ENVIRONMENTAL ENGINEERING SCIENCE
Volume 27, Number 5, 2010

DOI: 10.1089/ees.2010.0006

A Fixed Robotic Profiler System to Sense Real-Time Episodic Pulses in Corpus Christi Bay

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Received: January 7, 2010 *Accepted in revised form: March 10, 2010*

Abstract

Real-time observations of coastal environments are needed to capture episodic events that control aquatic ecosystem dynamics. The National Science Foundation established the Water and Environmental Research Systems Network to test various aspects of real-time observatory design and operation, and Corpus Christi Bay (TX) was selected as one of the Water and Environmental Research Systems test beds. Implementation of a real-time observation system faces challenges such as use of heterogeneous monitoring instrumentation, measurement of critical parameters at greater spatial and temporal resolution, reduction of sensor biofouling, reliable data acquisition and delivery, and data management. We developed a robotic profiler system that moves a suite of water quality sensors in the water column, collecting data at multiple depths. This system significantly reduces biofouling of the sensors and accommodates a diverse array of sensors that measure various environmental parameters. In addition, the associated cyberinfrastructure provides sensor data to stakeholders in real time and allows remote access to the fixed robotic platforms, which supports instrument management, data quality assurance and quality control, implementation of event-based sampling schemes, sensor troubleshooting, and so on. Moreover, it can process diverse data streams and reliably transfer measured data to the users. Two snapshots of observational data are presented in this article to illustrate the system capability in measuring parameters that can shed light on important processes controlling episodic events in the bay.

Key words: Robotic profiler system; cyberinfrastructure; Corpus Christi Bay; hypoxia; real-time monitoring system

Introduction

Coastal environments can be characterized as stochastic pulsed systems, where dynamics of these environments are dominated through episodic events and periodic processes. The temporal scale of coastal phenomena can vary from order of seconds to decades, as discussed in Carter (1998) and Steele (1995). Development of a sensor-based observation system offers long-term high-resolution measurements of critical environmental parameters (Isern and Clark, 2003), which provides insight regarding various phenomena controlling the dynamics of the coastal ecosystems and will assist in capturing events of interest. Moreover, recent advances in sensor technology in this decade provide an opportunity to collect data at high resolution with reasonable costs. The National Research Council (NRC) therefore recommends the development of a large-scale sensor-based observation system to address grand challenges in environmental science (NRC, 2001). The system can be used to collect data and to investigate questions related to global warming, infectious diseases, invasive species, pollution, land use, and other environmental issues. Prototype observing systems have been deployed in various parts of the United States, including Physical Oceanographic Real-Time System (PORTS; NOAA, 2010c), National Ecological Observatory Network (NEON, 2010), Global Lake Ecological Observatory Network (GLEON, 2010), Coral Reef Environmental Observatory Network (CREON, 2009), and Ocean Observatories Initiative (OOI; Consortium for Ocean Leadership, 2010).

The National Science Foundation has provided funding to establish the Water and Environmental Research Systems Network, to test various aspects of observatory design and operation at different test bed sites of the United States. This network will make available all data collected from various observatories and will help in investigating multiscale environmental phenomena (Montgomery *et al.*, 2007). Corpus Christi (CC) Bay, one of the test bed sites, is home of the

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nation's seventh largest port with numerous petrochemical facilities and various water quality issues (e.g., accidental oil spills, hypoxia, contaminant movement, harmful algal blooms, existence of high levels of bacteria, and sediment resuspension). Among these problems, recurring hypoxia (dissolved oxygen [DO]: <2 mg/L) has drawn national attention. Hypoxia in this shallow bay is not expected because of anticipated mixing of aerated surface water with low-DO water at the bottom of the bay. However, this condition occurs and can last in the order of hours to days (Ritter and Montagna, 2001). The development of a sensor-based monitoring system can assist in real-time measurements of water quality and hydrodynamic and meteorological parameters at high resolution and, thereby, aids in understanding the hypoxic and other episodic events that control CC Bay system dynamics.

With recent advances in technology, real-time measurements of water quality parameters are possible through the use of submersible *in situ* sensors (Visbeck and Fischer, 1995; Agrawal and Pottsmith, 2000; Boss *et al.*, 2002). *In situ* sensors allow the parameter of interest to be measured in real time, thereby omitting time gaps between sample collection and data analysis. Also, advances in communication technology, database management system, and computational power provide an opportunity to develop a cyberinfrastructure (CI) that can acquire data from various sensors and will make them available to stakeholders in real time. Implementing CI for environmental observatories is challenging because of use of heterogeneous instrumentation in environmental monitoring, complex data streams, unreliable communication networks, management of metadata, and so on. Moreover, sensor vendors have developed their own software to collect and process the raw data into meaningful units. So, accommodating this broad spectrum of sensors in observing systems requires the development of user-specified drivers to collect and process raw data. In addition, sensor systems are frequently deployed in remote, harsh environments, which contribute to unreliable network connections. Therefore, observation system design should allow for storing the data locally in the case of network failure and then transmitting the data to the base station when communication network is restored.

Long-term deployment of a sensor system on a fixed platform will not aid in capturing spatial variations involved in a dynamic system such as CC Bay. However, understanding the vertical gradient in hydrodynamic and water quality parameter variation in the bay is important in characterizing some episodic events such as hypoxia. For example, if the vertical salinity gradient is pronounced and the water column is stratified, oxygen levels at the bottom of the bay will be reduced because of insufficient mixing with aerated surface water. Also, long-term deployment of sensors at fixed platforms is subject to biofouling, which can seriously deteriorate sensor conditions and data quality. Therefore, a monitoring system needs to be developed that can measure the vertical variation of parameters at greater temporal resolution and can reduce biofouling of sensors.

Various researchers have been trying to develop an efficient vertical profiling system for the continuous measurements of various parameters in the deep and shallow waters. Purcell *et al.* (1997) successfully deployed vertical profilers in the coastal observatory, LEO-15, but faced challenges in long-term deployment of the profiler system when the sensors biofouled within a week. Also, measured data were not available to stakeholders in real time because of the lack of proper CI. The vertical profiler system developed by Honji *et al.* (1987) could only be used for deep-water applications, whereas the profiler system described in Luettich *et al.* (1993) was suitable only in the shallow areas of protected estuarine environments. As water quality parameters more often need to be monitored in the harsh unprotected environment, it is necessary to develop a robust ruggedized vertical profiler system for long-term autonomous monitoring of the aquatic system. Reynolds-Fleming *et al.* (2002) developed a portable autonomous vertical profiler using off-the-shelf parts with a minimal use of custom components. Their system was easily transportable and could be deployed in relatively unprotected areas. The biggest drawbacks of the system were that the sensor package payload hit against the platform and the sensors were quickly biofouled.

Commercial off-the-shelf vertical profiler systems are available, but typically these can only interface with their own sensor products. This seriously limits the use of profiler system in measuring parameters that were not resolved through their particular sensor products. Therefore, in this research study, a vertical profiler system was developed to interface heterogeneous instrumentation from different vendors, to reduce sensor biofouling, and is ruggedized and robust enough to be maintained in a harsh environment. This article describes the design, construction, test deployment, and evaluation of a vertical robotic profiler system that measures water quality parameters at multiple depths of the water column at high temporal resolution. This system was installed on several fixed platforms in CC Bay, and included sensors to measure hydrodynamic and meteorological parameters. In addition, CI was developed to collect data from platforms and to publish them on the web in real time. This CI also provides the framework to link our local observation network with the other sensor-based observational networks in the United States. The large datasets from our observational network can be used to drive numerical models (Islam *et al.*, 2008; Islam, 2009), which aid in understanding the processes controlling episodic events in the bay.

Study Area

CC Bay is located on the Texas coastline and covers an area of approximately 432.9 km^2 (Flint, 1985). Figure 1 shows characteristic features of the bay. It is connected to the Gulf of Mexico through a narrow ship channel ($\sim$15 m depth), which runs from east to west. 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 south-easterly winds, although northerly winds occur periodically during the winter months. Three fixed robotic platforms installed in the bay are shown as red solid circles in Fig. 1. 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

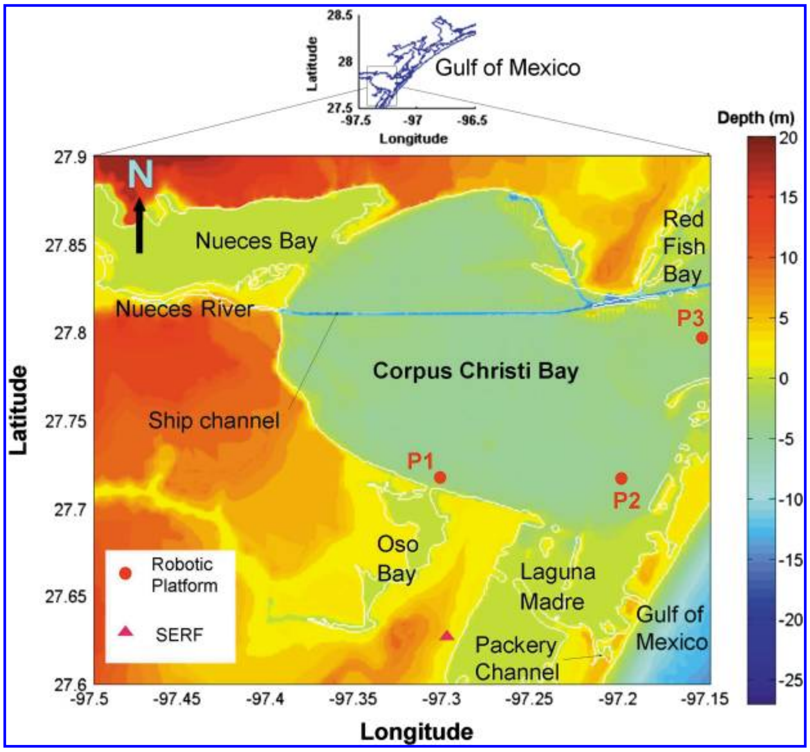

FIG. 1. Characteristic features of study area and platform locations.

positioned in the south-east 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 north-east part of the bay. The data collected from these platforms also provide necessary boundary conditions for the simulation of our three-dimensional mechanistic model to predict the DO distribution in the bay (Islam *et al.*, 2008). The magenta-colored solid triangle in the figure denotes the location of our research facility (Shoreline Environmental Research Facility, SERF) in CC, TX. SERF serves as a data aggregation point for all data collected from different platforms.

Robotic Profiler System (with Instrumentation Suite) on Fixed Platforms

A robotic profiler system has been designed in this study to measure vertical variation of various water quality parameters at a greater temporal resolution. This profiler system consists of four main parts: (a) the payload cage, which houses the instruments; (b) the profiler, which raises and lowers the payload; (c) the wincube (customized personal computer [PC]/104 computing module); and (d) CI, which makes measured data available to stakeholders in real time. Figure 2 shows the robotic profiler system at one of our fixed robotic platforms in the bay. The payload is suspended from the profiler by two cables, with a single power/data cable connecting the instruments. This single power/data cable is later diverted into data cable and power cable. The data cable is then serially linked with the wincube, whereas the power cable is connected with the 12 V battery fuse block, which is recharged through a wind turbine. The sensor suite currently includes a particle sizer (LISST-100X; Sequoia Sciences, Inc.), a DO sensor (Optode; Aanderaa), a conductivity, temperature, and depth (CTD) sensor (SBE 37 SIP "Microcat"; Sea-Bird Electronics, Inc.), and a fluorosensor (Eco-FL3; WET Labs Inc). The profiler is deployed off a tall pylon with an arm reaching over the side of the platform overlooking the water. Two suspension cables connect the payload to this arm, and an electric motor is responsible for winching the payload up and down. This motor is operated by an electronic controller

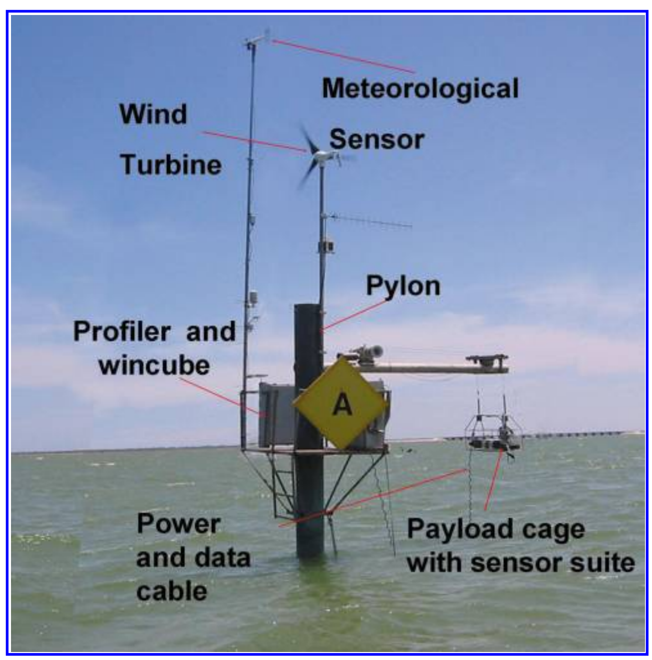

FIG. 2. Photograph of one of our fixed robotic profiler systems in the Corpus Christi Bay.

module, which in turn is operated by control software developed as part of our research effort. This software is installed in the wincube, which is a customized ruggedized PC/104 computing module. We have added multiport serial cards (Xtreme −8/104/RS-232; Connect Tech, Inc.) and 1.8 GB flash drive with this module. As PC/104 systems are small and have low power requirements, they have been used in various applications to meet the needs of an embedded system. Also, most of the development programs used in a PC can also be used in this system. The operating system of the wincube is WINDOWS 2000 server. Data collected from each sensor are written in text files and stored in a folder on the wincube for transfer to our shore-based research facility (SERF). A file transfer protocol server in a Microsoft Windows 2000 environment has been used to transfer data from the fixed robotic platforms to the data aggregation and communication server at SERF.

The control software operates the profiler and payload to provide vertical profiles of the water column by raising and lowering the payload into the water column and gathering measurements. This software is designed in such a way so that it first captures the reading from the fastest sensor and then sequentially records readings from the other sensors based on their stable response times. Prior to field deployment, laboratory experiments were performed to determine the response time for each sensor on the profiler, because various sensors require different amounts of time and differing numbers of measurements per sample to register a stable reading. For example, the LISST-100X particle sizer needs approximately 3 s to register a stable reading, whereas the DO sensor (Optode) requires 7 s. The CTD sensor (Microcat) and Flurosensor (ECO-FL3) have quicker response times, requiring approximately 1 and 2 s, respectively. The optimal sampling scheme for this robotic system was designed considering this information. Moreover, the control software is also flexible to handle an adaptive sampling scheme that facilitates the optimum use of real-time monitoring data. For example, the software can automatically adapt to a high sampling rate during storm event, which will help to characterize the stochastic processes due to this episodic event. Although these processes can be characterized through continuous measurements at high frequency using nonreal-time monitoring systems, it would be expensive and challenging because of the high volume of data, data management and postprocessing, operation and maintenance for data or device retrieval, data analysis, and excessive power requirements for measurements.

The current payload capability of our robotic system allows for four instruments, but can house additional sensors with minor modification. The control software is also designed in such a way so that it can accommodate future inclusion of more heterogeneous instruments with diverse data streams such as American Standard Code for Information Interchange (ASCII), binary, and image. It is configured through plain-text configuration files, making administration separate from programming maintenance. Along with the robotic profiling system, an upward-looking acoustic Doppler current profiler (Workhorse Monitor ADCP; Teledyne RD Instruments) has been installed at the base of each fixed platform to measure water column currents, and a meteorological sensor system (Windbird Monitor-MA 05106; RM Young, Inc.) is configured on the platform to measure wind speed and direction, wind gust, air temperature, and barometric pressure. An ADCP was placed in a weighted, trawl-resistant aluminum housing with a flat, 4-foot-diameter base, which was deployed at the sea-bed approximately 25 m away from the base of the platform and opposite side of the profiler arm. This prevents any hydraulic and acoustic interference from the platform that may disrupt ADCP performance because the divergence angle of acoustic beam is 20° from the vertical, and maximum depth of the water column around our platform can be around 5 m. Vendor software for these two sensors is customized to generate individual data files for the user-defined duration of measurements. As soon as these files are generated, they are stored in the temporary folder from where they are periodically pulled to the base station.

Power is the most critical factor for maintaining long-term autonomous monitoring system. The necessary power to maintain our fixed robotic platform is generated from the small wind turbine (AIR-X; Southwest Windpower, Inc.). It can generate 38 (kW h)/month at a wind speed of 12 mph. The entire robotic profiler system requires 21 W of continuous power and consumes an additional 6 W h of energy during each 4 m profile. Consequently, when performing one profile per hour, the system energy demand is 27 (W h)/h or 20 (kW h)/month. Biofouling is another important issue for the long-term deployment of sensors systems in the marine environment. Our robotic profiling system is designed to minimize sensor biofouling, which can significantly deteriorate sensor performance. As the profiler system keeps the sensor suite in a stationary position above the water surface between measurement cycles, this allows the sensors to dry through air contact and ultraviolet (UV) sunlight exposure. This significantly minimizes the growth of microorganisms on the sensor and therefore, the instrument duty cycle is longer. For our robotic sensor system, the instrument duty cycle is around 6 months. The control of biofouling through this method is more efficient compared with other available methods such as the use of copper-based materials, tributyl tin-based products, slowly dissolving chlorine (trichlorisocyanuric acid), underwater UV lights, and bromine tablets. Manov *et al.* (2003) has discussed the limitation of these methods in controlling biofouling of optical sensors. We have also tested many of these strategies and found that air drying and sunlight exposure (UV) worked the best. Moreover, the optical DO sensor installed on our profiler suite does not incur any damage from direct sunlight as the sensing foil of the optical sensor is equipped with a gas permeable coating, which provides optical isolation of the sensing element. We did not detect any deterioration in sensor performance during our routine quality assurance and quality control test of the sensor before and after the deployment cycle.

Description of the Developed CI

Measurements of water quality and hydrodynamic and meteorological parameters through *in situ* sensors at our fixed robotic platforms are made available to stakeholders (i.e., public, scientific community, resource managers and planners, etc.) in near real time using the developed CI in this study. The benefits of real-time availability of the measured data are many fold: for example, real-time water level and current information can assist in safe navigation of water vessels; real-time meteorological and hydrodynamic data are assimilated with various forecasting models, which are used in warning extreme events such as hurricanes and storm surges. Other applications of real-time data are search and rescue operations, oil spill trajectory predictions and clean up operations, prediction of harmful algal blooms, hypoxic conditions, and many other environmental problems that plague coastal regions.

The CI developed in this research work can be described as a computing and communications technology infrastructure system that can acquire and publish measured data in real time. Figure 3 presents the schematic diagram of the CI used to transfer data from the fixed robotic platforms to the user communities. Data collected at our robotic platforms through customized data acquisition and profiler control software are temporarily stored in the data logger (i.e., wincube). These data are then transmitted into the data aggregation and communication server at our base station in SERF through establishing communication link using various data telemetry techniques depending on the location of the platforms. Wireless data transceivers (FGR-115RE; Freewave Technologies, Inc.) with directional antenna have been installed at platform P1 and P3 for establishing radio links with platform P2 (Fig. 1). Also, wireless data transceiver with omnidirectional antenna has been installed at platform P2 for receiving signals from platforms P1 and P3. The other wireless data transceiver with directional antenna has been installed on platform P2 to relay data to an intermediate radio relay station. As wireless (radio) links are subject to distance limitations, intermediate radio relay stations have been established for the data telemetry to SERF. The wireless data transceiver with omnidirectional antenna at SERF is then connected with the data aggregation and communication server through which the administrator can control all geographically distributed platform sites. The remote control software (Real VNC; RealVNC Ltd.) has also been installed on the server to get access to the wincube at different platforms. This remote access will serve different purposes from instrument management to quality assurance of the data. It is expensive to visit the platform sites for troubleshooting instruments, detecting instrument failure, upgrading the data acquisition software, and so on. The remote access facilitates to reduce the number of such field visits and also provides opportunity to develop event-based sampling schemes for our robotic profiler system. During windy conditions, the wind turbine at the platforms can generate increased power levels and so our robotic profiler systems will not be limited by power constraints. We can then schedule to run robotic profiler control software at higher frequency to collect data at greater resolution and thereby to capture wind-dominated processes such as sediment resuspension events and turbulent mixing. This system has been applied to collect data at greater temporal resolution during oil-spill response studies in CC Bay using remotely configured adaptive sampling schemes.

We have developed a program (named "Transbot") that is installed on the data aggregation and communication server for the scheduled transfer and archival of real-time data from an arbitrary number of fixed robotic platform's data logger. Although originally conceived to gather environmental data from a variety of remote platforms, Transbot is also transparent and generic, that is, it is capable of managing any arbitrary data stream such as ASCII, binary, and image. It is configured through plain-text configuration files, making administration separate from programming maintenance. This software uses file transfer protocol to download data from the remote sensor sites. The software is also robust enough to control data transfer in the case of network failure. This ensures continuous operation of our robotic platforms in the case of communication loss with one or more platforms due to various reasons such as data-transceiver failure, disruptions in line-of-sight, or power failure. The data collected from each fixed robotic platform are then stored temporarily in the wincube and will be relayed to the data aggregation and communication server as soon as the network connectivity is restored.

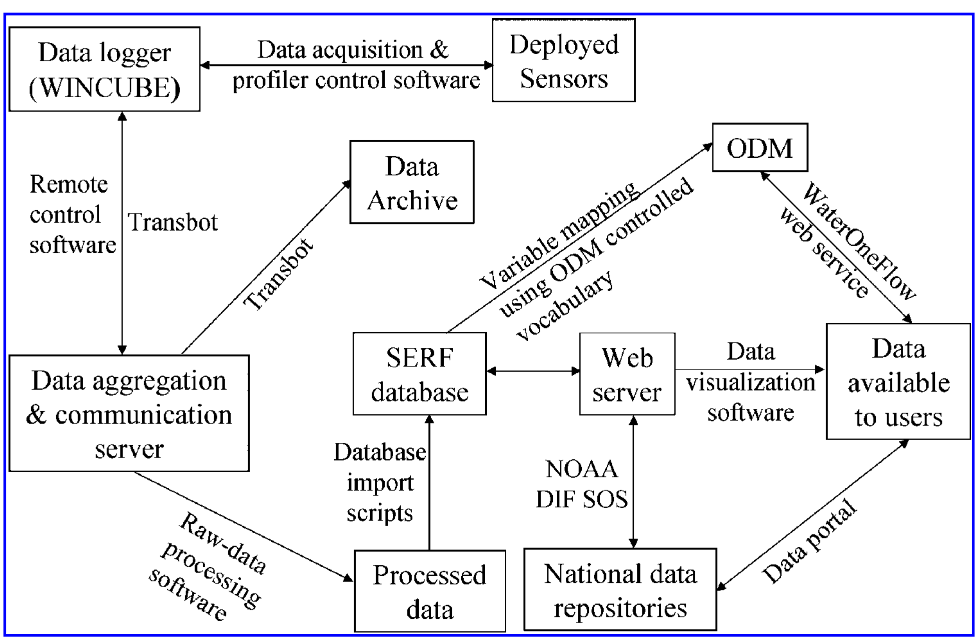

FIG. 3. Developed cyberinfrastructure for our fixed robotic profiler system.

Once data are transferred into the data aggregation and communication server, they are processed for conversion into meaningful units and are then standardized for insertion into the relational database system. These processed data are then imported into our relational SERF database through developed database import scripts. The management of diverse datasets into the relational database server provides long-term storage facility and also helps to determine the interrelated processes that contribute to the event of interest. The Microsoft database management system (Structured Query Language server 2005) has been selected as the relational database system to manage datasets collected from the platforms. The developed database schema in this study helps to store both point observations (i.e., sensor data collected at a point in space) and gridded observations (e.g., surface current maps captured by our high-frequency radar system) (Kelly *et al.*, 2003). In addition to measurement values, it stores metadata (i.e., ancillary information) related to sensor and the measured parameters. Sensor metadata such as sensor type and its serial number, model number, sensor-specific calibration coefficient, and location of specific sensor deployment assists in managing resources for various deployments at different platforms and for the conversion of sensor raw data into meaningful units. On the other hand, metadata related to measured parameters such as location of measurements, data-qualifying comments, analysis procedure, and type of sample medium (e.g., air, water) assist in unambiguous interpretation of measured datasets.

We have developed a data visualization software that queries into our observational database and draws contour plots of measured data for a specified time (e.g., the last 24 h, last 7 days, or last 30 days of measurement). These plots are populated in static web pages of our web server and are refreshed continuously. The real-time availability of measured datasets facilitates in performing quality assurance quality control tests. If any anomaly in the dataset is noticed, then those data are analyzed further to determine whether the anomaly arises from a sensor defect or from a change in the actual bay conditions. A platform service trip may be required to make the determination. If necessary, a faulty sensor can be replaced with a newly calibrated sensor and the original sensor is returned to the laboratory for postcalibration and diagnosis of the problem. All sensors on each profiler are calibrated before and after deployment.

Data collected from real-time monitoring systems should be disseminated to scientists, policy makers, educators, students, and the general public for the best use of it. Various government agencies are providing measured data online through their publication systems such as the United States Geological Survey's National Water Information System (http://waterdata.usgs.gove/nwis; USGS, 2010), the United States Environmental Protection Agency's Storage and Retrieval (STORET) system (www.epa.gov/storet; U.S. EPA, 2010), and the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (NCDC) (www.ncdc.noaa.gov/oa/ncdc.html; NOAA, 2010b). Also, measured data are published on websites from experimental watersheds such as Walnut Gulch (Nichols and Anson, 2008) and Reynolds Creek (Slaughter *et al.*, 2001). It becomes a challenge for the users to discover, access, and interpret data from these different sources as there exist syntactic and semantic heterogeneity in the data. The Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI), has developed a point observational data model (ODM) and adopted common controlled vocabulary to overcome these heterogeneities (Horsburgh *et al.*, 2008, 2009). Our developed database will be interfaced with the ODM using the controlled vocabulary listed by the CUAHSI and, thereby, will aid interoperability with other observational networks. Moreover, our database can handle gridded observations and sensor metadata, whereas ODM deals with only point observations and does not have the provision to record sensor metadata, which assists in management of the sensor resources. In addition, we will implement CUAHSI's WaterOneFlow web services (http://his.cuahsi.org/wofws.html; CUAHSI, 2010), which will make sensor data available to the users in real time. Through this web service, data requests from other organizations and observational networks will be queried into our developed database and then converted into the Extensible Markup Language format to facilitate the sharing of structured data on the web. Data collected from our monitoring platforms can also be shared with regional data centers and national data repositories by installing NOAA data integration framework Sensor Observation Services (SOS) (http://ioos.gov/dif; NOAA, 2010d) onto our web server. SOS will help to convert observation and sensor metadata into Extensible Markup Language format, which will be compatible with Integrated Ocean Observing System (IOOS) data management and communication standards and protocols. We will need to map our observational parameters with that of SOS supplied configuration parameters to avoid semantic differences. As we have processed raw sensor data through our developed software and also stored metadata into our developed database, no significant steps or postprocessing are required here to map parameters. A simple modification of SOS provided common gateway interface script, and registration of our observatory with national registries (www.obsregistry.org/map2009/index.php; NOAA, 2010a) will facilitate to discover and retrieve data from our database. This will provide general public access to data measured at our observatory and help researchers and scientists to analyze and understand various environmental phenomena that control the dynamics of CC Bay.

Results and Discussion

Along with meteorological sensors and ADCPs, our robotic profiler system is operational at three fixed robotic platforms in CC Bay for the continuous monitoring of hydrodynamic, meteorological, and water quality conditions. As a sampling scheme for regular monitoring of CC Bay, the robotic profiler system at each platform is set to hourly measure water quality data at five equidistant depth levels in the water column. This sampling scheme is designed to minimize power consumption, especially when wind conditions are very low. However, the sampling frequency can easily be increased depending on the availability of power. Our robotic profiler system is operational with minimum down time and with significant reduction in sensor biofouling. The reduction in biofouling increases the instrument duty cycle for our platform and saves resources on platform services. The instrument duty cycle for our robotic sensor systems is around 6 months. Normally, sensors are biofouled in the order of days or weeks in a productive system such as CC Bay and would require more frequent cleaning, calibration, and field visits to replace the biofouled sensors. In addition, our sturdy robotic profiler system prevents the sensor suite from striking the platform even under rough conditions and, therefore, can be deployed in an unprotected environment.

The reliable delivery of measured data from the platforms to the users is key to the successful implementation of a real-time monitoring system. The Transbot software developed in this research work is able to handle network failure, and therefore, platform monitoring activities are not disrupted because of this kind of failure. Data presented in Fig. 4 can be used to illustrate the robustness of our developed CI in reliable transfer of measured data from the platform to the data aggregation and communication server at SERF. This figure shows the time gaps between robotic profiler measurements and user availability of those measurements collected at platform P2 from January 1 to August 31, 2007. As the software, installed on the data aggregation and communication server, is set to import data from the fixed robotic platforms at 10 min intervals, data are normally available within 10 min of measurement. This is clear from the figure as time gap is close to zero (in terms of days, i.e., 10 min) during most of the 8-month time period. Each sudden spike represents the duration of a communication network failure during which measured data are not available. The subsequent reduction in the height of each spike illustrates the ability of our CI to reliably import the data as soon as the communication network is reestablished. As the robotic profiler system continues to operate during a period of network failure, the measured data are stored on the platform wincube. As soon as the network comes online again, these stored data are then imported into our database. Once all the stored data are imported, the time gap between measurements and data availability is reduced to the regular time interval (i.e., 10 min) at which Transbot is running on the data aggregation and communication server.

Two snapshots of observational data are presented here to illustrate the capability of our robotic profiler system in capturing various phenomena that will help to clarify the processes that can induce hypoxic conditions at the bottom of CC Bay. A significant vertical salinity gradient can be considered as a precursor to hypoxic events (Turner *et al.*, 1987). When this gradient is high and the vertical water current structure is weak, the denser, more saline bottom water cannot mix with fresher (less dense) water at the surface where DO levels are higher because of re-aeration. Because of lack of mixing, DO levels at the bottom decreases as respiration and other biological processes continue. The CTD sensor at our robotic profiling system can provide variation of this salinity gradient with time. In Fig. 5, the color-coded lines indicate the salinity variation at five different depths at platform P3 on July 23–25, 2007. There exists a significant salinity gradient (salinity difference over 2 m depth, $\Delta S > 4$ practical salinity unit) between the first and fifth level of measurements over time (0.00–1.60 days on x-axis), whereas this gradient is typically low (<2 practical salinity unit) most of the year. The solid blue line in this figure represents observed water surface elevation (WSE) variation, which was recorded by the pressure sensor installed on the ADCP. As this shallow bay is connected with the Gulf of Mexico through two narrow inlets (shown in Fig. 1), hydrodynamic conditions such as WSE are mainly dominated by wind forces, although minute changes in WSE may occur due to weak tidal forces. The significant change in WSE during a strong wind event (e.g., storm) may cause the water column to mix and reduce the vertical gradient in water quality parameters such as salinity and temperature. It is clear from the figure that our robot profiler system is able to successfully capture episodic events such as the occurrence of salinity-stratified water column in CC Bay during calm bay conditions.

The understanding of particle dynamics can also provide insight regarding DO distribution in the bay. The longer the oxygen-consuming particles (e.g., biochemical oxygen demand particulate) remain in the water column, the greater the oxygen demand they will exert on the aquatic ecosystem. The synchronous measurement of various parameters by the robotic profiler system assists in clarifying the processes controlling particle dynamics in the bay. A snapshot of the variation of some of these measured parameters near platform P1 on June 15, 2006 is presented in Fig. 6. The five color-coded depth levels of the measurements are presented in Fig. 6a. The corresponding concentrations for total particles, salinity, and DO at these depths are presented in Fig. 6b, c, and d, respectively. Data presented in Fig. 6b suggest that a sediment resuspension event might have occurred between 10:00 and 15:00 GMT, because particle concentrations at the lowest depth (denoted by black line) dramatically increased during that time period. Similarly, salinity variation during this time period showed the corresponding increase in salinity at the same depth level (Fig. 6c). However, this simultaneous increase of salinity and particle concentrations did not occur because of a local phenomenon such as a sediment resuspension event. Instead, highly saline and turbid water might move toward our platform P1 through underflows of hypersaline water from the neighboring shallow Oso Bay. Hodges and Kulis (2006) observed dense hypersaline water at the bottom of this bay. Moreover, several wastewater treatment plants discharge directly into Oso Bay or its tributary, which might contribute to increase in biogenic particulate concentration due to the release of nutrients from these plants and the availability of sufficient sunlight for photosynthesis

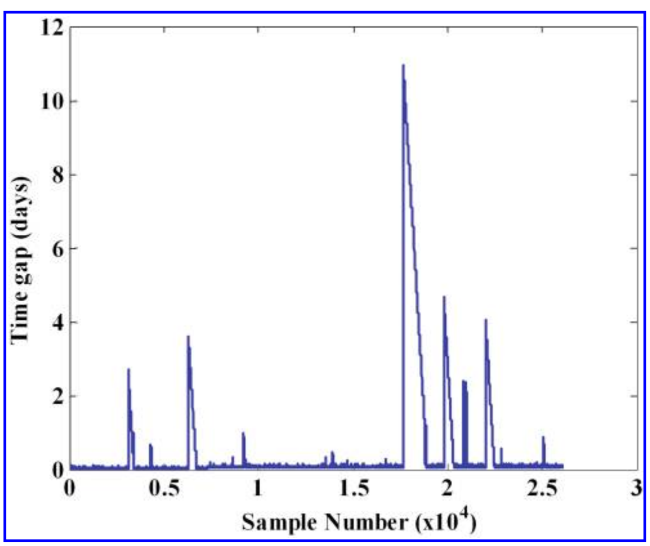

FIG. 4. Time gap between each sample collected at platform P2 and the availability of the same measured sample to the user via web. Sensors installed on the fixed robotic platform captured around 26,000 samples from January 1 to August 31, 2007.

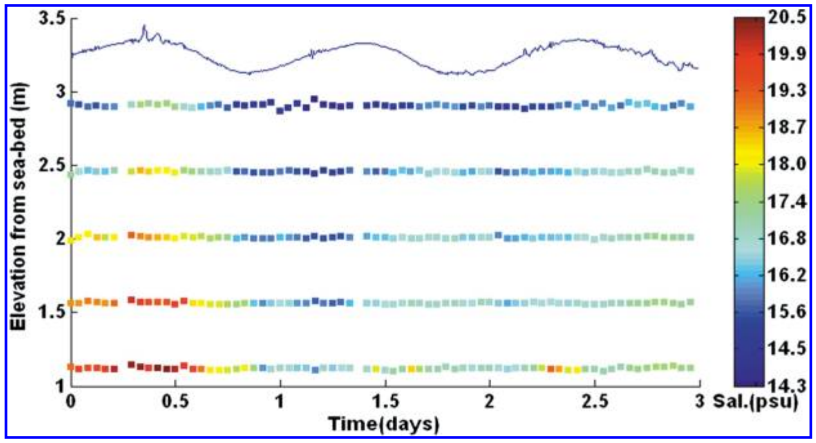

FIG. 5. Vertical variation of salinity in the water column at platform P3 on July 23–25, 2007. Note: Blue solid line represents observed water surface elevation, whereas colored squares represent observed salinity values.

due to the shallowness of this bay. If the vertical water current structure is not strong enough to mix highly saline bottom water (i.e., the condition captured by the robotic profiler system around our platform P1) with the fresher aerated surface water, respiration of microorganisms and decomposition of organic matter at the lower level of water column may exert significant oxygen demand and thereby can induce hypoxic conditions at the bottom of the water column. But DO level captured by the fixed robotic profiler system did not indicate such condition, although the fluctuation of DO level was observed following the time period of the presence of high saline and turbid water around the platform P1 (Fig. 6d).

Long-term analysis of all parameters measured at our fixed robotic platforms can shed light on important processes causing hypoxia in the bay. In addition, simulation of our three-dimensional mechanistic DO model with the observational data collected from these platforms can help to clarify the DO dynamics in CC Bay (Islam *et al.*, 2008). Data collected from this system can also drive other numerical models,

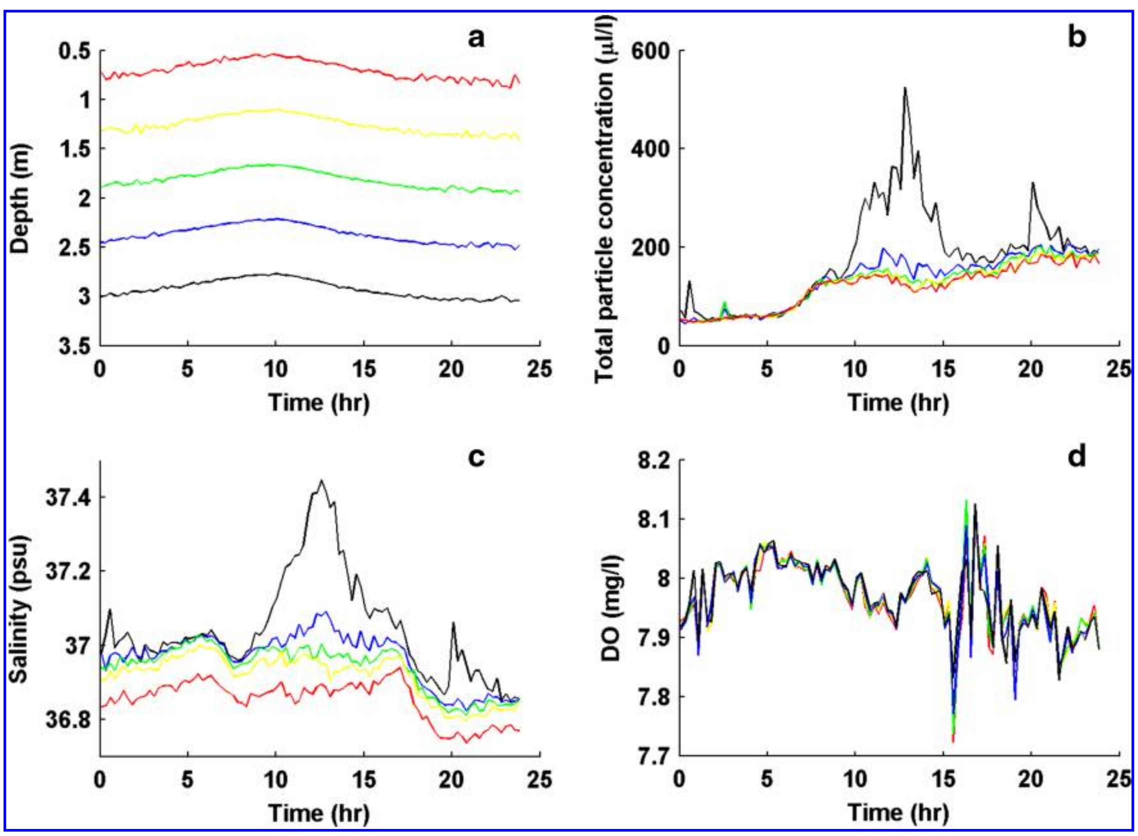

FIG. 6. Vertical variation of water column parameters as measured by the robotic profiler at P1 fixed platform on June 15, 2006. Robotic profiler measurements include (**a**) depth levels, (**b**) total particle concentrations, (**c**) salinity, and (**d**) dissolved oxygen. Measurements are color coded to correspond to each depth level of measurement.

which can provide greater insight in understanding the hydrodynamic and water quality conditions of the bay. For example, meteorological data measured at our fixed robotic platforms are used to generate the wind field necessary to drive our two-dimensional depth integrated hydrodynamic model of CC Bay (Islam, 2009). The output of the hydrodynamic model can then be used to simulate water quality models (Ernest *et al.*, 1991; Garton *et al.*, 1996; Lee *et al.*, 2002; Sterling *et al.*, 2004) and can predict water quality of the bay. Moreover, implementation of an event-based sampling scheme through integration of the fixed robotic platform system with our other monitoring systems such as the mobile platform system (research vessel equipped with instrumented undulating tow-body) and our remote sensing system (i.e., surface current mappers using high-frequency radar) helped to capture the extent of hypoxic event in the bay (Islam, 2009; Islam *et al.*, 2010) and other episodic events. Any unusual (i.e., nonbaseline) measurement 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. At that point in time, our research scientist(s) can further investigate/analyze the observed data (e.g., DO levels, density gradients, surface current maps and current structure of the water column). If water column conditions appear favorable for hypoxia or have already turned hypoxic, then a mobile platform deployment is warranted for further investigation. 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 DO conditions, which had no previously reported history of hypoxia. Therefore, the robotic monitoring system developed in this study serves as a valuable tool for the observatory in capturing and investigating various episodic events that can significantly impact the coastal environment.

Conclusions

The robotic profiler system developed in this study can measure vertical variation of various environmental parameters at high temporal resolution. This system reduces biofouling of sensors and therefore can be deployed for long-term autonomous monitoring of the bay. Moreover, the system can accommodate a broad spectrum of environmental sensors and thereby can measure the critical parameters in clarifying significant processes that control various episodic events in the bay. The system can also handle diverse data formats such as binary, ASCII, and image. The sturdy physical structure of this system makes it suitable to be deployed and maintained even in a remote harsh environment. In addition, the CI developed in this study allows remote access to the fixed robotic platforms and thereby facilitates activities such as instrument management, quality assurance and quality control of the data, implementation of event-based sampling scheme, and sensor troubleshooting. This system is robust enough to handle the communication loss in the case of network failures and can reliably deliver measured datasets from the fixed robotic platforms to the user. The developed CI also makes sensor data available to stakeholders such as researchers, educators, policymakers, and general public in real time for its optimum use. As demonstrated in this article, the capture of the salinity-stratified water column and the underflow of hypersaline turbid water by the robotic profiler system provides evidence of its capability in clarifying processes that may control episodic events such as an occurrence of hypoxia in the bay. In addition, the persistent storage of the measured datasets into the developed relational database provides opportunity to explore interrelated processes that control various episodic events and the determination of long-term trends in the variation of these processes. Moreover, observational datasets from the fixed robotic platforms can be used to drive numerical models for understanding and prediction of various episodic events dominant in this energetic system.

Acknowledgments

This work was funded 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 thank the staff members of the SERF, CC, TX, for assisting in laboratory experiments and field activities.

Author Disclosure Statement

The authors declare that no competing financial interests exist.

References

Agrawal, Y.C., and Pottsmith, H.C. (2000). Instruments for particle size and settling velocity observations in sediment transport. *Mar. Geol.* 168, 89.

Boss, E., Collier, R., Larson, G., Fennel, K., and Pegau, W.S. (2002). *Optical Measurements of Bigeochemical Variables in Crater Lake National Park, OR.* Santa-Fe, NM: Ocean Optics XVI.

Carter, R.W.G. (1998). *Coastal Environments*. London: Academic Press.

Consortium for Ocean Leadership (2010). *Ocean Observatories Initiative (OOI)*. Available at: www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi, last accessed on March 25, 2010.

Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) (2010). *Hydrologic Information System: WaterML Web Services*. Available at: http://his.cuahsi.org/wofws.html, last accessed April 14, 2010.

Coral Reef Environmental Observatory Network (CREON) (2009). Available at: www.coralreefeon.org, accessed February 1, 2009.

Ernest, A., Bonner, J.S., and Autenrieth, R.L. (1991). Model parameter estimation for particle transport. *J. Environ. Eng. ASCE* 117, 573.

Flint, R.W. (1985). Long-term estuarine variability and associated biological response. *Estuaries* 8, 158.

Garton, L.S., Bonner, J.S., Ernest, A.N., and Autenrieth, R.L. (1996). Fate and transport of PCBs at the New Bedford harbor superfund site. *Environ. Toxicol. Chem.* 15, 736.

Global Lake Ecological Observatory Network (GLEON) (2010). Available at: www.gleon.org, last accessed on March 25, 2010.

Hodges, B.R., and Kulis, P. (2006). Modeling gravity currents in shallow bays using a sigma coordinate model. In *The 7th International Conference on Hydroscience and Engineering*, September 10–13, Philadelphia, PA.

Honji, H., Kaneko, A., and Kawatate, K. (1987). Self-governing profiling system. *Cont. Shelf Res.* 7, 1257.

Horsburgh, J.S., Tarboton, D.G., Maidment, D.R., and Zaslavsky, I. (2008). A relational model for environmental and water resources data. *Water Resour. Res.* 44, W05406.

Horsburgh, J.S., Tarboton, D.G., Piasecki, M., Maidment, D.R., Zaslavsky, I., Valentine, D., and Whitenack, T. (2009). An integrated system for publishing environmental observations data. *Environ. Model. Soft* 24, 879.

Isern, A.R., and Clark, H.L. (2003). The ocean observatories initiative: a continued presence for Interactive Ocean Research. *Mar. Technol. Soc. J.* 37, 26.

Islam, M.S. (2009). Development of a coastal margin observation and assessment system (CMOAS) to capture the episodic events in a shallow bay. Ph.D. dissertation, Texas A&M University, College Station, TX.

Islam, M.S., Bonner, J., Ojo, T., and Page, C. (2008). A mechanistic dissolved oxygen model of Corpus Christi Bay to understand critical processes causing hypoxia. *Oceans '08 MTS/IEEE*, Quebec Technical Program, September 15–18, 2008, Quebec, Canada.

Islam, M.S., Bonner, J., Ojo, T., and Page, C. (2010). Integrated real time monitoring system to investigate the hypoxia in a shallow Wind-Driven Bay. *Environ. Monit. Assess.*, doi 10.1007/s10661-010-1316-8.

Kelly, F.J., Bonner, J.S., Perez, J.C., Trujillo, D., Weisberg, R.H., Luther, M.E., and He, R. (2003). A comparison of near-surface current measurements by ADCP and HF radar on the West Florida Shelf. In *Proceedings of the IEEE/OES Seventh Working Conference on Current Measurement Technology*, San Diego, CA, p. 70.

Lee, D.G., Bonner, J.S., Garton, L.S., Ernest, A.N.S., and Autenrieth, R.L. (2002). Modeling coagulation kinetics incorporating fractal theories: comparison with observed data. *Water Res.* 36, 1056.

Luettich, R.A., Kirby-Smith, W.W., and Hunnings, W. (1993). PSWIMS, a profiling instrument system for remote physical and chemical measurements in shallow water. *Estuaries* 16, 190.

Manov, D.V., Chang, G.C., and Dickey, T.D. (2003). Methods for reducing biofouling of moored optical sensors. *J. Atmos. Oceanic Technol.* 21, 958.

Montgomery, J.L., Harmon, T., Kaiser, W., Sanderson, A., Haas, C.N., Hooper, R., Minsker, B., Schnoor, J., Clesceri, N.L., Graham, W., and Brezonik, P. (2007). The WATERS network: an integrated environmental observatory network for water research. *Environ. Sci. Technol.* 41, 6642.

National Ecological Observatory Network (NEON) (2010). Available at: www.neoninc.org, last accessed on March 25, 2010.

National Oceanic and Atmospheric Administration (NOAA) (2010a). *IOOS Observation Registry*. Available at: www.obsregistry.org/index.php, last accessed April 14, 2010.

NOAA (2010b). *National Climatic Data Center (NCDC)*. Available at: www.ncdc.noaa.gov/oa/ncdc.html, last accessed April 14, 2010.

NOAA (2010c). *Physical Oceanographic Real-Time System (PORTS)*. Available at: http://tidesandcurrents.noaa.gov/ports.html, last accessed on March 25, 2010.

NOAA (2010d). *The U.S. Integrated Ocean Observing System (IOOS)*. Available at: http://ioos.gov/dif, last accessed April 14, 2010.

National Research Council (NRC). (2001). *Grand Challenges in Environmental Sciences*. *Committee on Grand Challenges in Environmental Sciences, National Research Council (NRC).* Washington, DC: National Academy Press.

Nichols, M.H., and Anson, E. (2008). Southwest Watershed Research Center Data Access Project. *Water Resour. Res.* 44, W05S03.

Purcell, M., Austin, T., Stokey, R., Von Alt, C., and Prada, K. (1997). A vertical profiling system for making oceanographic measurements in coastal waters. *OCEANS '97 MTS/IEEE Conference Proceedings*, Vol. 1, pp. 219–224, 6–9 October 1997, Halifax, Nova Scotia, Canada.

Reynolds-Fleming, J.V., Fleming, J.G., and Luettich, R.A. (2002). Portable autonomous vertical profiler for estuarine applications. *Estuaries Coast* 25, 142.

Ritter, C., and Montagna, P.A. (1999). Seasonal hypoxia and models of benthic response in a Texas estuary. *Estuaries* 22, 7.

Ritter, C., and Montagna, P.A. (2001). *Cause and effect of hypoxia (low oxygen) in Corpus Christi Bay, Texas. Technical Report 2001-001.* Marine Science Institute, University of Texas at Austin.

Slaughter, C.W., Marks, D., Flerchinger, G.N., Van Vactor, S.S., and Burgess, M. (2001). Thirty-five years of research data collection at the Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resour. Res.* 37, 2819.

Steele, J.H. (1995). Can ecological concepts span the land and ocean domains? In T.M. Powell and J.H. Steele, Eds., *Ecological Time Series.* New York: Chapman & Hall, p. 5.

Sterling, M., Bonner, J., Ernest, A., Page, C., and Autenrieth, R. (2004). Modeling sol-sediment aggregation in nearshore waters. *Environ. Sci. Technol.* 38, 4627.

Turner, R.E., Schroeder, W.W., and Wiseman, W.J., Jr. (1987). The role of stratification in the deoxygenation of Mobile Bay and adjacent shelf bottom waters. *Estuaries* 10, 13.

U.S. Environmental Protection Agency (U.S. EPA) (2010). *STORET*. Available at: www.epa.gov/storet, last accessed April 14, 2010.

U.S. Geological Survey (USGS) (2010). *USGS Water Data for the Nation*. Available at: http://waterdata.usgs.gov/nwis, last accessed April 14, 2010.

Visbeck, M., and Fischer, J. (1995). Sea surface conditions remotely sensed by upward-looking ADCPs. *J. Atmos. Oceanic Technol.* 12, 141.