Ocean Observing Collaboration to Improve Hurricane Forecasting and Modeling in the Gulf of Mexico

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***Abstract*—Shell Exploration & Production Company is working with academic, non-profit, and federal stakeholders in the Gulf of Mexico to develop and implement long term environmental monitoring programs. One such program uses autonomous underwater gliders to collect near real-time oceanographic data for enhancing the understanding of the offshore physical environment and to improve estimates of upper ocean heat content for enhanced hurricane prediction and forecast models. Through a Memorandum of Agreement in 2008 between Shell and the National Oceanic and Atmospheric Administration, this partnership leverages the strengths of each collaborator to build a comprehensive and sustainable data collection program to better assess environmental conditions and assure the environmental sustainability of Shell's activities in the Gulf of Mexico. An important element of the collaboration includes sharing data and results with the broader Gulf of Mexico stakeholder community by working with regional partners such as the Gulf of Mexico Coastal Ocean Observing System. In this paper, we focus on 2014 physical environment and glider results and public-private partnership model benefits to expanding regional ocean observing capacity in the Gulf of Mexico.**

Keywords—Gulf of Mexico, ocean observing, gliders, Loop Current, physical oceanography

I. INTRODUCTION

The Gulf of Mexico's physical environment is important to many stakeholders from coastal communities to the offshore oil and gas industry. Understanding the Gulf's circulation, primarily Loop Current dynamics, is essential to the health and safety of people working offshore and to protecting offshore infrastructure, and requires diligent monitoring. Events, such as hurricanes and tropical storms, are also influenced by the Gulf circulation and can have tragic impacts on Gulf residents, communities, and businesses. Hurricanes can range from relatively small events with limited impacts to large and powerful storms capable of seriously damaging coastlines and crippling infrastructure. Accurate predictions of hurricane size, path direction, and intensity in advance of storms are necessary to mitigate damage to the environment and property and to protect lives and infrastructure.

In 2008, Shell signed a Memorandum of Agreement with the National Atmospheric and Oceanic Administration (NOAA) to explore collaborative ways to improve tropical storm and hurricane predictions in the Gulf of Mexico. Since then, industry, academic, private, and government partners from Shell, NOAA National Data Buoy Center (NDBC), National Center for Environmental Prediction (NCEP),

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University of Southern Mississippi (USM), and the Gulf of Mexico Coastal Ocean Observing System (GCOOS) have been working together to operate and share data from integrated ocean observing platforms, including Acoustic Doppler Current Profiles (ADCPs), buoys, and profiling gliders, in the central and western Gulf of Mexico Outer Continental Shelf (OCS). In 2012, Shell and NOAA launched one glider in the central Gulf. Over two months, the glider sampled nearly 900 miles of the OCS and collected nearly 1000 profiles down to 1000 meters water depth [1]. Since then, this glider effort has grown to multiple gliders collecting observations in the central and western Gulf. In 2014, 4 gliders operated by 4 entities collected nearly 7000 profiles and sampled over 5000 miles. Gliders primarily were flown in the Loop Current and associated eddies to measure salinity and temperature to calculate water column ocean heat content (OHC), an indicator of ocean energy available for storm and hurricane development and intensity.

Monitoring the Gulf of Mexico's Loop Current is central to improving storm and hurricane predictions and forecasts. The Loop Current's strength is directly correlated to hurricane strength and intensity with hurricanes experiencing rapid intensification and increase in strength as the hurricanes pass over the Loop Current. Given the appropriate atmospheric conditions, storms can increase from Tropical Storm strength to Hurricane status while crossing the Loop Current and its associated eddies. Such a case occurred with Hurricane Opal in 1995. After reaching the Loop Current, the storm underwent rapid intensification from speeds of 75 knots and minimum pressure of 968 millibar to 130 knots and 916 millibar in less than 24 hours. More recently, during the 2005 season, Hurricanes Katrina and Rita intensified into Category 5 hurricanes on the Saffir-Simpson Scale after crossing the Loop Current.

Since 2005, ocean observations of the Loop Current have been steadily increasing. Forecasting research conducted by the National Hurricane Center has significantly advanced the lead time for reduced hurricane watch and warning zones, but has not improved intensity forecasting [4]. Such improvements in modeling rely heavily on estimating OHC, which signifies the energy available to storms. OHC in hurricane intensity models has been traditionally estimated from remote sensing identification of the Loop Current and associated eddies. The addition of NOAA and United States Air Force (USAF) Hurricane Hunter airborne radar data have continued to improve intensity estimates resulting in a 4-5 knot improvement in intensity forecasts. Air eXpendable BathyThermographs (AXBTs) dropped from Hurricane Hunter aircraft provide profiles of ocean temperature right before and during the storm. Furthermore, ADCPs mounted on offshore drilling rigs, have made in-situ currents readily available, but only when the Loop Current reaches rig areas. Even with the addition of these data, a need still exists for targeted Loop Current temperature and salinity profiles in the pre-storm environment with a particular emphasis on real-time observations. Real-time observations are needed to support intensity and forecast models, primarily NOAA NCEP coupled ocean model (HYCOM) and hurricane weather model (HWRF) known as HYCOM-HWRF. Unlike the previous atmospheric models that use static ocean information, the HYCOM-HWRF allows for a dynamic feedback between the ocean and atmospheric conditions. Provided with higher temporal and spatial initial conditions, such as profiles collected with gliders, allows HYCOM-HWRF to better calculate hurricane intensification due to near real-time data assimilation of ocean processes than previous dependence on ocean process climatological data.

II. 2014 Physical Environment

The 2014 Gulf physical environment was characterized by strong Loop Current circulation (Fig. 1). No hurricanes formed, but the Loop Current and eddies impacted the Mississippi Canyon region for most of the summer and fall (May to November) months. The Loop Current was exceptionally strong (persistent 3.5+ knots) and extended as far north as $29^{o}00$'N. Over the summer and fall, one eddy formed, re-formed, and separated from the Loop Current.

A. Lazarus

Although the development of Eddy Lazarus commenced in early May, the feature's circulation and dynamics underwent many changes – formation, complete dissolution, and re-formation – over the following two months (Fig. 1). The eddy did not detach from the Loop Current until the 2nd week of July by which time the latter had surged northward up to the Sigsbee Escarpment. Lazarus' circulation developed on a smaller scale at this time, culminating in the eddy's separation. Per the regular trend, the eddy's interaction with the Loop Current gradually diminished during the following days, and the Loop retreated southward. Eddy Lazarus remained along the Sigsbee Escarpment, impacting operations throughout northeastern Walker Ridge, eastern Green Canyon, Atwater Valley, and southern Mississippi Canyon with currents up to 3.0 knots in intensity, as indicated by Horizon Marine's drifting buoy coverage.

Eddy Lazarus remained in the region for the remainder of the month, exhibiting little to no migration or changes in intensity; however, the Loop Current resumed its northward migration, eventually re-connecting with the eddy. By mid-August, the eddy was entirely engulfed by the Loop Current's circulation, retaining only a very weak closed circulation of its own. Fresh inflow from the Loop Current resulted in a rapid northward surge of strong currents all the way into northern Mississippi Canyon with intensities up to 3.5 knots and the advection of Mississippi River waters into the OCS. As the combined feature interacted with its frontal cyclonic eddies and rotated clockwise, its impact on operations in the aforementioned lease areas alternately elevated and receded through the end of September. Eddy Lazarus reformed and strengthened during this time period, resulting in a brief separation from the Loop Current in late September and early October. Drifting buoys and vessel-mounted ADCP measurements within Lazarus' western front indicated increased current intensities up to 3.75 knots.

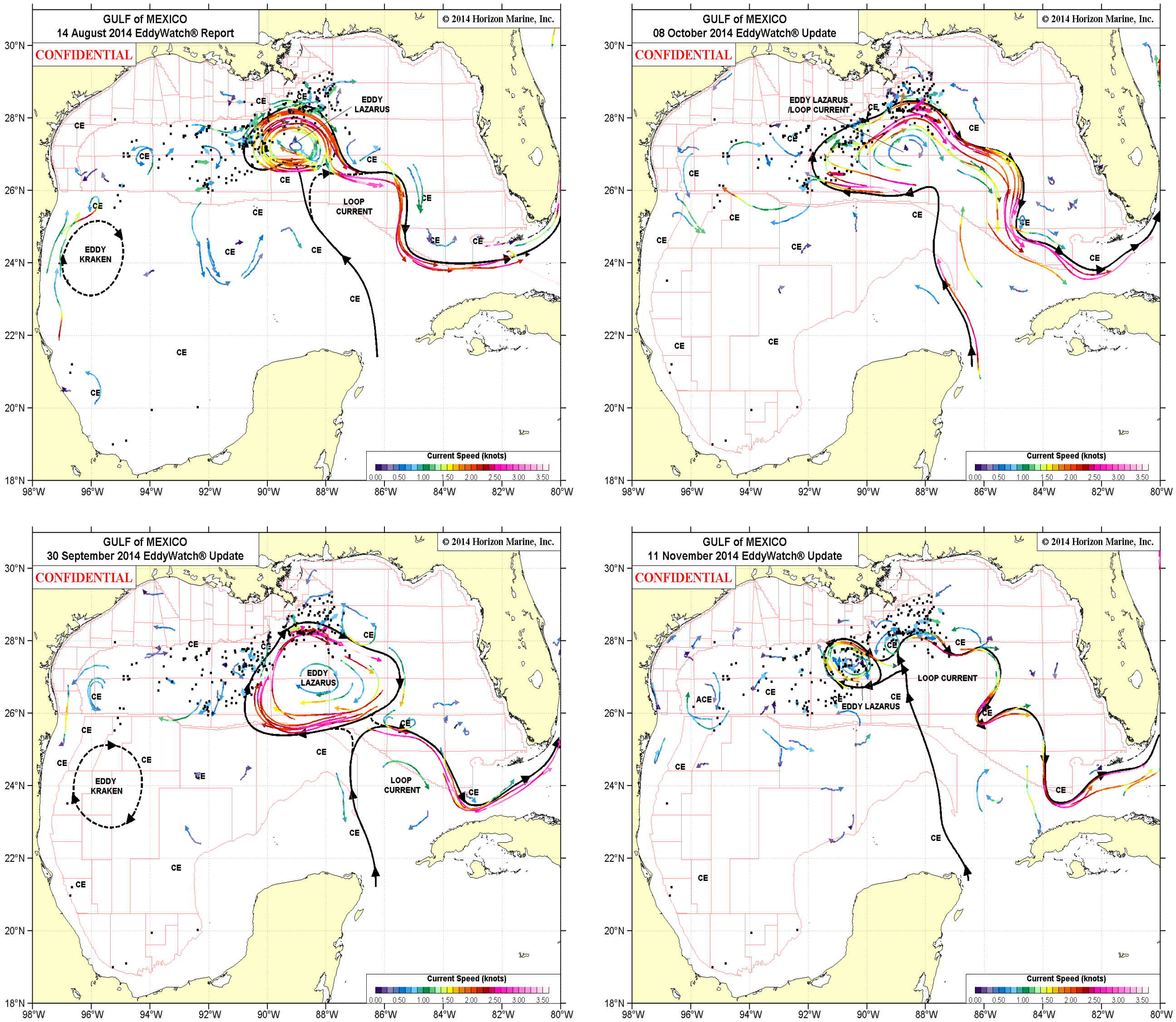

Fig. 1. Loop Current Dynamics (August – November). The panel series shows the Loop Current circulation and Eddy Lazarus formation, dissolution, re-formation, and separation. *Modified from Perry, R. et al. (2015) Autonomous underwater vehicle collaborations to improve hurricane forecasting and environmental monitoring in the Gulf of Mexico. Proceedings of the Annual Offshore Technology Conference.*

The eddy's short-lived detachment was quickly overcome as the Loop Current migrated northward again, creating a strong flux of water mass through the eddy. Several differences in the dynamics were apparent during this re-attachment with the most significant aspect being the eddy's larger size just prior to the process. This factor facilitated the merged feature's irregular inverted 'L'-shaped structure, extending well into western Green Canyon and Walker Ridge while its northern extent remained in southern Mississippi Canyon – a structure it maintained through mid-November. Maximum intensities throughout the feature remained over 3.0 knots. On 11 November 2014, Eddy Lazarus separated from the Loop Current for the third and final time as the latter's extended western lobe developed a closed circulation and detached from the parent feature. The Loop Current receded to the southeast while Lazarus moved westward, retaining weaker intensities (< 2.25 knots) within its circulation.

III. 2014 Glider Missions

Gliders owned and operated by NOAA NDBC, University of Southern Mississippi funded by Shell, and the Naval Oceanographic Office (NAVOCEANO) were deployed to collect data on the Gulf continental shelf and OCS. NDBC and USM coordinated the glider missions with Shell operational oceanographers and modelers at NCEP Environmental Modeling Center (EMC) to target specific ocean features. Adaptive targeting provided validation of satellite-derived OHC and provided high resolution datasets to assimilate into HYCOM-HWRF at the EMC. The combination of shallow (Teledyne Webb Slocum 200 meter) and deep gliders (Teledyne Webb Slocum 1000 meter, Kongsberg 1000 meter Seaglider) covered more than 3000 miles and collected over 2800 profiles near the Mississippi River Canyon shelf break and in the offshore central and eastern Gulf. Gliders were outfitted with conductivity-temperature-depth (CTD) profilers need to calculate real-time OHC, dissolved oxygen (Anderraa Oxygen), and color dissolved organic matter (CDOM, Wetlabs BBFL2) sensors to study interactions of freshwater (Mississippi River) and shelf waters with OCS waters. All glider data was uploaded to NOAA NCEI and to the GCOOS Data Portal, where the data were packaged into a 3-D visualizer that stakeholders can use to monitor the gliders' tracks in near real-time (*see Section V)*.

A. Adaptive Sampling with Gliders

Adaptive sampling and mission coordination in real-time with the EMC provided the ability to 'connect-the-dots' between well-established Eulerian metocean measurements (e.g. ADCPs on platforms and sensors on buoys) by obtaining (and validating) data between fixed metocean stations and validating satellite-derived OHC parameters [3]. The combination of shallow and deep gliders improved OHC estimations at the continental shelf slope boundary and in the Loop Current. An added value was ability of the shallow glider to adaptively sample advected nutrient-rich freshwater and productive coastal waters offshore. Tracking of fresher coastal waters provided an additional verification of estimating Loop Current and Eddy Lazarus boundaries and an opportunity to study and quantify biological productivity and water quality on the central Gulf shelf and OCS [4].

B. Glider Mission & Data Summary

Both gliders were deployed on 20 August and were recovered on 3 December. Glider tracks are shown in Fig. 2. The deep glider operated through the center of the Loop Current where the warmest waters were located. Due the Loop Current's strength in August, science and modeling teams decided to fly in and along the edge of the Loop Current estimated from JASON satellite altimetry sea surface height. Temperature readings along the track showed a large warm core with the 26°C isotherm depth (standard metric OHC depth boundary determination) at a near-record of 230 meters (Fig. 3). This indicated an exceptionally strong Loop Current system with a well-defined core extending nearly to the mouth of the Mississippi River as seen in Fig. 1. From 21 August to 23 September, the average upper OHC was 180 kilojoule per square centimeter (kJ/cm^2) with peak values above 200 kJ/cm^2 (Fig. 4). These OHC values indicated strong ocean energy conditions capable of supporting strong storm or hurricane intensification.

After flying through in the Loop Current, the glider was piloted through the Eddy Lazarus separation and re-attachment (23 September to 1 October). The depth of the 26°C isotherm decreased in thickness to an average depth of 30 meters with calculated OHC values of 20-30 kJ/cm^2 (Fig. 4) indicating weaker potential ocean energy for storm or hurricane intensification.

After this period, the glider was piloted eastward where it again encountered Eddy Lazarus rotating in the Loop Current. Speeds at the time were exceptionally strong with a 0-1000 meter depth average current of 1 meter per second (m/s). Due to the strong current speeds, the glider circumnavigated the Lazarus from 18 October to 7 November. OHC calculated from glider profiles showed significant values over 100 kJ/cm^2 (Fig. 4). As earlier in the season, high values indicated potential capability of central and eastern Gulf conditions capable of supporting hurricane intensification late into the season given the annual warmer temperatures in October and significant amount of heat energy available.

Eddy Lazarus and the Loop Current's northernmost boundaries persisted at the Louisiana continental shelf boundary, allowing the entrainment of a large volume of productive coastal water offshore. A wide filament of coastal water moved with Eddy Lazarus' western edge and eventually

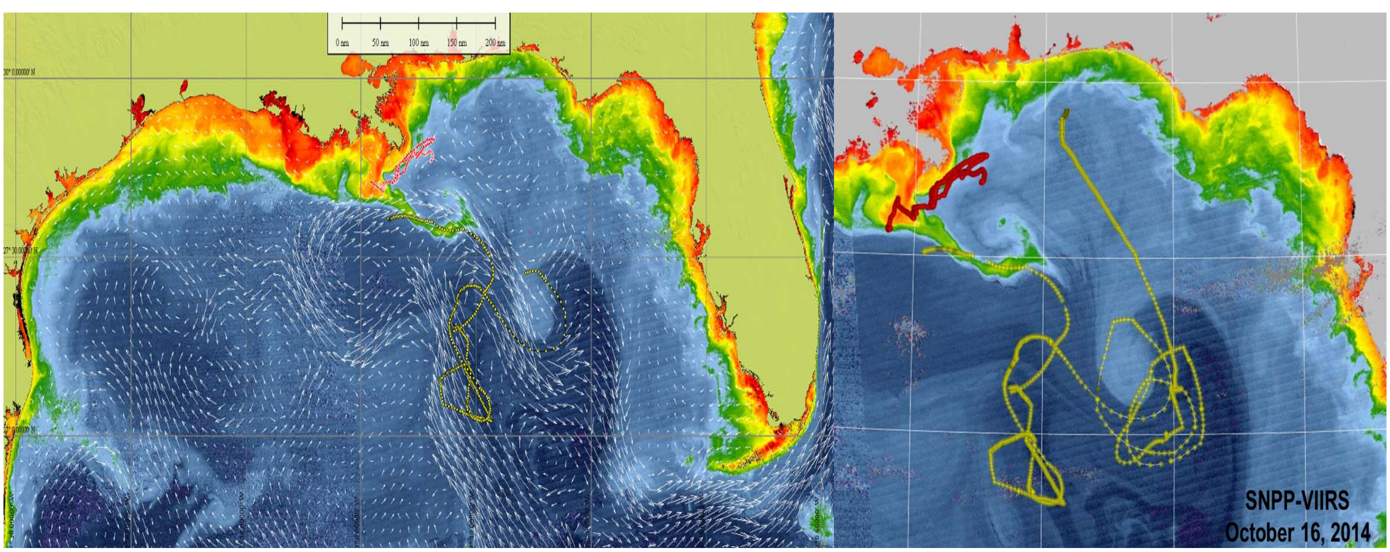

Fig. 2. 2014 Glider Tracks. The map on the left shows the shallow (red) and deep (yellow) glider tracks overlayed on SNPP-VIIRS images for 16 October 2014. The white arrows are current vectors, in which vector length indicates relative current surface speeds for the same day. The map on the right is zoomed into the glider tracks without current vectors. *Modified from Perry, R. et al. (2015) Autonomous underwater vehicle collaborations to improve hurricane forecasting and environmental monitoring in the Gulf of Mexico. Proceedings of the Annual Offshore Technology Conference.*

was entrained into the Loop Current as evident in remote sensing imagery (Fig. 1), lower measured salinities and higher chlorophyll α concentrations seen at the surface to depth of ~20 meters) [5]. It is probable that higher chlorophyll α concentrations are attributed to coastal eutrophication (increased nutrient availability) resulting in increased mid-summer and early fall primary production, which is currently under investigation at the time of this publication.

IV. Data Sharing with the Gulf of Mexico Community

The Gulf of Mexico is critical to the lives and livelihoods of approximately 50 million residents and an economic driver for the United States. Many anthropogenic and natural threats require rigorous and routine monitoring of the Gulf, from its estuaries and coastal wetlands to the deep water beyond the OCS. Development of a comprehensive ocean observing system, one that must include public-private partnerships (PPPs), is a sound economic investment that supports the Gulf ecosystem, as well as the national and regional economy.

Another key partner in the Shell-NOAA PPP is the Gulf of Mexico Coastal Ocean Observing System Regional Association (GCOOS-RA). GCOOS-RA, a collaborative non-governmental organization comprised of representatives from government, the private sector, research entities, and the outreach and education sector, has been developing this comprehensive ocean observing system over the last 10 years. The GCOOS-RA has outlined a long-term vision of regional observing and monitoring priorities in the GCOOS Build-out Plan (BOP). The BOP was developed with the input of 631 stakeholders from 297 organizations, with 13 expert writing teams. The plan also incorporated priorities listed in 90 existing regional plans. The BOP was developed to take advantage of existing capacities in the Gulf region with the understanding that different entities will be best suited to implement different projects to meet the monitoring priorities.

Several of these Gulf monitoring priorities are being addressed through the PPP presented in this paper (Table 1). Many of the partners involved in the Shell-NOAA PPP are active member organizations of the GCOOS-RA.

TABLE I. GCOOS BOP Priorities Being Address Through PPP Projects in the Gulf of Mexico

GCOOS BOP Priorities	Shell-NOAA Tropical Storm & Hurricane Prediction PPP
Improve hurricane severity forecasts	X
Enhance measurements of water quality parameters	X
Improve real-time, offshore meteorology measurements	X
Improve severe weather monitoring, forecasting, and dissemination	X
Produce upper ocean profiles of temperature, salinity, & currents	X

In turn, the GCOOS-RA is contributing to the success of this and other Gulf PPPs. As an example, the GCOOS-RA has established the Gulf Glider Task Team (GGTT). The GGTT is a group of glider developers, owners, operators, tool/product developers, and users, charged to coordinate, plan, and implement Gulf glider operations. This team is a mechanism to link glider expertise and capabilities around the Gulf. These linkages then enhance specific projects, such as the one

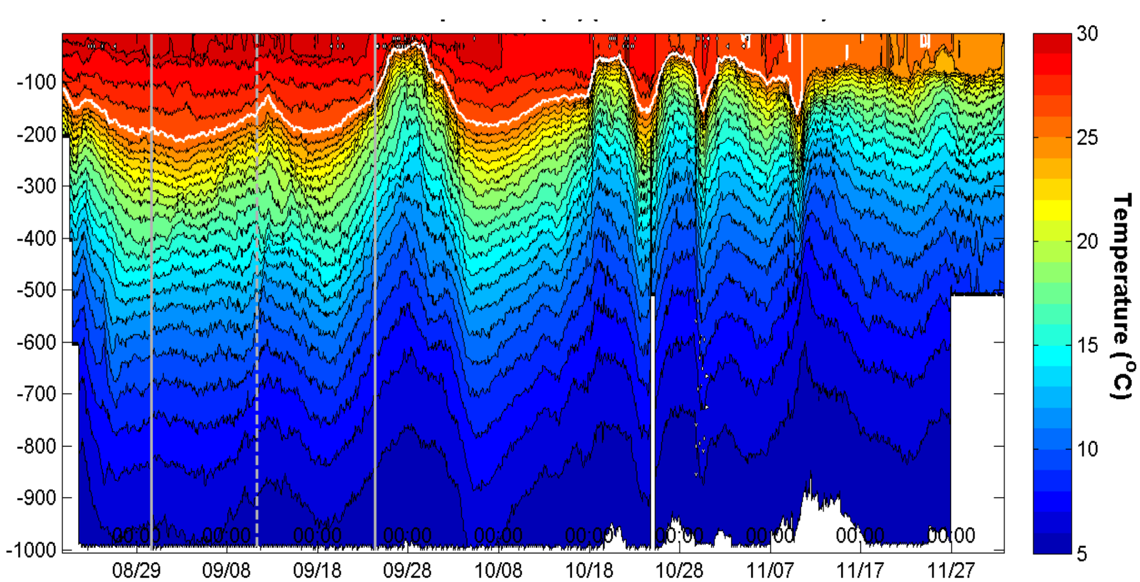

Fig. 3. 2014 Deep Glider Vertical Temperature Profile. The panel series shows vertical temperature data collected from the glider from August to November. The white line indicates the 26°C isotherm. The upper OHC layer was thick during summer months reaching down ~230 meters before decreasing in thickness and depth in late September and mid-October.

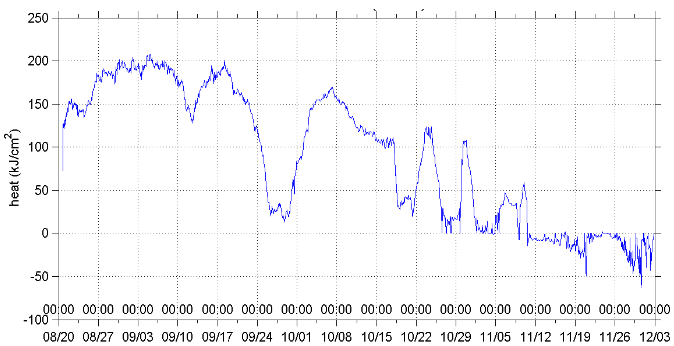

Fig. 4. Glider-derived Upper Ocean Heat Content. The time series shows OHC calculated from the glider temperature data (26°C isotherm) over the duration of the 2014 mission. Heat content was high, indicating availability of energy and thus higher potential for stronger storm intensification, during the first half of the mission. Variability of heat content correlates to the piloting of the glider within the Loop Current and Eddy Lazarus as seen in Fig. 1 and 3.

discussed in this paper (*See Section V.B)*. As another example, the GCOOS-RA has developed tools to help disseminate and share data collected through these projects. The GCOOS-RA has a near real-time data portal, displaying data on 12 different parameters from over 1912 sensors throughout the Gulf (http://data.gcoos.org/). The GCOOS-RA has also developed tools specifically for glider data, including: a) an interactive and real-time data mission viewer with a Web Graphics Library (webGL) visualizer in three dimensions [6], and b) an online glider data portal, the Gulf AUV Network and Data Archive Long-term storage Facility (GANDALF), to display the tracks and data of both currently deployed and archived glider missions [7]. GCOOS-RA Data Management and Communications Staff regularly provide technical support to Gulf researchers wishing to contribute and share their data.

V. 2015 Glider Plan & Conclusions

A. 2015 Mission Planning – Expanding the NOAA-Shell PPP

The Shell-NOAA PPP is continuing to grow in 2015 with the addition of new gliders and collaborators. Shell, NOAA, and the aforementioned partners are continuing glider deployments in 2015 with intended launch date in late August. At present time, two gliders will be launched. The first is a Teledyne Webb Slocum 1000m glider owned by NAVOCEANO and second is a Kongsberg 1000m Seaglider owned by newest partner- the Virginia Institute of Marine Science.

Remote sensing, drifter, and ADCP observations show another strong Gulf physical environment indicated by strong Loop Current with continued 2014 eddy activity (i.e. westward movement of Eddies Lazarus and Lazarus II) and formation of new eddies (i.e. Eddy Olympus). At the time of publication, Tropical Storm Erika is moving towards Florida and could potentially enter the Gulf.

The Seaglider will be equipped with similar sensor suite as in previous years (CTD, Chl α, CDOM, Oxygen), with an additional experimental sensor. An automated piloting code will be programmed in order to have all sensors recording during the overpass of Suomi National Polar-orbiting Partnership (SNPP) satellite with the Visual Infrared Imaging Radiometer Suite (VIIRS) to allow for ocean-satellite data validation [8]. In addition, the Seaglider will be equipped with a Vembco Mobile Transceiver to track tagged fish, in conjunction with the University of South Florida, Florida Fish and Wildlife Research Institute, GCOOS iTAG Network, and the Ocean Tracking Network. This effort with be the combination of two concurrent PPPs in the Gulf as facilitated by linkages formed with the establishment of the GGTT.

B. Benefits of a Collaborative Public-Private Partnership

The Shell-NOAA PPP discussed in this paper, along with its affiliation to a larger GCOOS regional comprehensive ocean observing system (also built on PPPs), demonstrate that PPPs are effective and efficient in that they meet needs, while leveraging the complementary strengths and benefits between industry, government, academic, and NGO collaborators. For Shell, the improvement in hurricane predictions, both forecast and severity, helps Shell protect workers offshore and along the coast and to better engineer and protect onshore and offshore assets. For NOAA, Gulf of Mexico Ocean observing and hurricane modeling are identified as top current and future research priorities. Partnering with Shell allowed NOAA to collect new and timely datasets in data-sparse Gulf areas by utilizing offshore infrastructure important to filling critical gaps in storm and hurricane models.

PPPs are successful in collecting data to answer specific scientific research questions and meet operational needs for industry, but are also valuable in numerous other ways. Information collected from these missions will have long term benefits in helping to understand the physical environment and ecological health of the Gulf and to provide spatial and temporal long-term data coverage to support the health of the environment and safety of the people working in the Gulf.

PPPs have increased the capacity of the ocean monitoring systems in the GOM. The data collected provide critical information required to ensure minimal impact to the people, property, and environment of the GOM from tropical storms and other changing conditions, such as ocean acidification, in the ocean environment. Collaborative partnerships that leverage the complementary strengths and benefits of each partner are an efficient and effective approach to meeting many the challenges associated with operating in the offshore environment.

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