ASSESSING THE VERTICAL STRUCTURE OF THE ANTICYCLONIC LOOP CURRENT EDDIES WITH AUTONOMOUS UNDERWATER GLIDERS

Tenreiro, M. (1), E. Pallàs-Sanz (1), T. Meunier (1), E. Portela (1), S. Cusi (1), M.J. Ulloa (2), A. Ruíz-Angulo (3), and J. Ochoa (1)

(1) CICESE, Physical Oceanography Department Carretera Ensenada-Tijuana No. 3918, Zona Playitas, C.P. 22860, Ensenada, B.C. Mexico. Email: tenreiro@cicese.mx

(2) INSTITUTO POLITECNICO NACIONAL, CICATA-ALTAMIRA, Km 14.5 Carretera Tampico - Puerto Industrial de Altamira 89600 Altamira, Tamaulipas, Mexico.

(3) CCA-UNAM, Cto. Exterior s/n C.P. 04510 Ciudad Universitaria, Distrito Federal México, D. F.

ABSTRACT

This manuscript describes the ongoing work conducted by the Grupo de Monitoreo Oceanográfico con Gliders (GMOG), an oceanographic group created in Mexico to monitor the mesoscale anticyclonic Loop Current eddies ubiquitous in the Gulf of Mexico with autonomous underwater gliders. GMOG has four SeaGliders with a maximum depth reach of 1000 m and, to date, has successfully completed three glider missions in the central and western Gulf of Mexico, collecting over 6 months ~42600 vertical profiles, of physical and biogeochemical variables, along 4200km tracks length. Several mesoscale structures have been sampled. In particular, the Loop Current Eddy Poseidon was surveyed just after its release. It showed a geostrophic velocity maximum (>1 m/s) at the subsurface on the outer edges of the eddy. The vertical sections of temperature and salinity show a warm and weakly stratified water between 70 and 180 m in the core and the typical subsurface salinity maximum between 180 and 300 m depth, which is the salinity signature of the Subtropical Underwater. The salinity minima at ~800 m identifies the Antarctic Intermediate Water core. The Gulf Common Water is found outside and at the periphery of the Loop Current eddies. Crossing the Loop Current eddies following a trajectory with a slightly angle to the thermohaline gradients was a satisfactory strategy to study their vertical structure. Images, trajectories and general information of GMOG’s missions can be found at www.gliders.cicese.mx.
Since the Deepwater Horizon oil spill on 20 April 2010, there has been an increasing effort to create multi-disciplinary consortia in the Gulf of Mexico (GoM) emphasizing the physical, chemical, biological, and ecological measurements to define the actual state of the GoM, ultimately to understand the interaction between the ecosystems and oil dispersion due to offshore oil industry activities. Three clear examples are the Gulf of Mexico Research Initiative created on 2011 (GoMRI; http://gulfresearchinitiative.org/), the Consorcio de Instituciones de Investigación Marina del Golfo de México y del Caribe formed on 2012 (CIIMAR-GOMC; http://ciimargomc.org/), and the recently constituted, Consorcio de Investigación del Golfo de México (CIGoM; http://www.cigom.info/). As a fundamental component of the latter, the Grupo de Monitoreo Oceanográfico con Gliders (GMOG; https://gliders.cicese.mx/), was promoted on 2015 by scientists of the Centro de Investigación Científica y Educación Superior de Ensenada (CICESE). The GMOG aims to provide new insights and understanding of the regional thermohaline and biogeochemical conditions, as well as their variability to support a sustainable management and exploitation of the fossil fuels and minerals in the deep GoM. Thus, the characterization of the thermohaline and dynamical vertical structure of the mesoscale structures ubiquitous in the GoM is crucial.

The circulation in the GoM is strongly influenced by the dynamics of the Loop Current (LC) system and the sporadic shedding of Loop Current Eddies (LCEs). The LCEs are warm mesoscale features that propagate westwards following three preferred paths (Vukovich 2007) and they typically, dissipate over the continental platform of the western region (Hamilton et al. 1999). With translation speeds of 4-5 km/day and lifespan from months to a year (Oey et al. 2005, Sturges and Lugo-Fernandez 2005), they carry anomalously warm and salty water along their westward drift contributing significantly to the heat and salt budget of the GoM (Morrison et al 1983).

Even though LCEs have been intensively studied using altimetry since the 90's, their vertical thermohaline structure remains largely unknown. The lack of in-situ data can be mainly attributed to the high rental cost of large research vessels and per diem rates of the crew. Underwater gliders are autonomous platforms that minimize offshore operational costs and generally do not require advance consent of the U.S. Department of State for Marine Scientific Research within the U.S. Exclusive Economic Zone (https://www.state.gov/e/oes/ocns/opa/rvc/). Therefor, they are indeed a very convenient platform to monitor the vertical structure of the LCEs ubiquitous in the central and western GoM.

**Figure 1.** Trajectories of the gliders during the three GMOG’s missions performed in the Gulf of México: 0001 (blue line), 0002 (red line), 0003 (green line). The trajectory of the mission 0004 (brown line) is only shown from December 7 2016 trough February 7 2017.
GMOG glider’s missions were designed and planned to repeatedly and systematically sample the vertical structure of the LCEs, from their separation from the LC to their final dissipation, by crossing them in and out, up and back to their cores. The GMOG’s fleet consists of four yellow Kongsberg SeaGlider™ AUV systems (SG622, SG623, SG624, and SG625) with ogive fairing and depth range of 0-1000m. Each glider is equipped with a basic sensor configuration: Seabird CT-Sail (Conductivity-Temperature), WET Labs triplet optical sensor (backscatter at 700nm, chlorophyll-a, and chromatographic dissolved organic matter), and an Aanderaa Dissolved Oxygen Optode (dissolved oxygen). In addition, GMOG has 1 pumped Seabird GPCTD (Conductivity-Temperature-Depth) and 1 Nortek Acoustic Doppler Current Profiler (ADCP).

GMOG successfully completed three glider missions in the central and western GoM during 6 months of continuous monitoring; the 4th mission designed to sample a colliding LCE on the western GoM, started on December 2016, and it is currently ongoing (see Figure 1 and Table 1). Overall, GMOG’s gliders completed over 46,400 vertical profiles, of physical and biogeochemical variables, representing 11 months of data along 4800 km during the four missions. The collected data has provided detailed information of the vertical structure of two LCEs (Olympus and Poseidon, as named by www.horizonmarine.com). As shown in Table 1, young LCEs refers to a LCE located in the central or eastern Gulf of Mexico with a water mass structure and strength typical of their formation region, i.e., Antillean Caribbean waters. Oppositely, a mature eddy refers to a weaker LCE that has reached the western Gulf of Mexico and its water mass structure has been transformed.

<table>
<thead>
<tr>
<th>Mission ID</th>
<th>Glider SN</th>
<th>Installation date</th>
<th>Sensor configuration</th>
<th>LCE surveyed</th>
<th>Number dives</th>
<th>Distance [km]</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001</td>
<td>sg624</td>
<td>14-May-2016</td>
<td>Basic</td>
<td>Mature Olympus</td>
<td>554</td>
<td>1400</td>
<td>Western GoM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25-Aug-2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>sg622</td>
<td>23-Jun-2016</td>
<td>Basic + GPCTD</td>
<td>Mature Olympus</td>
<td>483</td>
<td>1360</td>
<td>Western GoM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25-Aug-2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0003</td>
<td>sg623</td>
<td>05-Aug-2016</td>
<td>Basic</td>
<td>Young Poseidon</td>
<td>625</td>
<td>1475</td>
<td>Central GoM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15-Nov-2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0004</td>
<td>sg623</td>
<td>07-Dec-2016</td>
<td>Basic</td>
<td>Mature Poseidon</td>
<td>317</td>
<td>812</td>
<td>Western GoM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>07-Feb-2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. GMOG’s completed and ongoing detailed missions performed in the central and western Gulf of Mexico using the three of the SeaGliders (SG622, SG623, and SG624) of the GMOG’s fleet.

The results of mission 0003 are of particular interest as the glider performed two full cross-sections through the center of the LCE Poseidon, shown in Figure 1 (green line), sampling the detailed thermohaline structure of a young LCE at an unprecedented high resolution: dx=O(3km) and dz = O(1m).

A map of the glider trajectory from August 6th to September 4th, 2016 is shown in Figure 2a. The approximate position of Poseidon at regular time intervals during the glider mission can be inferred from the Absolute Dynamic Topography (ADT) contours z = 70 cm (obtained
from [http://www.aviso.altimetry.fr](http://www.aviso.altimetry.fr). The curvy and somehow hesitant trajectory shows the difficulty of mapping a rapidly evolving structure with a slow vehicle at a satisfactory synoptic level. The piloting strategy was focused on keeping the glider heading as parallel to the thermohaline gradients as possible and involved heading changes as the eddy center shifted westward. The latter strategy gave satisfactory results as the glider crossed the eddy approximately through its center following a trajectory along the ADT gradient lines for almost all the section.

The temperature and salinity vertical structure of Poseidon are shown in Figures 2c and 2d, respectively. The core of the eddy is characterized by a thick layer of warm and weakly stratified water between 70 and 180 m. Below 180 m, the temperature distribution shows a much stronger stratification and the warm anomaly remains intense until 1000 m. The salinity signature of the eddy’s water is given by a maximum of about 36.9 psu within a pancake-like shaped core. Similar to the isotherms, the isohalines continuously slope downward as deep as 1000 m. It is worthwhile to notice that the calculation of geostrophic velocities need no reference level. The glider dynamics allow by itself, independent of the hydrographic measurements, an estimate of the vertically averaged horizontal velocity, thus providing the constant of integration in the thermal wind equation. The geostrophic velocity (Figure 2b) reaches its maximum at the subsurface, on the outer edges of the eddy where the horizontal density gradients are maximum. It reaches over 1 m/s within the maximum velocity annulus.

![Figure 2](image)

**Figure 2.** GMOG’s mission 0003 (Table 2): (a) trajectory of the glider across the young LCE Poseidon seen as regular time intervals inferred from Absolute Dynamic Topography contours $z = 70$ cm, (b) geostrophic velocity estimated from the glider profiles, (c) vertical section of temperature (°C), and (d) vertical section of salinity (psu) along the trajectory shown in panel(a).

The pioneering *in-situ* observations of Elliott (1982) show that LCEs acquire the water mass structure typical of their region of generation, i.e., the LC-system. The LC typically holds water masses from the Antillean Caribbean waters, which remain trapped within the LCEs.
core. The main water masses found within the LCEs are the Subtropical Underwater (SUW) with a subsurface salinity maximum above 36.5 psu and temperature of 22.5 °C (Wüst, 1964) and the Antarctic Intermediate Water (AAIW) characterized by the salinity minimum below 35.0 psu (Nowlin 1972; Vidal et al. 1994). Vidal et al. (1994) showed the presence of modified SUW within the LCEs interacting with the western platform of GoM and concluded that this water mass is the precursor of the Gulf Common Water (GCW) with a characteristic salinity between 36.3 psu and 36.4 psu at 22.5°C (Nowlin 1972).

Figure 3 shows the T-S diagram associated with the glider trajectory from August 6th to September 4th, 2016 (Figure 2a). The SUW is characterized by its subsurface salinity maximum of 36.9 psu, found between 180 and 300 m depth, with a temperature about 22.5°C in its core, which has been reported previously (Merrel and Morrison, 1981; Danne and Sen Gupta, 1991; Vidal et al., 1994). The depth of the high-salinity layer deepens as one moves from the LCEs periphery towards the LCEs center (Figure 2d). The salinity minima at ~800 m identifies the AAIW core (Vidal et al., 1994). The GCW is barely present on the T-S diagram between 100 and 200m depth because it is mostly found when the glider is outside the LCEs (not shown).

Although the relatively slow horizontal speed of the platform (~20km/day), autonomous underwater gliders can be used in conjunction with altimetry to determine trajectories along the thermohaline gradients and study the vertical structure of the LCEs and the water mass transformation they experience during their westwards propagation. On February 10th, GMOG deployed SeaGlider sg624 on the continental platform of the GoM with the objective of continuing to monitor the colliding LCE Poseidon. GMOG’s observations are supported by Secretaría de Energía (SENER), Consejo Nacional de Ciencia y Tecnología (CONACyT),

![Figure 3. T-S diagrams along the trajectory shown in Figure 2a. Dashed lines represent the limits established in the literature for the Gulf Common Water (S<36.5 and T~22.5 °C) and the Subtropical Underwater (S>36.5 and T~22.5°C). The solid black line is the average profile, and the white dots represent the average depths of 100 m, 200 m and 300 m. The dotted contours correspond to the isopycnals.](image-url)
and Petroleos Mexicanos (PEMEX). This project will continue until March 2020. More information about GMOG’s missions can be found at [www.gliders.cicese.mx](http://www.gliders.cicese.mx).

REFERENCES


