Project Title: NGOMEX 2015 Mechanisms Controlling Hypoxia – Glider Application to Gulf of Mexico Hypoxic Zone Monitoring: Pilot Study and Transition to Operations

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NOAA Buoyancy Glider Implementation Plan: Northwest Gulf of Mexico

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Executive Summary

Generally, the presence of sustained or recurring hypoxia conditions can negatively impact coastal ecosystems and has the potential to lead to living resource mortalities, loss of habitat, ecosystem alteration, and impacts to fisheries. In the northern Gulf of Mexico, this issue is well known and documented as the recurring "Dead Zone" along the coast of Louisiana, Mississippi and the upper Texas coast. Along the remainder of the Texas coast, little is known about the extent and duration. The capacity to quickly sample and assess environmental and human health and well-being is paramount to the success of an effective coastal monitoring program. This Plan documents the development of a scalable glider monitoring implementation plan for Texas-Louisiana Shelf coastal waters that can be used for monitoring coastal issues such as hypoxia and potentially for ocean acidification and harmful algal blooms related environmental early warning, assessment and impact.

1. Introduction

1.1 Water Quality and General Circulation of the Texas Shelf

Hypoxia, defined as occurring when the oxygen content of a body of water decreases below 2 mg l^{-1} (1.4 ml l^{-1} or 63 μmol l^{-1}), occurs annually in water below the pycnocline in late spring and summer in the northern Gulf of Mexico, west of the Mississippi delta. The northern Gulf hypoxic region, commonly referred to as the Deadzone, is the largest in the US and second largest in the world. Reviews of hypoxia in this region are given in Rabalais et al., 2007, Dale et al. 2010, and Bianchi et al. 2010 and globally in Diaz and Rothstein 2018 and Zhang et al. 2018 and a special issue of Biogeosciences (see for example Zhang et al, 2010). The decreased oxygen concentration can have a catastrophic effect on bottom-dwelling organisms and is thought to affect the local shrimp and demersal fishing industry. The size of the region affected in the northern Gulf of Mexico varies from year to year; the mean area affected has increased from about 8000-9000 km^2 during 1985-1992 to about

15,000-17,000 km^2 from 1993-1997 (following the 1993 flood). In 1998 and 2000 smaller areas were affected, as river flows were well below average, otherwise the hypoxic area since 1999 has generally exceeded 19,000 km^2 except in 2003 and 2005 when tropical storms and hurricanes mixed the water column immediately before the monitoring cruise (Rabalais et al., 2007). The extent of the hypoxic zone in early summer 2016 is shown below in Figure 1. Of particular note is the observations of low dissolved oxygen concentration over much of the Texas coast at the time of the survey.

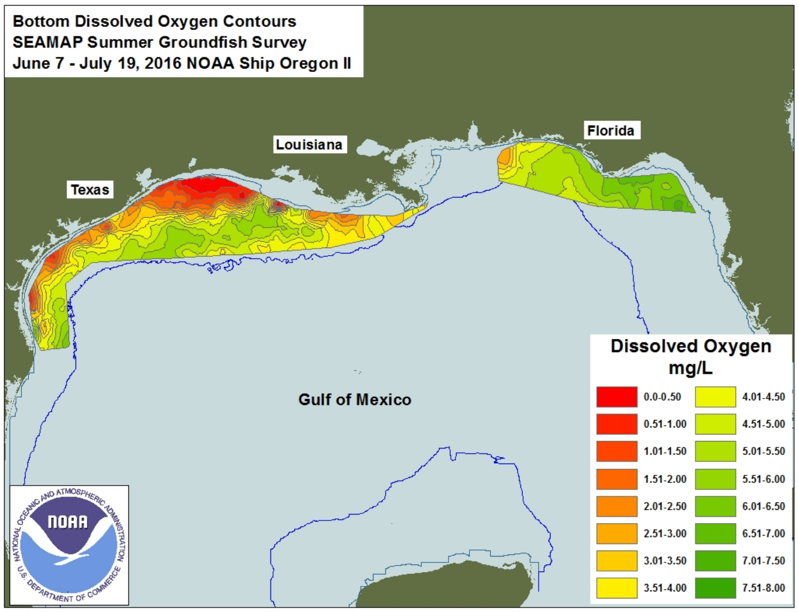

Figure 1. Map of Gulf of Mexico showing near bottom dissolved oxygen concentration in June/July 2016. Data collected by the NOAA-NMFS SEAMAP (Oregon II). Bathymetry contours shown are 20 and 500 m. SEAMAP data courtesy NOAA-NMFS: http://gulfhypoxia.net).

Generally, the presence of sustained or recurring hypoxia conditions can negatively impact coastal ecosystems and has the potential to lead to living resource mortalities, loss of habitat, ecosystem alteration, and impacts to fisheries. In the northern Gulf of Mexico, the recurring large size and proximity to commercially and recreationally important fishing areas has led to considerable scientific and management attention. Additionally, this issue has impacted the watershed management of the source waters of the Mississippi River, a key contributor of nutrients, particulate material, and freshwater volume to the Gulf of Mexico, which derive from more than 40% of the contiguous US. The key organization charged with the tasks of overseeing management activities of the Deadzone is the Interagency Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (regarded herein as the Hypoxia Task Force or HTF). The HTF is authorized through the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (HABHRCA). In 2001, an Action Plan was created (and revised in 2008) with the stated Goal to reduce the areal size of the hypoxic zone to 5000 km2 by 2015. The Action Plan uses combinations of voluntary and incentive-based strategies to reduce nutrient (nitrate and phosphate based) concentration in the Mississippi River through application reductions and altered agricultural practices.

1.2 Hypoxia of the Texas Shelf

In a study published in 2012, DiMarco et al. show, using stable isotopes of oxygen found in surface waters, that a freshwater event associated with flood waters derived from Texas river sources contributed to a hypoxic event offshore of Freeport, Texas.

1.3 Oceanographic Threats to the Flower Garden Bank National Marine Sanctuary and other Northern Gulf of Mexico Ecosystems

The Flower Garden Banks National Marine Sanctuary is located approximately 120 miles southeast of Galveston Bay. This region is home to a complex and diverse ecosystem of coral reefs, benthic and pelagic organisms, invertebrates, marine mammals, fish, and microbial communities. The fragileness of this region was revealed in the summer of 2016, when a mortality event impacted more than 20% of the Sanctuary reefs of the East Bank. Species affected included star fish, and other invertebrates. Low oxygen conditions were observed at several sites within the Sanctuary and along the Sanctuary periphery. (Reference: M Johnson et al. 2018).

1.4 Objectives of the Buoyancy Glider Implementation Plan

Autonomous vehicles are increasingly being used globally to address a variety of oceanographic, climate, and environmental issues (see special issue of Oceanography 2017). These applications include, but limited to, global warming and climate change, tropical storm prediction and upper-ocean heat content, internal tides, sea ice, animal tracking, and ocean noise. The physical and biogeochemical processes that control and maintain the hypoxic zone in the northern Gulf of Mexico are complex and their relative strengths are known to vary temporally and spatially at many scales. Although close to the Mississippi River Delta, the mechanisms that maintain and sustain the hypoxia are mostly driven by biological processes, further downstream the dominant controlling processes are mostly physical as currents and winds combine to break down the vertical stratification necessary to sustain the low dissolved oxygen. National and global ocean observing trends increasingly has included the use of ocean buoyancy gliders and hybrid (buoyancy plus power assisted) gliders for routine monitoring of the coastal and open ocean zones.

Recently, observing strategies in the northern Gulf of Mexico have placed increasing emphasis on the use of gliders to monitor key metrics of the coastal hypoxic area. These metrics include spatial extent, severity, seasonal timing of shelfwide onset, duration, and the associated variability of each of these parameters. However, many challenges exist which question 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 (> 1 m/s) coastal currents, large vertical and horizontal stratification, large numbers of surface piercing and subsurface offshore industry platforms, heavy commercial and recreation fishing activity, active and heavily used shipping lanes, and frequent tropical weather.

The objective of this plan is to develop a scalable glider monitoring implementation plan for Texas-Louisiana Shelf coastal waters that can be used for transitioning glider applications over the whole coast of the Shelf and that can monitor coastal issues such as hypoxia, harmful algal blooms, and other issues related to water quality and transport of freshwater, biomass, and nutrients.

1.5 BGIP Report Structure

The Buoyancy Glider Implementation Plan report is structurally divided into 4 main sections: 1: Introduction, 2: Methodology, 3: Plan and Recommendations, 4: Conclusions. Subsections of Section 2 include a discussion of glider operations and sensors, data, and data processing tasks. Section 3 includes discussion of required facility, personnel, metrics, and budget considerations. Section 3 also briefly acknowledges the use of other types of autonomous ocean vehicles for water quality monitoring. The last Section contains a brief summary of the report recommendations.

2. Methodology

2.1 Glider Operations

Ocean buoyancy gliders, henceforth referred to as simply “gliders”, are a class of unmanned ocean vehicles that use buoyancy of the vehicle as a mechanism to impart horizontal momentum to the vehicle, which allows the vehicle to navigate in the water. The vehicles do not use propeller or other similar mechanical means for propulsion. Each glider is equipped with a Lithium battery to power communication systems, scientific sensors, buoyancy engines, and other electronic and mechanical systems of the glider. The gliders are all manufactured by Teledyne-Webb Research (TWR) of Falmouth, MA. The gliders are all model G2 Slocum gliders.

Glider missions considered for this report. There are seventeen glider missions considered for this report. These missions were conducted by the Glider Team at the Texas A&M University Geochemical and Environmental Research Group (GERG) during the years 2014-2018. The 17 missions will be referred to by their GERG Mission numbers. In this case, Missions 7, 8, 10, 13, 14, 18, 19, 20, 21, 22, 25, 26, 27, 29, 31, and 34. The dates, available sensors, and glider serial numbers are summarized in Table 1.

GERG maintains a dedicated glider lab facility in College Station, Texas. The glider lab contains equipment to service, maintain, ballast, and operate the GERG glider fleet. The human resources available include up to two dedicated and certified Slocum glider pilots. Certification is administered by the glider manufacturer TWR.

Gliders are monitored 24/7 when in the water and performing a mission. The glider pilots work with the scientific principal investigator. The PI defines mission objectives and goals. The pilots then determine ballasting conditions, propose power strategies and waypoints, and suggest deployment and recovery strategies and vessels. Glider pilots also program the glider for mission related duties, communication intervals, surfacing strategies, notification of hazards. Hazards include shipping lanes, potential to encounter strong currents (which may render the glider unable to navigate efficiently, presence of offshore structures (both at surface, i.e., platforms and rigs, and subsurface, i.e., pipelines, geological structures), presence of freshwater lenses, and federally protected regions (e.g., the Flower Garden Banks Sanctuary).

Gliders are generally programmed to surface at 4-6 hour intervals. Data are only transmitted to shore during glider surfacings. Data are transmitted via Iridium satellite through the satellite antennae contained in the glider tail. Roughly 5% of the total collected data are transmitted at surfacings. This reduction in data transmission is done to limit communication costs (Iridium service costs are dependent on volume of data transmitted). All data collected by the glider during the mission are recovered upon completion of the mission and recovery of the unit. Data transmissions are also shortened to reduce risk of ship strike and system theft by opportunistic pilferage; time at the surface is usually schedule to be less than 15 minutes.

Gliders are powered using Lithium batteries. Lithium batteries allow for deployment durations to be 30 to 90 days. Power consumption is highly dependent on multiple factors and include: average depth of undulation, ambient current magnitude and direction, data collection rate, and number of sensors employed.

Relief piloting is performed from suitably trained technicians to monitor glider performance while in the water and to inform pilot of system problems while underway. Suitably trained undergraduate and graduate students and GERG Interns also participate in piloting and glider lab activities in some circumstances and under supervision of professional glider personnel.

The gliders move through the water in response to changes in their buoyancy, which is controlled by an internal buoyancy pump rather than movement using a propeller or other thrusting mechanism (Simonetti, 1992). Prior to deployment, the glider is ballasted for the expected range of water densities to be encountered, which limit the glider's range of navigable waters. For the missions described in this manuscript, the gliders were ballasted to be neutrally buoyant at a density of 1,022 kg/m^3. The glider forward speed is approximately 25-50 cm/s (1 knot is roughly 51 cm/s). The glider collects data while undulating through the water column.

Structural Hazards As our glider missions were designed to collect data in the Gulf coastal hypoxic zone, glider pilots were required to navigate and maneuver around the more than 5,000 surface piercing oil and natural gas structures on the Texas-Louisiana shelf that occur in water depths up to 500 m. 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 (BOEM 2017). To reduce the chance of glider collision with large ships, gliders were programmed to remain below 5 m depth while traversing major ship lanes.

Table 1. Glider mission summary

Mission	Begin	End	Days in water	Variables collected
Mission 7#	11 Jul 2014	12 Aug	33	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 8#	11 Jul 2014	4 Aug	25	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 10#	30 Aug 2014	1 Oct	33	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 13#	1 Jul 2015	20 Jul	18	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 14#	1 Jul 2015	20 Jul	18	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 18*	5 Jun 2016	6 Jun	1	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 19*	5 Jun 2016	9 Jun	4	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 20	30 June 2016	18 July	19	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 21	29 June 2016	20 July	22	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 22	5 August 2016	10 Sept	37	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 25	14 Nov 2016	15 Nov	1	None
Mission 26	7 Dec 2016	19 Jan 2017	42	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 27	20 Jan 2017	7 May	106	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 28*	29 Jun 2017	5 Jul	6	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 29*	27 July 2017	5 Aug	9	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 31^	24 Sept 2017	11 Oct	18	Temperature, salinity, oxygen, fluorescence, turbidity
Mission 34	25 Jan 2018	31 Jan	6	Temperature, salinity, oxygen, fluorescence, turbidity

*NOAA planned missions

^ Hurricane Harvey

#Pre-award missions considered in this report

2.2 Glider Sensors

All GERG Slocum gliders are equipped with a suite of oceanographic sensors: CTD, ECO-Puck fluorometer, and dissolved oxygen sensor. Conductivity was used to determine salinity of the water using the Equation of State (TEOS-10), while depth was used to determine the pressure. The sampling rate for the scientific sensor package is 1 Hz.

Slocum gliders configured with standard buoyancy pumps have about ± 2 kg/m^3 of density range for efficient operations. A buoyancy pump modification allowed some glider missions to more efficiently operate in stronger density gradients and larger density ranges. An addition of small propeller (thruster) also allowed the glider to "push" through strong density gradients outside the mission-planned buoyancy range (at a cost of increased power requirements) for short periods of time. This was particularly useful in the coastal zone of the northern Gulf where frequent occurrences of surface freshwater lenses derived from the Mississippi River and other freshwater sources can impact glider operations by reducing maneuverability and limiting forward progress. The thruster is not typically engaged while inflecting, i.e., when the glider is reversing vertical direction.

Oxygen Probes: The RINKO oxygen sensor consists of an oxygen probe and associated temperature probe and was calibrated in the lab according to manufacturer protocol prior (~1-2 days) to deployment (Rockland Scientific 2017). The RINKO sensor response to oxygen concentration is considered linear in the temperature ranges encountered in the ocean; therefore, calibration points were obtained in nitrogen gas (anoxic conditions) and in air (normal oxic conditions). The RINKO temperature probe was calibrated by the manufacturer and shows no drift when compared to other temperature sensors in the glider instrument package. Raw oxygen probe voltages were combined with the associated temperature probe data to yield dissolved oxygen concentration estimates using manufacturer supplied software routines. The Aanderaa Optode probe is a self contained unit that is calibrated by the sensor manufacturer. Routine maintenance and comparison to water titrations are used to verify that the Optode remains within appropriate calibration.

The Seabird (Glider Payload) GPCTD is a low-power continuously pumped instrument package designed for use on autonomous gliders (http://www.seabird.com/glider-payload-ctd). The GPCTD records temperature, conductivity, and pressure at 1 Hz; data are recorded in engineering units. GPCTD's were calibrated at the Teledyne Webb Research facility prior to glider deployment. Conductivity measurements were converted to practical salinity using the practical salinity scale (PSS-78; McDougall and Barker, 2011). Accuracy of the GPCTD temperature and conductivity sensors is listed with the sensor manufacturer. All observational quantities were rigorously quality controlled according to guidance provided for in situ temperature, salinity, and dissolved oxygen concentration by the Integrated Ocean Observing System's (IOOS®) Quality Assurance of Real Time Oceanographic Data (QARTOD) (https://ioos.noaa.gov/project/qartod/). Data were initially plotted as time series and histograms to range check and identify outliers (DiMarco et al., 2001). Fluorometer data were not specifically analyzed for this aspect of the overall study but were useful for interpreting oceanographic features found in the temperature and salinity data.

Each glider was equipped with a 170-kHz altimeter in the vehicle forward section and provided estimates for distance in meters above bottom. Altimeter data were recorded at 1 Hz and simultaneously with scientific sensors. Altimeter data were added to the glider depth values to provide an estimate for total water depth.

3.3. Buoyancy Glider Data (mission summaries)

The gliders were all deployed on the Texas-Louisiana Shelf near the 50 m isobath (Figure 2). The gliders were ballasted in accordance with the water densities that were expected to be encountered.

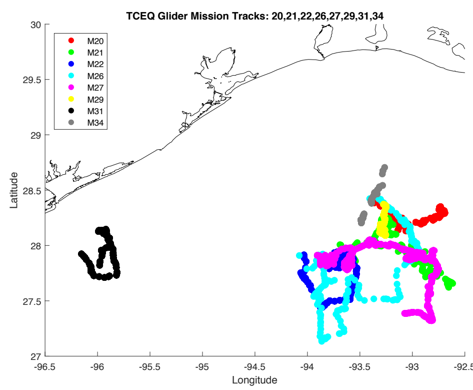

Figure 2. Glider mission tracks for missions M20, M21, M22, M26, M27, M29, M31, M34. Time period for these missions is 2016-2017. See table 1 for dates of deployment.

3.4 Data Processing

There are two types of data collected by the glider: mission and science. Mission data are engineering system based data that inform status of navigational units, performance metrics, power consumption, and status of overall system health. More than 2000 individual mission variables are recorded at 1 Hz. Science data include variables collected by the science bay package of the glider. Science variables include all raw and internally processed scientific sensors, and variables that control the scientific sensor package. Science variable sampling frequency is controlled by the pilots and is alterable depending on mission needs.

Data processing of the glider mission occurs in two phases: real-time and deyated mode. Real-time processes begins when the shore station receives glider mission and science data through the Iridium communications service. As stated previously, real-time data represent approximately 5% of the total data collected. However, these data are more than adequate to provide a thorough understanding of the environmental conditions being encountered by the glider and the system status of the glider.

While at sea, the Gulf of Mexico Coastal Ocean Observing System (GCOOS) openly distributed the near real-time observations on the GCOOS Data Portal (http:/gcoos.org) site using the GANDALF representation system. GANDALF provided up-to-date maps of the glider trajectory and location as well as time versus depth graphics of each scientific sensor. Examples of the real-time data plots are provided in the mission summaries section of this Plan. All telemetered data will be archived and backed-up onto secure devices and servers to prevent loss of collected data.

3. Plan and Recommendations

3.1 Facilities and Infrastructure

<u>Vehicle Hardware Requirements</u>

Recommendations for facilities and infrastructure requirements for successful collection of buoyancy glider data are divided into several components: shore facility, glider equipment, power consideration, personnel, and vessels. It should be noted that the glider specific recommendation below are referenced to the use of Slocum G2 type gliders, i.e, the gliders used to inform this plan. When possible, gliders available from other manufactures are references to allow for difference among glider brands.

It is recommended that a dedicated glider lab with capability to service, maintain, and ballast the gliders be assessable. A ballasting tank, with electronic hoist, that is capable of completely immersing a buoyancy glider (1.5 m x 5 m minimum) with the ability to recirculate salt water and maintain a near constant temperature (i.e., controlled indoor environment).

<u>Power</u>

Slocum G2 gliders have the capability to be powered using alkaline and Lithium batteries. The capability of Lithium-ion rechargeable batteries has just recently (2017) become available and were not available for use during the project. There is considerable differences in cost and capability of alkaline and Lithium batteries for gliders. Alkaline battery pack are significantly cheaper (~$2800) than Lithium

(~$18000), however, the number of amp/hrs available are 153, 170 amp-hr, respectively.

3.2 Metrics

Glider Ability to reach bottom

Examination of the glider data collected on the Texas shelf shows that buoyancy gliders are capable of navigation in the challenging coastal region of the northern Gulf of Mexico coastal zone and can produce observations of key oceanographic quantities of interest to coastal managers monitoring water quality. The eight missions totaled more than 260 days of observations focused principally on the broad shelf region with water depths up to 100 m. The gliders were consistently able to obtain sub-pycnocline observations. The distributions of closest approach show that suitably ballasted and equipped gliders can come within 2 m of the bottom more than 95% of the time. Our statistics indicate that it may be possible to get closer, within 1 meter of the bottom (Figure 3); however, this would mean a substantial increase in the probability of encountering the bottom, which will increase the risk of damage to or failure of the glider.

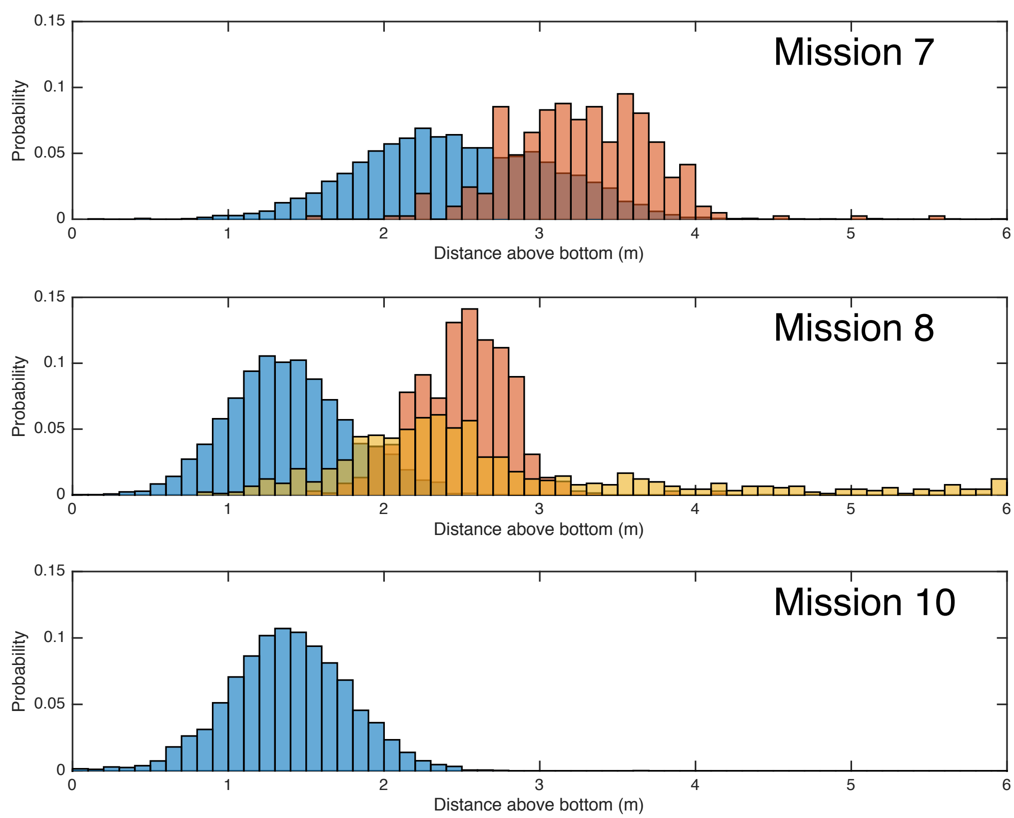

Figure 3. Histograms of closeness to bottom. Blue histograms are calculated when inflection depth above bottom was set at 4 m. Red histograms are for 5 m above bottom. Yellow histogram for mission 8 is near mission's end and when glider is believed to have lost a wing.

Coming within an average of 1.4 m of the ocean bottom is sufficient to reach sub-pycnocline depths and thus to characterize the hypoxic area in the Gulf, satisfying the Gulf of Mexico Coastal Ocean Observing System (GCOOS) Glider Task Force requirement for gliders to get close to the sea floor. [text here on responding to RESTORE objectives concerning resilience and water quality] The data produced by the glider data are of sufficient time and spatial resolution for objective mapping of the region. However, with just one or two gliders simultaneously in the water, the data are not sufficiently distributed to create a map of the region. While gliders do not travel as quickly as oceanographic research ships (less than one nautical mile per hour versus greater than eight), 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 on all missions. For all missions, the planned mission trajectories were generally planned as a series of onshore/offshore trajectories that gradually moved from west to east. However, the strong eastward current at times prevented the gliders from moving either onshore or offshore.

Some missions used a glider that was modified with a shallow water (800 cc) buoyancy pump; this pump has a larger volume than the standard shelf 200 m buoyancy pump (400 cc). These modifications allow the glider to operate more efficiently 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 lenses derived from the Mississippi/Atchafalaya River and the Texas Rivers can impact glider operations. While density gradients are an obstacle for glider operations, measures are being taken to overcome such limitations. We are in the process of fully assessing the glider performance using combinations of thruster/no-thruster and shallow/shelf buoyancy pumps. However, that assessment is outside the scope of the BGIP.

<u>Glider Ability to Resolve Vertical Structure</u>

The glider has demonstrated the ability to resolve strong vertical gradients of environmental parameters in the ocean. The oxygen gradients encountered have exceeded 4 mg/L in 2 m; salinity changes have exceed 5 units in 5 m. The data collected by the glider are collected at 1 Hz; the vertical movement through the water column is on the order of 0.25 m per second. The response speed of the sensors given the rate of movement through the gradient indicated that the sensors are more than capable of resolving the gradients encountered.

Mapping Areal Extent with Buoyancy Gliders.

The mapping of an area of the ocean with buoyancy gliders is challenging due to the environmental variability of the coastal ocean, limited long-term variability and design criteria and limitations of the buoyancy gliders. Traditionally, the mapping of the low oxygen area of the northern Gulf of Mexico and the Texas-Louisiana Shelf relied on manned ship board surveys that were of about one week duration. Observations of dissolved oxygen concentration were collected using a CTD-rosette system that was lowered over the side of the ship. Stations were planned along a regular or semi-regular grid that spanned the region of interest. Observations closest to the bottom were assembled into an analysis database, which was then interpolated (optimally or linearly) to estimate a field of the observed parameter. This process necessarily relied on a reasonable spatial distribution of point across the region to do the interpolation and construct a field with reasonable error. Further, data must be collected within time frames consistent with known temporal scales of variability of the system. For example, if observations collected at the end of mission are well after those collected at the end of the mission, then the assembly of a quasi-synoptic field has little to no meaning.

Gliders, by their design, are programmed to linearly follow and achieve waypoints in succession. Therefore, to collect data that is sufficient for mapping, the glider must collect spatially distributed data. Ways to achieve suitable spatial distribution include: multiple parallel transects (either cross or along shore), crossing patterns, and zigzag patterns.

We have determined that the use of a single buoyancy glider to collect data suitable for mapping the coastal ocean is not possible. Multiple factors lead to this conclusion. Glider speed: the forward speed of a glider is 25 cm/s (~about 0.5 nautical miles per hour). Therefore, a glider can therefore cover 12 miles per day or 84 miles per week. At this rate of speed, a buoyancy glider will only be able to linearly transit from Galveston Island to Matagorda Island, i.e., a small percentage of the coast. The results of the missions shown above conclusively have shown that a single glider was consistently unable to repeat lines, repeat transects or make smooth and reliable turns.

Multiple Vehicle Coordination

Our recommendation is that multiple gliders be deployed simultaneously, along parallel off-shore transects (from inshore to offshore). Spacing of the gliders transects should be at most 50 km to ensure observations are taken at appropriate spatial scales. Gliders should be deployed near or about the 25 m isobath, i.e., the minimum depth for efficient navigation and be programmed to achieve waypoints approximately 30 miles off shore or the 60 m isobath. The glider should then turn and head back toward shore. These transects will accomplish and satisfy the requirement of semi-synopticness for the observations (60 miles can be transected in less than one week), suitable spatial distribution (10 lines along the Texas coast) for map creation.

Deploying multiple gliders simultaneously along the Texas coast necessarily implies the use of multiple deployment vessels. At most five vessels would be need to deploy; if environmental conditions allow it may be possible to reduce the number of vessels to three, i.e., two vessels could deploy a glider at two locations.

3.3 Budget Estimate

The following budget estimate is assembled based on the recommendation above that include suitably trained workforce personnel, suitably equipped gliders systems, and infrastructure capable for glider ballasting, servicing, and maintenance.

Hardware

Slocum glider base price without scientific instrumentation is roughly $130k. Necessary scientific equipment include: G-CTD, Eco-Puck fluorometer, dissolved oxygen sensor, and altimeter add about $50k to the cost. The addition of coastal buoyancy (800 cc) pump and thruster assembly is approximately $60k. Therefore, each Slocum costs approximately $240k; $1.2M for five.

Power costs

As previously stated, two power options are available for the TWR Slocum gliders: alkaline ($2500) and Lithium ($18000). It is recommended that alkaline batteries be avoided because they carry larger risk of power depletion during the demanding coastal mission. The Lithium battery will allow for sufficient power for the needed thruster usage and to collect scientific sensor data. The largest power consumers on the glider are the buoyancy pump and thruster assembly. Communications and scientific sensors draw considerably less power. Because the gliders will be encountering strong vertical gradients of density, strong coastal currents, relatively shallow water depths, and frequently cross active ship lanes, the engagement of the thruster to navigate the strong gradients and currents will use power. Additionally, in order to move vertically in the water, requires the use of the buoyancy engine. Because the glider will be in the shallow environment of the coast, the glider will make frequent dives. The number of dives will be much more often that gliders require when in deep water (>200 m) or on the outer continental shelf (50-200 m). The frequent use of the buoyancy pump and the thruster assemble will significantly increase the missions power requirements and shorten the battery life. Therefore, it is recommended that new Lithium batteries be used in each glider for each mission.

Batteries: $100k per year.

Supplies and communications

The glider requires satellite communications to transmit mission and scientific data to shore stations in near real time. The cost of data transmission for typical glider deployments is on the order of $2000 per month per glider (or $70 per day per glider). The cost for five gliders per 7-day mission is about $2500. Additional communications costs may be incurred for long missions (either intentional or unintended).

Standard laboratory supplies include sea salt for ballasting, electronic consumables, water, laboratory equipment. Supplies are about $1000 per year.

Scientific Sensor Calibration

All science package sensors require at least annual calibration to ensure data quality and integrity. Science sensors require manufacturer calibration at TWR facilities. Costs incurred include shipping to and from the manufacturer, calibration service, and personnel time. The cost to fully calibrate the glider science sensor package is roughly $8k per glider. $40k per year.

Buoyancy pump assembly

Because of the increased demands on the buoyancy pump in shallow water, the pump will require increased servicing and maintenance. The glider manufacturer recommends that buoyancy pumps be replaced after 20000 inflections (an inflection is defined to be one complete cycle of the pump assembly and therefore is one transition of the glider from moving down in the water to up and from up to down). Because of the shallow water conditions, the entire lifetime of the buoyancy pump can be used in one or two missions. Therefore, we recommend careful monitoring of the buoyancy pump during missions and careful inspection of the pump diaphragm and membrane upon recovery for signs of wear and weakness. We recommend a new pump assembly each year for each glider. Each pump assembly costs roughly $10k.

Shallow water buoyancy pump assemblies: $50k per year.

Personnel and training

The challenges of flying a buoyancy glider in the shallow environment of the coastal ocean of Texas requires skilled and trained professionals. The hazards are numerous and the piloting requires more attention and more time watching than for missions in deep water. Therefore, for a glider fleet of 5, we recommend two trained pilots, to actively pilot and navigate the gliders in the water.

Five deployment/recovery specialists who are trained to deploy and recover the gliders at sea. The specialist would be required to transport the gliders from the shore facility to the ship of opportunity and then ride with the glider to the drop off or recovery point. The specialist would oversee recovery and deployment operations while on the vessel to ensure and document safe recovery procedures and protocols. Specialists: $250 per day, times 20 days: $5000 per year.

Some costs of routine laboratory maintenance and servicing tasks can be devoted to student workers, volunteers and interns. We feel the training of the next generation of oceanographic professionals requires the exposure to technology and experience in an operational setting. Student training $2500 per year.

Ship time Requirements

Buoyancy gliders require suitable vessels for deployment and recovery. Buoyancy gliders weigh more than 150 lbs in air (near zero in water). Therefore, handling of a glider can be particularly challenging in rough and stormy conditions. Suitable vessels are typically in the $3500 per day range and include small commercial fishing boats (35’) and recreational vessels. We have used large research vessels for this purpose, often time in conjunction with research cruises of opportunity. Large research vessels are considerable more expensive than small charter vessels. We recommend $50k per year for ship charters to deploy and recover the gliders.

Insurance

The cost of a glider is a significant investment and therefore insurance should be purchased to protect that investment from loss or damage. Currently, we insure the gliders at a rate of $5k per glider per year. There is a $25k deductible on this rate.

Facility

The use of gliders requires a dedicated facility that is powered, heated/air conditioned, has phone and other business amenities. The facilities costs incurred are typically a line item in the budget as Indirect Cost (IDC). We will use a typical major Tier-1 research university IDC rate of 48.5% applied to all Modified Direct Costs in the above.

Budget summary

Hardware		
	5 Buoyancy Gliders	$1.2M
Communications		
	Iridium Satellite	$2500
Personnel		
	Pilots (2 pilots)	$120k
	Specialists	$5k
	Students/Interns	$5k

Batteries		$100k
Pumps		$50k
Calibration		$40k
Training		$10k
Supplies		$1
Travel		$2k
Shipping		$10k
Insurance ($5k per glider)		$25k
Shiptime (10 trips at $5k per trip)		$50k
Subtotal		$420k
Facility	(48.5%)	$225k
	Grand total	$625k

Therefore, an initial one-time $1.2M investment in five gliders (capital equipment) is necessary. The M&O costs per year are roughly $420k. Indirect facility charge is roughly one half of the Direct Costs, giving a grand total of $625k per year ($3M over five years). Power and personnel are the largest single items associated with the planned objectives. Some cost savings could be incurred by sharing human resources among multiple glider activities and effective offshore research vessel management.

3.4 Use of Other Autonomous Vehicles

New technologies on materials, renewable power, vessel design, communications, and sensors are constantly evolving. Emerging unmanned technology like Liquid Robotics Wave Gliders, Sail Drone, and ASV Global C-Workers are also being developed and adapted for coastal applications. We envision that the use of unmanned surface vessels with winch capability will soon be cost effective for coastal application such as water quality monitoring and management, coastal hazard mitigation, navigation guidance, environmental monitoring during tropical weather, search and rescue operations, and oil spill response operations. Costs of these vessels, piloting, and maintenance is presently well above that of buoyancy gliders. However, we anticipate that the costs of the autonomous surface vehicles will become significantly less expensive in the future (through more reliable renewable power and operation costs) and be of comparable price or less expensive than buoyancy gliders

4. Conclusions

In conclusion, we have presented a Buoyancy Glider Implementation plan to monitor key oceanographic variables of the Texas-Louisiana coastal ocean that are related to water quality associated with coastal hazard such as hypoxia and harmful algal blooms. The Plan calls for the use of five suitably equipped (for coastal ocean operations) buoyancy gliders to be simultaneously deployed along the Texas-Louisiana Coast and spatially distributed to provide broad areal coverage of the continental shelf region between the 20 and 50 m isobaths. The gliders should be programmed to achieve cross-shore transect lines of about 30 miles and return to predetermined pick up points. The plan necessarily requires the use of commercial and/or recreational ships for deployment and recovery operations. There is some risk that gliders deployed in the coastal ocean can be damaged or lost due to ship strike, platform entanglement, encounters with commercial fishing fleets, and other hazards. Therefore, emergency contingencies must be considered. The gliders have demonstrated the capability to adequate provide the vertical resolution of oceanographic variables that can lead to informed management decisions. The gliders are also capable of reaching to appropriate near-bottom and sub-pycnocline depths. However, the gliders are susceptible to weather and environmental factors that can limit their ability to navigate effectively in the coastal environment. The plan includes an estimate of costs for a five-year glider program. Total is $4.2M for five years, which includes an initial one-time capital equipment investment of $1.2M for five suitable equipped buoyancy gliders. Economies of scale and leveraging of multiple use can lead to significant cost savings.