoxia at the lower depths of this region in previous years.

Figure 12 displays the vertical variation of salinity along the same transect route. Salinity levels at all depths were higher at the Upper Laguna Madre (early part of the cruise, t = 0–1,300 s) as compared to salinity levels in CC Bay (mid and latter parts of the cruise, t = 1,300–5,800 s). The temperature profile (Fig. 13) varied in a similar pattern along the travel route. It may be hypothesized from these temperature and salinity profiles that a salt wedge might move from the shallow Upper Laguna Madre toward the platform P2 area and induce a significant vertical salinity gradient around this platform. The salinity level in the shallow Laguna Madre (average depth $<$ 1 m) is generally very high at summer due to the high evaporation rate and low freshwater inflow (Texas Department of Water Resources 1983). If the salinity-stratified water column is not able to vertically mix, low DO conditions may occur at the bottom of the bay. The current profile can shed light on the vertical mixing condition along the transect route. However, due to higher cruise speeds (~6 kt) and calm bay conditions, the water current profile data (measured by the ADCP on the mobile platform) were not reliable on that day and so could not be used to infer vertical mixing condition of the water column.

The vertical variation of chlorophyll along the transect route is presented in Fig. 14. The chlorophyll concentration, an indirect measure of phytoplankton biomass, was much higher in the Upper Laguna Madre compared to the bay area. As the water column was vertically well mixed in the Upper Laguna Madre (Fig. 12), large amount of phytoplankton produced in the euphotic zone could travel below that level and so chlorophyll concentrations were high at all depths of the water column of the Upper Laguna Madre. On the other hand, total particle (organic and inorganic) concentrations (represented by "totvol" in Fig. 15) did not change significantly along the transect route except in the region near platform P2 where the low dissolved oxygen conditions were observed (Fig. 11). The increase in particle concentrations in the lower depths around the platform area (t = 2,800–3,800 s) may be due to the increase of dead non-fluorescing biogenic particles as chlorophyll concentrations did not change and remained very low (2–4 ug/L, Fig. 14). This high amount of non-fluorescing particles resulted from the decomposition of organic particulate that comes from the Upper Laguna Madre and trapped at the lower level of stratified water

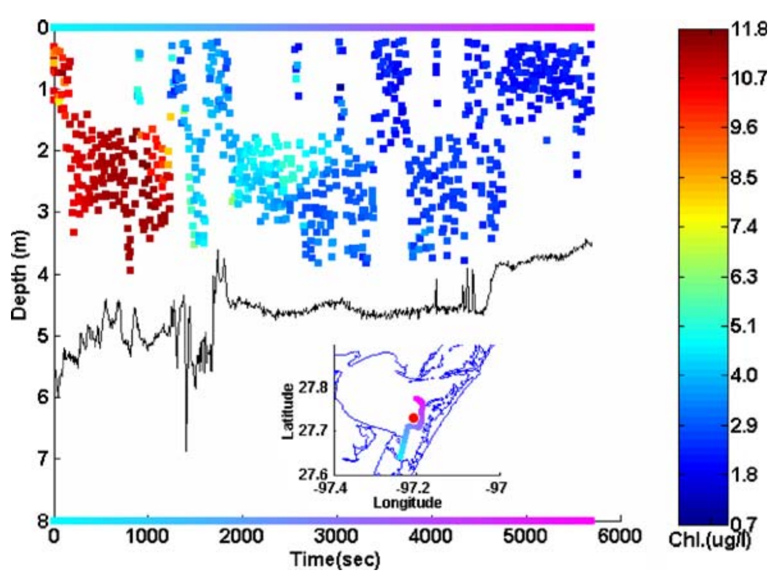


Fig. 14 Scatter plot of actual chlorophyll (*Chl. a*) variation along the first transect route on July 24, 2007 (*square*, chlorophyll (*Chl. a*) concentration (μg/L); *circle*, platform P2 location; *solid line*, seabed profile)

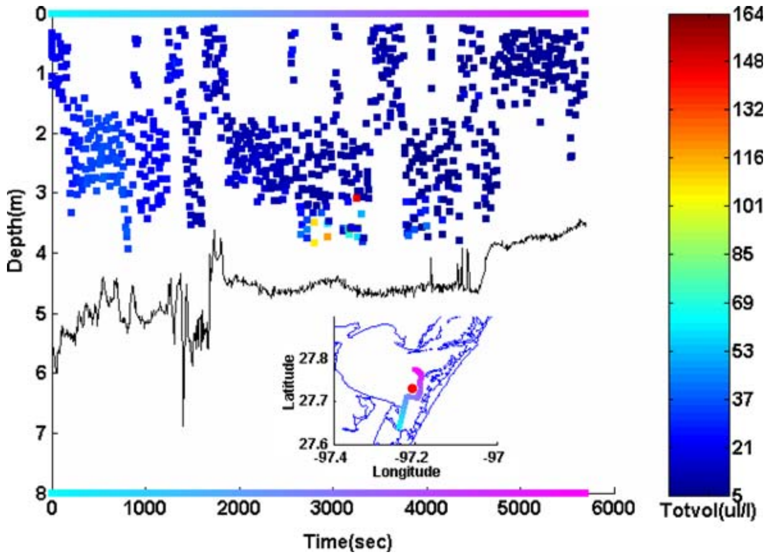


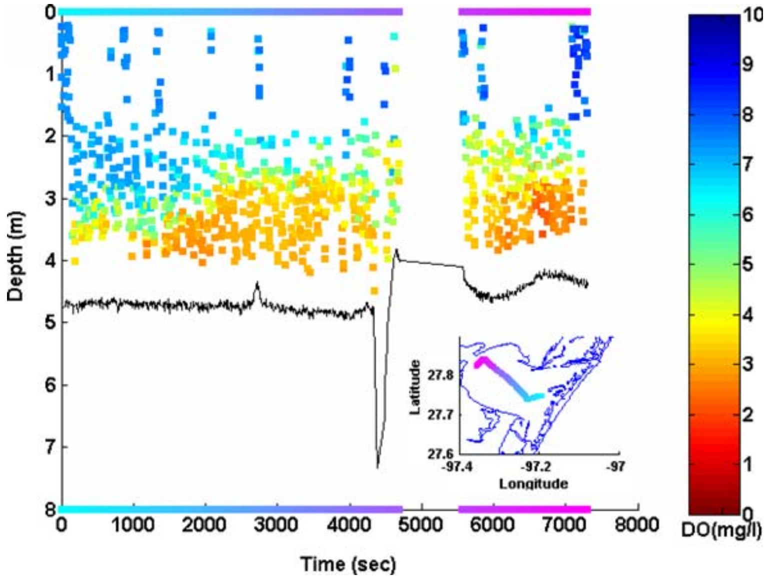
Fig. 15 Scatter plot of actual particle concentration variation along the first transect route on July 24, 2007 (*square*, total particle concentration (μl/L); *circle*, platform P2 location; *solid line*, seabed profile)

column. Since there was a fairly sharp salinity gradient at the lower depths near platform P2, the denser bottom water column may not have mixed with the less dense, more aerated waters in the upper water column. If the water column cannot vertically mix, oxygen levels at the bottom of the bay may be further reduced due to the decomposition of these biogenic particulate matters which exert oxygen demand in the water column. In contrast, the higher oxygen levels in the Upper Laguna Madre may be due to the unstratified water column and the presence of relatively high levels of phytoplankton and sea grasses that produce oxygen through photosynthesis. These speculative statements are examples of possible explanations which can be hypothesized and tested when large datasets such as those provided by our integrated monitoring system are available. Ultimately, this information can shed light into the understanding of environmental processes associated with hypoxia and other phenomena.

A primary objective of this study was to determine the extent of hypoxia, and this was achieved through the selection of a relevant transect route, as guided by our mobile monitoring system. The observed data from the profiler at platform P3 showed high dissolved oxygen concentrations (~8 mg/L, data plot not presented) and uniform salinity levels (Fig. 3, *x*-axis: t = ~2 days) at all depths of measurement. Therefore, we completed our first transect after we had completely traversed the pocket of hypoxic waters near platform P2. At that point, we changed our direction of travel and headed southwest toward Oso Bay where hypoxia had been observed previously (Hodges et al. 2009). However, as we moved toward Oso Bay, we noticed a low DO gradient in the other direction (i.e., northwest direction toward Nueces Bay). We then followed that direction and surprisingly found another pocket of low dissolved oxygen levels at the mouth of Nueces Bay which had no previously reported history of hypoxia.

Vertical variation of dissolved oxygen concentration and salinity along our second transect route are shown in Figs. 16 and 17, respectively. It should be noted that at two points during this transect, we had to pull our instruments onto the boat deck and stop collecting data due to the sudden gradient in seabed levels and a bottom hit by the tow body. The first brief gap in the dataset (t = ~4,500 s) occurred when we crossed the ship channel and the tow body was not capable of undulating in a sharp seabed gradient; the second gap (t = 4,800–5,500 s) occurred when the tow body hit the seabed. Dissolved oxygen levels were very low in the lower water column (3- to 4-m depths) along the entire second transect route, and surprisingly, hypoxic conditions were observed at the mouth of Nueces Bay (t =

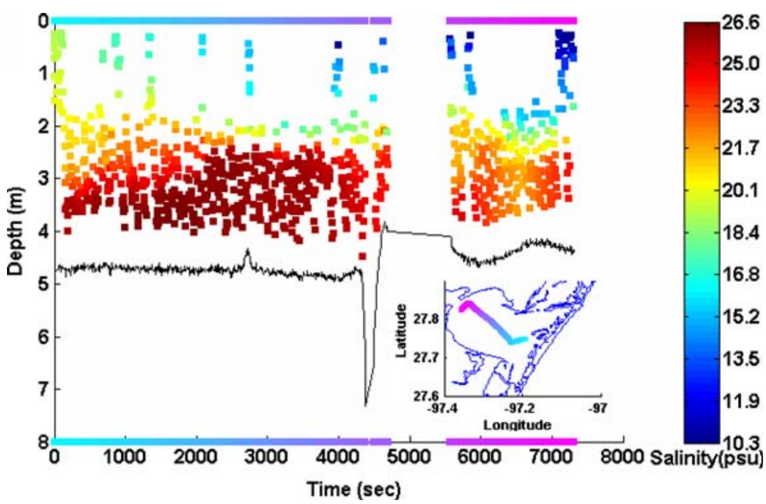
Fig. 16 Scatter plot of actual DO variation along the second transect route on July 24, 2007 (*square*, DO data points (mg/L); *solid line*, seabed profile)



~7,000 s, Fig. 16). This was not expected as previous researchers found oxygen-deficient conditions only in the southeast parts of the bay (Montagna and Kalke 1992; Ritter and Montagna 1999). Therefore, our integrated systems helped us to explore the extent of a hypoxic event in summer 2007.

The salinity profile also shows two distinct water layers along the entire second transect route (Fig. 17). The top layer (0–2.5 m) was much less saline than the bottom layer (2.5- to 4.0-m depth). The water column was salinity-stratified due in part to the inflow of highly saline water from the Upper Laguna Madre and Oso Bay. Also, the inflow of freshwater from the Nueces River and Nueces Bay might have contributed to the induction of salinity stratification in the water column at this location in CC Bay. The precipitation data, recorded by the National Weather Service station at Corpus Christi Airport (approximately 10 km from the mouth of the Nueces Bay), indicated a significant rainfall event on July 23 which may have contributed to a large freshwater input into the upper waters of this bay. As proposed before, the denser bottom water layer may not mix with less dense, more aerated upper water layer,

Fig. 17 Scatter plot of actual salinity variation along the second transect route on July 24, 2007 (*square*, salinity data points (psu); *solid line*, seabed profile)



and so the dissolved oxygen levels may be reduced as respiration and decomposition of organic matter exerted oxygen consumption in the lower water depths. The detailed hydrodynamic information predicted by hydrodynamic models may shed more light on the actual physical processes contributing to stratified conditions of the water column (Islam 2009) and thereby can assist in predicting the extent and duration of hypoxic events in the bay. The other measured parameters (e.g., total particle volume, chlorophyll concentration, temperature) did not change significantly along this transect; therefore, no results are presented in this paper.

The processes that induce hypoxia at the mouth of Nueces Bay (a newly observed hypoxic region) need to be further investigated using observational datasets. As our mobile monitoring platform gives a spatial snapshot of hydrodynamic and water quality parameters, we propose to deploy an additional fixed robotic platform in the new observed hypoxic region (i.e., the mouth of Nueces Bay). The integration of this new platform with our existing monitoring platforms can provide crucial datasets to explore the dynamic processes inducing hypoxia in the bay. In addition, the present version of the profiler data acquisition software needs to be modified as it does not generate an alarm if there is any fault in profiler performance. At the current time, regular checking of the measured data with the visualization tools is the only way to ensure quality of the data and profiler performance. In the future, the current software will be extended so that it will alert us if it fails to collect data from different sensors or there is any problem in moving the sensor suite. In addition, the profiler data acquisition software will also have the provision to cross-check the depth readings from two different sensors (i.e., the particle sizer and CTD sensor) at a level of measurement and will alert us if any significant discrepancy exists between those readings. These modifications will assist in better control of profiler operation.

The integrated system discussed in this study can also be implemented in other aquatic systems for regular monitoring and characterizing episodic events dominant in those waterbodies. The available historical datasets of the target waterbody need to be analyzed to gaining insights regarding the processes controlling the dynamics of the aquatic system. A HF radar system can be deployed on remote platforms to generate surface current maps which will provide further insight about the circulation patterns of the waterbody. The knowledge inferred from these historical datasets and measured surface current data will then guide the researcher in selecting the initial deployment locations of the mobile platform. Hydrodynamic and water quality data captured by the mobile platform can be examined and also be used to simulate numerical models (Islam et al. 2008; Ojo et al. 2007) which will help to point out optimum locations for fixed robotic platform deployments. After initial deployment of monitoring platforms, observational datasets need to be analyzed for the development of an adaptive sampling scheme and reevaluation of the platform locations in measuring the environmental parameters that will help to understand the event of interest.

Conclusions

Monitoring of water quality parameters and environmental indicators that influence the physical processes of hypoxia and other episodic events poses a challenge due to the spatial extent and dynamics involved. Profiling systems installed on fixed robotic platforms can measure various parameters at greater temporal resolution but limited spatial resolution. A mobile monitoring platform can address the limitation of the spatial coverage but has limited temporal resolution. HF radar systems installed on remote platforms can generate continuous surface current maps for CC Bay. The integration of these monitoring systems can help in characterizing the various environmental processes at a multitude of spatial and temporal scales of interest. The development of cyberinfrastructure in this study helps to integrate these systems and makes data available in real time to stakeholders. The real-time availability of these data provides an opportunity to develop coordinated sampling schemes for capturing hypoxia or other episodic events in the bay. All data presented in this paper provide evidence of the potential capacity of our integrated systems to determine the extent and timing of hypoxia in CC Bay and help to better understand the processes that control hypoxic events in this ecosystem. The hypoxia occurs due to inflow of biogenic particulate matter from the Upper Laguna Madre which are trapped at the stratified water column and exert oxygen demand in the lower level of water column during decomposition.

With our integrated system, we were able to capture a hypoxic event in summer 2007 and found a new area of the bay with low dissolved oxygen conditions that had no previously reported history of hypoxia. This integrated system can also be used for regular monitoring of the water quality of the bay and thereby for characterizing/ monitoring other episodic events such as oil spills, harmful algal blooms, sediment resuspension events, etc. Data collected from these monitoring systems can be used to drive water quality and hydrodynamic models (Islam et al. 2008; Ojo et al. 2007; Islam et al. 2006) which are valuable resource tools for predicting water quality of the bay.

Acknowledgements Funding for this work was provided by the Texas General Land Office (Oil Spill Prevention and Response Division), the National Science Foundation (grant no. 0528847), and the Texas Water Research Institute. The authors would like to thank staff members of the Shoreline Environmental Research Facility (SERF), Corpus Christi, TX for their support in research cruises and maintenance of platforms.

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