Real-time Environmental Monitoring from a Wind Farm Platform in the Texas Hypoxia Zone

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Abstract- **Ocean observing systems (OOS) are useful tools for assisting coastal managers with informed decision-making. OOS are designed to monitor environmental, oceanographic, and atmospheric parameters and can be installed on a variety of offshore platforms. In the summer of 2009, a multi-disciplinary real-time OOS, *Galveston Instrument Garden for Environmental Monitoring* (GIGEM), was deployed off the coast of Galveston, Texas (Location: 29°08'29.654''N, 094°44'51.339''W) to monitor coastal waters and provide data to investigate the processes controlling coastal Texas hypoxia. Hypoxia occurs in the Gulf of Mexico and refers to low dissolved oxygen concentrations in the bottom waters caused by a combination of environmental and physical parameters. Hypoxic events commonly occur along the Louisiana and Texas coasts however, little research has been conducted to investigate the processes responsible for Texas hypoxia formation. GIGEM was designed to help solve this problem by contributing real-time measurements to compare with historical coastal data series. Unlike traditional coastal OOS, GIGEM is installed on an experimental wind farm platform, operated by Wind Energy System Technologies Inc. (WEST). GIGEM is comprised of two components, the underwater mooring and bottom package, with all instrumentation connected by a unique, intricate design of seawater and surface inductive modems. GIGEM is also the only coastal OOS collecting real-time environmental water quality measurements on the Texas shelf. The work presented describes the obstacles and challenges with deploying GIGEM, the flow of information from the water column to the user, and future plans for constructing a comprehensive picture of Texas coastal hypoxia. Details are also presented on how this type of OOS compares with additional OOS in the Gulf of Mexico and how the societal goals for protecting coastal ecosystems and improving coastal weather and ocean predictions implemented by the Integrated Ocean Observing System (IOOS) are fulfilled.**

I. INTRODUCTION

To assist coastal managers with informed decision-making, ocean observing systems (OOS) are increasingly deployed to monitor environmental, oceanographic, and atmospheric parameters. The trend towards alternative energy sources, including those derived from wind power, has led to increased planning and installation of offshore platforms capable of housing real-time OOS. As described by the Integrated Ocean Observing System (IOOS), ocean observing systems should be designed to fulfill a suite of societal goals, including those designed with an environmental focus, serving a variety of users, and natural hazard mitigation [1]. The two main components of IOOS are global and coastal systems with more recent efforts focusing on the development of regional coastal systems for climate monitoring and hazard mitigation [1]. Texas A&M University is involved in numerous Gulf of Mexico National and International OOS activities and is home to the Gulf of Mexico Coastal Ocean Observing System Regional Office (GCOOS) and to the Texas Automated Buoy System (TABS) operated by the Geochemical and Environmental Research Group (GERG). TABS, established in 1995, originated as a system designed to predict oil spill trajectories based on ocean currents along the Texas (TX) and Louisiana (LA) coasts and now assists with environmental water quality monitoring along and climatology for the TX-LA coast [2]. This and other OOS in the Gulf have been extremely successful collecting data in the surface waters, but a system has not been deployed to measure properties throughout the vertical water column. As oceanographic research has shifted from studying deep GOM shelf waters to coastal processes, the demand for more environmentally sensitive OOS, that include vertical column profiles and real-time observations, has increased. One such demand is investigating the processes controlling hypoxia along the TX-LA coasts. Preliminary analysis has shown distinct spatial and temporal separations between the well-studied 'LA dead zone' and Texas coastal hypoxia events [3]. However, little is known about the hypoxic regions forming off the Texas coast whereas the 'LA dead zone' has been routinely monitored for over 25 years [4]. In order to investigate the temporal formations of Texas hypoxia, a multi-disciplinary real-time reporting OOS, *Galveston Instrument Garden for Environmental Monitoring* (GIGEM) was deployed in summer 2009, 10 nautical miles south of Galveston, Texas (Location: 29°08'29.654''N, 094°44'51.339''W), on an experimental wind farm platform operated by Wind Energy System Technologies Inc. (WEST Inc.) (Figs. 1, 2, & 3).The platform is located in the coastal waters of Texas (18 meter(m) water depth) often affected by seasonally occurring coastal hypoxia and is the only OOS measuring environmental water quality data off the Texas coastline. This paper will elaborate on the design process, deployment, and examine applications with the real-time data for investigating Texas coastal hypoxia.

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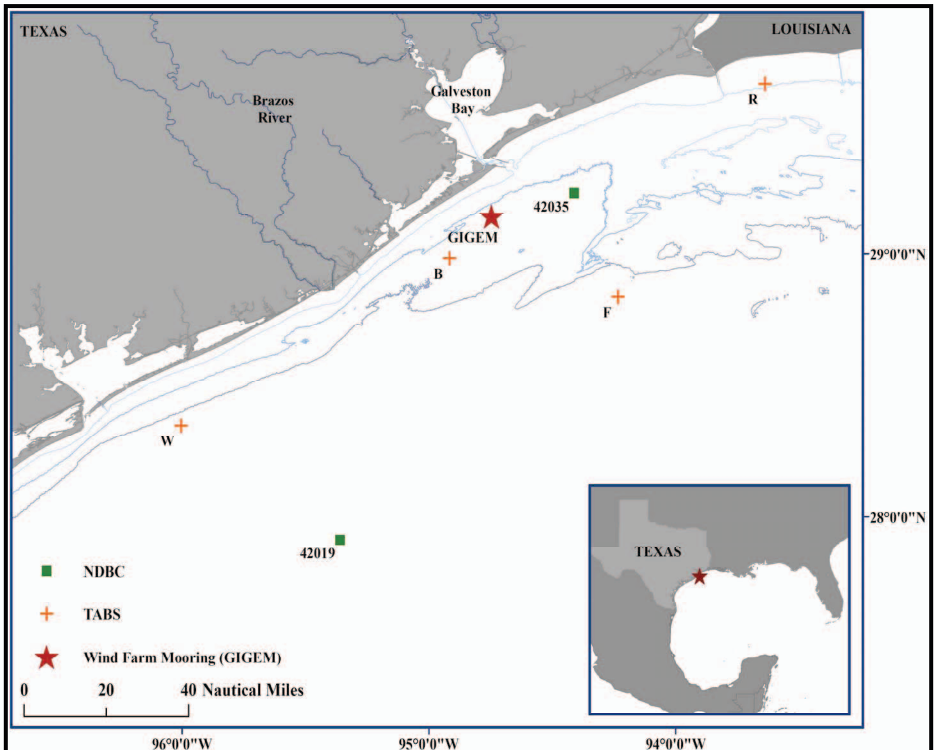

Figure 1. Map Location of the Galveston Instrument Garden for Environmental Monitoring (GIGEM) OOS.

The GIGEM system is location at 29°08'29.654''N, -094°44'51.339''W, 10 miles offshore from the Galveston Bay Shipping Channel and is the only OOS designed to provide a vertical water column profile and water quality data. Surface moorings and buoys operated by NDBC and GERG are within close proximity and are useful for historical data comparisons. Bathymetry lines are mapped 10, 15, and 20 meters outward from the coastline.

A. Hypoxia along the Texas Coast

Hypoxia, defined as dissolved oxygen concentrations of 2.0 mg·l-1(or equivalently 1.4 ml·l-1), is a global problem increasing in severity and frequency due to anthropogenic inputs of nutrients into coastal environments [5] [6]. Hypoxia can have detrimental effects on marine organisms and lead to catastrophic consequences for coastal ecosystems and for local economies that rely on commercial and recreational fisheries resources [7] [8]. Hypoxic events along the Texas Coast were believed to be aperiodic and principally associated with driving mechanisms of the local Texas River discharge and Mississippi and Atchafalaya River effluent [9][10]. The causes of hypoxia in the north Gulf of Mexico are principally derived from anthropogenic sources found in the Mississippi River drainage basin [11]. However, there is considerable evidence that non-Mississippi riverine sources of coastal Louisiana and Texas also play a role in providing organic material and nutrients to the coastal system [12][13][14]. Analysis of water quality data collected by the Texas Parks and Wildlife Department (TPWD) at the heads of the five major freshwater passes along the Texas coast between the years 1985 and 2008 show Texas coastal hypoxia to be frequent, persistent, and capable of occurring at locations that span the TX coast from Sabine to Rio Grande, and independent of the LA hypoxic zone [3]. In the summer of 2007, central Texas experienced an unusually heavy and persistent rainfall leading to inland flooding. Discharge rates increased considerably during this time in response to the rainfall. Discharge of the Brazos River near the coastal city of Freeport, TX, were at or exceeded, historical maximum rates for June and July. This resulted in the stratification of the coastal waters offshore of Freeport and Galveston, TX. The stratification inhibits vertical mixing of the water column. Benthic processes leading to the biodegradation of organic material utilize and deplete dissolved oxygen concentrations near bottom. Due to the lack of vertical mixing, the oxygen depleted benthic waters are not ventilated by the oxygen rich surface waters. Given time, the benthic waters become hypoxic. The Brazos River flooding event established conditions favorable for hypoxia development along the coast. This event lasted approximately two months, before finally dissipating as Hurricane Humberto passed over the shelf, caused a breakdown in the water column stratification, and re-ventilated the oxygen depleted bottom waters.

Despite the event in 2007, historical evidence shows that hypoxia along the TX coast is frequent and not always present in the summer months. Low near-bottom dissolved oxygen concentrations on the inner shelf have occurred in 21 of the last 23 years since 1985, and can last weeks to months. Low concentrations are most frequent during the summer (May-August), but have occurred in all months [3]. The low oxygen results primarily from freshwater discharge locations along the TX coastlines rather than an influx of agricultural fertilizers from farmlands as common to the LA dead zone. The sources of organic material to the TX shelf are still under investigation, but appear to be substantially derived from local estuaries and primary production due to the upwelling off south TX. Areas of relatively large freshwater inflow are commonly found along Galveston, Freeport, and Matagorda resulting in a continuous connection of a potential hypoxic zone along the entire TX shelf. Current surveying activities off coastal TX conducted by TPWD and the National Oceanographic and Atmospheric Administration (NOAA-NMFS SEAMAP) provide coverage of the low oxygen waters on the shelf, but do not investigate the potential processes leading to and sustaining hypoxia formation. One of the major difficulties with investigating aperiodic hypoxic events is the ability to respond efficiently and effectively due to increasing costs for ship time and acquiring appropriate instrumentation. This platform described here fulfills IOOS societal goal by providing a practical solution to aid in better planning and response to potentially harmful events along the TX coast.

B. The Role of Stratification for the GIGEM OOS

In addition to real-time monitoring to address aperiodicity, this platform also is designed to provide a vertical water column profile near the major freshwater influences off the Galveston coast. The physical processes and currents on the TX coast influence vertical stratification and the transport of organic and inorganic material across and along the TX shelf. These processes include wind-driven [15], buoyancy driven [16] [17] [18], sea-breeze/near inertial currents, [19] [20] [21] [22] and upwelling [26]. Current GOM OOS provided detailed surface current observations for the TX coast and have been responsible for identifying and studying the aforementioned processes. However, hypoxia forms in the bottom coastal waters and is a balance between the input of freshwater, nutrients, organic material and stratification [4]. Hetland and DiMarco [24] introduced the concepts of *hypoxic potential* and *stratification envelope* to differentiate between the biological and physical drivers that cause hypoxia. The hypoxic potential represents the amount of organic material available for respiration to fuel hypoxia formation. The stratification envelope is the area of the shelf that is sufficiently stratified to inhibit mixing and the ventilation of lower water layers. We can expect that the hypoxic potential and stratification envelope to vary independently and with characteristic temporal and spatial scales. Thus, hypoxic conditions are variable as the balance shifts between these two indicators and factors influencing the strength of the potential and envelope. When the relative contributions of hypoxic potential and the stratification envelope at a given location are suitable, i.e. oxygen demand exceeding ventilation, hypoxia can occur. This platform provides a unique OOS design to provide observations that will independently quantify the variability of the stratification envelope and the underlying water quality.

II. METHODS

A. Mooring and Platform Design

This state-of-the-art OOS is the first to monitor the water and biological quality of the TX coastal ocean. There are two main components to the system: underwater mooring and bottom package instrumentation. The system was deployed over three single-day trips between May to June 2009 and fully operational on June 23, 2009. The system will remain deployed until fall 2009, when it will be recovered for servicing and calibrations and redeployed in May 2010. Fig. 2 illustrates the instrument lay-out under the sea surface and the communication channels and distance relationship to the platform. Starting from the sea floor, a bottom mounted upward-looking Aanderaa 600 kHz acoustic Doppler current profiler (housed in a trawl resistant bottom mount, TRBM) sits on the bottom and provides estimates of current velocity and backscatter throughout the water-column. Directional waves spectra, temperature, salinity, dissolved oxygen concentration, and pressure are also collected by additional sensors on the acoustic current profiler.

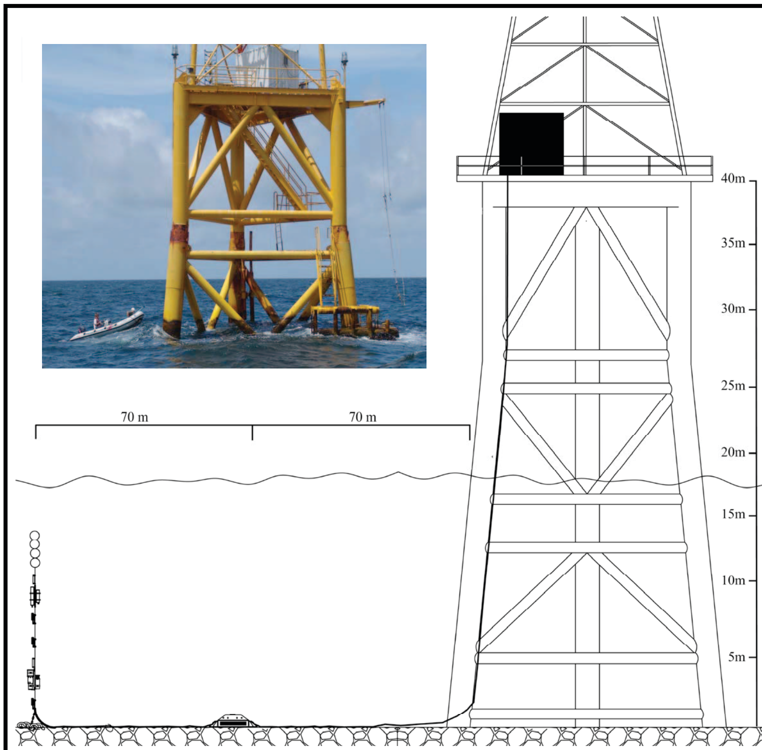

Figure 2. Schematic of GIGEM System.
There are two components to the GIGEM design: the mooring and the platform. The mooring is approximately 140 meters outward and is connected to the RDCP, which is approximately 70 meters from the platform. The system is connected by underground cables to the surface inductive modem and instrument housing (*black box*) on the standing level of the platform. Housed on the platform is the computer system and satellite equipment for real-time communication with TAMU.

On the sub-surface mooring, several instruments are distributed throughout the water column, which include sensors for dissolved oxygen, temperature/salinity, and nutrient (nitrate). These are distributed above and below the pycnocline on the mooring roughly 40m from the TRBM. Seabird Electronics SBE-37IMP-IDO MicroCats equipped with dissolved oxygen sensors are positioned above and below the pycnocline. The dissolved oxygen sensors on these instruments are frequency output versions of the SBE 43 dissolved oxygen sensor used on the Seabird CTD profilers.

Nutrient measurements are taken by two different sensors for quality assessment. Nitrate concentration will be determined using either an Envirotech NAS-3E nitrate analyzer or Satlantic ISUS nitrate sensor. The NAS analyzer uses the standard cadmium reduction method for nitrate analysis [25]. The Satlantic system in contrast uses multiple wavelength UV spectrophotometry to measure the nitrate concentration directly.

Data from the system is telemetered to shore in near real time using a combination of inductive, and satellite communications packages (Fig. 3). The design and implementation of the inductive modems is the reason that this mooring design is unique compared to other similar coastal OOS. The Seabird MicroCats have the inductive modems integrated into the datalogger electronics, while the other instruments on the mooring line and at the bottom use Seabird SBE44 Underwater Inductive Modems to transmit data from the instrument to an IMM nodal interface. A controller is utilized specially for this design to allow for unique communication with underwater electromagnetic transceivers. An inductive cable coupler combines data from each instrument's inductive modems and transmits data along an encased ground line to a self-contained miniature control computer housed on the platform. At the platform, incoming data are relayed in real-time to the shore using a satellite communications package, Garmin Global Positioning System and Globalstar Satellite Data Modem, similar to that used by the TX Automated Buoy (TABS, tabs.gerg.tamu.edu) program.

B. Quality Assurance/Quality Control (QA/QC)

Data are downloaded from the Globalstar modem and into the GERG laboratories and undergo two orders of QA/QC. The first order involves outlier removal in the data series and statistical comparisons of the datasets based on manufacturer specifications. Outlier removal includes both statistically significant and gross outlier removals. The statistical control includes data series comparisons with historical limits and with calibration coefficients resulting from laboratory tests before deployment. Additionally, the data undergoes identification of long-term trends and evidence of bio-fouling based on previous measurements with TABS moorings. The second order QA/QC involves advanced statistical analysis, including the partitioning of variance and post-calibrations of datasets after mooring recovery [26].

Data are transformed into graph products and displayed for public access on a website monitored by the Department of Oceanography and the Geochemical and Environmental Research Group (GERG) at TAMU (http://tabs.gerg.tamu.edu/hypox/). Current measurements are received on the hour and oxygen concentrations and nutrients are received on the half-hour during a 24-hour day. Before publication to data products, the data undergo calibration corrections specific to the instrument-type and are compared with the TABS measurements to determine the quality of the measurements. The QA/QC procedures also help to determine the maintenance cycle for the instrumentation, as well as help to identify potential offsets primarily with the oxygen and salinity measurements. The data are formatted into functional American Standard Code for Information Interchange (ASCII) files describing the time, depth, and parameter relayed by the mooring computer. The individual files then undergo transformation to a real-time series of graphs displayed on the webpage and are combined with an existing

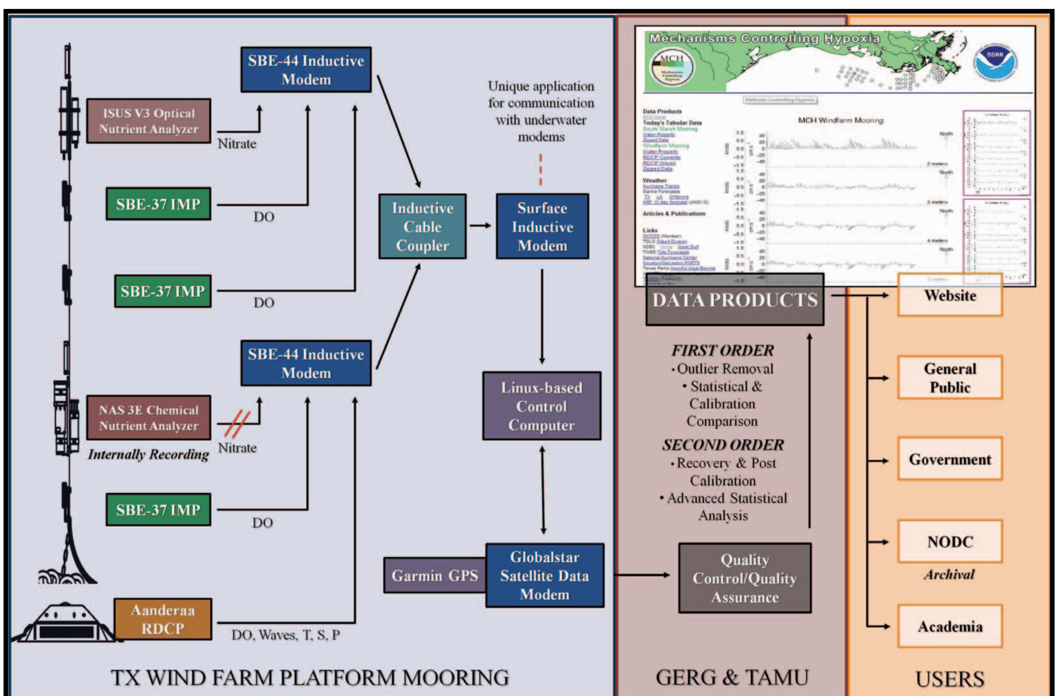

Figure 3. Information Transfer From GIGEM System to the Users
The flowchart shows the GIGEM design and transfer of data through the intricate modem systems into the unique adaptation of the surface inductive modem. This modem has been configured to allow for seamless communication between air and saltwater interfaces as data travels from offshore Galveston into TAMU for QA/QC before dissemination of information to a variety of users.

file of data. Therefore, an updated file containing the deployment is placed in a zipped folder accessible to the public on the aforementioned website. Products published on the website include weekly-truncated series of depth categorized current profiles, wave characteristics (period, energy, height), and water quality (temperature, salinity, dissolved oxygen, nutrients) plots. The products are updated on the quarter-hour during a 24-hour day and the larger data series is uploaded every 24 hours. Data are additionally distributed to the GCOOS [27] and served via the web through the GCOOS Data Portal, the National Data Buoy Center (NDBC), archived to the National Ocean Data Center (NODC).

C. Mooring Deployment

Construction and deployment was organized into a multi-stage effort extending over the course of six to eight months. Initial collaborations were discussed between WEST and Department of Oceanography at TAMU to utilize a wind energy observational platform as the mooring base (Fig. 2). The observational platform is designed to collect atmospheric data for future wind turbine installations off the Galveston coast. As the design was laid out, instruments were purchased by TAMU and GERG and assembled by a series of GERG technicians on-site at TAMU. The intricate communication system between the instruments and the inductive modems were programmed and tested at GERG facilities by undergoing numerous submersion trials in small pools and performing calibrations in freshwater and saltwater standards.

Deployment to the platform was the next stage and consisted of three one-day cruises aboard rented vessels based in Galveston or aboard the NOAA *R/V Manta*. Initially, deployment was budgeted as one cruise; however ship time, safety constraints, and weather forced this stage into three separate day trips. The goal of the first trip was transporting and securing the computer system on the platform and the mooring. The second trip consisted of deploying the bottom-mounted TRBM with RDCP and securing the cable system from the computer to the bottom package. Due to inclement weather, divers were unable to safely complete the second goal of this cruise, resulting in the third trip. The third cruise completed the connections between the major components by connecting the mooring to the bottom package and by connecting the communication cables between all sensors and the computer on the platform. The cruise was completed after successful communications between the modems, computer, and transfer of data back to GERG laboratories at TAMU. The next stage is the on-going QA/QC processing and data analysis from the mooring to investigate processes controlling TX hypoxia and ocean observing educational efforts through interactive website monitoring. The final stage of this year will be the recovery of the mooring for servicing and storage until deployment next May 2009 as it is the intention to develop a multi-year water quality observing system off the Galveston coast.

III. RESULTS

The primary goal for this OOS is to investigate the processes affecting TX coastal hypoxia and to develop future OOS to determine the extent of Gulf of Mexico hypoxia and forecast future hypoxic events based on water quality. Considerable effort focuses on joining real-time data with historical data to build a comprehensive database for the TX coastal hypoxia. Sources of the historical data include water quality (nutrients, optical, particulate) and hydrographic (CTD) data of the TX-LA Shelf, time-series of moored instrumentation, and available NOAA, Oceansat, and NASA imagery. The data will come from several large federal and state funded research projects including: NOAA NECOP, NOAA SEAMAP, TPWD, TGLO – TABS, MMS LATEX, and NOAA NGOMEX. The real-time component of the database is derived from the GIGEM OOS, which has successfully been recording and transmitting since June 23, 2009.

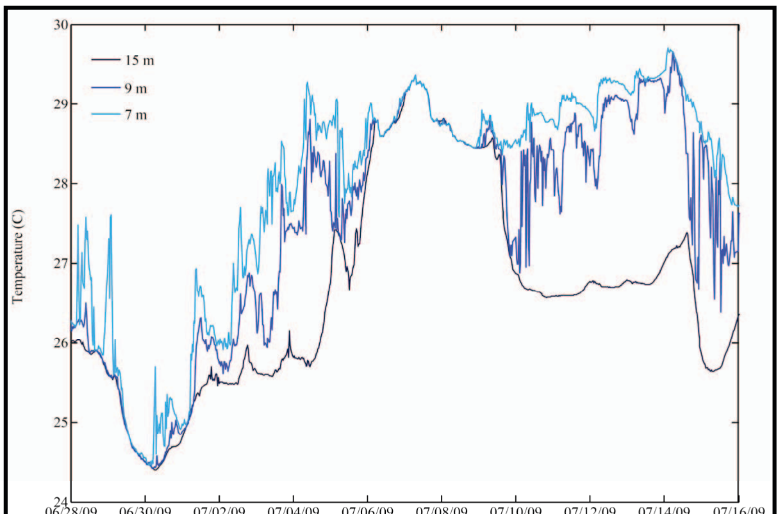

Figure 4. Temperature Profiles for GIGEM System Mooring Instrumentation. Temperatures at the three depths are variable and range from 24 to 29.7°C. Instruments record at three depths: 7, 9, and 15 meters indicated by the light to dark blue line coloration. The 15m profile shows long period variability of greater than 24hrs whereas the 7m profile details a shorter period of less than 24 hrs. The middle depth, 9m, shows the greatest variability due to proximity to the pycnocline.

A. GIGEM OOS Results

Data archived from the OOS includes temperature (T), salinity (S), and dissolved oxygen (DO) profiles for 4 depths: 7, 9, 15, and 16 meters (Figs. 4, 5, 6, & 7). The shallowest depths are the mooring instrument locations and the deepest depth is of the instrument package containing the RDCP. Current velocities are recorded with a bin size of 1 meter. The wave height, peak wave period, and energy period are estimated from pressure and current velocity measurements. The mean period and mean zero crossing is calculated and displayed on the Internet with other data products (Fig 3).

The deployment and transmission were successful for all the parameters listed as no data were lost due to interruption in communication or catastrophic instrument failure. Data integrity for the 16 meter is still being analyzed as outlined in the QA/QC section. The nutrient data are not being transferred from either the ISUS V3 Optical Nutrient Analyzer of the NAS 3E Chemical Nutrient Analyzer was not available. Due to the sensitivity of the pump and filter for this system, it was initially planned, but not deployed on the mooring. Additionally, real-time communication to the NAS 3E Chemical Nutrient Analyzer, but the system is internally recording the nutrient data. During recovery and after the completion of post-calibrations, the data will be downloaded directly from the instrument, processed for QA/QC, and distributed to the Internet or disseminated to appropriate users. Complications with data recovery for the NAS 3E Chemical Nutrient Analyzer are not anticipated because this is a common analyzer for numerous TAMU and GERG projects.

B. Data Analysis Results: T, S, & DO

Temperature profiles for mooring are plotted in Fig. 4 from the start of transmission until July 16, 2009. The T record was truncated for this publication. Temperature for the water column ranges between 24 and 29.7 degrees Celsius. The near-bottom (15m) temperature record shows long period (greater than one day) variability associated with mesoscale shelf circulation changes where warm and salty water from the southwest shelf moves upcoast toward the Louisiana shelf. This tends to weaken stratification and ventilate bottom waters, this increasing subpycnocline oxygen values. The surface-most (7m) temperature record exhibits long period variability with shorter period (less than one day) variability superimposed. The short period variability is thought to be associated with daily heating and cooling, as well as shoreward/seaward movement of the coastal freshwater surface front. The front dynamics are thought to be influenced by tidal current variability [28], sea/land breeze forcing [20] [21] [22], and upwelling/downwelling favorable wind events. The temperature record at 9m shows the most variability with characteristics found in both the 7m and 15m records, plus additional short period variability. The increased variability is likely due to the proximity of the sensor to the pycnocline and the associated vertical movement of the pycnocline.

The S and DO mooring data are displayed in Figs. 5 and 6 for two 7-day periods. The first period begins June 29, 2009 and extends until July 7, 2009. The salinity values at different depths are coherent and nearly equal for the first half of the time period and gradually separate toward the end of the time period. The 15m profile remains constant at 35.25 increasing slightly near the end of the time period. The 7m and 9m profiles are coherent for the duration of the 7 days, the exception being about 24 hours on June 3, 2009. The associated DO records are plotted below the S records and show a uniform decrease in concentration during the first three days of the period and gradually increasing during the last three days. The lowest values approach the hypoxic DO level, but do not cross 2.0 mg/l. As a course proxy for water column stability, the difference in S (ΔS) between the 7m and 15m profiles is also plotted with the DO profiles. However, we note that because the shallowest salinity estimate is from 7m below surface, a significant part of the upper water column is not observed. We have used salinity observations from the nearby TABS Buoy B (Fig. 1), which has a salinity sensor 1.5 m below surface to assist with interpreting total water column stratification. The salinity difference time-series (Fig. 5) is near zero, indicating little stratification during the first three days of the record. Comparison with the salinity record at TABS Buoy B, shows that a freshwater signal was present in the upper water column. Therefore, the pycnocline was above the 7-m instrument and inhibited ventilation of the lower layers. As a result, all three GIGEM DO sensors recorded very low values. The salinity difference is positive, indicating stratification of the water column, during the second half of this 7-day period, however, larger

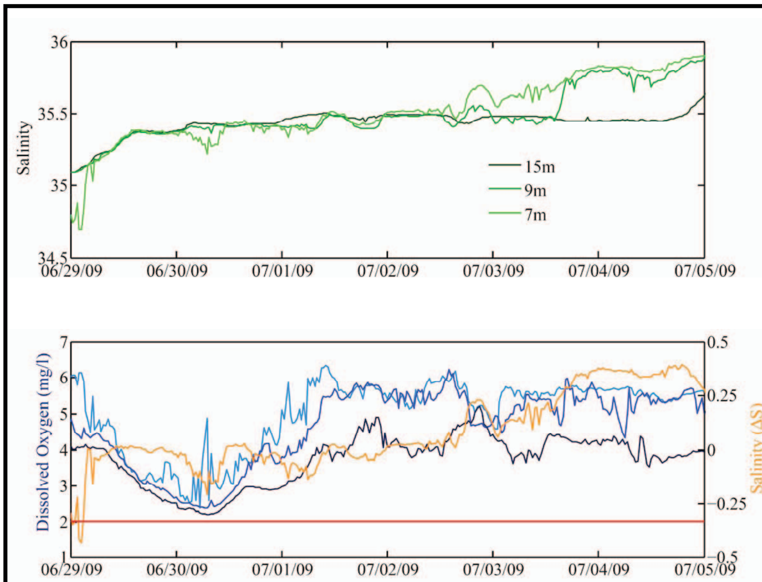

Figure 5. Salinity and Dissolved Oxygen Profiles for the GIGEM Mooring Instrumentation.

The top figure is the salinity profiles for the mooring with the depths labeled. The bottom graph plots dissolved oxygen concentrations at 7m (light blue), 9m (royal blue), and 15m (navy blue). The red line indicates the dissolved oxygen concentration (2.0 mg/l) for hypoxic conditions. Also on the lower panel is a measure of the water column stratification, calculated as the difference between the bottom profile (15m) and near-surface profile (7m). The 7m and 9m profiles are more variable than 15m in both panels. No hypoxia was measured over the 7- day time period from June 29 to July 5, 2009.

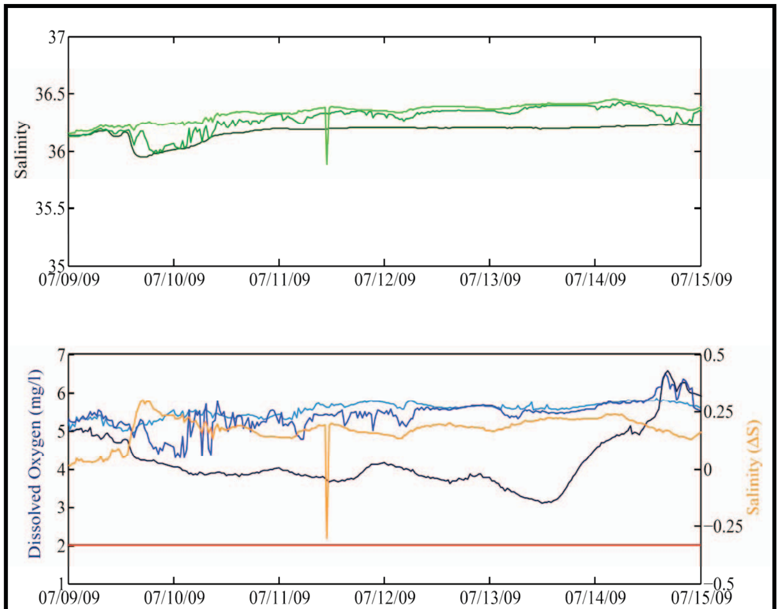

Figure 6. Salinity and Dissolved Oxygen Profiles for the GIGEM Mooring Instrumentation.

The top figure graphs the salinity profiles for the mooring with the depths labeled. The bottom graph plots dissolved oxygen concentrations at 7m (light blue), 9m (royal blue), and 15m (navy blue). The red line indicates the dissolved oxygen concentration (2.0 mg/l) for hypoxic conditions. Also on the lower panel is a measure of the water column stratification, calculated as the difference between the bottom profile (15m) and near-surface profile (7m). The 7m and 9m profiles are more variable than 15m in both panels, and show a sharp peak in surface salinity. No hypoxia was measured over the 7-day time period from July 9 to July 15, 2009.

salinity values were found higher in the water column. The unstable situation also promotes vertical mixing and as a result, no near-hypoxic conditions were observed.

Another 7-day period in the middle of July 2009 starting at July 9 and ending July 15 is similarly represented in Fig. 6. The S and DO records depict oceanographic conditions that are different as compared to the first series of Fig. 5. During this period, each S record is coherent with les variability, with range from 36 to 36.5. This record occurs in mid-July, when the annual summer coastal current reversal occurs along the TX coast (Vastano et al., 1996, Nowlin et al. 2005). Therefore, the relatively high salinity waters throughout the water column are likely derided from the southern shelves. The near-bottom record experiences a sharp decrease late in July 9, 2009, then increases to a nearly constant 36.2 for the remainder of the period. The 9m record is similar to that at 15m. However, the 7m profile remains constant and near 36.3 for the time period, except for a spike late July 11, 2009 falling to approximately 35.8. This spike is not an outlier as determined during the QA/QC process and is also seen in the ΔS profile in the plot beneath. Further, analysis of this spike and others like it in the record will be evaluated during post-QA/QC. The DO records are less variable and generally higher concentrations during this time period than the previous period. The 7m and 9m profiles are similar in concentrations with the exception of short period (less than one day) variability on July 10, 2009. The 16m profile falls and fluctuates between 3.0 and 4.0 mg/l until the end of the 7-day window before becoming oxygenated and reaching values found in the 7m and 9m record.

IV. DISCUSSION & FUTURE DIRECTIONS

A. GIGEM OOS Discussion & Future Directions

To date, this OOS has been successful in providing real-time environmental water quality data aiding in the investigation of TX coastal hypoxia. The location is ideal for environmental studies in the Galveston coastal waters due to the spatial proximity to the Brazos River discharge and seasonal flow up-coast, as well as the down-coast flow of water from Galveston Bay. Though the primary focus is hypoxia, the data are useful for studying the oceanic response to atmospheric events passing over the location, and assistance with oil spill recovery and emergency response. The RDCP and wave data are useful in examining the coastal surface currents to identify and monitor physical processes and historical currents, as well compare to additional regional OOS in the proximity. This physical data will also be effective for accomplishing the IOOS multidisciplinary coastal monitoring objectives and achieving the ability to fulfill all seven societal goals.

The GIGEM OOS is a valuable array and had an extremely successful first deployment. The entire water column package will be recovered in the fall months and brought back for calibration, modifications, and winter storage at TAMU. Considerations were entertained for not recovering the OOS, but rather performing routine maintenance throughout the year. However, due to the unpredictable nature of severe weather in the northern Gulf of Mexico, it was decided that full recovery would be most feasible option. We hope to continue the operation of this system in the future. We have proposed to deploy the GIGEM in May 2010 in the same location to continue efforts for the long-term environmental monitoring off Galveston Bay. The planning, operational set-up, and deployment were designed for simple and rapid turn around and can be accomplished in one cruise contingent on vessel availability and weather. This design and unique incorporation of the surface inductive modem provided the foundation for developing the first real-time environmental monitoring along the TX coast. This system design can be easily adapted to various types of platforms and will be extremely effective in the IOOS ‘system of systems’. The design and applications are not specific to coastal hypoxia, but will also be useful for researchers searching for a real-time method for investigating vertical water column processes in coastal environments.

B. Data Discussion & Future Directions

The primary scientific focus of the GIGEM OOS is providing insight into the processes controlling TX coastal hypoxia. Though the nutrient data are not available at this time, the real-time T, S, and DO profiles provide valuable insight of the vertical water column processes. The T profiles at the three depths show an oscillating transfer of thermal energy, which is further magnified after demeaning the data series. Initial analyses show energy transfer in time, but also with depth as thermal energy propagates vertically over period of approximately 24 hours. Further investigations will quantify the temporal and spatial cycles for this location and assist in developing a seasonal thermal profile for this location. The water column temperatures will also be compared with atmospheric data collected from the GIGEM platform and assist in isolating atmospheric disturbances responsible affecting the water column stratification. Additional instrumentation for further insight into the processes responsible for coastal hypoxia is also envisioned. These include the deployment of bio-optical fluorescence and turbidity sensors, phytoplankton counters, and benthic landers to measure respiration rates. Ultimately, the parameters estimated will be used as skill assessment for a suite of coupled physical-biological-geochemical-sediment numerical modeling element that is concurrently underway. The modeling component promises to offer a powerful predicative and diagnostic tool for coastal program managers.

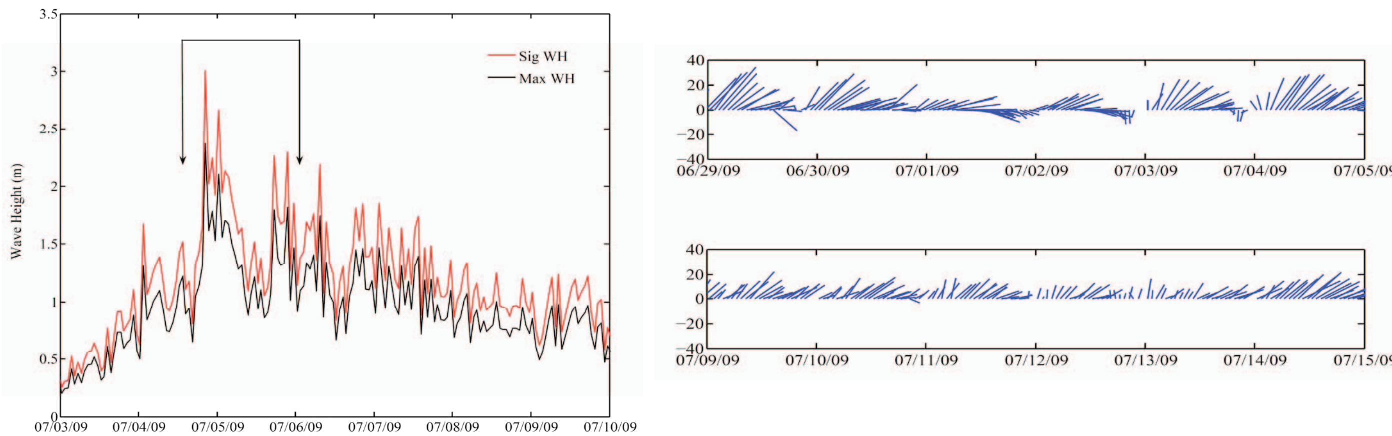

Figure 7. Wave Heights and Current Velocities from the GIGEM RDCP over 7-day Windows.
The signification and maximum wave heights and current velocities from the 3m bin are plotted. The wave data on the left plot shows the influence of atmospheric winds on the near-surface measurements from GIGEM instruments. The arrows highlight the passing of a short-lived atmospheric front passing over GIGEM location. This front forced mixing vertically in the water column disrupting low dissolved oxygenated bottom waters. The figure on the left shows the corresponding 3m bin current velocities in centimeters per second. The times on the x-axis correspond to the same time periods represented in Figs. 5 and 6. As with the water quality data, the near-surface current velocities are also variable and further emphasize the lack of persistent stratification in the water column resulting in no observed hypoxic events.

The well-mixed water column for the majority of the summer is due to unusual weather, especially a series short-lived frontal passages crossing over the OOS location. These series of fronts interrupted the seasonal offshore wind patterns typical for the TX coast and provided the energy to cause vertical mixing in the water column. Examples of these fronts were seen in the current velocity and wave profiles (Fig. 7) recorded by the GIGEM OOS. Additional analysis will be conducted to investigate and quantify the frequency and magnitude of these events and their quantitative role in controlling stratification.

This manuscript provides an initial insight in the role this OOS plays for investigating TX coastal hypoxia. Future efforts for the data include compiling profiles for the deployment durations and advanced statistical analyses to quantify parameter spatial and temporal variance at this particular location. The current and future data from this system is an integral component for determining the role of stratification in hypoxic events. The analyses results will build a comprehensive picture of how water quality and stratification interact to lead to and sustain aperiodic hypoxic events in the TX coast. The data and analyses resulting will be incorporated into a larger Gulf of Mexico database at TAMU for advancing the efforts investigating the role of hypoxia in the LA and TX coastal waters. More so, it is a future goal to continue deployment of similar systems throughout the LA and TX coastal waters for providing additional sources of environmental data imperative to understanding the role hypoxia in the Gulf of Mexico and to successfully monitor event occurring in real-time rather than relying on vessel response efforts. The GIGEM OOS is a successful and obtainable solution for such types of environmental monitoring goals and the design will serve as a strong template for future systems.

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REFERENCES

[1] "An Integrated and Sustained Ocean Observing System (IOOS) for the United States: Design and Implementation," in *Ocean.US.2000b,* vol. 2. Virginia: Ocean.US Publication, 2000, pp. 1-21. (Available at http:www.ocean.us)

[2] L.C. Bender et al., "Development, operation, and results from the Texas Automated Buoy System," *Gulf of Mexico Science*, vol. 1, pp. 33-60, 2007.

[3] S.F. DiMarco et al., "Climatology of hypoxia on the Texas coast: 1985-2008," 2009, unpublished

[4] N.N. Rabalais, et al., "Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia? " *Estuaries and Coasts*, vol. 30(5), pp. 753-772, 2007.

[5] R.J. Diaz and R. Rosenberg, "Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna," *Oceanography and Marine Biology Annual Review*, vol. 33, pp. 245-303, 1995.

[6] R.J. Diaz and R. Rosenberg, "Spreading Deadzones and consequences for marine ecosystems," *Science*, vol. 321, pp. 926, 2008.

[7] D.F. Boesch, "Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems," *Estuaries,* vol. 25, pp. 744-758, 2002.

[8] R.J. Diaz et al., "Proc. 7th International Symposium on Fish Physiology, Toxicology and Water Quality, Tallinn Estonia," in *U.S. EPA 600/R-04/049,* G.L. Rupp and M.D. White, Eds., Georgia, 2003, pp. 1-33.

[9] D.E. Harper Jr., L.D. McKinney, J.M. Nance, and R.R. Salzer, "The occurrence of hypoxic bottom water off the upper Texas coast and its effect on the benthic biota," *Contributions in Marine Science*, vol. 24, pp. 53–79,

[10] D.E. Harper Jr., L.D. McKinney, J.M. Nance, and R.R. Salzer, "Recovery responses of two benthic assemblages following an acute hypoxic event on the Texas continental shelf, northwestern Gulf of Mexico," In *Modern and Ancient Continental Shelf Anoxia***,** vol. 58, R.V. Tyson and T.H. Pearson, Eds. London: The Geol. Soc., pp. 49–64, 1991.

[11] Science Advisory Board, "Hypoxia in the northern Gulf of Mexico: An update by the EPA Science Advisory Board," *EPA-SAB-08-003*, Washington D.C., 2008.

[12] T.S. Bianchi et al., "Controls and consequences of hypoxia on the Louisiana Shelf (USA): Beyond the nutrient-centric view," *EOS*, vol. 89(6), pp. 236-237, 2008.

[13] T.S. Bianchi, S.F. DiMarco, R.W. Smith, K.M. Schreiner, "A gradient of dissolved organic carbon and lignin from Terrebonne-Timbalier Bay estuary to the Louisiana shelf (USA)," *Marine Chemistry*, 2009, in press.

[14] R. Green, T.S. Bianchi, and M.J. Dagg, "An organic carbon budget for the Mississippi River turbidity plume and plume contributions to air-sea CO2 fluxes and bottom water hypoxia," *Estuaries*, vol. 29, pp. 579-597, 2006.

[15] A.C. Vastano, C.N. Barron Jr., E.W. Shaar Jr., "Observations of the Texas Current," *Continental Shelf Research*, vol. 15(6), pp. 729-754, 1995.

[16] J.D. Cochrane and F.J. Kelly, "Low-frequency circulation on the Texas-Louisiana continental shelf," *Journal of Geophysical Research*, vol. 91, pp. 10645-10659, 1986.

[17] K. Cho, R.O. Reid, W.D. Nowlin Jr., "Objectively mapped stream-function fields on the Texas-Louisiana Shelf based on 32 months of moored current meter data," *Journal of Geophysical Research*, vol. 103, pp. 10377-10390, 1998.

[18] W.D. Nowlin Jr., A.E. Jochens, R.O. Reid, and S. F. DiMarco, 1998. "Texas-Louisiana Shelf Circulation and Transport Processes Study: Synthesis Report, Volume I: Technical Report," *OCS Study MMS 98-0035.* U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region*,* New Orleans, LA. 502 pp.

[19] C. Chen, R.O. Reid, and W.D. Nowlin, Jr., "Near-inertial oscillations over the Texas-Louisiana Shelf," *Journal of Geophysical Research*, vol. 101, pp. 3509 -3524, 1996.

[20] S.F. DiMarco, M.K. Howard, and R.O. Reid, "Seasonal variation of wind-driven diurnal cycling on the Texas-Louisiana continental shelf," *Geophysical Research Letters*, vol. 21(7), pp. 1017-1020, 2000.

[21] X. Zhang, S.F. DiMarco, D.C. Smith IV, M.K. Howard, and A.E. Jochens, "Near-resonant ocean response to sea breeze on a stratified continental shelf," *Journal of Physical Oceanography*, 2009, in press.

[22] X. Zhang, D. Smith IV, S.F. DiMarco, and R.D. Hetland, "A numerical study of sea breeze driven ocean *Poincare* wave propagation and mixing near the critical latitude," *Journal of Physical Oceanography*, 2009, in press.
[23] N.D. Walker, "Wind- and Eddy-Related shelf/slope circulation processes and coastal upwelling in the northwestern Gulf of Mexico," In *Circulation in the Gulf of Mexico: Observations and Models*, W. Sturges and A. Lugo-Fernandez Eds. San Francisco: AGU Geophysical Monograph Series, 2005, pp. 295-314.
[24] R.D. Hetland and S.F. DiMarco, "How does the character of oxygen demand control the structure of hypoxia on the Texas-Louisiana Shelf?" *Journal of Marine Systems*, vol. 70, pp. 49-62, 2008.
[25] J.D.H. Strickland and T.R. Parsons, "A practical handbook of seawater analysis, 2nd ed.," *J. Fish. Res. Bd. Canada*, vol. 167, pp. 167-311, 1972.
[26] S.F. DiMarco, A.E. Jochens, M.K. Howard, "LATEX A Data Report: Current Meters Vol I. thru X," *TAMU Department of Oceanography Ref. No 97-1-T*, pp. 1-3800, 1998.
[27] M. K. Howard, F.C. Gayanilo, and A.E. Jochens, "Establishing the GCOOS Regional Association's Data Portal," *MTS OCEANS 2009 Proceedings*, this volume, 2009.
[28] S.F. DiMarco and R.O. Reid, "Characterization of the principal tidal current constituents on the Texas-Louisiana Shelf," *Journal of Geophysical Research – Oceans*, vol. 103(2), pp. 3093-3110, 1998.