An Environmental Information System for Hypoxia in Corpus Christi Bay: A WATERS Network Testbed

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Abstract

This project is creating and demonstrating a prototype Environmental Information System (EIS) that couples sensor measurements with end-to-end cyberinfrastructure to improve understanding of hypoxia in Corpus Christi Bay (CC Bay), Texas. Hypoxia is a common estuarine phenomenon that occurs when dissolved oxygen concentrations fall below 2 mg/L, and has resulted in about a ten-fold reduction in benthic standing stock and diversity in CC Bay. The hypoxia in CC Bay is correlated with salinity-induced stratification of the bay, but the stratification forcing and the spatial and temporal patterns of the hypoxia remain uncertain. In this project, an interdisciplinary team of hydrologists, environmental engineers, biologists, and computer scientists are collaborating to improve understanding of hypoxia by: (1) creating an Environmental Data Access System for CC Bay data archives, leveraging CUAHSI Hydrologic Information System (HIS) Web service developments to create data services that automatically ingest observed data in both national and local remote data archives; (2) developing an Environmental Modeling System for CC Bay hypoxia, leveraging NCSA Environmental Cyberinfrastructure Demonstrator (ECID) CyberIntegrator technology to combine numerical hydrodynamic, dissolved oxygen, and oxygen demand models with data mining using hierarchical machine learning algorithms; and (3) demonstrating the effectiveness of the EIS for supporting adaptive hypoxia sampling and collaborative research using ECID's CyberCollaboratory. This paper will give initial results and future plans for the project.

Introduction

The environmental engineering and hydrologic communities are collaborating, with support from the National Science Foundation (NSF), to define a national environmental observatory network called the WATERS (WATer and Environmental Research Systems) Network to enhance understanding of water science. Elements of an observatory program include sensor networks for real-time measurement of water conditions and cyberinfrastructure to integrate streams of observed data and simulation model results into a coherent information framework to support collaboration among scientists at remote locations. These components may together be considered to constitute a *real-time environmental information system*. This project is creating a prototype of such a system and demonstrating how it can be used to understand the occurrence of hypoxia in Corpus Christi Bay, Texas. It is anticipated that the template created for this project will later be applicable to other phenomena and water bodies elsewhere in the nation.

To address these issues, we have assembled an interdisciplinary team of hydrologists, environmental engineers, biologists, and information technology researchers to couple real-time sensor data and simulation models within a unique cyberinfrastructure. The CUAHSI Hydrologic Information System (Maidment, 2005) for describing digital watersheds is being generalized to form an Environmental Information System to depict a digital bay, including its three-dimensional hydrodynamic and water quality conditions. The resulting framework is a demonstration of the benefits of end-to-end cyberinfrastructure, from sensor data to models to decision support.

The research questions motivating this research are directed at understanding, modeling and observing hypoxia in Corpus Christi Bay, and building environmental information systems. These may be detailed as:

- **Understanding Hypoxia.** What is the space and time pattern of the occurrence of hypoxia in Corpus Christi Bay? How is hypoxia interrelated with dissolved oxygen dynamics, hydrodynamics, and hypersalinity? How do we evaluate the impact of engineered systems on hypoxia? With what precision can the occurrence of hypoxia be predicted?
- **Observing System.** How can data from fixed platform sensors, mobile sensors and remote sensing using high frequency radar be combined to depict hypoxic conditions? Is it possible to do this in real-time as the events occur? How can this information be used to guide sampling strategies for more precise measurement of hypoxic events?
- **Modeling System.** Can the three-dimensional hydrodynamic and salinity conditions occurring during hypoxic events be successfully simulated? Can the associated dissolved oxygen conditions be modeled using known water quality mechanisms? Can predictive models for hypoxia occurrence be created by applying machine learning (data mining) to the data obtained during historical hypoxic events and numerical models fit to the historical data?
- **Building Environmental Information Systems.** How can the design of an Environmental Information System for hypoxia in Corpus Christi Bay be generalized so that it can serve as a template for the investigation of this phenomenon at other locations? What data models best integrate observed and simulated information in three-dimensional water bodies?

Subsequent sections of this paper provide background on the hypoxia in Corpus Christi Bay, the methodologies that are being used to study the hypoxia in this project, and some early results.

Background on Hypoxia in Corpus Christi Bay

The Corpus Christi Bay system is an urban estuary with complex hydrodynamic and water quality conditions (Figure 1). The bay is home to the Port of Corpus Christi (the nation’s seventh largest port), a very large complex of petrochemical facilities, and to the City of Corpus Christi, which has a population of 280,000. The average depth of the bay is 3.6m (Ward 1997) and it is separated from the Gulf of Mexico by a barrier island. Due to restricted channel entrances and the low tidal range in the Gulf of Mexico, water circulation in the bay may be dominated by wind rather than tides. Freshwater inflows enter the bay as pulses during storm events, mainly from the Nueces River, which parallels the southern edge of Nueces Bay.

Hypoxia is a common estuarine phenomenon defined to occur when dissolved oxygen (DO) concentrations fall below 2 mg/L (Dauer et al., 1992). Hypoxia in Corpus Christi Bay, Texas was first documented in 1988 (Montagna and Kalke, 1992) and later observed every summer (Martin and Montagna, 1995; Applebaum et al. 2005). Hypoxia is a serious disturbance because few animals can tolerate the physiological stress of extended exposure to low oxygen concentrations (Diaz and Rosenberg, 1995). Hypoxia in Corpus Christi Bay results in about a ten-fold reduction in benthic standing stock and diversity. In Corpus Christi Bay, hypoxia is correlated with salinity-induced stratification of the bay, which occurs in summer when temperature and evaporation are high and precipitation is low (Ritter and Montagna, 1999). The water quality sampling stations shown in Figure 1 are maintained by Dr Paul Montagna of Texas A&M University-Corpus Christi (TAMUCC), who collects continuous data there each summer from late June to early August, which is the main period during which hypoxic events occur. These data include dissolved oxygen concentration, dissolved oxygen saturation, salinity, conductivity, depth, pH, and temperature.

Stratification of Corpus Christi Bay is induced by underflows of hypersaline water (up to 50 ppt) from neighboring bays: the Laguna Madre and Oso Bay. Hypersalinity occurs in the Laguna Madre because the inflow of freshwater is less than the bay evaporation, and because the Laguna Madre is also separated from the Gulf of Mexico by a barrier island. Hypersaline conditions also occur in Oso Bay, because the Barney Davis Power Plant draws a 400 MGD flow of cooling water from the upper Laguna Madre through an intake shown in the lower part of Figure 1, and discharges this flow into Oso Bay. Several wastewater treatment plants discharge directly into Oso Bay or its tributary streams. The Texas Commission on Environmental Quality is currently investigating the effects of wastewater nutrients on dissolved oxygen conditions in Oso Bay. The City of Corpus Christi is presently investigating developing a desalinization water treatment plant that would be co-located with the Barney Davis Power Plant – the brine output from this desalinization plant would discharge into Oso Bay and raise its salinity even higher!

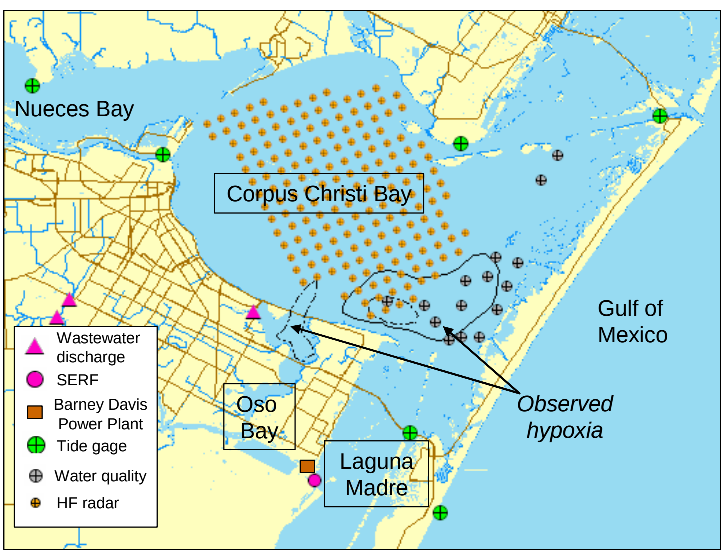

Fig. 1. Corpus Christi Bay features.

During August 2005, Hodges and co-workers from the University of Texas at Austin made a field survey of hydrodynamic and hypoxia conditions along a 2km transect leading out from Oso Bay into Corpus Christi Bay. Measurements 1 km from Oso Bay (Figure 2) showed a distinct patterns in the bottom water with hypersaline pulses (associated with tidal flows from Oso Bay) and diurnal oscillations in DO and temperature. Further out in Corpus Christi Bay (Figure 3), the DO levels lose their diurnal signature and show continuous hypoxic or near-hypoxic conditions near the bottom. Hodges and Furnans (2007) showed low DO conditions develop due to limited mixing between Corpus Christi Bay water and a hyper-saline gravity-current underflow out of Oso Bay. Because the bottom water is isolated from the surface, oxygen demand in the benthos rapidly depletes DO, despite periodic pulses of high DO water (visible in Figure 2, but not in Figure 3).

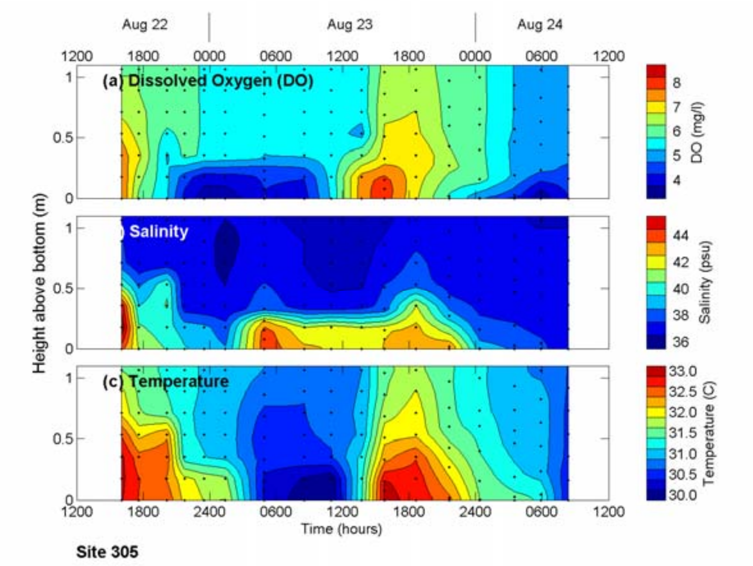

Figure 2. Water characteristics approximately 1 km from the nexus of Oso Bay and Corpus Christi Bay. Water depth is 3.0 m at this site. Dots indicate sampling stations.

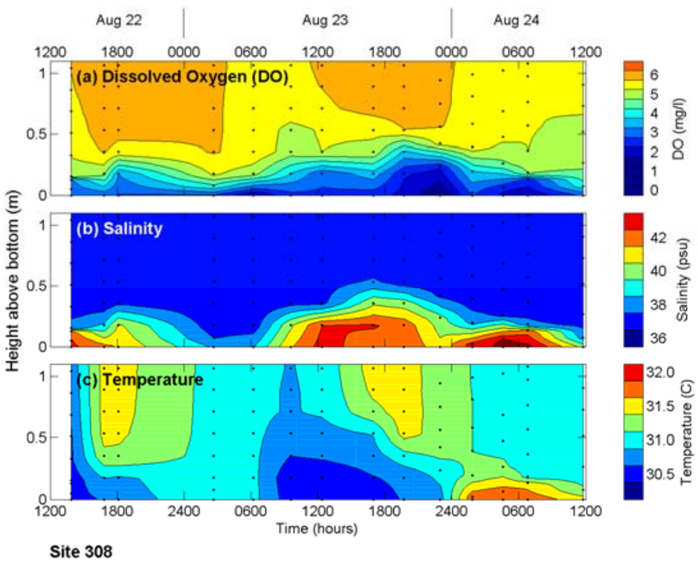

Figure 3. Water characteristics approximately 2 km from the nexus of Oso Bay and Corpus Christi Bay. Water depth is 3.8 m at this site. Dots indicate sampling stations.

The water quality and hydrodynamic surveys conducted by Montagna and Hodges and their co-workers demonstrate that hypoxia occurs in Corpus Christi Bay but much remains uncertain about its patterns and forcing – how does the spatial extent and intensity of these events vary though time? Does the interaction between the Laguna Madre and Corpus Christi Bay behave like that between Oso Bay and Corpus Christi Bay? Does hypoxia occur only when the bay is vertically stratified because of hypersaline underflows or do other effects play a role? Under what conditions can wind cause sufficient mixing to break up salinity-induced stratification? Do wastewater treatment plant discharges produce nutrients that stimulate organic matter production, which could accelerate sediment oxygen demand during hypoxic periods? With what precision can the onset and intensity of hypoxia be predicted?

Background on Corpus Christi Bay Observing Systems

Existing observing systems for hypoxia in Corpus Christi Bay, summarized below, have the ability to make measurements across space, through depth and over time for the key driving variables: hydrodynamics, salinity, and water quality. From these measurements, the bio-geochemical cycling processes are being inferred through modeling in order to fulfill the objectives of this project.

SERF Sensor System

The Shoreline Environmental Research Facility (SERF, http://www.serf.tamus.edu/), directed by James Bonner, is located adjacent to the Barney Davis Power Plant near the shore of the Laguna Madre (see Figure 1). SERF has an existing sensor test bed in Corpus Christi Bay that measures the parameters listed in Table 1 with a broad spectrum of operational sensors and three sensor deployment platforms:

- **High Frequency Radar.** Surface currents are mapped using high frequency radar to provide approximately 100-sq-km of 10-minute surface currents, wave height and direction at one-square-km grid spacing – the measurement grid is shown as the mesh of points covering most of Corpus Christi Bay in Figure 1.
- **Stationary Sensor Deployment Platforms.** Two operational platforms are currently deployed and three more are scheduled for deployment in 2007.The movable fixed sensor-deployment platforms are designed to observe the environmental parameters detailed in Table 1 at multiple depths by profiling through the water column. This is achieved under robotic control by moving the suite of sensors up and down through the whole water column in ~20% depth increments (“vertical profile” in Table 1). The locations of these platforms were selected on the basis of fluxes in the bay system. This will allows us to capture important features of hypoxia and other transport phenomena in this complex dynamic environment.
- **Mobile Sensor Deployment Platforms.** The same spectrum of environmental parameters measured at the stationary sites are also measured using a mobile vessel with an undulating tow-body equipped with a suite of sensors. This provides multiple environmental parameters at a much higher spatial resolution than can be achieved using the stationary platforms.

The SERF sensor network is currently undergoing extensive modification and adaptation through other NSF projects The important physical processes in this water body that directly influence the onset of hypoxia are being measured with this sensor system, including wind-driven surface processes related to threshold water column energy dissipation and vertical mixing, and their effects on stratification that contribute to hypoxic conditions. The difficulty lies with obtaining the BOD (biological oxygen demand) measurements in real-time and to overcome this limitation, the SERF sensors will be used to construct surrogate measurements for BOD using CDOM (chromophoric dissolved organic matter) and chlorophyll-*A* values derived from fluorescence, as well as particle size distribution derived from laser diffraction, optical backscatter (OBS) and acoustic backscatter (ABS) measurements. In addition, total ecosystem respiration rates, which are analogous to BOD, can be estimated from continuous oxygen measurements and wind speeds gathered from sensors (Russell et al., 2007). These surrogates will be regressed against laboratory analyses of periodic grab samples, measuring BOD in order to develop a correlation with real-time measurements. Dr Paul Montagna’s laboratory (TAMUCC) will perform the lab work required for this effort through funding from other projects.

Table 1. Physical-chemical properties measured by SERF sensors.

Instrument	Parameter	Static Station	Vertical Profile	Mobile (Vessel mounted)
FL3 Fluorometer	CDOM	Yes	Yes	Yes
	Chlorophyl A	Yes	Yes	Yes
	Fluorosceine/OBS	Yes	Yes	Yes
Optode	Dissolved oxygen	Yes	Yes	Yes
Seabird Microcat	Conductivity	Yes	Yes	Yes
	Temperature	Yes	Yes	Yes
	Depth	Yes	Yes	Yes
LISST Particle Size analyzer	Particle size distribution/OBS	Yes	Yes	Yes
ADCP	Wave/currents/ABS	Yes	Yes	Yes
RMYoung	Wind speed/direction	Yes	No	No
	Barometric pressure	Yes	No	No
	Air Temp	Yes	No	No

Texas Coastal Ocean Observing Network

The Texas Coastal Ocean Observation Network (TCOON) is a set of observing stations at fixed locations along the Texas coast that measure water level and a variety of environmental conditions, including water and air temperature, wind speed, direction and gusts, and barometric pressure (all stations report water level and a selection of environmental parameters). The data are reported continuously at one-minute intervals in near real-time (a latency of about 15 minutes) on the TCOON web site http://lighthouse.tamucc.edu/TCOON/HomePage . Six TCOON stations are located in and around Corpus Christi Bay, as shown in Figure 1. Historical data going back to 1993 are available for most parameters at these stations. The TCOON stations describe surface environmental conditions around the periphery of Corpus Christi Bay.

Water Quality Monitoring Data

An extensive water quality monitoring database for Corpus Christi Bay and its surrounding bays called TRACS (Texas Regulatory and Compliance System) is maintained by the Texas Commission for Environmental Quality (TCEQ). These data are collected to satisfy the monitoring requirements for the Federal Clean Water Act. The current Coastal Bend Bay and Estuary Program (CBBEP, http://www.cbbep.org/) is the permanent legacy of a federally support National Estuary Program study that occurred during the 1990's, during which the most comprehensive compilation and study of water quality conditions in the bay done to date was made. Ward and Armstrong (1997) compiled all historical water quality data for the bay system and conducted a status and trends study of this information for CBBEP. The TAMUCC has extensive nutrients, salinity, and DO data starting from 1988, and the CBBEP has been funding monitoring since 2000 to characterize the spatial and temporal dynamics of hypoxia. Quenzer et al. (1998) produced a total loadings model for nitrogen, phosphorus, oil and grease and toxic metals from all sources to the bay system.

As is apparent from this description, there is a plethora of historical and real-time information available about Corpus Christi Bay, and a significant ability to collect more information targeted towards understanding hypoxia. The challenge is, however, how do you understand all these data? How can you visualize the data in forms that lead to understanding of phenomena related to hypoxia? What is the role of historical versus real-time data? And, more than all of these – there is simply the question of data access – where are all these data and how can they be obtained and synthesized into a coherent body of information?

Methodology

To create an environmental information system (EIS) to help researchers to address these questions, this project is combining data from the above sensing systems with numerical hydrodynamic and water quality models, statistical models, and cyberinfrastructure technologies under development within the CUAHSI Hydrologic Information System (HIS) project and the National Center for Supercomputing Application (NCSA) Environmental CyberInfrastructure Demonstrator (ECID) project. Figure 4 shows the general structure of the EIS technology integration. The EIS will access historical sensor data via an Environmental Data Access System that consists of a workgroup server operating with the HIS observations data model (ODM) schema and Web services to access the data from remote servers where the original data are archived. The data will also stream directly to the ECID event-driven "cyberenvironment" technology that will enable automated creation of near-real-time hypoxia forecasts. The cyberenvironment integrates desktop tools with remote services that trigger hydrodynamic and hypoxia models, integrated with a tool called CyberIntegrator, to forecast hypoxia. Forecasts that indicate high likelihood of hypoxia are then fed to subscribors' desktop dashboard and e-mail, from which users can launch a collaboration tool called the CyberCollaboratory to examine the data and modeling results in more detail and, if warranted, organize field exercises to study the hypoxia in more detail. Brief background on each of the technology components are given below.

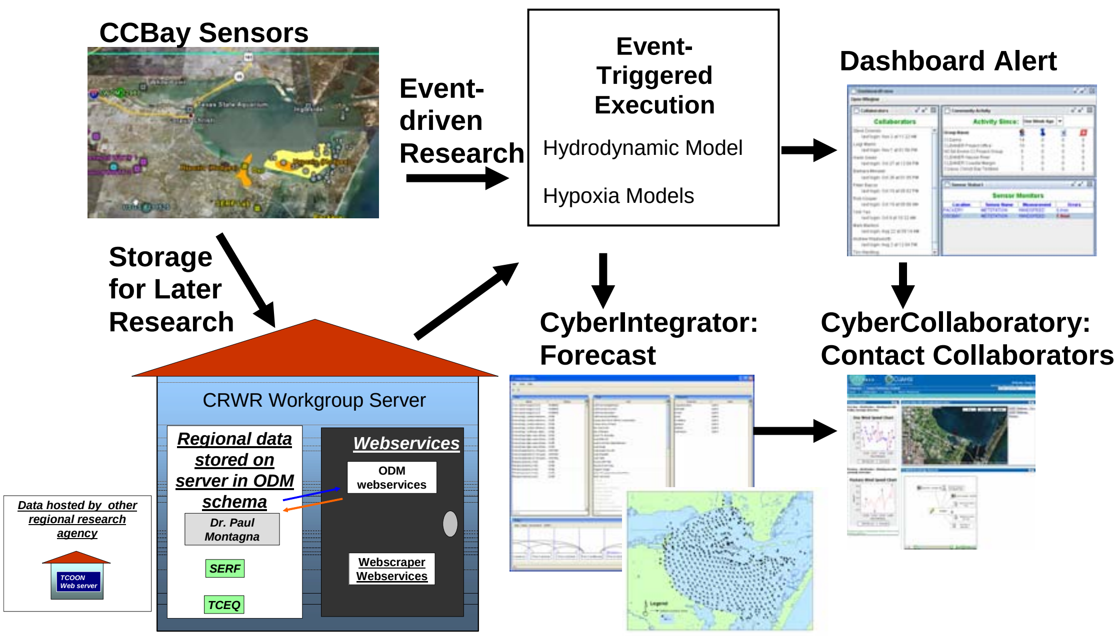

Fig. 4. Environmental Information System for studying hypoxia in Corpus Christi Bay.

Environmental Data Access System

As part of the HIS project (led by David Maidment), a great deal of study has been made of methods for remote access to data archives using Web services. In a Web services approach, each component/application provides Web services (either as a provider or a requester) and these services are invoked by any other component that needs to interact with that component using Simple Object Access Protocol (SOAP). The Web service information is published using the Web Services Description

Language (WSDL) format. This XML format is used to describe network services as endpoints operating on messages containing information describing either a document or a procedure.

CUAHSI HIS has built Web services (see http://water.sdsc.edu/wateroneflow) that allow a user to automatically ingest observed data in remote archives, including streamflow, water quality and groundwater level information in the USGS National Water Information System, vertical atmospheric carbon, moisture and heat fluxes from the Ameriflux network, and some information from the National Climate Data Center's Automated Surface Observing System. Using Web services, it is not necessary that the user download the data onto a local disk – data access is rapid enough such that the information can be left in the original archive and retrieved when necessary – it is as if the national data archives are on local disks so far as the user is concerned. This is a remarkable development that opens up a range of study and consideration of national water observational data not previously possible.

This project is creating a prototype Environmental Data Access System for Corpus Christi Bay by extending the national CUAHSI HIS Web services just described to access data from regional and local sources at SERF, TCOON, TCEQ, and TAMUCC. Creation of web services involves building a Web services library of elementary functions, such as "GetSiteInfo", "GetVariableInfo", "GetValues" using the Web Service Definition Language, a W3C Technical Standard for web service development. This library can be accessed by a variety of applications, such as Excel, web browsers, ArcGIS, and Matlab. Fortunately, since the mechanisms of constructing data Web services (hereafter called "data services") have been mastered, constructing new data services to many internet data sources is fairly straightforward.

CyberIntegrator:

The CyberIntegrator is a prototype "meta-workflow" technology to support modeling and analysis of complex environmental systems. Workflows execute a sequence of tasks on one or several local or remote processors (e.g. obtaining data from remote servers, transforming data as needed for analyses, performing analyses or modeling, and visualizing results). Meta-workflows allow heterogeneous workflows and software tools, often created by different users using multiple software technologies and existing scientific workflow engines, to be linked and executed within a user-friendly, interactive system using distributed computational resources. CyberIntegrator is integrated with an event management system that enables workflows to be triggered automatically via user subscriptions. This capability will be used to automatically process data and make hypoxia predictions each day.

CyberCollaboratory and Dashboard:

The CyberCollaboratory is a Web-based collaborative environment where communities of researchers, practitioners, policy-makers, and others come together to share knowledge and information. Digital observatories require online portals where data, models, and resources are easily accessible by a community. The CyberCollaboratory is a prototype portal to fulfill this need by providing: a space where communities can come together to share knowledge and information, analyze data, solve problems; customized workspaces where each community can integrate and utilize the specific cyberinfrastructure tools that they find useful; and a knowledge network for finding & sharing information. Activities in the CyberCollaboratory are mined to notify users about other people, data, documents, and information of interest. The Dashboard is a desktop tool that provides summaries of current activities in the portal as well as alerts from the event management system, including hypoxia forecasts.

Hydrodynamic Model:

Hypoxia in Corpus Christi Bay is highly dependent on hydrodynamics because stratification reduces vertical turbulent mixing of heat, momentum, mass and constituents (Ralston and Stacey, 2005; Armenio and Sarker, 2002; Ojo et al, 2006), and therefore limits the replenishment of DO in a stratified layer. Simulating the physics that allow temporal and spatial development of hypoxia requires understanding: (1) creation and transport of hypersaline waters and (2) relationships between wind and tidal-driven mixing that allows dissolved oxygen replenishment of the near-sediment water. Hodges' ELCOM model (Dallimore, et al. 2003, 2004) has been shown to adequately predict thin-layer gravity current propagation, but the response of the hypersaline layers to wind mixing and tidal currents remains unquantified.

Hydrodynamic model development in this project is linked to Hodges' project that is assisting the Texas Water Development Board (TWDB) in evaluating hydrodynamic models for Corpus Christi Bay using ELCIRC (Zhang et al. 2004), a finite-volume model with unstructured grids. An example of flow three-dimensionality in a combined wind and tidally-driven circulation is shown in Figure 5. The model will be validated using historical data and integrated into the CyberIntegrator, using real-time wind and surface condition forecasts from the North American Forecast Model of the National Centers for Environmental Prediction to drive the model boundary conditions.

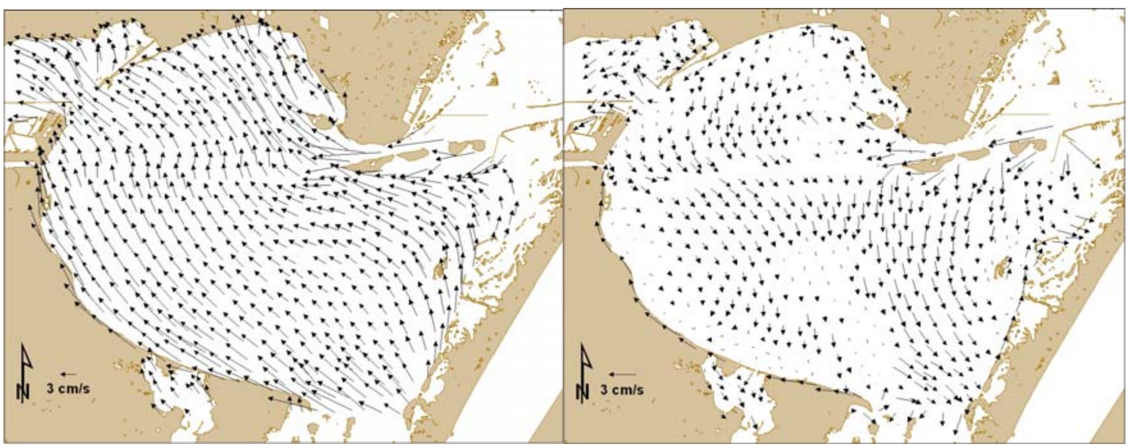

Figure 5. Model predicted surface velocity (left) and near-bottom velocity (right) during typical southeasterly wind event. Surface velocity is dominated by wind forcing with weaker return flows near the bottom. Simulation results using ELCIRC with Mellor-Yamada 2.5 turbulence closure, 20 grid layers in the vertical direction (15 cm resolution), and 4200 grid cells in the horizontal plane (for clarity, only a portion of velocity vectors are presented).

Dissolved Oxygen Model:

SERF investigators (Bonner, Ojo) are implementing a water quality simulation with dissolved oxygen (DO) as the model state variable and biochemical oxygen demand (BOD) as the kinetic term. This is based on the 3D data-driven Constituent Transport Model (3D-CTM) that takes hydrodynamic data for the advective component as input and uses autocorrelation functions of the velocity time-series to infer the dispersive components (Ojo et al., 2006). The first step in this part of the work will be to ingest hydrodynamic model output from the hydrodynamic model in order to evaluate the performance of the model in predicting the transport of conservative material. The second step will be the incorporation of terms for BOD with DO as the state variable.

Using CyberIntegrator, the 3D-CTM will be linked to the hydrodynamic model, which provides the "advection coefficients" that drive the ADR governing equations. However, the "diffusion coefficients" are typically not generated through such hydrodynamic schemes. The required dispersion coefficients will be generated from current time series (observed or predicted) using algorithms developed by Ojo et al. for evaluating diffusivities through direct observations of hydrodynamic information. The CTM output will be validated against real-time DO measurements.

Hypoxia Machine Learning Model:

While the hydrodynamic and DO models described previously provide useful information for better understanding the mechanisms that lead to hypoxia, they are not presently able to capture all the complexities of the biological systems operating in the bay in real time. Therefore, in this project we will use the forecasts from these "physics-based" models as inputs to machine learning models that use the available data and model forecasts to statistically predict hypoxia. Given that the hypoxia forecasts required for this project are only one-day-ahead forecasts, we expect that this approach may give more accurate results. Figure 6 shows how such a system would be created by linking the various models using CyberIntegrator.

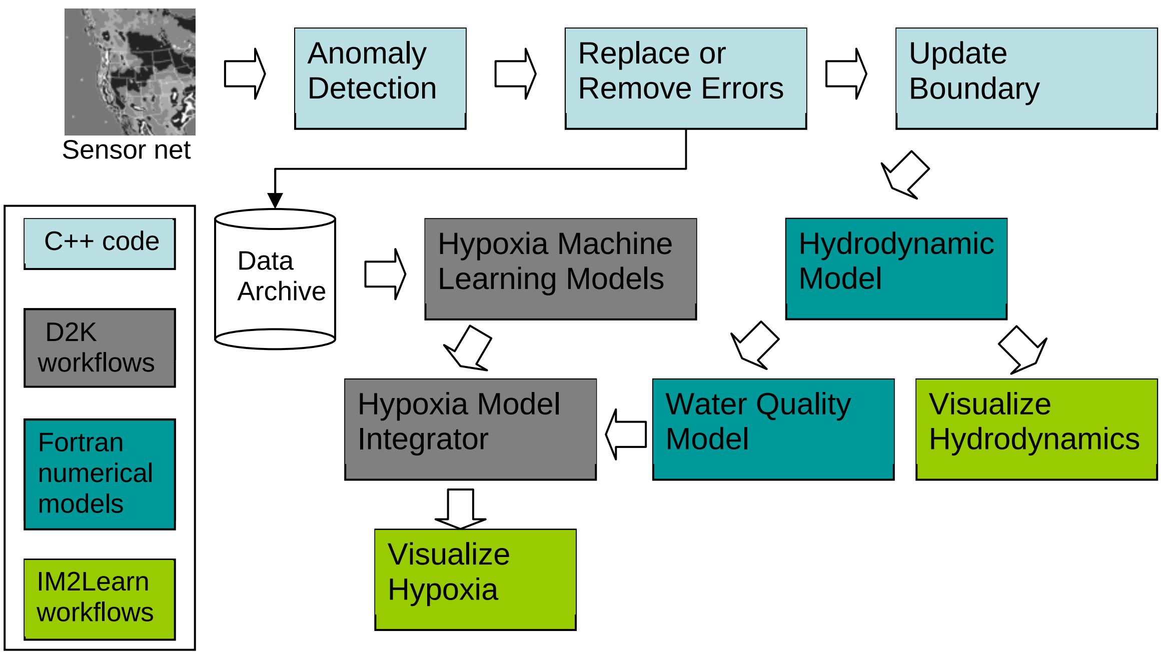

Fig. 6. Environmental Modeling System for Corpus Christi Bay hypoxia.

The machine learning models will predict the likelihood of hypoxia in the southeast region of Corpus Christi Bay where hypoxia has been observed most frequently (see Figure 1). Prior to creating the machine learning models, however, the trends in the DO data must first be addressed, which is the focus of our current efforts. The dissolved oxygen levels in CCBay with respect to time are governed by trends on three differing time scales: the long-term trend that describes the slow and steady decrease in dissolved oxygen over the last twenty-plus years, the seasonal trend that depicts the tendency of dissolved oxygen to decrease during summer months and increase during winter months, and the diurnal trend that describes daily oscillations in dissolved oxygen. Typically, photosynthetic processes increase dissolved oxygen during daylight hours and animal respiratory functions consume the oxygen supply after the sun has set (Russell et al., 2006). The result is a cyclical diurnal function that reaches a minimum in the early morning and peaks in the late afternoon. To address these trends, a sequential normalization approach with Fourier transform models is used to depict the relevant periodic functions. Initial results of this approach are presented in the next section. A similar approach will also be used for modeling trends in the temperature data.

Once the data with trends are addressed, we intend to compare several non-parametric forecasting methods for dynamically updating hypoxia forecasts as newer data are gathered, leveraging the data and modeling services described previously. Methods currently under consideration include a baseline approach of sequential normalization to address trends beginning with the longest time scale and concluding with the most brief (Maidment and Parzen 1984), hierarchical machine learning approaches that couple expert and specialty models to combine diverse data sources, and dynamic Bayesian networks (Murphy 2002). Once the best forecasting approaches are identified, hypoxia errors will be calculated using bootstrapping approaches to create spatial maps of errors over time. These maps will be used to identify locations and times that could benefit from additional sampling.

Results

To model oxygen trends, we begin with the long-term trend, which is modeled with a simple linear regression:

$$DO_{long-tern}(t) = k_1 t + k_2$$

k_1 has dimensions of [DO]/time and k_2 is measured in [DO]

Superimposed upon this gradual decline in dissolved oxygen is the annual periodic function. Figure 3 shows a long-term hypoxia dataset for Corpus Christi Bay from the Texas Parks & Wildlife Department after normalization to remove the long-term trend. The R^2 value for the annual cycle fit to this dataset (shown in Figure 7) is 0.244. The original R^2 value for the linear model was 0.071. This implies that 7% of the variance in DO readings was removed when the long-term trend was extracted, and 24.4% of the remaining variance is removed via the annual cycle.

The seasonal oscillations are effectively described through a discrete fourier transform (two harmonics) using the normalized dataset:

$$DO_{seasonal}(t) = k_3 \sin\left(\frac{2\pi t}{365} - k_4\right) + k_5 \sin\left(\frac{2\pi t}{182.5} - k_6\right) + k_7$$

Here, t is measured in days, k_3 and k_5 are dimensionless measures of amplitude, k_4 and k_6 represent dimensionless phase shifts and k_7 is a vertical shift of [DO].

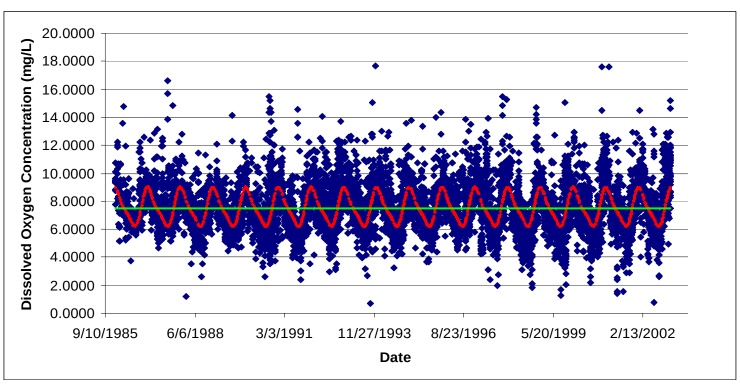

Fig. 7. Texas Parks & Wildlife Department surface data, long-term trend removed through normalization

By repeating this process of normalizing to remove a trend, adjusting the data set accordingly, and then modeling the next smallest periodic function, we can address all three temporal patterns. One station located in the hypoxic zone has gathered data at the bay floor during summers between 1999 and 2005. Having removed the long-term and seasonal variances, the diurnal cycle emerges as shown in Figure 8.

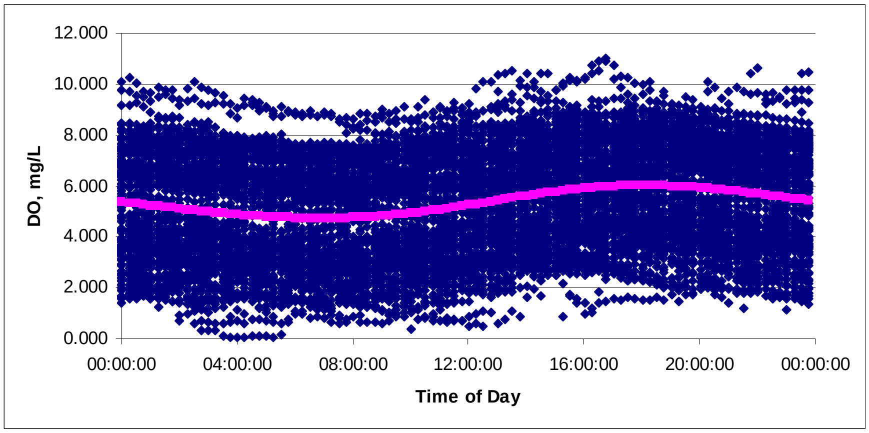

Fig. 8. Diurnal oscillations, hypoxic zone, bay floor

With three normalized cycles, any value from *any* data set DO_t (provided that we are aware of the time at which it was taken) can be adjusted three times and is therefore comparable to any other value DO_t:

$$DO_{thrice-adjusted,t} = DO_t \frac{\left(\frac{\sum_{i=0}^{n_1} DO_i}{n_1}\right)}{[k_1 t + k_2]} \frac{\left(\frac{\sum_{i=0}^{n_2} DO_i}{n_2}\right)}{\left[k_3 \sin\left(\frac{2\pi t}{365} - k_4\right) + k_5 \sin\left(\frac{2\pi t}{182.5} - k_6\right) + k_7\right]} \frac{\left(\frac{\sum_{i=0}^{n_3} DO_i}{n_3}\right)}{\left[k_8 \sin\left(\frac{2\pi t}{1} - k_9\right) + k_{10} \sin\left(\frac{2\pi t}{0.5} - k_{11}\right) + k_{12}\right]}$$

This detrending approach removes variance through systematic and sequential normalization, extracting smaller and smaller periodic functions by negating the oscillations of the larger cycles. We can calculate the overall quantity of variance eliminated by addressing all three-time dependent cycles as follows:

$$R^2_{overall} = (1 - R^2_{long-term})(1 - R^2_{seasonal})(1 - R^2_{diurnal}) = (1 - .071)(1 - .244)(1 - .048) \approx 0.33$$

In other words, approximately one-third of all variance in dissolved oxygen readings can be described using only the three time-dependent cycles. The remaining variance is due to other factors that will be modeled in the next phase of the research by including other exogenous factors (e.g., temperature and salinity).

Conclusions

This project aims to demonstrate the value of an end-to-end environmental information system, integrating sensor data with models in real time, toward improved adaptive monitoring and understanding of hypoxia. By leveraging emerging cyberinfrastructure and sensing technologies, we can feed forecasting models in near-real-time – effectively combining the various resources at our disposal to estimate the probability of future hypoxic conditions at any user-specified degree of severity. As time elapses and further data gathering takes place, these new results can easily be included into our data access system and improve the precision of hypoxia predictions over time. Ultimately, this interaction between data-gathering, analysis, and prediction will lead to more accurate forecasts today and more streamlined collaboration tomorrow.

Acknowledgments

This research is supported by the National Science Foundation under grants BES-0414259, SCI-0525308, and EAR-0413265, the Office of Naval Research under grant N00014-04-1-0437, the Advanced Technology Program under grant 003658-0162-2003, and the Texas Water Development Board under grant 2005-001-059.

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