Glider Implementation Plan for Hypoxia Monitoring in the Gulf of Mexico

April 2014

A White Paper from the Gulf Hypoxia Glider Application Meeting, convened by the NOAA National Centers for Coastal Ocean Science, Northern Gulf Institute, and the NOAA National Data Buoy Center on 17-18 April 2013 at the Mississippi State University Science and Technology Center at NASA's Stennis Space Center in Mississippi.

Writing Team
Stephan D. Howden, University of Southern Mississippi
Robert A. Arnone, University of Southern Mississippi
Justin Brodersen, Naval Research Laboratory at Stennis Space Center
Steven F. DiMarco, Texas A&M University
L. Kellie Dixon, Mote Marine Laboratory
Hernan E. Garcia, National Oceanographic Atmospheric Administration, National Ocean Data Center
Matthew K. Howard, Texas A&M University
Ann E. Jochens, Texas A&M University
Sherwin E. Ladner, Naval Research Laboratory at Stennis Space Center
Chad E. Lembke, University of South Florida
Alan P. Leonardi, National Oceanographic Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory
Andrew Quaid, Naval Research Laboratory at Stennis Space Center
Nancy N. Rabalais, Louisiana Universities Marine Consortium

Editors
Alan J. Lewitus, National Oceanographic Atmospheric Administration, National Centers for Coastal Ocean Science
Stephan D. Howden, University of Southern Mississippi
David M. Kidwell, National Oceanographic Atmospheric Administration, National Centers for Coastal Ocean Science

This report should be cited as:
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. Edited by A.J. Lewitus, S.D. Howden, and D.M. Kidwell. White Paper from the Gulf Hypoxia Glider Application Meeting, 17-18 April 2013 at the Mississippi State University Science and Technology Center at NASA's Stennis Space Center in Mississippi, 21 pages.

Table of Contents

A. Abstract .... **Error! Bookmark not defined.**
B. Background .... **Error! Bookmark not defined.**
B.1 Introduction .... **Error! Bookmark not defined.**
B.2 Northern Gulf of Mexico Hypoxic Zone .... **Error! Bookmark not defined.**
B.3 Glider Integration 7
B.4 Other Glider Monitoring Plans for the Gulf of Mexico....... **Error! Bookmark not defined.**
C. Priority 1 .... **Error! Bookmark not defined.**
C.1 Tier 1 Glider Sensor Package .... **Error! Bookmark not defined.**
C.2 Glider Transects.. **Error! Bookmark not defined.**
C.3 Missions for Mapping of Hypoxic Bottom Waters .... **Error! Bookmark not defined.**
C.4 Tier 1 Moorings.. **Error! Bookmark not defined.**
C.5 Glider Platforms.. **Error! Bookmark not defined.**
C.6 Pilot Projects .... **Error! Bookmark not defined.**
D. Priority 2: Enhanced number of gliders with Tier 1 sensor packages for lines and mapping .... **Error! Bookmark not defined.**
E. Priority 3: Effects on Living Marine Organisms and Observing System Simulation Experiments 17
F. Data Management 18
References .... **Error! Bookmark not defined.**
Appendix 1. Participants in Glider Implementation Plan Working Session .... **Error! Bookmark not defined.**

A. Abstract

The 2012 revision of the Gulf of Mexico Monitoring Implementation Plan included the need to hold a workshop to determine the optimal glider design and glider monitoring strategy for temporal/spatial coverage that would complement ship surveys and observing systems. On 17-19 April of 2013 the workshop was held as part of the Forum for Gulf of Mexico Hypoxia Research Coordination and Advancement. The glider implementation plans in this document were developed from the presentations and discussions that occurred during the forum. The Priority 1 plan includes 4 hypoxia glider transects in the northern Gulf of Mexico between the 10 and 60 m isobaths, with one glider in operation continuously on each line. The transects are chosen to coincide with the LUMCON hypoxia station lines F, K and C and the USM line on the east side of the delta. At least one instrumented mooring or platform on each of these four lines is part of the Priority 1 plan. The Priority 2 part of the plan is an expansion of the glider fleet to 1) expand the glider transects westward, 2) have twice a month "sawtooth" surveys extending from the mouth of the Mississippi River to Port Arthur, TX from May through September, and

3) increase the sampling frequency along the glider transects. The Priority 3 section includes sensors for determining the effects of hypoxia on living marine resources.

B. Background

B.1 Introduction

There is a recognized, and well documented, need for enhanced monitoring of seasonal hypoxia in the northern Gulf of Mexico beyond the mid-summer surveys. Among the citations that follow, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force through their Monitoring, Modeling and Research Workgroup Report (USGS 2004) cited the need for at least monthly monitoring from May through September, year-round monitoring at some selected sites, and expanded sampling to provide boundary conditions for models. With funding scarce to pay for hypoxia cruises, one alternative is to augment the shelf-wide sampling cruises with gliders. Indeed, the use of gliders as part of a broad Gulf hypoxia monitoring strategy was first identified in the Gulf of Mexico Hypoxia Monitoring Implementation Plan, which was completed in 2009 and revised in 2012. In 2012 the Gulf of Mexico Hypoxia Monitoring Implementation Plan Revision Steering Committee introduced the need for a "Workshop to determine optimal glider design and glider monitoring strategy for temporal/spatial coverage that complements ship surveys and observing systems". On 17-19 April 2013 the Gulf Hypoxia Glider Application Meeting was held as part of the Forum for Gulf of Mexico Hypoxia Research Coordination and Advancement. A Glider Implementation Plan Writing Team (authors of this document) was selected by the Forum Steering Committee to develop "an implementation plan for the deployment of gliders for monitoring the size of the hypoxic zone", and "evaluate technological limitations prohibiting or limiting the successful deployment of gliders in the hypoxic zone." The glider implementation plans in this document are developed from the presentations and discussions that occurred during the forum.

B.2 Northern Gulf of Mexico Hypoxic Zone – Current Monitoring Activities

The importance and national scale of hypoxia and nutrient pollution in United States waters is evidenced by the passage of the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) in 1998, its reauthorization in 2004, and scheduled reauthorization for 2014 (16 U.S.C. 1451 note) as amended by draft Senate bill (2013-06-19). The HABHRCA legislation, several national reports, the United States Commission on Ocean Policy Report, and the Scientific Advisory Board of the U.S. Environmental Protection Agency (USEPA 2007) describe the need and identify priorities for research related to hypoxia and nutrient pollution, and its mitigation through nutrient control (Mississippi River/Gulf of Mexico Nutrient Task Force 2001, 2008).

The largest zone of human-caused oxygen-depleted coastal waters in the United States, and the second largest for the world's coastal ocean, is in the northern Gulf of Mexico extending from Mississippi and Alabama to Texas, but primarily on the Louisiana continental shelf. Analyses of paleo indicators of increased primary production and worsening oxygen conditions in sedimentary records, and model hindcasts suggest that hypoxia in this region has intensified since the 1950s, and that large-scale hypoxia began in the 1970s (reviewed in Turner et al. 2006, Justić et al. 1997, Rabalais et al. 2007a, b, 2010). The areal extent of the hypoxic zone, monitored in mid-summer since 1985, has increased from an average of 6,900 km^2 from 1985-1992 to 15,600 km^2 from 1993-2012, with a peak of 22,000 km^2 in 2002 (http://www.gulfhypoxia.net). Scientific consensus (CENR 2000, SAB 2007) supports the conclusion that the worsening hypoxia in this region is linked to eutrophication driven by increased nutrient loading to the Mississippi River and adjacent Gulf of Mexico.

Since 1985, a Louisiana Universities Marine Consortium (LUMCON)/Louisiana State University (LSU) research cruise, primarily on the R/V *Pelican*, has been conducted in mid- to late-July over an 80-100 station grid from which the area of bottom-water less than 2 mg l^{-1} dissolved oxygen was estimated (Fig. 1, blue circles). The long-term method of assessing the mid-summer extent of northern Gulf of Mexico continental shelf hypoxia is critical to support the Action Plan in assessing whether the five-year running average of the bottom-water hypoxic area is less than 5,000 km^2. It also has the advantage that it reflects the early history of research in the area, can be consistently acquired, and addresses the public interest of how large the 'Dead Zone' is.

Over 29 years, the protocol for the LUMCON/LSU cruises was for CTD casts and a rosette with Niskin bottles to measure and collect water. In addition, a separate CTD (Hydrolab or YSI) was lowered to within 0.5 m of the seabed to obtain data 1 to 2 m below where probes on the rosette were able to sample. A separate 5-l Niskin bottle was also deployed as close to the bottom as possible, within 0.5 m to collect bottom water for ancillary measurements. The instrumentation and probes have changed over the years, but the basic principle of reaching the deepest water possible to document thin lenses of hypoxic bottom water and to document the often thin surface layers with regard to freshwater signatures and associated dissolved oxygen values have dictated sampling protocols. An additional asset provided by the R/V *Pelican* is the underway flow-through data acquisition, underway ADCP current measurements, and meteorological conditions, all linked to a GPS system.

Additional cruises were added in 2009 for the months of June and August in which the Texas A&M University (TAMU) hypoxia research group utilizes a towed scan-fish from aboard NOAA's R/V *Manta* to map hypoxia and related parameters over a larger grid that encompasses the area of the longer-term cruises aboard the R/V *Pelican* (Fig. 2) The TAMU cruises also conducted CTD profiles at many stations along the scan-fish grid.

Cruises specifically for summer hypoxia have been conducted east of the Mississippi River off Mississippi and Alabama by researchers at the University of Southern Mississippi (USM), Dauphin Island Sea Lab (DISL), and the LUMCON/LSU group, and more inshore by the Lake Pontchartrain Basin Foundation. USM carried out monthly sampling that included bottom dissolved oxygen measurements on an offshore transect in the Mississippi Bight between 2007 and 2011 (Figure 3), and mapped the extent of hypoxia east of the delta in 2006, 2008 and 2011 (Figure 4). In addition, cruises by LUMCON/LSU on the grid to the east of the Mississippi River (Fig. 1, red triangles) occurred in 2011, as well as by DISL in 2012 and 2013.

Greater temporal variability of conditions within the hypoxic area of the Louisiana shelf are provided by cruises conducted over the years by LUMCON/LSU on a bimonthly to monthly basis on a cross-shelf transect off Terrebonne Bay and another off Atchafalaya Bay. These cruises were terminated in 2012 due to lack of funding. Additionally, deployed oxygen meters at observing systems along the Louisiana shelf have provided high temporal resolution but on limited spatial scales. The single remaining system is now at LUMCON Hypoxia Station C6C, WAVCIS CSI-6.

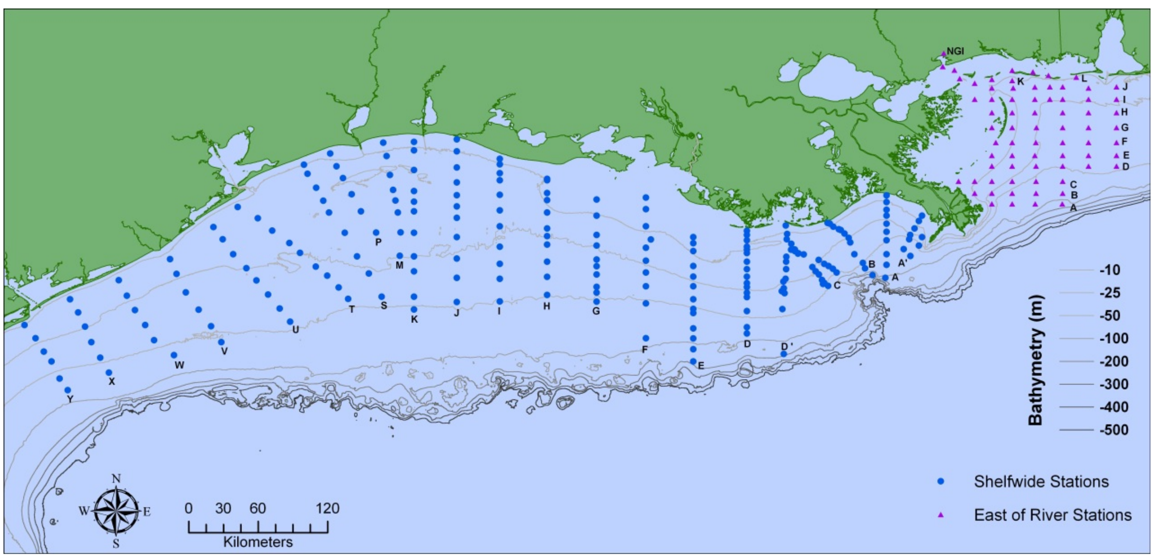


Figure 1. Existing shelfwide grid west of the Mississippi River, which was expanded to the east of the Mississippi River in the flood year of 2011.

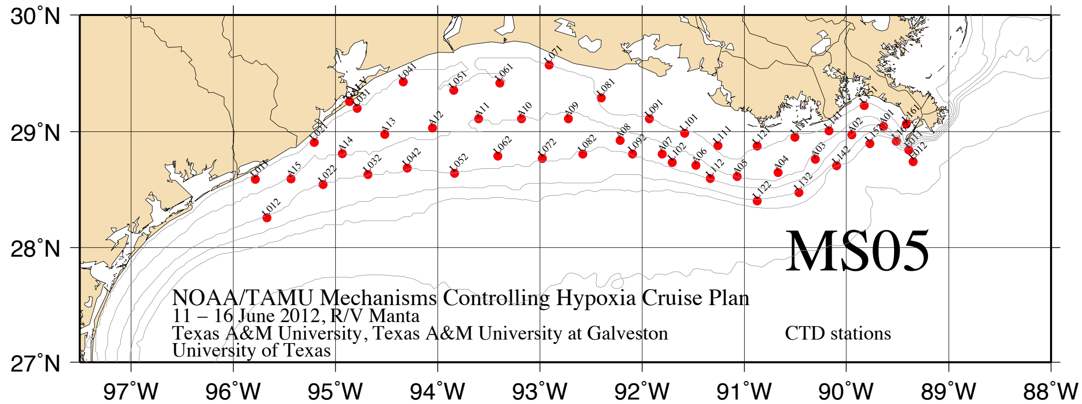
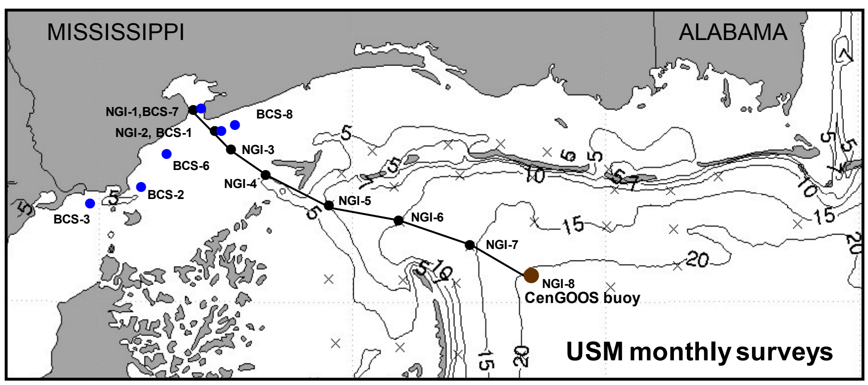


Figure 2. Sample TAMU station grid for CTD profiled. Scan-fish is operated through the water column over the entire area.



Blue dots = Bonnet Carré Spillway (BCS) stations
Black dots = Northern Gulf Institute (NGI) stations
From Gundersen et al., USM

Figure 3. Sampling sites along transects sampled monthly between 2007 and 2011 by USM to monitor hypoxia in the Mississippi Sound/Bight, showing the Northern Gulf Institute (NGI) transect line (●), the Bonnet Carré Spillway (BCS) stations (●), and S.P. Milroy's 2010 high-resolution hypoxia stations (♦) currently sampled at monthly intervals by the Department of Marine Science, USM.

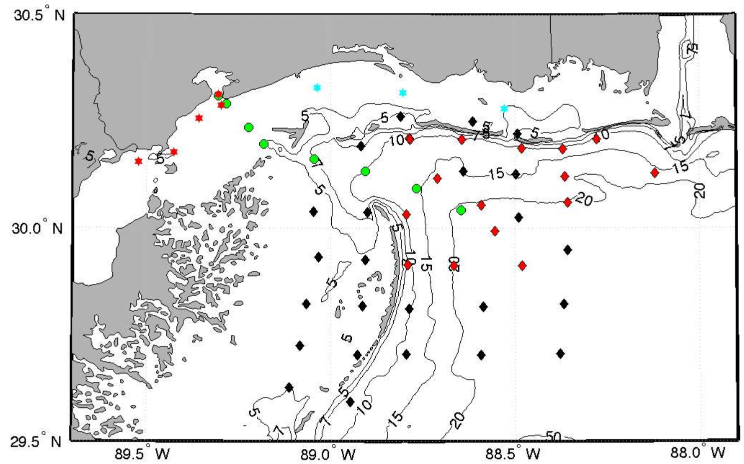


Figure 4. Green dots are the NGI line stations shown in the previous figure. Red stars are the USM "BCS" line that was established after the Bonnet Carre Spillway was opened in 2008. The red diamonds are the stations that USM occupied during a hypoxia event in 2006. The black diamonds are the additional hypoxia stations USM sampled during hypoxia events in 2008 and 2011. Similar stations sampled by LUMCON/LSU are in Fig. 1.

The Gulf of Mexico Hypoxia Monitoring Implementation Plan has as its Tier 1 priority (includes Core System Requirements): to determine the annual maximum area and volume of hypoxia in support of the 2008 Gulf Hypoxia Task Force Action Plan Coastal Goal metric, and to disseminate this information to managers. Because of varying freshwater discharge, nutrient loads, seasonal climate conditions and local weather patterns that affect currents, the bottom area of hypoxia may change over short periods (e.g. days to weeks). Greater spatial and temporal coverage during the summer was therefore recommended to compensate for variability and pre-cruise storm events. One of the Core System Requirements to achieve this objective was "deployments of Autonomous Underwater Vehicles (AUVs) with dissolved oxygen sensors". The use of of autonomous underwater vehicles (e.g. gliders) for higher resolution of the hypoxic zone in future monitoring required a pilot study to demonstrate the technique's effectiveness, efficiency, and accuracy, and to determine whether gliders could fully document the extent of hypoxia (i.e., sufficient closeness to both the seabed and the surface, adequate response time of sensors to strong gradients in physical and biological parameters, ability to maintain buoyancy in a highly variable salinity field and other considerations).

One issue for AUVs or gliders is the ability to map bottom and surface waters in a coastal environment where salinity, temperature, dissolved oxygen and associated parameters change rapidly over small spatial scales. Important in the determination of areal and volumetric extent of hypoxia is the ability to gather data as close to the bottom as possible. One potential sampling strategy would be to have the gliders hover at the seafloor for a certain amount of time for some fraction of the profiles. A pilot project would be required to determine the feasibility of this sampling mode, and to quantify the related effects on spatial coverage.

Obenouer et al. (2013) demonstrated the importance of near-bottom sampling, using a geostatistical modeling framework to estimate both the areal and volumetric extent of hypoxia in the northern Gulf of Mexico from data collected during midsummer, quasi-synoptic monitoring cruises (1985-2011). They combined data from the full rosette/CTD profile with the smaller CTD lowered to the seabed to develop a single profile. For cruises where the smaller CTD was not used, they quantified this bias by comparing data from events where both instruments were used. For these cases, bottom water dissolved oxygen (BWDO) and thickness were calculated for the synthesized profile (from both instruments) and from the rosette/CTD-only profile. Probabilistic relationships were then developed between the synthesized results and the rosette/CTD-only results. When performing the conditional realizations (described below), they adjusted the rosette/CTD-only observations by sampling from these relationships. In years when only the rosette/CTD was used, the uncertainty in the measurement of hypoxia area increased because bottom water conditions had to be estimated from an instrument that did not reach the sea floor. For 1985-1994 the mean statistically derived hypoxic area was 39% greater than previous estimates calculated from stations for which the dissolved oxygen probe did not reach within 0.5 m of the seabed.

B.3 Glider Integration

The utilization of robots for work too difficult or costly for humans to do has increased dramatically in recent decades and the marine environment is no exception. Technological advancements have taken oceanographic robots to a truly operational level, as demonstrated by the thousands of drifting profilers of the ARGO program. Unsurprisingly, these advancements have resulted in a diverse multitude of impressive platforms capable of a wide variety of capabilities. From profiling floats to autonomous propeller driven submarines to wave gliding surface vehicles to seafloor crawling rovers, the successes of the past decade are providing unique opportunities for scientists. As with any technology developed, each of these systems is engineered to operate with a specific set of capabilities, often geared toward a specific mission or set of missions. Matching the sampling needs to the sampling platform is necessary for efficient and effective data collection.

Autonomous underwater profiling gliders have been in development by a number of research groups for over two decades. This has resulted in several successful versions with robust track records. They all use changes in buoyancy to profile vertically and glide horizontally on wings (e.g. Figure 5). With minimal energy they cycle repeatedly, directing themselves with attitude adjustments and control surfaces. The movement is slow but efficient, so that they can stay deployed for weeks to months at a time. This sawtooth progression provides the user with data from the surface to depth, 24 hours a day, regardless of sea states, nearly wherever the user wants to send it. They periodically surface to communicate with their pilots via satellite communications, allowing for real time analysis and mission redirection. They can carry sensor packages that measure a multitude of water state and other biological variables essential to the understanding of oceanic processes and biology. Glider deployments can be expected to last for weeks to months, covering 100s to 1000s of km. And in the past decade their use has steadily increased as the systems have become more versatile and reliable, to the point now that much of the work they do can be called routine.

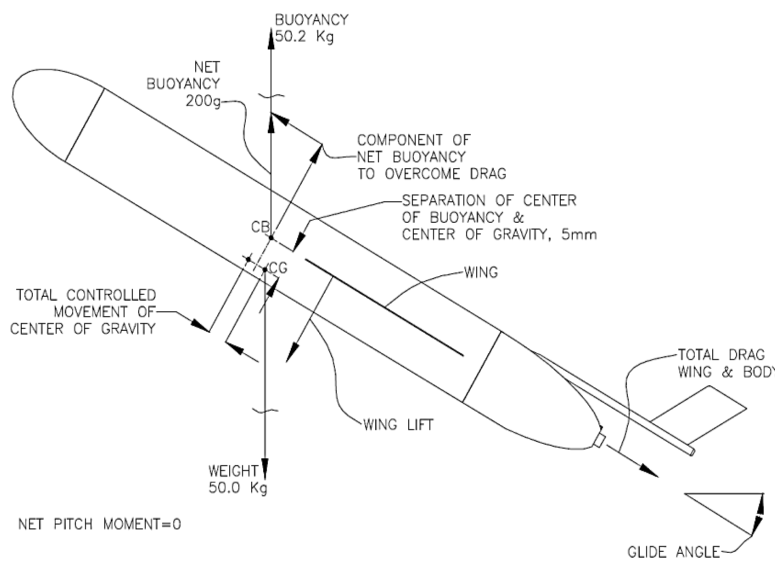


Figure 5. Teledyne Webb Research Slocum Glider.

Gliders typically weigh 52-60 kg and measure 0.2-0.3 m x 1.5-2.5 m, making them deployable from small vessels with minimal equipment. They operate using a combination of buoyancy adjustment and center of gravity manipulation to profile in a sawtooth pattern at rates of 0.15 - 0.3 m/s and transit from waypoint to waypoint at 15-25 km/day. This method of propulsion is extremely efficient yet does present limitations in the density differences that they can overcome and currents that they can navigate. They operate to depths of 1000 m and as shallow as 7-10 m, depending on the buoyancy engine used. In shallow water, deployment durations are typically 1-3 months, heavily dependent on the battery pack used, mission objectives, sensor loads, ocean stratification, communication needs, and area of operations. They typically profile underwater for a period of 2-10 hours, then surface to receive commands, transmit data collected, and obtain positions via satellite modem. This allows the gliders to typically spend over 90% of their time submerged, out of harm's way, collecting subsurface data.

Beyond the gliders themselves, infrastructure and operational investments are modest. Deployment preparation is typically completed by an experienced operator in several days. Such preparation includes battery replacement / recharging, re-ballasting, hardware evaluation, calibration, and mission software programming. Additionally, modest maintenance and sensor calibrations are typically done annually to ensure reliability. Deployment and recovery are often accomplished using small vessels such as Rigid-Hulled Inflatable Boats (RHIBs) or charter boats with a minimal crew of 2-3 operators. Once a glider is performing its mission, manpower needs can be reduced to periodic checks on glider performance, perhaps more if the mission objectives dictate. A shore-based communications server is usually maintained by each operator for communicating with gliders. Once established, these servers can be run with minimal maintenance. In all, an operational team of 1-3 full time experienced members are capable of maintaining and deploying a fleet of several gliders.

In order to adequately sample hypoxia in the northern Gulf a buoyancy glider has to meet several specifications. First, since the management metric is the areal extent of seafloor hypoxia gliders have to sample within the bottom 1 m of the water column. Further research may provide information on missing fractional area detected as a function of the minimum depth above seafloor measured, but until then we are uncertain how much hypoxia will be missed with gliders that do not sample close enough to the seafloor. The second specification is that the gliders have to be able to fly through density changes of some 15-20 kg/m^3. The third specification is that the gliders be able to operate efficiently in 10-60 m of water depth.

As with any platform, gliders have been optimized for the measurement of certain scientific variables, most notably the physical properties of salinity and temperature. In addition, by the nature of their operation, they provide water velocity averaged over their dive depth and the distance traveled between surfacings. Currently sensors such as fluorometers and dissolved oxygen sensors are commonplace. The Slocum Gliders currently offer two dissolved oxygen sensor installations, the Aanderra Optode and the Rinko.

B.4 Other Glider Monitoring Plans for the Gulf of Mexico

A glider hypoxia implementation plan needs to consider other plans in the Gulf of Mexico in order to avoid duplication of efforts and to make the larger effort better integrated. The U.S. Integrated Ocean Observing System (IOOS) has a draft plan for a National Glider Network (NGN). In that draft plan 30 cross-shore “Baseline Sections” glider lines are planned along the nation’s coast, with some subset in the Gulf of Mexico. A Glider Network Steering Group (NSG) will choose these glider lines and will incorporate IOOS Regional Associations (RAs) requirements and additional funding sources as well as other information to assist in defining where the lines will be placed. Additionally, the plan will allow for gliders to sample recurring and event based phenomena such as harmful algal blooms and hypoxia, and for event response such as oil spills. In the northern Gulf where large seasonal density changes occur from onshore to offshore, and surface to bottom, baseline sections that run from nearshore to far offshore may need more than one type of glider: one optimized for the shallower nearshore to midshelf where these large density changes are more likely to exist, and one optimized for the deeper shelf and open Gulf. The northern Gulf of Mexico is unique in this regard and will require some adaptation of plans designed for the rest of the nation's coastal and offshore waters. As part of the NGN, a glider Data Management and Communication (DMAC) plan is being developed. This includes a Glider Data Assembly Center (DAC) that has been established and can be found here. Additionally, information about the format of the data and use of the DAC can be found here. The hypoxia glider monitoring system can utilize this for its DMAC system.

The IOOS RA, Gulf of Mexico Coastal Observing System (GCOOS), has a glider implentation plan within its overall Build Out Plan. The continental shelf portion of that plan consists of a glider conveyor belt, with at least 3 gliders at any time transiting along a sawtooth route (Figure 6). At the present time this plan is under review and subject to revision, but if GCOOS receives funding to implement this or a revised plan, a slight revison of the sampling route along the northern Gulf could serve to provide monthly hypoxia mapping information.

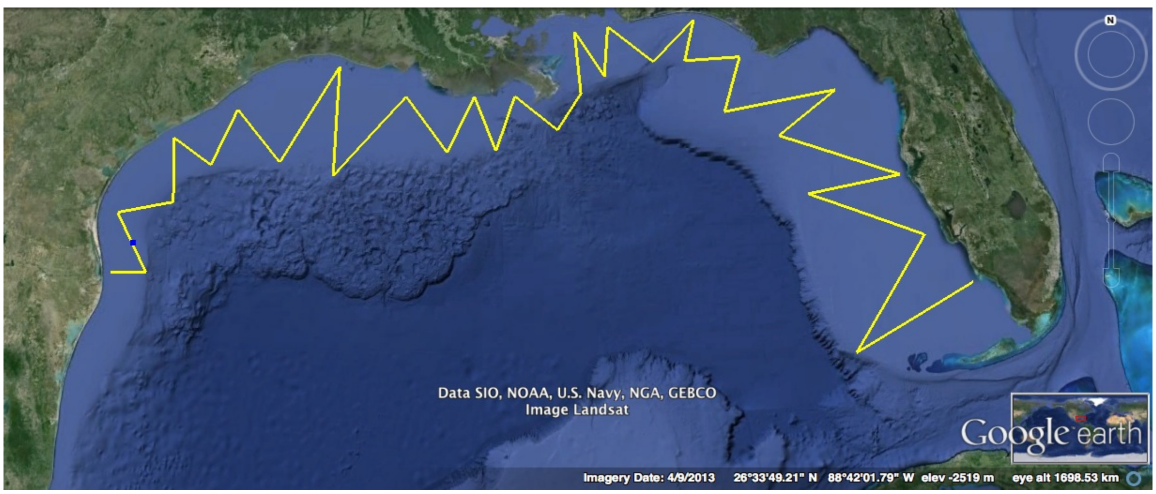


Figure 6. GCOOS Build Out Plan glider conveyor belt. At any given time three to four gliders would be traversing the yellow zig-zag path along the US continental shelf.

C. Priority 1

A question posed to the hypoxia forum participants was whether the glider missions should be planned to better inform hypoxia modeling efforts, and the answer from the modelers was that the glider mission planning should focus on what provides the best stand-alone information for understanding hypoxia development. To that end, although some of the advantages of gliders are their ability to adaptively sample, and to conduct surveys over a large region, the majority of the participants at the forum concluded that the highest priority as a hypoxia glider sampling network gets spun up, was to have the gliders run across-shore, repeat transects. Repeat transects provide higher temporal sampling, given a fixed set of glider assets, and produce data sets that are easier to analyze for both short term variability and changes due to longer term climate variability.

Along with the weekly to seasonal to interannual variability of hypoxia that the gliders can sample, there are shorter timescales of variability that are important for understanding the effects of hypoxia on living resources and for ensuring that hypoxia areal extent measured from ship and glider surveys is not aliased (Bianchi et al., 2010). A fixed sampling site, such as a mooring or fixed platform, with at least an hourly sampling interval, can provide the necessary information. These moorings/platforms can provide a record at a controlled depth from the seafloor and can serve as a calibration check for instruments on the gliders. One fixed mooring/platform for each of the glider transect lines would meet this need.

C.1 Tier 1 Glider Sensor Package

The Tier 1 sensor package for gliders in the network would have sensors for pressure (P), conductivity (C), temperature (T), dissolved oxygen (dO), chlorophyll *a* concentration, colored dissolved organic matter (CDOM) concentration and turbidity. It has been found that the relatively slow movement of gliders does not flush out conductivity cells quickly enough for accurately capturing salinity gradients. SeaBird now makes the low-powered pumped glider payload CTD (GPCTD) for gliders and this sensor could be used on the gliders in the hypoxia network. Likewise, a fast response dissolved oxygen (dO) sensor is required to accurately capture the gradients in dO. The RINKO-II optode fast response dissolved oxygen sensor is the instrument of choice for the glider package, with a response time of less than 1 second to reach 90% of final value for a step change in oxygen. The Wetlabs ECO Puck is ideal for measuring Chlorophyll fluorescence, CDOM fluorescence and backscatter.

Manufacturer/Distributer	Model	Parameters Measured
SeaBird	GPCTD	Pressure, Temperature, Conductivity/Salinity
Rockland Oceanographic Services, Inc.	RINKO-II	Dissolved oxygen concentration
Wetlabs	ECO BBFL2	Turbidity, Chlorophyll and CDOM fluorescence

Table 1. Tier 1 glider instrument package.

C.2 Glider Transects

It is suggested that the initial glider hypoxia monitoring system have four transects running between the 10 m and 60 m isobaths (Figure 7). The locations of the transects were chosen to be along cross-shelf lines of previous or existing hypoxia sampling stations (Figure 8), with a maximum repeat time ~10 days.   The forum participants selected the LUMCON K, F and C transect lines and the USM line on the east side of the delta. Where the stations did not reach the 60 m isobath, the lines were extended to cover that depth.

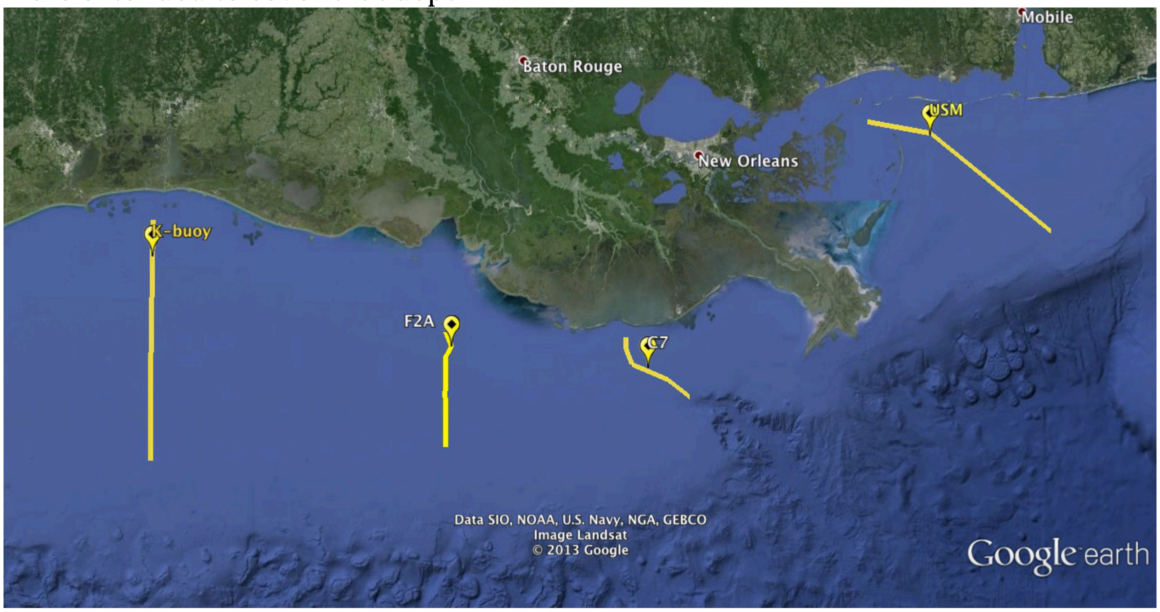


Figure 7. Proposed repeat glider transects. Each of these transects runs from the 10 m to the 60 m isobath. Mooring USM is operational, but it requires a bottom package for seafloor dO. Real-time mooring stations at F2A, C6 and along the K-line are proposed.

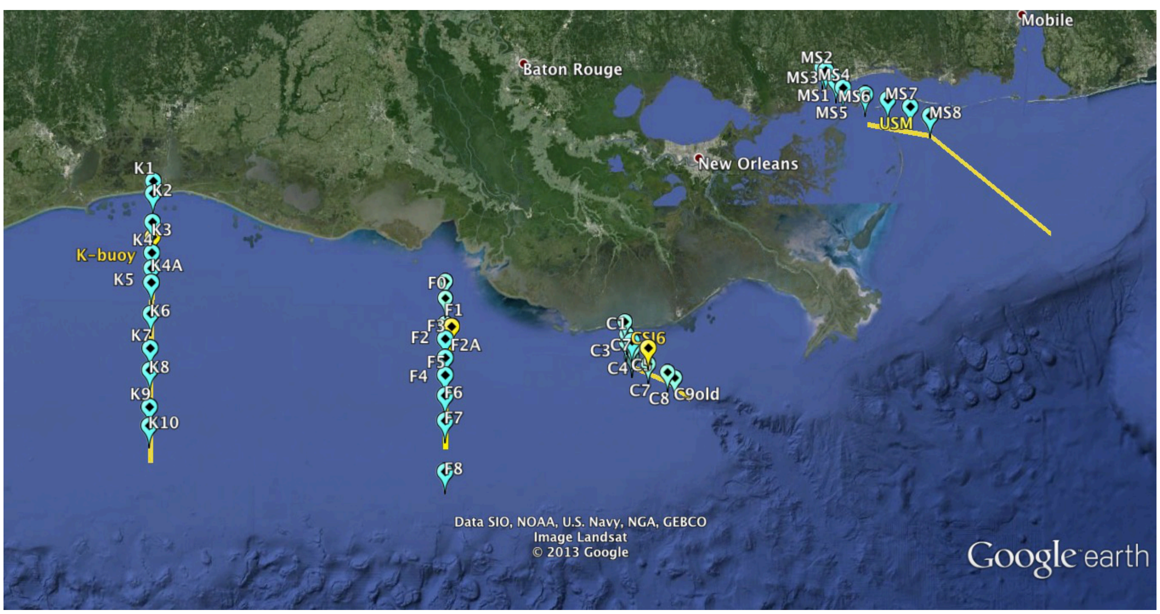


Figure 8. Same as Figure 7 with historical hypoxia stations along transects superimposed.

One glider would always be out on each transect. This would require at least 2 gliders/transect, or 8 gliders overall. It is hoped that some subset of these lines would be chosen as glider transects for the GOM portion of the IOOS national glider plan. Those gliders are meant to operate further offshore and would not be suitable for the highly stratified inner and mid-shelf of the northern GOM. Thus they could be operated from the offshore extent of the hypoxia glider transects and into the deep GOM, and some operational efficiencies could be realized by combining operations of the two programs.

C.3 Missions for Mapping of Hypoxic Bottom Waters

There were 3 shelf-wide cruises each summer to measure hypoxia on the LATEX shelf. More information is required to understand how representative those three cruises are of late spring through summer hypoxia. From May through September monthly glider hypoxia surveys could be carried out to map the areal and volumetric extent of hypoxia and provide more information on temporal variability. This can be accomplished by dedicated gliders, pulling gliders off of the transects to run mapping missions, or some combination of the two. For example, if the glider fleet could not be expanded, then the gliders for each transect could be assigned a region on either side of the transect to map out once a month (Figure 9, yellow tracts). Also modifications could be proposed for the glider portion of the GCOOS Build Out Plan in the northern Gulf (Figure 9, red tracts) to improve its applicability to hypoxia monitoring.

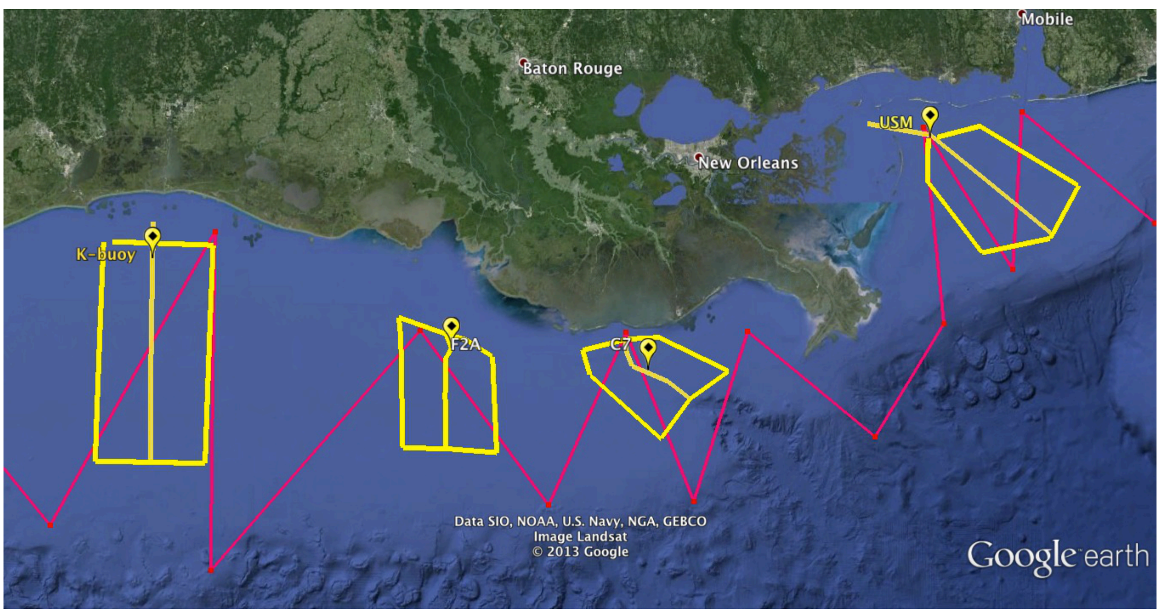


Figure 9. Glider transects from Figure 7 with optional lines to the west and east of those lines that could be run episodically to provide more spatial information. This is only one example of optional transects that could be run to obtain better spatial information. Superimposed (red) is the GCOOS glider conveyor belt running through the study region.

C.4 Tier 1 Moorings

At least one mooring or fixed platform along each glider transect was suggested by forum participants. These sites should at least measure winds, waves, air temperature, water temperature (surface and bottom), salinity (surface and bottom), dissolved oxygen (surface and bottom), chlorophyll_*a* (surface), and CDOM (surface). LSU has an operational WAVCIS station at station CSI-6 and USM operates a mooring along the USM line, but these stations require upgrades to meet the requirements.

CSI-6 measures meteorological and oceanographic parameters. The instrument package on the station is shown in Table 1.

Meteorological Package	
Instrument	*Parameters Measured*
Anemometer	Wind speed and direction
Barometer	Barometric pressure
Thermometer	Air temperature
Oceanographic Package	
Instrument	*Parameters Measured*
Pressure transducer (digquartz)	Water level
Current meter (March-McBirney)	Currents Waves
Thermometer	Surface temperature

Table 2. Instrument package on the LSU WAVCIS CSI-6 station.

The USM CenGOOS mooring has meteorological and oceanographic packages as well as a NOAA/Pacific Marine Environmental Laboratory (PMEL) ocean acidification package. The initial mooring in 2004 had a bottom package with CTD and dO, but the entire package was lost in 2005 during hurricane Katrina. Funding has not been received for a replacement. The CenGOOS buoy instrumentation is listed in Table 3.

Meteorological Package	
Instrument	*Parameters Measured*
Anemometer 1 (Gill Windsonic)	Wind speed and direction
Anemometer 2 (RM Young)	Wind speed and direction
Barometer (Vaisala)	Barometric pressure
Temperature and Humidity (Rotronic MP101A)	Air temperature & humidity
Oceanographic Package	
Instrument	*Parameters Measured*
SBE-37SMP Microcat	Temperature, conductivity (salinity), pressure
Teledyne RDI 600 WHS	Vertical profiles of currents
Crossbow IMU and Honeywell 3-axis digital compass	Waves
NOAA PMEL Ocean Acidification System	
MAPCO2	$xCO2_{air}$ & $xCO2_{sw}$
SBE-37SMP Microcat	Temperature, conductivity (salinity), pressure
SBE-43	dO

Wetlabs ECO	Chlorophyll fluoresence

Table 3. CenGOOS buoy instrumentation.

C.5 Glider Platforms

As far as the authors are aware, at the present time there are two gliders that can meet the specifications listed in section B-3: the Teledyne Webb Slocum glider and the EXOCETUS glider. However, at the present time only the former has been proven to operate successfully in multiple missions.

C.6 Pilot Project

An initial pilot project should have, at a minimum, one glider running a transect on the western and eastern sides of the Balize delta. For each glider, a ship should cruise in tandem with the glider on at least one of the full transects taking water samples from a Niskin bottle within the lower 0.5 m for salinity and dO, and water profiles with a package optimized for the relatively thin stratified waters of the northern GOM during that time of year. The pilot project should also include some hovering maneuvers just off the seafloor, to test the ability of a glider to obtain reliable measurements in the lower 0.5 m of the water column.

D. Priority 2: Enhanced number of gliders with Tier 1 sensor packages for lines and mapping

Once the priority 1 hypoxia glider monitoring plan is implemented the priority two plan calls for increasing the glider fleet to improve the monitoring system. Adding a transect further west would require an additional two gliders (Figure 10). The repeat visit time for any location along the transects could be reduced by adding additional gliders for each transect.

Additional gliders dedicated to mapping could be used to continuously map hypoxia from May through September. A sawtooth glider track between the 10 m and 60 m isobaths from the mouth of the Mississippi River to Port Arthur, TX with spacing of approximately 22 km would take about a month, with no counter-flowing currents. Four gliders in rotation, with two gliders out at any time deployed near the mouth of the Mississippi River and at the longitude halfway between the end points, respectively, could sample the region completely every 15 days.

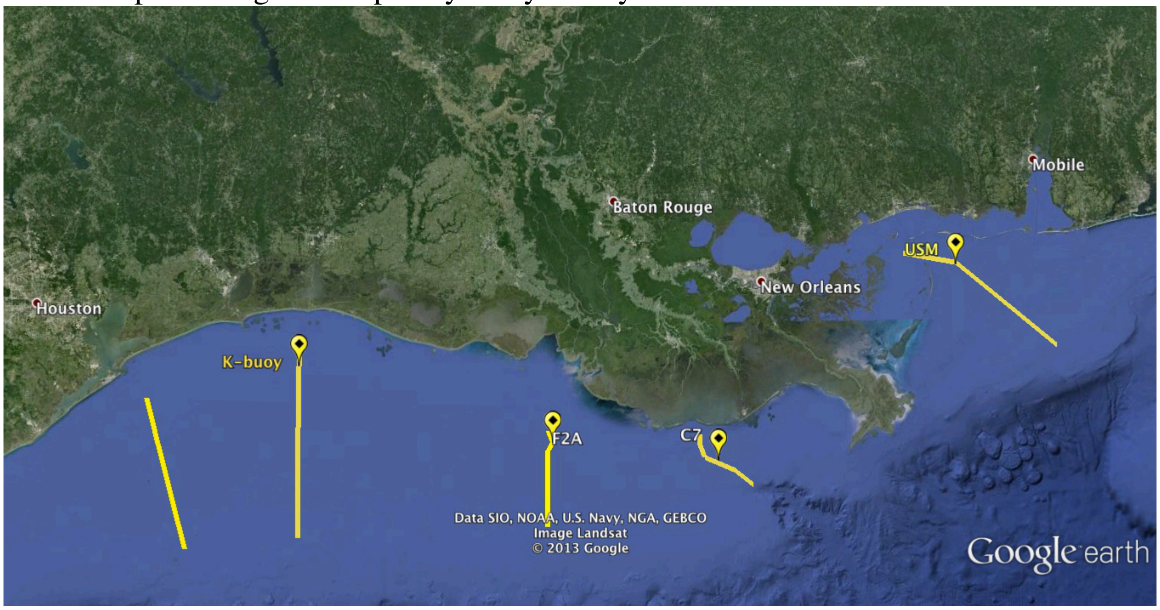


Figure 10. Potential placement of a fifth glider transect west of the "K-line"

E. Priority 3: Effects on Living Marine Organisms and Observing System Simulation Experiments

Enhancements to the glider hypoxia monitoring system to include platforms and instruments that can provide much needed information about the effects of hypoxia on living marine resources have been characterized as Priority 3 enhancements. Both acoustic and optical sensors have proven useful for monitoring plankton, fish and other marine organisms.

Because acoustic instruments are capable of profiling in the water column, the Wave Glider which has solar panels on the surface for recharging onboard batteries, and utilizes wave motion for propulsion, is a suitable platform for extended missions with these sensors. A demonstration of a fisheries survey with a BioSonics dual frequency echosounder, towed by a Wave Glider, was presented at the Oceans 2012 conference (Meyer-Gutbrod et al., 2012). Surveys with a similar system over the hypoxia region from early spring before hypoxia develops to fall would improve our understanding of the effects of hypoxia on zooplankton and fish.

Other enhancements to gliders and moorings could include instruments to acoustically query fish tags, and passive acoustic instruments for tracing marine mammals. Airborne Lidar surveys could also prove useful for monitoring hypoxia effects on marine living resources, but such assets are beyond the scope of this plan.

Observing System Simulation Experiments (OSSE) hold the promise of developing optimal designs for observing/monitoring systems, such as this glider hypoxia monitoring network. Since OSSEs are not yet mature for the physicalbiogeochemical modeling that is required for the deterministic modeling of hypoxia, this was included under Priority 3.

F. Data Management

Data management for glider operations includes sensor set-up and calibration, onboard data logging, logging of the navigation data and piloting commands, data telemetry, archiving "raw" data, performing quality control (QC), archiving of the QC'ed data, processing QC'ed data to create higher level data products and archiving them, and serving of the data. The data management system for this plan could utilize that being constructed for the NOAA/IOOS National Glider Network Plan, with augmentation and adaptation as necessary.

Much of the Data Management portion of the Draft NOAA/IOOS National Glider Network Plan is at the conceptual level. A view of data flow in that plan is shown in

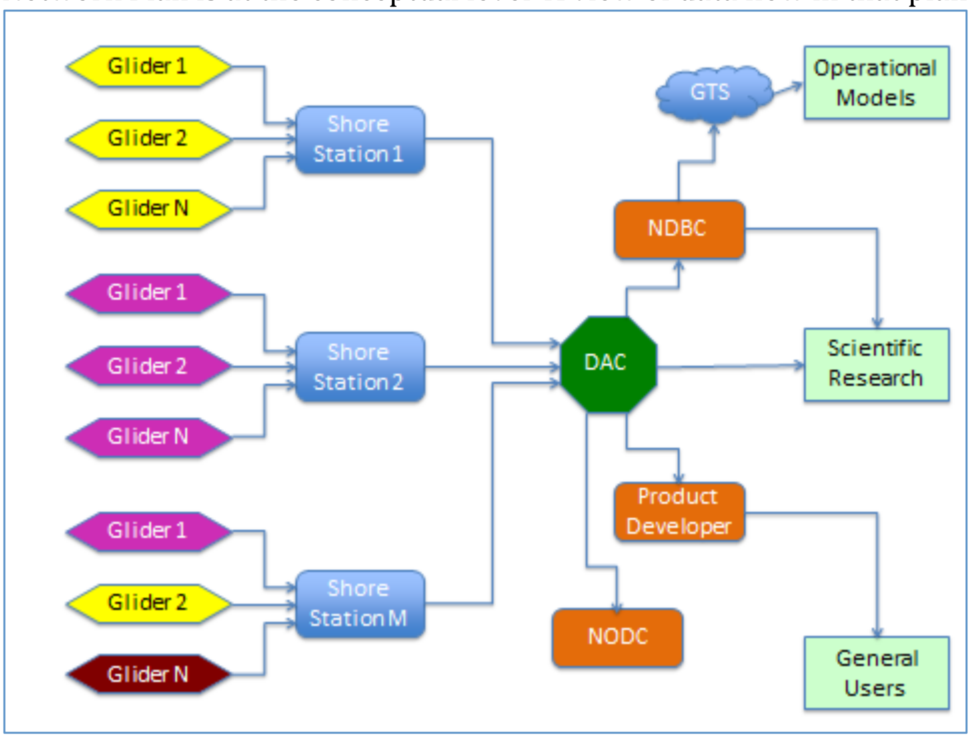


Figure 8: From the March 2013 draft US IOOS National Glider Network Plan. "Data flow chart for glider data. Gliders send data to appropriate shore station, where it is in turn delivered to the DAC. From there, the DAC will deliver it to NODC for archival, NDBC for transmission onto GTS and to the rest of the world for the public to access."

Figure 8. The plan calls for automated QA/QC to be applied at the shore stations before being packaged into network compliant netCDF files and sent to the DAC. At the DAC, those data would be archived and served, and subsequently delayed mode

QA/QC would be performed and higher level products produced, archived and served.

The Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) has been funded by NOAA to build the national DAC. A netCDF file content and format standard has been developed and a description can be found at https://github.com/IOOSProfilingGliders/Real-Time-File-Format.

Although there is considerable community expertise and familiarity with ocean glider data issues and processing, a common, agreed upon set of protocols for QC and assurance is required so that the multiple universities, agencies and commercial entities can conform to these protocols. The details of the automated QA/QC performed at the shore station, as well as the delayed mode QA/QC performed at the DAC have not yet been developed (or at least publically released) for the NOAA/IOOS National Glider Network Plan. Thus much remains to be done to create an "end to end" system from glider data collection to integration into a National Glider Database. A resource that could be utilized for these operational QA/QC procedures, and for generating higher level products as well, is the LAGER system designed by the Naval Research Laboratory at Stennis Space Center for the Naval Oceanographic Office, which utilizes it for their glider operational system. The writing team suggests that a workshop be held with people presently running operational glider monitoring systems at the program managerial, data management and IT levels to develop the "end to end" protocols for glider monitoring systems.

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. Sci. Total Env. 408, 1471-1484.

Committee on Environment and Natural Resources (CENR). 2000. Integrated Assessment of Hypoxia in the Northern Gulf of Mexico, National Science and Technology Council, Washington, D.C..

Gulf of Mexico Hypoxia Monitoring Implementation Plan Steering Committee. 2009. Gulf of Mexico Hypoxia Monitoring Implementation Plan. An outcome from the Summit on Long-Term Monitoring of the Gulf of Mexico: Developing the Implementation Plan for an Operational Observation System

Justić, D., N. N. Rabalais and R. E. Turner. 1997. Impacts of climate change on net productivity of coastal waters: Implications for carbon budget and hypoxia. Climate Research 8: 225-237.

Meyer-Gutbrod, E., C. H. Greene, A. Packer, H Dorn and J. Griffith. 2012. Long term autonomous fisheries survey utilizing active acoustics. Proceedings Oceans2012, 14-19 October 2013, Virginia Beach, Virginia.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico,

Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency, Washington, D. C.
Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2004, A Science Strategy to Support Management Decisions Related to Hypoxia in the Northern Gulf of Mexico and Excess Nutrients in the Mississippi River Basin: prepared by the Monitoring, Modeling, and Research Workgroup of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, U.S. Geological Survey Circular 1270, 58 p.
Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2008. Gulf Hypoxia Action Plan, Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency, Washington, D.C.
Obenouer, D. R., D. Scavia, N. N. Rabalais, R. E. Turner and A. M. Michalak. 2013. A retrospective analysis of mid-summer hypoxic area and volume in the northern Gulf of Mexico. Environmental Science and Technology 47:9808-9815.
Rabalais, N. N., R. J. Díaz, L. A. Levin, R. E. Turner, D. Gilbert and J. Zhang. 2010. Dynamics and distribution of natural and human-caused coastal hypoxia. Biogeosciences7:585-619.
Rabalais, N. N., R. E. Turner, B. K. Sen Gupta, D. F. Boesch, P. Chapman, and M. C. Murrell. 2007a**.** Characterization and long-term trends of hypoxia in the northern Gulf of Mexico: Does the science support the Action Plan? Estuaries and Coasts 30(5): 753-772.
Rabalais, N. N., R. E. Turner, B. K. Sen Gupta, E. Platon and M. L. Parsons. 2007b. Sediments tell the history of eutrophication and hypoxia in the northern Gulf of Mexico. Ecological Applications, 17(5) Supplement: S129-S143. [Special Issue, Nutrient Enrichment of Estuarine and Coastal Marine Environments]
Turner, R. E., N. N. Rabalais and D. Justić**.** 2006. Predicting summer hypoxia in the northern Gulf of Mexico: riverine N, P and Si loading. Marine Pollution Bulletin 52: 139-148.
U.S. Environmental Protection Agency (USEPA). 2007. Hypoxia in the Northern Gulf of Mexico An Update. Science Advisory Board, EPA-SAB-08-004, 333 p..
USGS 2004. A Science Strategy to Support Management Decisions Related to Hypoxia in the Northern Gulf of Mexico and Excess Nutrients in the Mississippi River Basin. U.S. Geological Circular 1270, U.S. Geological Survey, Reston, VA.

Appendix 1. Participants in Glider Implementation Plan Working Session at the Forum

The following list is of people who signed-in to the Glider Writing Team Working Session of the Forum. There were people shuttling back and forth between sessions at the forum and so this list probably gives an incomplete accounting for everyone who contributed to the session.

Bob Arnone	University of Southern Mississippi
Becky Baltes	NOAA/NOS/Integrated Ocean Observing System
Landry Bernard	NOAA/National Data Buoy Center

Julie Bosch	NOAA/NESDIS/National Coastal Data Development Center
Justin Brodersen	Naval Research Laboratory at Stennis Space Center
Steve DiMarco	Texas A&M University
L. Kellie Dixon	Mote Marine Laboratory
Kjell Gundersen	University of Southern Mississippi
Alan Hails	Mote Marine Laboratory
Matt Howard	Texas A&M University
Stephan Howden	University of Southern Mississippi
David Kidwell	NOAA/NOS/National Centers for Coastal Ocean Science
Josh Kohut	Rutgers University
Jan Kurtz	EPA/Gulf Ecology Division
Sherwin Ladner	Naval Research Laboratory at Stennis Space Center
Chad Lembke	University of South Florida
Kevin Martin	University of Southern Mississippi
Nelson May	NOAA/National Marine Fisheries Service/Southeast Fisheries Science Center
Shannon McArthur	NOAA/OOS/National Data Buoy Center
Robert Moorhead	Mississippi State University/Northern Gulf Institute
Ruth Mullins-Perry	Texas A&M University
Troy Pierce	EPA Gulf of Mexico Program
Andrew Quaid	Naval Research Laboratory at Stennis Space Center
Nancy Rabalais	Louisiana Universities Marine Consortium
Dan Rudnick	University of California at San Diego/Scripps Institution of Oceanography