

**MONITORING THE EXTENT OF THE DEAD ZONE IN THE GULF OF
MEXICO WITH GLIDERS**

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Monitoring the extent of the Dead Zone in the Gulf of Mexico with gliders. (May 2015)

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The Gulf of Mexico Coastal Hypoxia Glider Experiment was designed to test the feasibility of using ocean glider technology in the coastal hypoxic zone of the northern Gulf of Mexico between 10 July and 1 October 2014. The objectives were 1) to coordinate and operate multiple autonomous buoyancy ocean gliders and 2) to test methodologies and strategies for objective mapping of the hypoxic zone. The coastal area of the northern Gulf of Mexico is characterized by strong vertical and horizontal stratification gradients, strong coastal currents, and low oxygen conditions that occur within the lower water column. These environmental conditions combine with the presence of more than 5,000 surface piercing oil/gas structures to make piloting and navigation in the region challenging. I present preliminary observations of the experiment to quantify glider performance (forward speed, vertical cycling (yo) frequency, distance above bottom, and ability to navigate between waypoints). Science data (CTD (conductivity, temperature, and depth), ECOPUCK (chlorophyll and CDOM (colored dissolved organic matter) fluorometer), and Rinko dissolved oxygen) were plotted and analyzed, showing that the gliders consistently came within 1.6 meters of the ocean bottom. The pycnocline, below which hypoxia occurs, was successfully found by each of the gliders, demonstrating that this 1.6 meter distance gives sufficient water column data to monitor coastal hypoxia.

DEDICATION

I would like to dedicate this thesis to my loud, loving, and amazing parents, Bill and Angela Ramey. They have sat through hours of me practicing presentations, proofread countless drafts of my academic papers, and have always gone out of their way to help me when I needed it the most. Without their support, I never would have undertaken the challenge of writing an undergraduate thesis.

Mom, thanks to you Spain was the most memorable trip of my life. From wine tastings, to salsa dancing, to limnology presentations, sleepless nights and long bus rides, to egg sandwiches in bed; every moment was a blast. Pop, thank you for sending my best friend across the Atlantic Ocean with me. I wish you could have been there too.

Thank you guys for everything; you really are the best.

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Also influential were the Texas A&M University (TAMU) College of Geosciences and its Department of Oceanography, as well as the TAMU Vice President for Research. A special thanks goes to Emily Dykes and Dr. Christian Brannstrom for their role in awarding me a College of Geosciences scholarship for my trip to Spain.

A huge thanks goes to my research advisor, Dr. Steve DiMarco, without whom I likely would not have gotten involved in undergraduate research. His passion for data and its ethical representation piqued my interest in his research. Every day in class, he would come in and share some new tidbit about what was happening with his research. I was so happy to become a part of that work. By providing me the opportunity to perform my research under him, I have had an extremely enriching undergraduate research experience. My time at Texas A&M University would not have been the same without learning to make movies in MATLAB and getting to the point where I can construct multiple data histograms on the fly. I cannot thank him enough for the opportunities he has given to me over the last year and a half, especially being able to present

my research at the ASLO Aquatic Sciences meeting in Granada, Spain. That was the experience of a lifetime.

I also must thank Dr. Matt Howard for his patience and assistance with my data analyses when Dr. DiMarco was out of town. I would not have made some of my deadlines without his help.

Thank you also to the wonderful glider pilots Heather Zimmerle and Karen Dreger for providing me with information when I needed it, as well as for their support and guidance over the last two semesters.

NOMENCLATURE

CDOM	Chromorphic Dissolved Organic Matter
CTD	Conductivity, Temperature, and Depth
DO	Dissolved Oxygen
hPa	Hectopascal
HTF	Hypoxia Task Force
L	Liters
MCH	Mechanisms Controlling Hypoxia
mg	Milligrams
mL	Milliliters
NGOMEX	Gulf of Mexico Ecosystems and Hypoxia Assessment
NOAA	National Oceanic and Atmospheric Association
NTU	Nephelometric Turbidity Unit
ppb	Parts Per Billion
yo	a single downward inflection, and a single upward inflection
°C	Degree(s) Celcius
µg	Micrograms
µS	Microsiemens

CHAPTER I

INTRODUCTION

1.1 Factors Controlling Hypoxia

The hypoxic zone in the Gulf of Mexico has been a significant subject in American science and policy for decades. Hypoxia (oxygen depletion) is defined as those waters with dissolved oxygen (DO) concentrations less than 1.4 mL/L, or equivalently 2.0 mg/L (*Rabalais et al.*, 2007; *Bianchi et al.*, 2010; *DiMarco et al.*, 2012; *Obenour et al.*, 2012, 2013). The hypoxic zone of the northern Gulf of Mexico is the largest coastal hypoxic zone in the western hemisphere (*Rabalais et al.*, 2002b, 2007; *Bianchi et al.*, 2010; *Obenour et al.*, 2013). It is driven by the combined effects of high phytoplankton growth fueled by high nutrient fluxes and strong local stratification from high freshwater discharge of the Mississippi River in the late spring (*Bianchi et al.*, 2010; *Obenour et al.*, 2013). Every summer, coastal hypoxia occurs on the Texas-Louisiana shelf when this high nutrient input from the Mississippi and Atchafalaya River System combines with strong vertical stratification exacerbated by freshwater discharge to cause sub-pycnocline oxygen depletion of coastal waters (*Wiseman et al.*, 1997; *Rabalais et al.*, 2002a, 2007; *Hetland and DiMarco*, 2008; *Bianchi et al.*, 2010; *Dale et al.*, 2010; *DiMarco et al.*, 2012).

Figure 1 shows the surface phytoplankton distribution in the northern Gulf of Mexico. High phytoplankton productivity prompted by high nutrient fluxes increases the flux of organic material to the lower water column through sinking cells and zooplankton fecal pellets (*Walsh et al.*, 1989; *Diaz et al.*, 2004; *Bianchi et al.*, 2010). The strength of the pycnocline then prevents oxygen from diffusing down from the upper mixed layer so that respiration causes oxygen

depletion at the bottom (*Diaz et al.*, 2004; *Rabalais et al.*, 2007; *Diaz and Rosenberg*, 2008; *Bianchi et al.*, 2010; *DiMarco et al.*, 2012; *Hetland and DiMarco*, 2012; *Obenour et al.*, 2013). These depleted oxygen levels make life in such an area difficult to impossible for other marine organisms (*Breitburg*, 2002; *Rabalais et al.*, 2007; *Bianchi et al.*, 2010). Such a hypoxic zone is exacerbated by significant water column stratification in the summer months, primarily from greater surface water heating due to higher temperatures along with freshwater runoff from the Mississippi River decreasing the salinity of the surface water and further preventing vertical mixing within the water column (*Diaz et al.*, 2004; *Hetland and DiMarco*, 2008; *Bianchi et al.*, 2010; *DiMarco et al.*, 2012). In fall, strong winds and declining freshwater volume break down the stratification and ventilate bottom waters. Hypoxia is typically found near bottom in stratified waters of 10-40 meters total depth (*Dale et al.*, 2010).

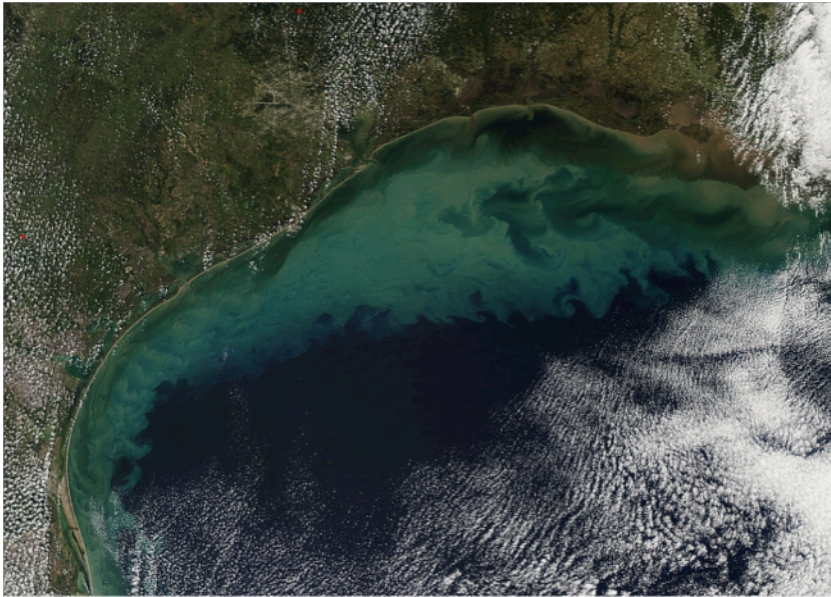


Figure 1. Surface phytoplankton distribution in the northern Gulf of Mexico, true color MODIS satellite image.

1.2 Impacts of Hypoxia in the Northern Gulf of Mexico

Generally, the presence of sustained or recurring hypoxic conditions can negatively impact coastal ecosystems (*Rabalais et al.*, 2002b; *Obenour et al.*, 2012). Hypoxia is recognized as one of the greatest worldwide threats to fishery productivity (*Breitburg*, 2002; *Diaz et al.*, 2004). The northwestern Gulf of Mexico supports some of the United States' "most important commercial and recreational fisheries, which annually generate over \$2 billion" (*O'Connor and Matlock*, 2007). The current Gulf hypoxic zone exists in what was an area of high fisheries productivity area from the mid-twentieth century (*Moore et al.*, 1970). Hypoxia contributes to habitat shift and loss of some shrimp species that are important in marine fisheries (*Zimmerman and Nance*, 2001; *Craig and Crowder*, 2005). Due to its recurring large size and proximity to commercially and recreationally important fishing areas, the hypoxic zone has garnered considerable scientific and management attention. Furthermore, the hypoxia problem has impacted watershed management of source waters of the Mississippi River, which is a key contributor of nutrients, particulate material, and freshwater volume of the Gulf of Mexico (*Rabalais et al.*, 2002a, 2007; *Hetland and DiMarco*, 2008; *Bianchi et al.*, 2010; *DiMarco et al.*, 2012). All of these inputs are derived from more than 40 percent of the contiguous United States (*Milliman and Meade*, 1983).

1.3 Monitoring Gulf Hypoxia

The hypoxic zone has been monitored since 1985. The size of the affected region varies annually; the mean affected area has increased from about 8,000 to 9,000 square kilometers from 1985 to 1992, to about 15,000 to 17,000 square kilometers from 1993 to 1997 (*Obenour et al.*, 2013). In 1998 and 2000, smaller areas were affected, as river flows were well below average these years. Otherwise, the hypoxic area since 1999 has generally exceeded 19,000 square

kilometers except in 2003 and 2005 when tropical storms and hurricanes mixed the water column immediately before the monitoring cruise (*Rabalais et al., 2007; Obenour et al., 2013*). In 2008, the observed hypoxic area exceeded 31,000 square kilometers (*DiMarco et al., 2012*). The distribution of hypoxia in 2008 can be seen in Figure 2. With its significant impact on coastal ecosystems, rigorous and efficient monitoring of the hypoxic zone is essential. Greater monitoring helps scientists to better understand the physical system driving Gulf hypoxia (*Hetland and DiMarco, 2012*). This better understanding in turn helps to inform policy to reduce the hypoxic zone (*Mullins et al., 2011*).

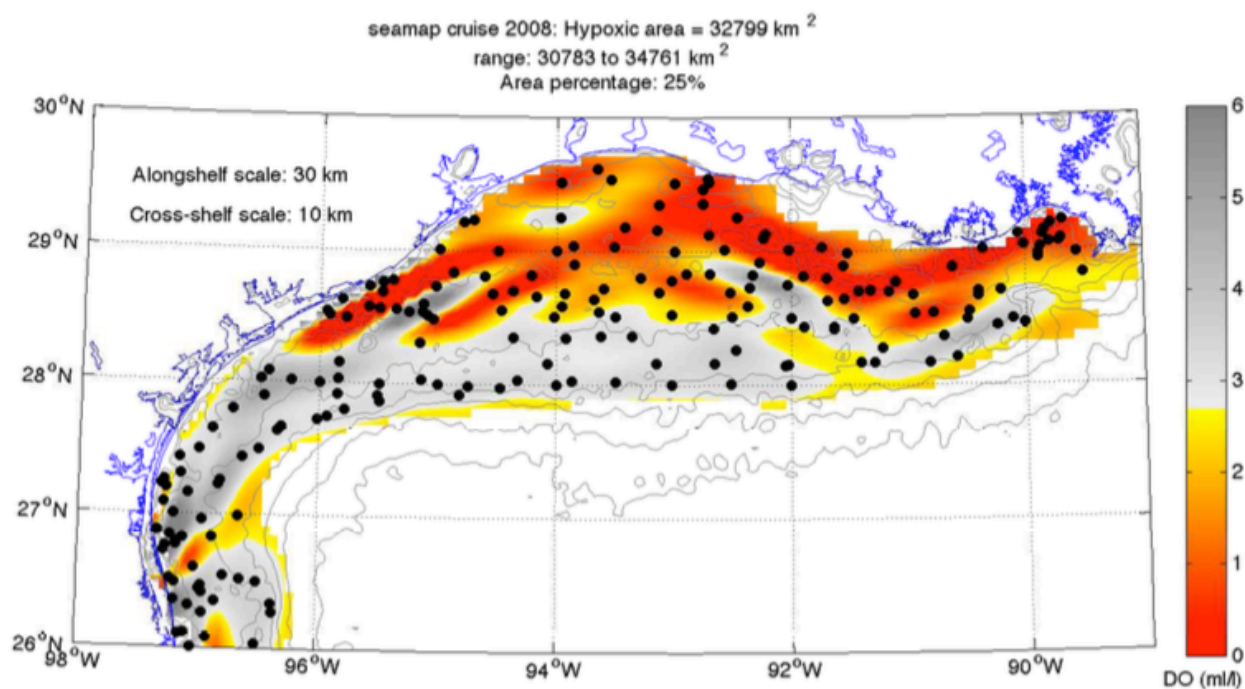


Figure 2. Dissolved oxygen concentrations along the northern Gulf of Mexico, 2008.
Source: DiMarco et al. Aquatic Geochemistry 2012.

Shipboard surveys have been the traditional method of collecting data to monitor hypoxia.

To monitor hypoxia, Dr. Nancy Rabalais' major cruise occurs in July (*Rabalais et al., 2002*). Dr. Steve DiMarco and colleagues conduct two cruises around Rabalais'—in June and August—to collect more data to pinpoint the contributing factors of hypoxia in a given year (DiMarco,

personal communication, 2014). These cruises coincide with the peak of hypoxia, in the summer months, as hypoxia is a seasonal phenomenon in the northern Gulf of Mexico (*Wiseman et al.*, 1997; *Rabalais et al.*, 2002a, 2002b; *Hetland and DiMarco*, 2008; *Mullins et al.*, 2011; *DiMarco et al.*, 2012; *Obenour et al.*, 2012, 2013). Despite the rigorous data collection that occurs on these cruises, three data sets over time from each of these three cruises may not be enough to accurately characterize the hypoxic zone.

Temporally, there is high-frequency variability of dissolved oxygen concentrations near bottom and throughout the water column (*Wiseman et al.*, 1997; *Hetland and DiMarco*, 2008; *Mullins et al.*, 2011; *DiMarco et al.*, 2012; *Obenour et al.*, 2012). Bottom waters change rapidly, within hours, from hypoxic to normoxic conditions and this variability persists throughout the summer months. A conventional survey of the northern Gulf of Mexico transect using traditional CTD (conductivity, temperature, and depth) casts spaced at 10 kilometers would not resolve and would perhaps miss the multiple oxygen minima and stability structures (*Mullins et al.*, 2011). This could lead to a mischaracterization of any encountered hypoxia.

1.4 Policy of Gulf Hypoxia

The Interagency Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (HTF for Hypoxia Task Force) is the key organization tasked with overseeing management activities of the northern Gulf of Mexico hypoxic zone. The HTF is authorized for this task through the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998. In 2001, an Action Plan was created and revised in 2008 to reduce the areal extent of the hypoxic zone to 5,000 square kilometers by 2015 (*Gulf Hypoxia Action Plan*, 2008). This Action Plan uses both voluntary and

incentive-based strategies to reduce nutrient concentrations in the Mississippi River through both application reductions and shifts in agricultural practices along the watershed.

The Action Plan recognizes the need to develop a comprehensive monitoring plan for the region and to characterize the processes leading to the development, maintenance, distribution, and seasonality of the hypoxic zone (*Gulf Hypoxia Action Plan*, 2008). Since 2003, the NGOMEX-funded Mechanisms Controlling Hypoxia (MCH) study has provided critical insights into these processes through observations from more than 30 research cruises in the Gulf and numerical output from a coupled physical-biogeochemical modeling system. These MCH project results have been annually reported to the HTF.

In 2007, the Summit on Long-term Monitoring of the Gulf of Mexico Hypoxic Zone: Developing the Implementation Plan for an Observational System was held to develop “an implementation plan for achieving a comprehensive, integrative, and sustainable monitoring program for the Gulf hypoxic zone” (*Howden et al.*, 2013). Largely informed by the MCH project, this Summit resulted in the Gulf of Mexico Hypoxia Monitoring Implementation Plan in 2009 (revised in 2012), which included provisions for utilizing autonomous underwater vehicles equipped with dissolved oxygen sensors to efficiently monitor oxygen levels in the hypoxic region. In 2013, the Gulf Hypoxia Glider Application Meeting resulted in the production of the Glider Implementation Plan for Hypoxia Monitoring in the Gulf of Mexico. This meeting and resulting document was also informed by the MCH project.

It was decided that a pilot study was necessary to assess glider effectiveness, efficiency, and accuracy in the northern Gulf of Mexico to satisfy the observational requirements set by the HTF. One challenge associated with glider usage as identified by the Glider Application Meeting was the ability to map bottom and surface waters in the coastal environment where spatial and temporal scales of key parameters (salinity, temperature, vertical and horizontal stability, and dissolved oxygen) are highly variable (*Wiseman et al.*, 1997; *Hetland and DiMarco*, 2008; *DiMarco et al.*, 2012; *Obenour et al.*, 2012). It was concluded that collecting observations as close to the ocean bottom as possible was necessary to determine areal and volumetric extent of the hypoxic area (*Howden et al.*, 2013). Along with glider implementation, further challenges identified included mechanical limitations of buoyancy-driven vehicles in the presence of large vertical and horizontal density gradients, navigation in a region with large spatial density of offshore structures, high commercial and recreational fishing fleets, and occasional tropical weather (*Howden et al.*, 2013).

1.5 Glider Implementation

Through the use of the Slocum Gliders, we propose that we can more efficiently define the size of the hypoxic zone and the relative contribution of factors influencing its severity in a given year. These Slocum Gliders are made by Teledyne Webb Research and are autonomous; they can navigate the water column independently of a research ship, thereby collecting more data for less money than traditional shipboard surveys. The gliders also move in response to changes in buoyancy due to an internal bladder rather than requiring a propeller (*Simonetti*, 1992). This bladder must be calibrated for a select range of water densities, limiting the glider's range of navigable waters. The glider moves slowly, at about half a knot, while ships travel at roughly 8-

12 knots. The glider collects data while undulating through the water column. The glider transmits collected data to a shore station via satellite each time it surfaces. Transmission protocol allows the glider to be monitored remotely while deployed. If any errors occur with the glider during deployment, rapid recovery is possible. Gliders are limited by their battery lives; use of a standard alkaline battery will result in approximately 30 days of data collection on a mission, while lithium battery packs can last up to 90 days. So, while battery life is a limiting factor of glider usage, batteries greatly extend the possible duration of data collection beyond that of traditional shipboard surveys.

As previously stated, traditional shipboard surveys could miss the rapidly variable hypoxic conditions in bottom waters (*Mullins et al.*, 2011). High temporal and spatial variability produce challenges when constructing representative maps of the areal and volumetric extent of the low oxygen waters, as a delay of even just one hour or movement of a couple of kilometers of any given station can significantly impact objective analysis and optimal interpolation estimates. Ocean gliders therefore offer the combined capability of high spatial and temporal resolution and prolonged endurance that can provide spatial and temporal context to individual observations. As the operational forward speed of a glider is less than 1 knot (0.5 cm/s), it is still uncertain whether a glider or fleets of gliders can produce enough data to construct maps that accurately represent the quasi-synoptic oceanic conditions, which is subject to known strong variability (*Wiseman et al.*, 1997; *Hetland and DiMarco*, 2008; *DiMarco et al.*, 2012; *Obenour et al.*, 2012).

There are challenges associated with glider utilization to monitor hypoxia. These challenges may negate the utility of gliders in the northern Gulf of Mexico to provide quantitatively reliable estimates for these metrics. These include near-bottom proximity for oxygen depletion, strong coastal currents, large vertical and horizontal stratification, large numbers of surface piercing and subsurface offshore industry platforms, heavy commercial and recreational fishing activity, active and heavily used shipping lanes, and frequent tropical weather (*Howden et al.*, 2013).

An autonomous device collecting oceanographic data could change how research is conducted. Gliders are a low cost alternative that can supplement ship-based operations. Typical glider operations in 2014 cost approximately \$1,000 per day. When compared to a typical research vessel with an operational cost of \$15,000 per day, the advantage of glider usage is clear.

CHAPTER II

METHODS

2.1 Data Collection

In 2014, two Teledyne Webb Research Slocum G2 ocean buoyancy gliders were deployed in the northern Gulf of Mexico. The missions were designed to collect data in the Gulf coastal hypoxic zone. On-shore pilots controlled these gliders. Ships were used only for deployment and recovery of the gliders before and after missions. Pilots navigated the gliders and had to consider and maneuver around the more than 5,000 surface piercing oil and natural gas structures on the Texas-Louisiana shelf, shown in Figure 3. In addition to these 5,000 structures that occur in water depths up to 500 meters, pilots also had to account for the more than 20,000 sub-surface obstructions, well-heads, pipelines, and other obstacles known to exist on the shelf. To reduce the chance of glider collision with large ships, gliders were programmed to remain below 5 meters depth while traversing major ship lanes.

An internal bladder controlled each glider's position in the water column. This internal bladder inflated to change glider buoyancy to account for density changes in the water column; therefore, each glider had to be calibrated for the expected density of the seawater in the areas where the gliders were deployed. A glider is neutrally buoyant; when the buoyancy pump is retracted, negative buoyancy results, and the glider sinks. After the glider satisfies an argument, such as achieving maximum dive depth, the pump is extended, resulting in positive buoyancy, and the glider rises.

Density on the Texas-Louisiana shelf is mostly determined by salinity variability due to freshwater discharge and, to a lesser extent, temperature variability. Salinity ranges on the shelf can be from 0 to 36. Spatial gradients of salinity can be very strong. For example, in the eastern region of the shelf, salinities are typically low, e.g. 25-30. South of the Atchafalaya Bay, salinities can be in the low 30's, and near the Texas-Louisiana border, salinities are in the middle-30's. Because of this, ballasting the gliders to an expected salinity range becomes critical. The salinity range for the ballast pump of a 200-meter Slocum glider is only about 3 salinity units. The addition of the thruster assembly allows for an additional 2 salinity units of range.

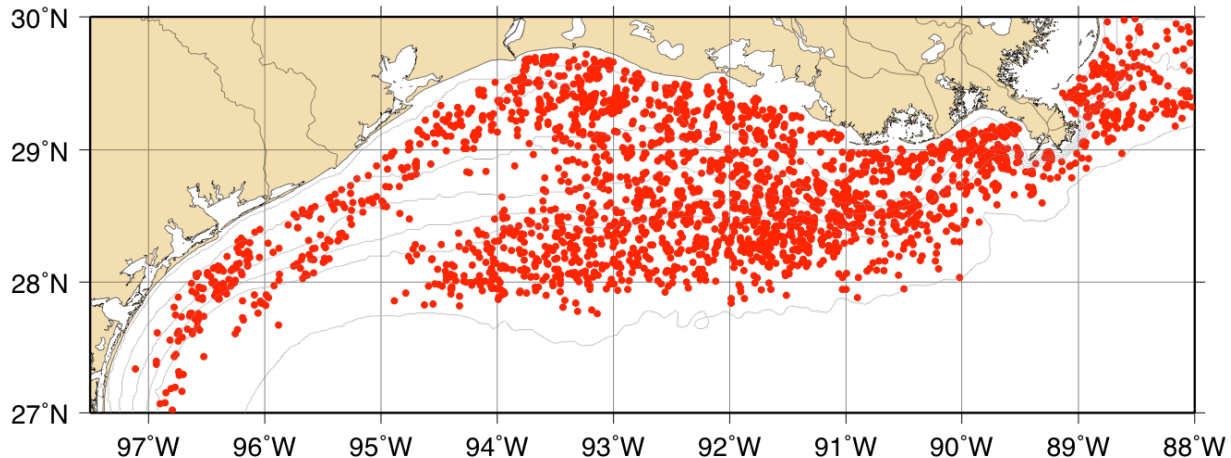


Figure 3. Oil and gas structures in the northern Gulf of Mexico at depths up to 500 meters
Source; www.boem.gov.

Each glider was equipped with oceanographic sensors, including a CTD sensor (conductivity, temperature, and depth), a PUCK Fluorometer that measures CDOM (chromophoric dissolved organic matter) and chlorophyll fluorescence, and a RINKO dissolved oxygen sensor.

Conductivity was used to determine salinity of the water, while depth was used to determine the pressure. In addition to these sensors, several other modifications were made to each glider for ease of use and recovery (see Table 1).

Table 1. Summary of glider sensors for summer 2014.

Manufacturer	Sensor/Part	Property/Note	Range, Accuracy	Units
Wet Labs	PUCK Fluorometer	CDOM (370/460 nm)	0-375, 0.184 ppb	ppb
		Chlorophyll-a (470/695 nm)	0-30, 0.015 µg/L	µg/L
		Turbidity (700 nm)	0-10, 0.005 NTU	NTU
Seabird	CTD Sensor	Conductivity Temperature Depth	± 0.0003 S/m ± 0.002 °C ± 1% of full scale range	µS °C hPa
RINKO	Fast Response Optical Oxygen Sensor	Dissolved oxygen (DO) Temperature	± 2% (at 1 atmosphere, 25 °C)	mg/L
Teledyne	Thruster (307 only)	800 cc buoyancy		
Teledyne Webb Research Assembly	Nose Recovery	Recovery in formidable conditions		
Teledyne Webb Research Assembly	Strobe Light	Recovery at night		

Source: wetlabs.com, seabird.com, rocklandscientific.com, webbresearch.com

Figure 4 shows the GPS locations of four missions associated with the glider experiment. The first mission, Mission 5 occurred in October 2013 as a shake down mission in relatively deep waters of the outer shelf and was designed to test operational procedures of the glider. The three other missions occurred in summer 2014 in shallow waters of the inner shelf typically less than 30 meters. Over these three missions with the use of two different gliders, Glider 307 and Glider 308 in Missions 7, 8, and 10, over 500,000 observations were collected per 30-day deployment to accurately characterize the hypoxic zone in the Gulf of Mexico. Details of deployment dates

of each mission are in Table 2, below. Glider 307, used for Mission 7, was also equipped with a thruster assembly to help extend the depth range and efficiency of the glider. This assembly was not on Glider 308, which was used for Missions 8 and 10.

Table 2. Summary of glider deployment in the hypoxic zone in summer 2014.

Deployment	Glider #	Start Date	End Date	Points Collected	Modification
Mission 7	307	7/11/14	8/12/14	864,477	Thruster
Mission 8	308	7/11/14	8/4/14	545,836	None
Mission 10	308	8/30/14	10/1/14	498,492	None

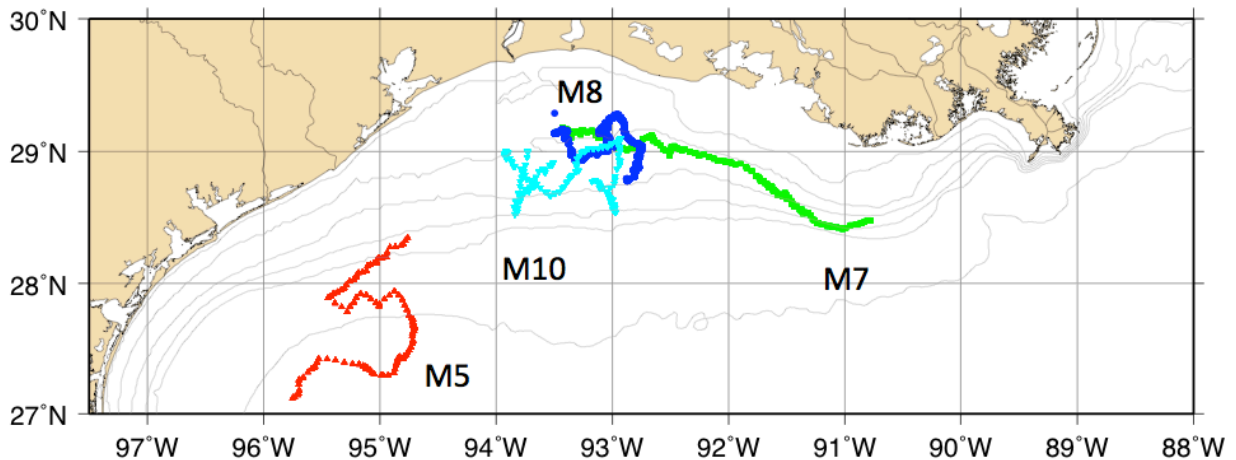


Figure 4. Glider routes for Missions 5, 7, 8, and 10. Mission 5, a shake down mission to test operational procedures of the gliders, is shown in red; Mission 7 is shown in green; Mission 8 is shown in dark blue; Mission 10 is shown in cyan.

Glider 307 has since these missions been modified with a small propeller and shallow (800 cc) buoyancy pump to allow for a greater density range of operations. Slocum gliders configured with standard buoyancy pumps have about ± 2 sigma units of density range for efficient

operations. The modifications to Glider 307 will therefore allow this glider to operate in stronger density gradients and larger density ranges. The small propeller will also allow the glider to “push” through strong density gradients outside the mission-planned buoyancy range for short periods of time. This will be particularly useful in the coastal zone of the northern Gulf where frequent occurrences of surface freshwater lens derived from the Mississippi River can impact glider operations.

2.2 Data Analysis

Gliders initially collected data in raw binary format. To make the data meaningful, data were converted from these unreadable .ebd and .dbd files into .ascii files through bash scripts and a conversion file employed in Terminal. In this new format, the glider files could be effectively analyzed in MATLAB®, which is a “high-level language and interactive environment” used for many applications such as numeric computation, data analysis, visualization, and programming (Math Works, 2015).

RINKO calibrations were performed using MATLAB to convert raw data counts into conventional property quantities for analysis (K. Dreger, personal communication, 2015). Quantities such as temperature and salinity, both of which were derived from RINKO data, were initially plotted as time series to investigate quality of the raw data prior to analysis. For example, short time series (about 24 hours) of temperature and salinity show how data were collected by the gliders. While the glider collected data on properties such as chromophoric dissolved organic matter (CDOM) and chlorophyll, these quantities were not analyzed for the purposes of this thesis.

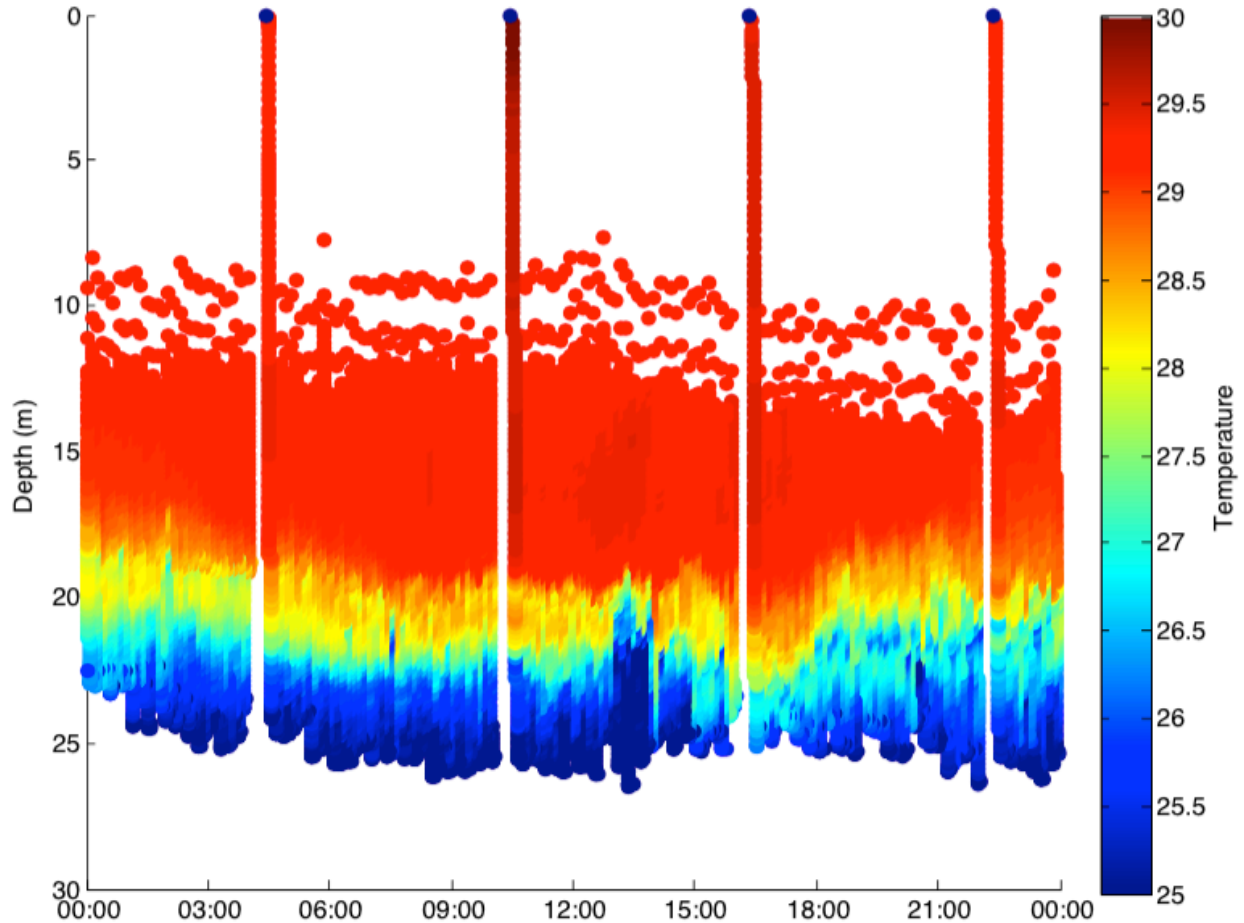


Figure 5. 24-hour detail of Glider 307 data as a function of depth and time for RINKO temperature. The blue dots at the top have values of 0, when the scientific package turned on at the surface of the water. These values were identified and removed prior to further analyses.

The glider was configured only to collect scientific data when moving down in the water column. Figure 5 shows glider location in the water column as a function of depth and time for RINKO temperature. Once the glider reaches the bottom of the yo (a single downward inflection (dive) and a single upward inflection (climb)), the science package turns off during the ascent. This is represented by a gap in the time series. The science package is turned on when the glider reaches the surface. Note that the scientific property value just after surfacing is zero; these values were identified and removed prior to further analyses.

Inspection of histograms of each parameter assessed overall data quality. Figure 6 shows an example of the histograms for Mission 8 sensors. The histograms of the raw data indicated a significant number of zero values when the glider came to the surface.

While there was not a significant number of zero or less than zero values recorded, any estimates of mean values would be skewed by including these values. As the zero values were not representative of the true population and were caused by buffering of the sensor memory cache, these values were identified and eliminated.

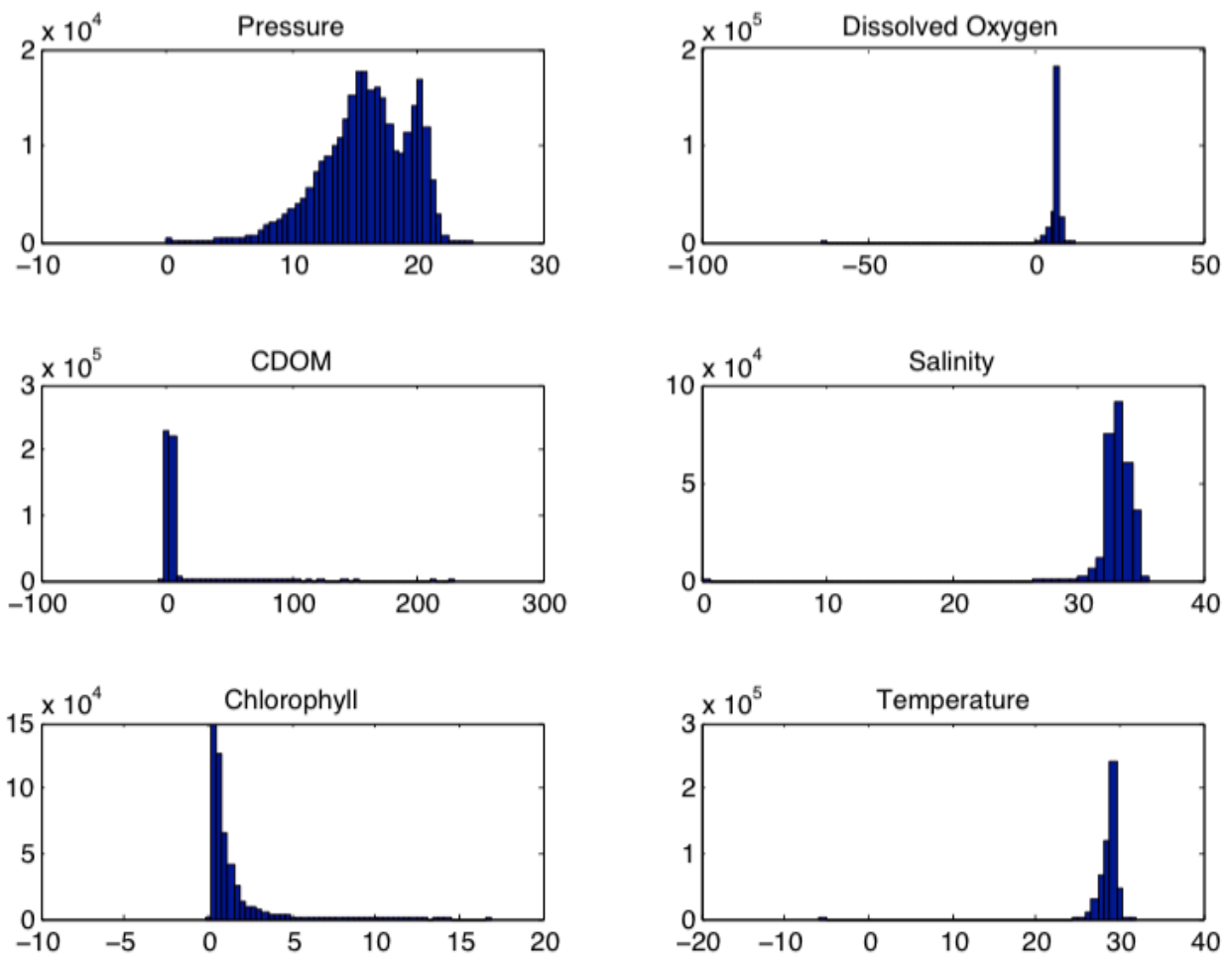


Figure 6. Histograms of Mission 8 scientific property values showing many buffering values of zero.

Figure 7 shows the vertical distribution of properties in the upper 0.2 meters of the ocean. These figures clearly show the erroneous observations at the surface. For example, in the upper right panel, dissolved oxygen measurements were on the order of 6 mg/L; however, the blue dots indicate zero values at zero depth (dark blue color).

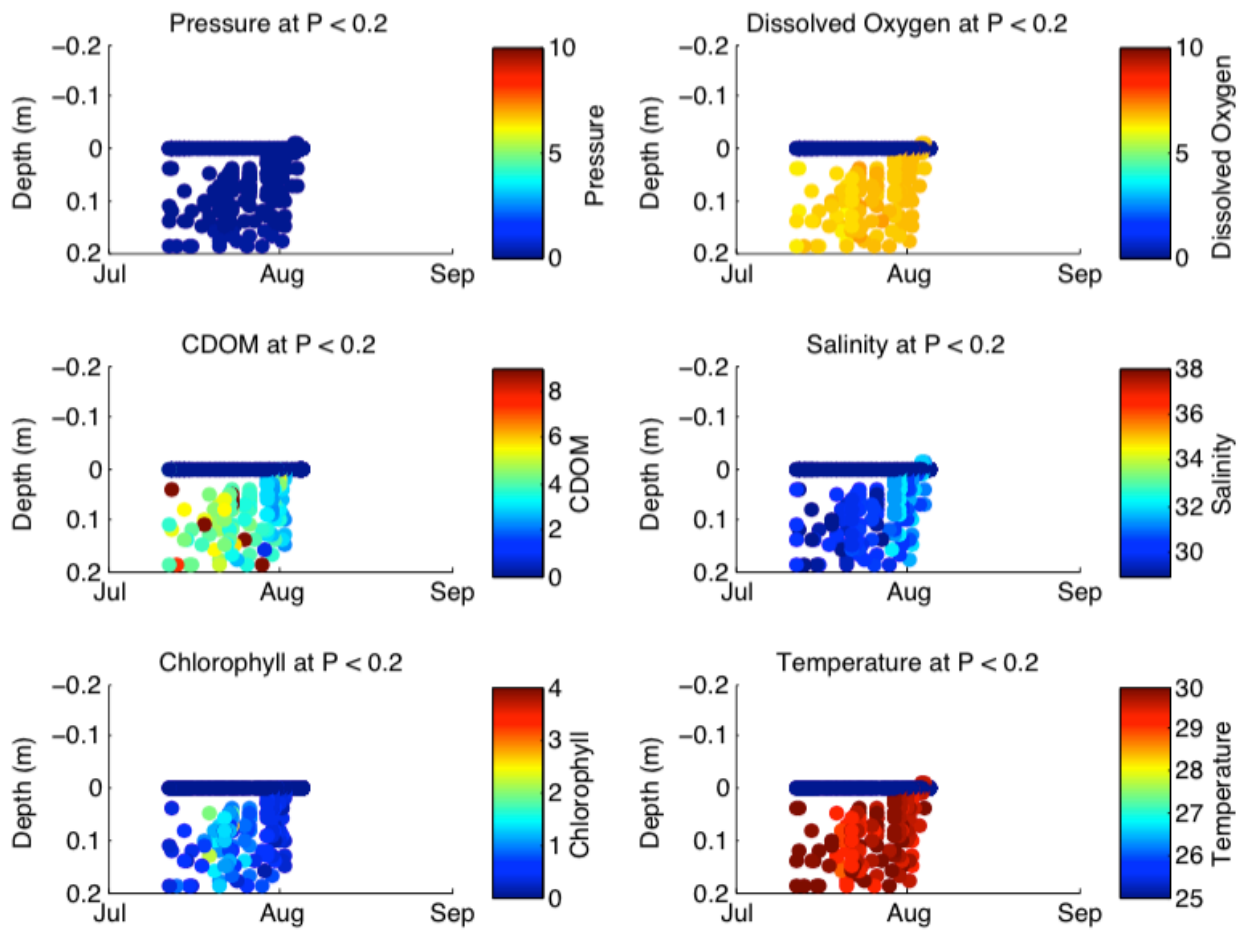


Figure 7. Time series of glider sensors from Mission 8 detailing the buffering of sensor values near the surface.

Figure 8 shows a detail of the upper 0.2 meters in a similar fashion as that of Figure 6. Here the erroneous values are shown as a significantly large number of occurrences. In the upper right and lower right panels (dissolved oxygen and temperature), the erroneous values are largely negative

values. This is because both the RINKO dissolved oxygen and temperature estimates are derived post-deployment using calibration coefficients. The zero values for voltages for these sensors therefore are then converted into negative, non-zero values.

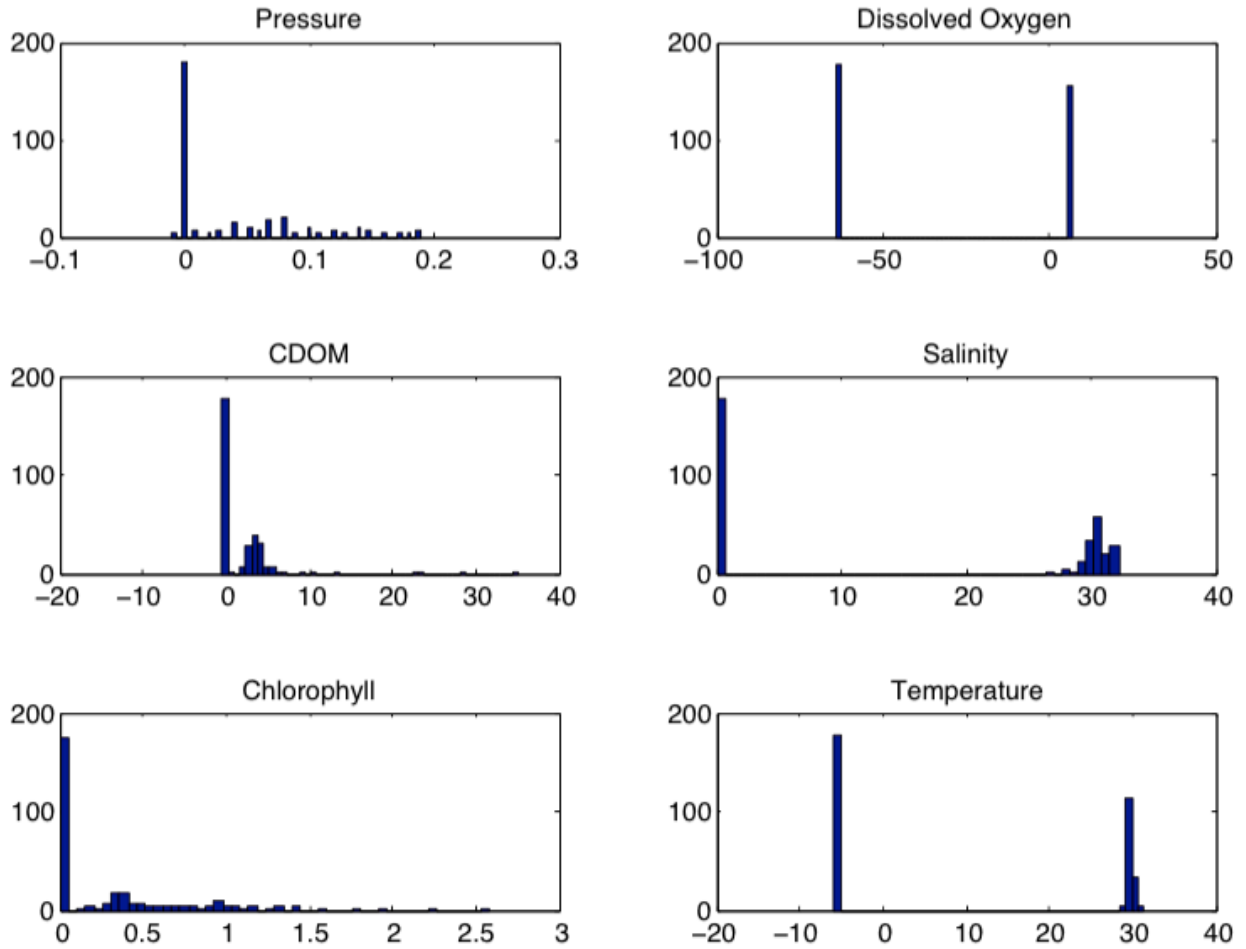


Figure 8. Histograms of Mission 8 scientific property values at depth less than 0.2 meters. Formatting is similar to that in Figure 6.

CHAPTER III

RESULTS

3.1 Dissolved Oxygen and Salinity Measurements

Over 500,000 property observations were recorded by the gliders during each of the three missions. With dissolved oxygen, measurements of 2.0 mg/L or less are considered hypoxic (*Rabalais et al.*, 2007; *DiMarco et al.*, 2012; *Obenour et al.*, 2012, 2013). In the dissolved oxygen plots below, the deep blue colors represent this low oxygen range. In both Missions 7 and 8, hypoxia was found, as multiple measurements falling within the hypoxic range were identified; however, no hypoxia was found during Mission 10. This is coincident with the seasonal pattern of hypoxia; Mission 10 occurred from late August through September, during late fall and early summer conditions. Stratification is greatly reduced during this time period, restoring oxygen to formerly hypoxic areas of the lower water column (*Wiseman et al.*, 1997; *Hetland and DiMarco*, 2008; *Bianchi et al.*, 2010; *DiMarco et al.*, 2010, 2012; *Obenour et al.*, 2012, 2013).

The thick blue lines at the bottom of the graphs below represent the bottom depth as identified by each glider's altimeter sensor. For Mission 8, there are multiple occurrences of low oxygen water near the ocean bottom (Figure 9). Figure 10 shows the salinity structure encountered during Mission 8. As expected, fresher water of about 32-33 dominates the upper water column. Saltier, denser water with a salinity of 35 and greater occupies the lower water column. The pycnocline is readily identified as the interface between fresh and salt water, evidenced by the sharp vertical gradient in color around 15-20 meters depth. Comparing Figures 9 and 10, depleted sub-

pycnocline oxygen concentrations are coincident with salinity stratification, as salinity stratification promotes water column stability and inhibits ventilation of the lower layer with waters from the oxygen-rich surface layer (Wiseman *et al.*, 1997; Hetland and DiMarco, 2008; Bianchi *et al.*, 2010; DiMarco *et al.*, 2010, 2012).

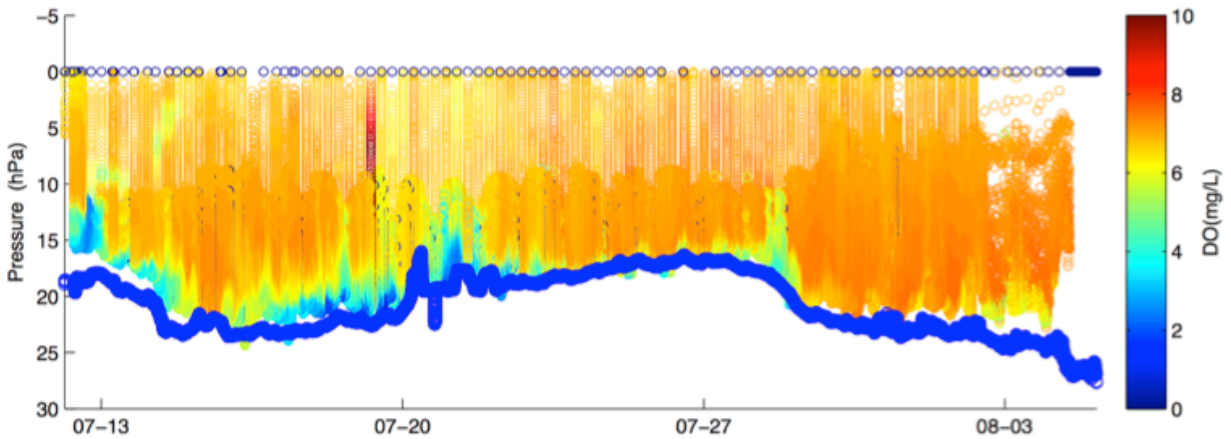


Figure 9. Mission 8 dissolved oxygen (DO) measurements.

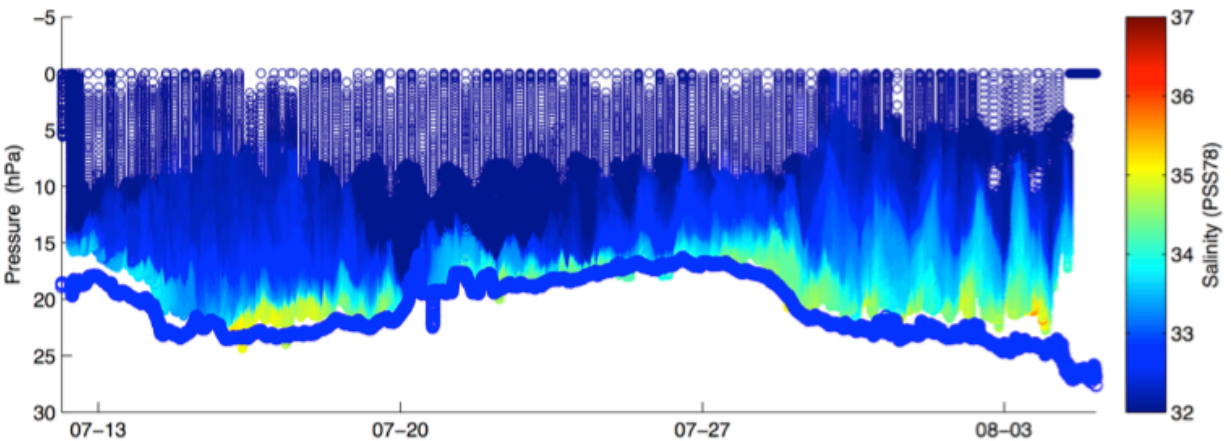


Figure 10. Mission 8 salinity measurements.

Just as in Mission 8, Mission 7 shows multiple occurrences of low oxygen near the ocean bottom and beneath the main pycnocline (Figure 11). The vertical stratification in Mission 7 is stronger than that in Mission 8. Toward the end of the Mission 7 deployment, Glider 307 became entrapped in a strong eastward coastal current that directed the glider east and offshore. This caused a sharp delineation of offshore water around August 8, resulting in weaker stratification

and ventilation of the lower water column due to the decreased stability (Figure 12) (Wiseman et al., 1997; Hetland and DiMarco, 2008).

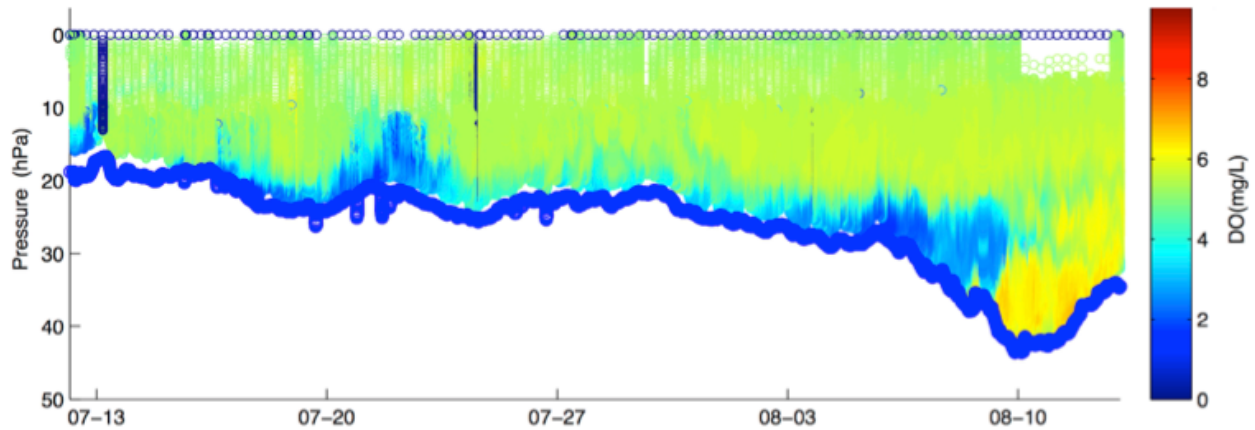


Figure 11. Mission 7 dissolved oxygen (DO) measurements.

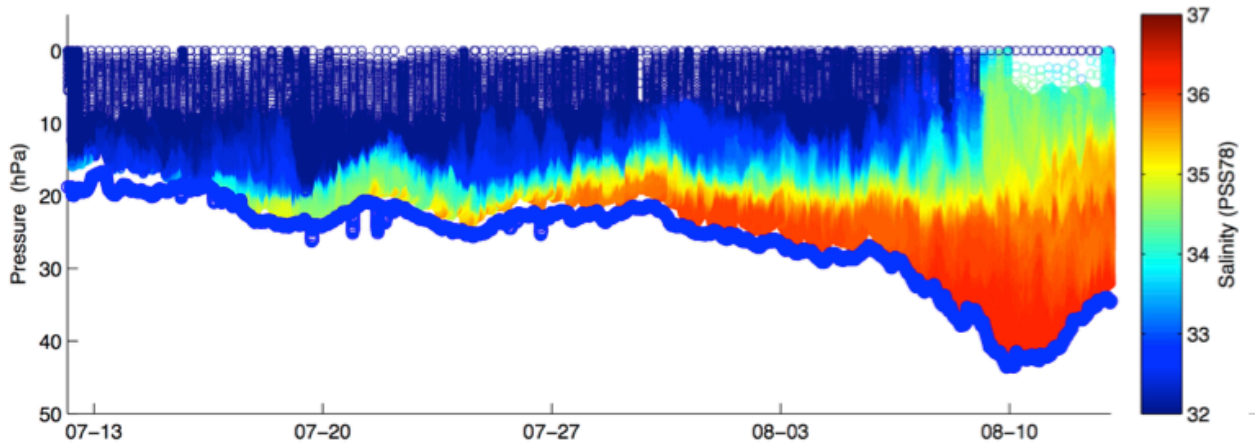


Figure 12. Mission 7 salinity measurements.

The undulating bottom depths of the Mission 10 graphs show the onshore and offshore trajectory of this deployment. Salinity values are smaller near shore, closer to freshwater sources. Oxygen values are mostly greater throughout the water column, typical for late summer and early fall conditions when energetic wind driving breaks down stratification and ventilates the water column (Figure 14) (Wiseman et al., 1997; Hetland and DiMarco, 2008; Bianchi et al., 2010; DiMarco et al., 2010, 2012; Obenour et al., 2012). Dissolved oxygen concentrations shown in

Figure 13 show some depletion in regions of high salinity stratification; however, no hypoxia was found during this mission.

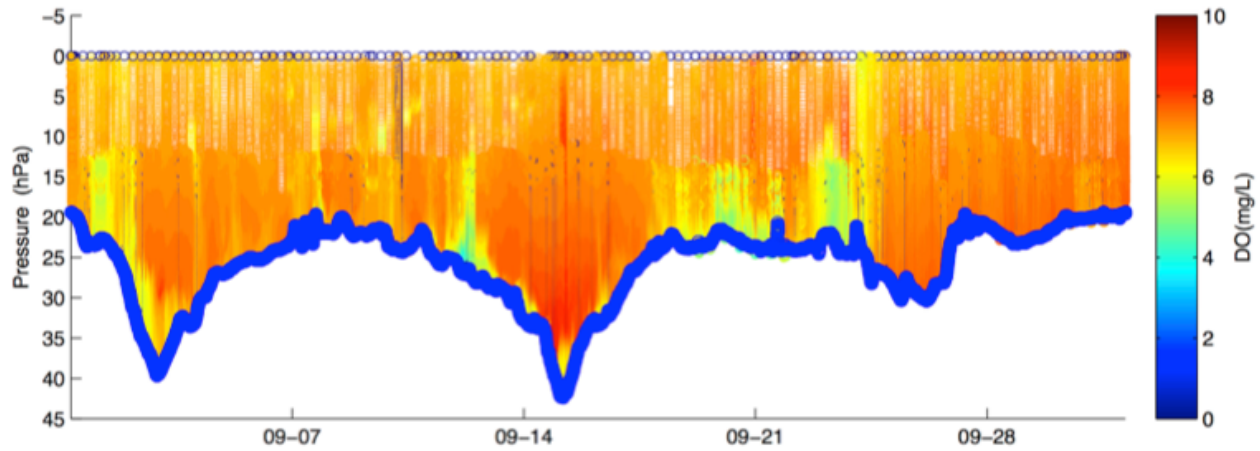


Figure 13. Mission 10 dissolved oxygen (DO) measurements.

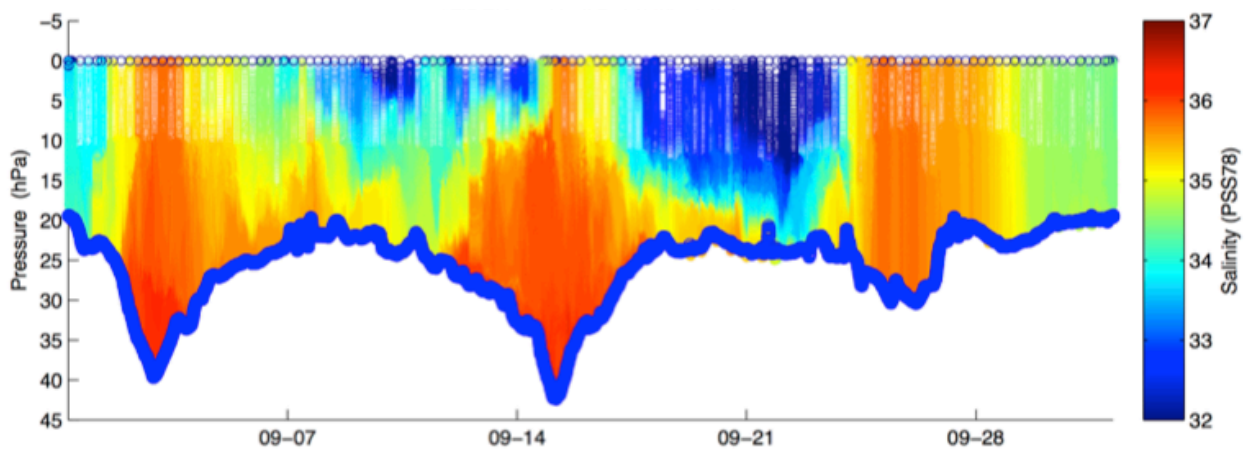


Figure 14. Mission 10 salinity measurements.

3.2 Bottom Depth Accuracy

Once data were collected and plotted, evaluation of the effectiveness of the gliders to get beneath the pycnocline and provide accurate observations of temperature, salinity, and dissolved oxygen near the ocean bottom was necessary.

Figure 15 is a time series of observations as a function of depth for Mission 10. Each red dot shows the depth of each one-second observation during the duration of the entire deployment. Dark blue dots show the ocean bottom as sensed by the glider's altimeter sensor. The dark green line shows a 200-point smoothed running average of the altimeter data, and the cyan line marks the deepest descent of each yo of the glider. Note the data density is different above 10 meters, due to a firmware issue that reduced data estimates in the upper water column. The quality of collected data was not impacted by this firmware issue; only the number of points recorded per meter.

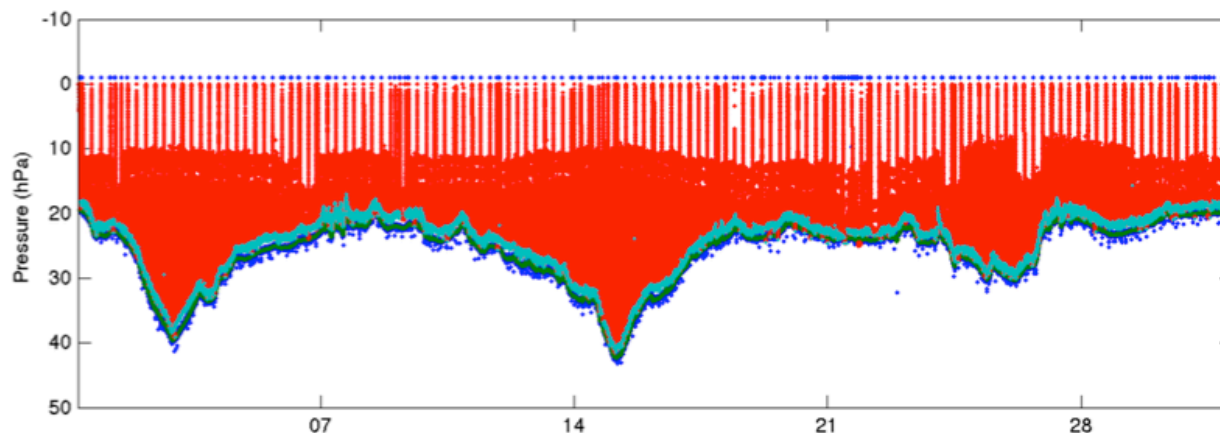


Figure 15. Mission 10 pressure and altimeter time series. Red dots are individual pressure recordings; blue dots are data points above the surface when the glider was at the surface; cyan dots indicate the deepest descent of each yo of the glider; dark blue lines are the raw altimeter data indicating ocean bottom depth as sensed by the glider; the dark green line is a 200-point smoothed running average of the altimeter data.

Figure 16 is a histogram of the difference between the smoothed bottom depth and the deepest descent of each yo of the glider. This figure is therefore a quantification of how close the glider came to the ocean bottom during Mission 10. The distribution is normal with a peak near 1.5 meters and a standard deviation of 0.33 meters. The thin vertical blue line shows the 2 meters above bottom value. During this deployment, the glider came within 2 meters of the bottom 95 percent of the time.

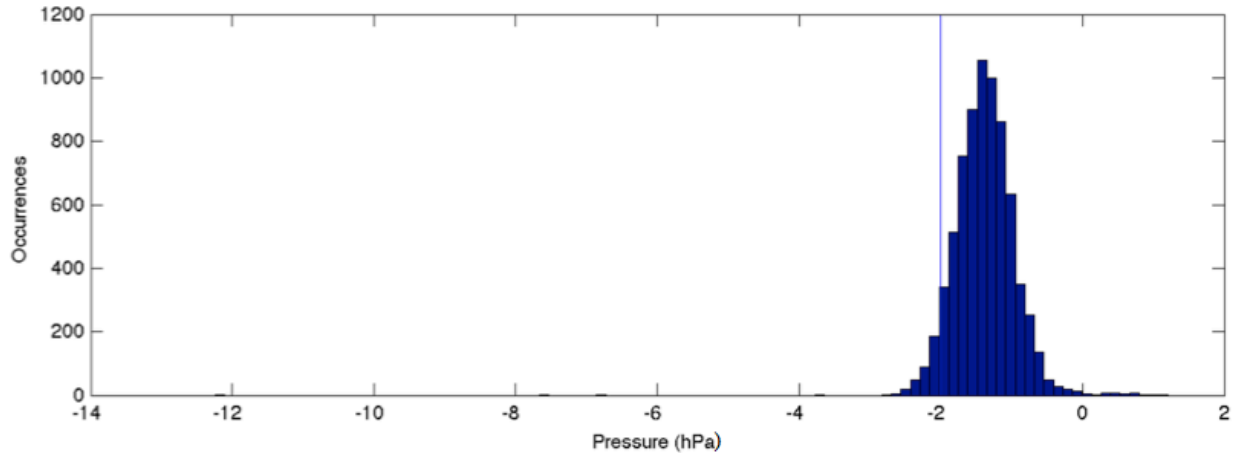


Figure 16. Histogram of Mission 10 glider distance from bottom.

Representations in Figure 17 are the same as those in Figure 15, except for Mission 8. Figure 18 is a histogram of the difference between bottom depth and the deepest descent of the glider as in Figure 16. In Figure 18 though, the distribution of this quantification of how close to bottom the glider came is not as normal as in Mission 10. The distribution for Mission 8 can be interpreted as a superposition of two normal distributions, and is due to two factors. First, the glider was programmed to turn one meter higher of the bottom at the beginning of the mission, resulting in a shift in the distribution to the left. Second, this glider lost a wing toward the end of the mission, which impacted the glider's ability to effectively glide during its last week. For most of the mission though, between the 18th and 30th of July, the glider was consistently 1.5 meters above the bottom and within a standard deviation of 0.33 meters.

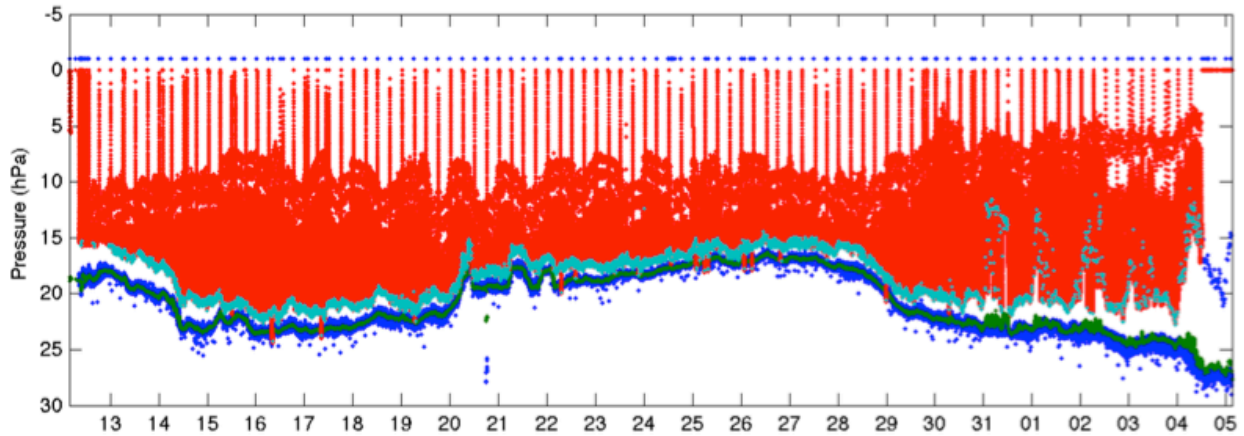


Figure 17. Mission 8 pressure and altimeter time series. Red dots are individual pressure recordings; blue dots are data points above the surface when the glider was at the surface; cyan dots indicate the deepest descent of each yo of the glider; dark blue lines are the raw altimeter data indicating ocean bottom depth as sensed by the glider; the dark green line is a 200-point smoothed running average of the altimeter data.

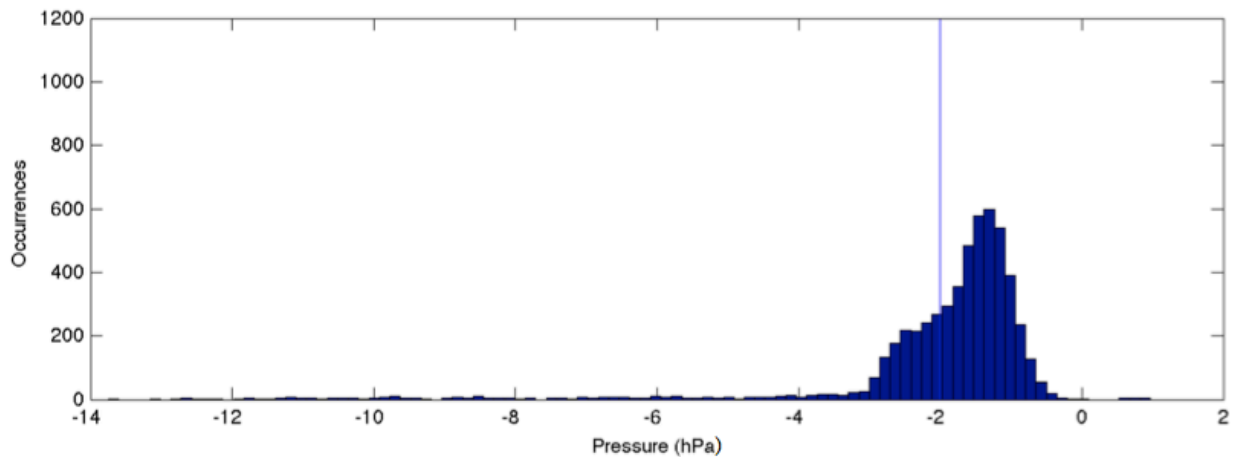


Figure 18. Histogram of Mission 8 glider distance from bottom.

For Mission 7, the glider was equipped with a thruster assembly. The thruster assembly consists of a small propeller to assist the glider in descent and ascent. The Mission 7 glider, 307, was programmed identically to Glider 308, except the thruster-equipped Glider 307 only reached 2.2 meters above the bottom (Figures 19 and 20). This nearly one-meter difference is thought to be caused by a combination of the thruster assembly making the bottom turn more efficiently and thereby faster, as well as the thruster assembly placement in the stern of the glider. The position

of the assembly impacts the pitch and balance of the glider, leading to less time for glider attitude adjustment, which can also result in a faster change from descent to ascent. Both of these factors are under further investigation.

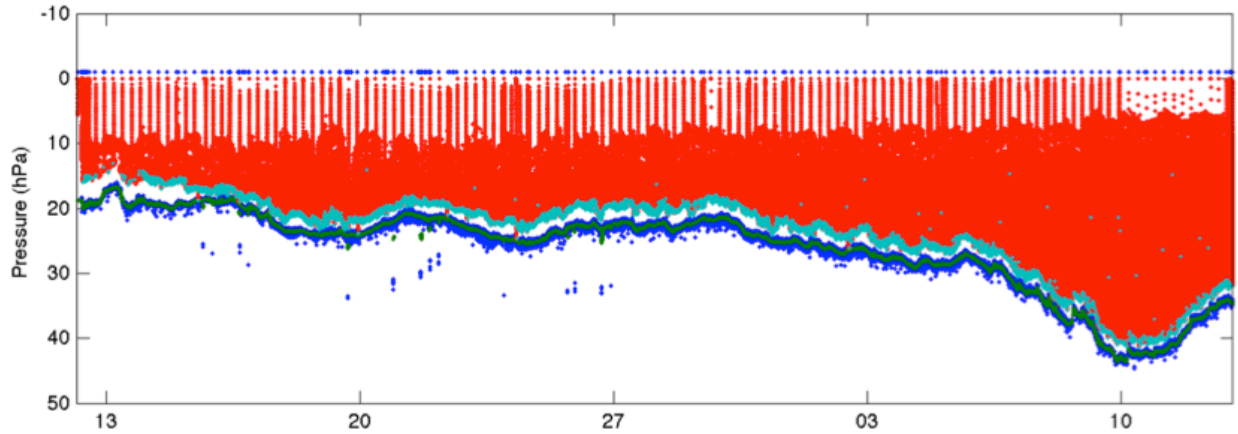


Figure 19. Mission 7 pressure and altimeter time series. Red dots are individual pressure recordings; blue dots are data points above the surface when the glider was at the surface; cyan dots indicate the deepest descent of each yo of the glider; dark blue lines are the raw altimeter data indicating ocean bottom depth as sensed by the glider; the dark green line is a 200-point smoothed running average of the altimeter data.

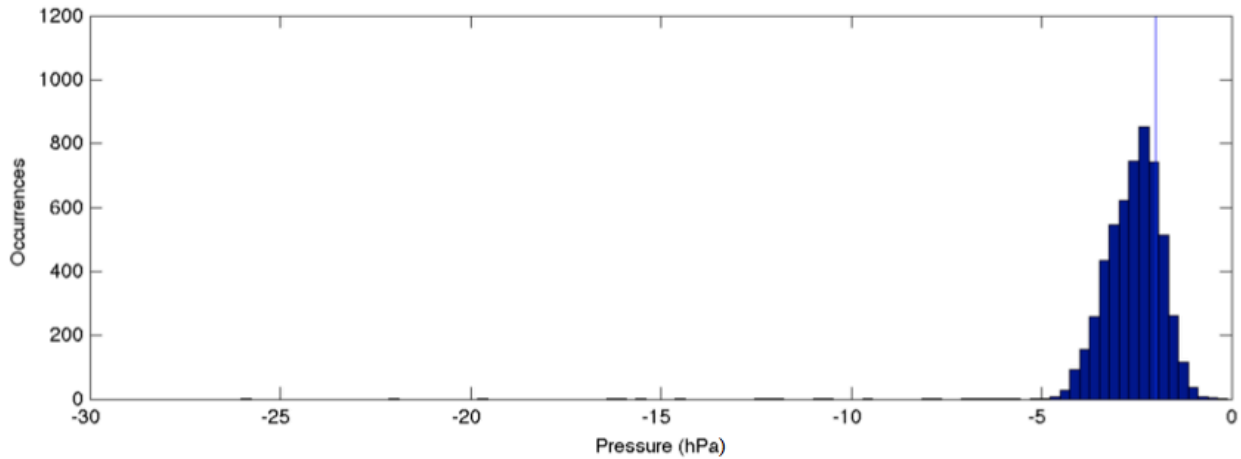


Figure 20. Histogram of Mission 7 glider distance from bottom.

CHAPTER IV

CONCLUSIONS

The results of the demonstration experiment show that gliders are capable of navigation in the hypoxic region and can produce observations of key quantities of interest to the Hypoxia Task Force. Two ocean buoyancy gliders were successfully operated in the hypoxic zone of the northern Gulf of Mexico in the summer of 2014. Three missions lasted in total about 100 days, and they focused principally on the 20-meter isobath. The gliders consistently came within 1.6 meters of the bottom during the three missions. Our statistics indicate that it may be possible to get closer, within 1 meter of the bottom; however, this means there is a substantial increase in the probability of encountering the bottom, which will increase the risk of damage to or failure of the glider.

Coming within an average of 1.6 meters of the ocean bottom sufficiently characterized the hypoxic area in the Gulf, satisfying the Glider Application Meeting's desire for gliders to get as close to the bottom as possible. The figures produced by the glider data were of sufficient time and spatial resolution, requiring no contouring or smoothing. While gliders do not travel as quickly as ships when recording data, the quantity of the data produced by the gliders and duration of glider deployments compensate for the slower rate of glider movement.

Density variation due to freshwater input and strong coastal currents were issues encountered in Mission 7. Glider 307 has since this mission been modified with a small propeller and a shallow (800 cc) buoyancy pump. These modifications will therefore allow this glider to operate in

stronger density gradients and larger density ranges. This is particularly useful in the coastal zone of the northern Gulf where frequent occurrences of surface freshwater lens derived from the Mississippi River can impact glider operations. While density gradients are an obstacle for glider operations, measures are being taken to overcome such limitations.

This study only employed two gliders in a large area. Future work should employ multiple gliders covering the entire hypoxic region simultaneously, providing data at appropriate spatial and temporal scales to monitor how hypoxia develops, how it is maintained, and how it gets broken up by physical processes in the fall. The number of gliders needed for this purpose, the spacing of the gliders to be used, and the economic costs and benefits over traditional shipboard surveys are beyond the scope of this thesis; however, the data reported here give a quantifiable starting point for future research.

REFERENCES

Bianchi, T. S., S. F. DiMarco, J. H. Cowan Jr., R. D. Hetland, P. Chapman, J. W. Day, and M. A. Allison (2010), The science of hypoxia in the northern Gulf of Mexico: A review, *Science of the Total Environment*, 408(7), 1471-1484.

Breitburg, D.L., (2002), Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries, *Estuaries* 25, 767–781.

Craig, J.K., and Crowder, L.B. (2005), Hypoxia-induced habitat shifts and energetic consequences in Atlantic croaker and brown shrimp on the Gulf of Mexico shelf, *Marine Ecology Progress Series*, 294, 79–94.

Dale, V. H., C. L. Kling, J. L. Meyer, J. Sanders, H. Stallworth, T. Armitage, D. Wangsness, T. Bianchi, A. Blumberg, W. Boynton, D. J. Conley, W. Crumpton, M. David, D. Gilbert, R. W. Howarth, R. Lowrance, K. Mankin, J. Opaluch, H. Paerl, K. Reckhow, A. N. Sharpley, T. W. Simpson, C. S. Snyder, and D. Wright (2010), *Hypoxia in the northern Gulf of Mexico*, New York, Springer.

Diaz, R.J., J. Nestlerode, and M.L. Diaz (2004), A global perspective on the effects of eutrophication and hypoxia on aquatic biota, in *The 7th International Symposium on Fish Physiology, Toxicology, and Water Quality, Tallinn, Estonia*, edited by G. L. Rupp and M. D. White, Athens, GA, U.S. Environmental Protection Agency Research Division, 1–33.

Diaz, R.J. and R. Rosenberg (2008), Spreading dead zones and consequences for marine ecosystems, *Science*, 321, 926-929.

DiMarco, S. F., P. Chapman, N. Walker, and R. D. Hetland (2010), Does local topography control hypoxia on the western Texas-Louisiana shelf?, *Journal of Marine Systems*, 80, 25-35.

DiMarco, S. F., J. Strauss, N. May, R. L. Mullins-Perry, E. L. Grossman, and D. Shormann (2012), Texas coastal hypoxia linked to Brazos River discharge as revealed by oxygen isotopes, *Aquatic Geochemistry*, 18(2), 159-181.

Forrest, D. R., R. D. Hetland, and S. F. DiMarco (2011), Multivariable statistical regression models of the areal extent of hypoxia over the Texas-Louisiana continental shelf, *Environmental Research Letters*, 6(4), 045002-045012.

Hetland, R. D., and S. F. DiMarco (2008), The effects of bottom oxygen demand in controlling the structure of hypoxia on the Texas-Louisiana continental shelf, *Journal of Marine Systems*, 70, 49-62.

Hetland, R. D. and S. F. DiMarco (2012), Skill assessment of a hydrodynamic model of circulation over the Texas-Louisiana continental shelf, *Ocean Modeling*, 43-44, 64-76.

Howden, S.D., R.A. Arnone, J. Brodersen, S.F. DiMarco, L.K. Dixon, H.E. Garcia, M.K. Howard, A.E. Jochens, S.E. Ladner, C.E. Lembke, A.P. Leonardi, A. Quaid, and N.N. Rabalais. (2014), Glider Implementation Plan for Hypoxia Monitoring in the Gulf of Mexico, 21 pp., edited by A.J. Lewitus, S.D. Howden, and D.M. Kidwell, Gulf Hypoxia Glider Application Meeting, 17-18 April 2013, NASA's Stennis Space Center, MS.

Math Works (2015), MATLAB: The language of technical computing: Overview. (Available online at <http://www.mathworks.com/products/matlab/>)

Milliman, J. D., and R. H. Meade (1983), World-wide delivery of river sediment to the oceans, *Journal of Geology*, 91, 1-21.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2008), Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin, Washington, D.C.

Moore, D., H. A. Brusher, and L. Trent (1970), Relative abundance, seasonal distribution, and species composition of demersal fishes off Louisiana and Texas, 1962–1964, *Contributions in Marine Science*, 15, 45–70.

Mullins, R. L., S. F. DiMarco, J. Walpert, and N. L. Guinasso Jr. (2011), Interdisciplinary ocean observing on the Texas coast, *Marine Technology Society Journal*, 45, 98-111.

Obenour, D. R., A. M. Michalak, Y. Zhou, and D. Scavia (2012), Quantifying the impacts of stratification and nutrient loading on hypoxia in the northern Gulf of Mexico, *Environmental Science and Technology*, 46, 5489-5496.

Obenour, D. R., D. Scavia, N. N. Rabalais, R. E. Turner, and A. M. Michalak (2013), Retrospective analysis of midsummer hypoxic area and volume in the northern Gulf of Mexico, 1985-2011, *Environmental Science and Technology*, 47(17), 9808-9815.

O'Connor, T. P., and G. C. Matlock (2005), Shrimp landing trends as indicators of estuarine habitat quality, *Gulf of Mexico Science*. 23, 192–196.

Rabalais, N. N., D. Scavia, and R. E. Turner (2002), Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River, *BioScience*, 52(2): 129-142.

Rabalais, N. N., R. E. Turner, Q. Dortch, D. Justic, V. J. Bierman Jr., and W. J. Wiseman Jr. (2002), Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present, and future, *Hydrobiologia*, 475-476, 39-63.

Rabalais, N. N., R. E. Turner, B. K. Sen Gupta, D. F. Boesch, P. Chapman, and M. C. Murrell (2007), Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia?, *Estuaries and Coasts*, 30(5), 753-772.

Simonetti, P. (1992), Slocum glider: Design and 1991 field trials, Webb Research Corp., North Falmouth, MA.

Walsh, J. J., D. A. Dieterle, M. B. Meyers, and F. E. Miiller-Karger (1989), Nitrogen exchange at the continental margin: a numerical study of the Gulf of Mexico, *Progress in Oceanography*, 23(4), 245-301.

Wiseman, J., W. J., N. N. Rabalais, R. E. Turner, S. P. Dinnel, and A. MacNaughton, (1997), Seasonal and interannual variability within the Louisiana Coastal Current: Stratification and hypoxia, *Journal of Marine Systems* 12: 237-248.

Zimmerman, R. J., and L. M. Nance (2001), Effects of hypoxia on the shrimp fishery of Louisiana and Texas, in *Coastal Hypoxia: Consequences for Living Resources and Ecosystems*, edited by N. N. Rabalais and R. E. Turner, Washington, D. C., American Geophysical Union, 293–310.