

**STUDY TITLE:** Variability of Deep Water Mass Properties and the Loop Current in the Eastern Gulf of Mexico

**REPORT TITLE:** Observation of Deep Water Manifestation of the Loop Current and the Loop Current Rings in the Eastern Gulf of Mexico

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**BACKGROUND:** The upper-layer circulation in the eastern Gulf of Mexico (GOM) is dominated by the Loop Current (LC) and the separation of anticyclonic eddies or LC rings. The LC rings migrate westward and dominate the circulation in the central and western GOM. In contrast, deepwater in the GOM below the sill depths is completely isolated. Despite the isolation of deep water below the Yucatan sill depths, deep water in the GOM appears to be well ventilated and oxygenated. This suggests some energy propagation from the upper layer to deep water inside the GOM contributing toward vertical mixing of deep water.

In order to observe deep water currents at the center of the eastern GOM away from the rough topography of the northern slope water region, the first three successful yearly deployments using a deepwater mooring were carried out at the 25.5°N and 87°W. This particular location turned out to be an ideal location not only to monitor the LC in the eastern GOM but also to observe deepwater currents under the LC and LC rings away from the rough topography of the northern slope water region. The mooring data

suggest the dominance of a two-layer flow system at the mooring site with the interface located near 700-1,000 m. The upper-layer currents are dominated by the LC and Loop Current eddies (LCE) while the lower-layer currents appear to be manifestation of eddies in deep water. The upper- and lower-layer currents in general appear to be decoupled except occasional establishments of coupling between the two layers. Deepwater at the mooring site appears to be barotropic throughout the lower layer and relatively energetic characterized by 40-50 day variability with  $10\text{-}30\text{ cm s}^{-1}$  currents. Short-duration energetic events lasting a few days could result in strong deepwater currents reaching  $30\text{-}50\text{ cm s}^{-1}$  all the way to the bottom. These energetic events in deepwater appear to take place when the LC makes notable northward extension preceding the formation of LCEs. Deepwater currents at mooring site appear to be manifestations of a modon pair which forms underneath a LC ring in the eastern GOM. Shorter time scales associated with deepwater flow at the mooring site is a reflection of smaller deepwater eddies resulting from deepwater eddies interacting with the bottom topography including the topographic constriction located between the eastern and the central gulf. So far, every one of the three deployments turns out to be unique, confirming the previous observation that every LC ring formation is unique with predominant time scales of several months.

**OBJECTIVES:** Despite the success of the first three deployments, a couple of important questions remained unanswered. The first was related to the details of the interface between the upper- and lower-layers. Due to the paucity of the instrumentation near the depths of the interface, great details of the interface were not captured. The second question is related to the detailed variability of water mass characteristics in deepwater. Again due to the paucity of the instrumentation used in deep water to measure temperature and salinity, detailed variability of temperature and salinity in deep water was not measured. This is an important question, as it is related to the dynamics of the LC and LCEs, and ultimately to the mixing of water masses in deep water below the sill depths in the eastern GOM. For example, even though the basic idea of “a modon pair” in deep water appears to fit the observations at the mooring site, deep water currents driven by the vertical excursion of the interface between the upper- and lower-layers should exhibit corresponding variability in temperature and salinity in deep water. Moreover, there is simply a great value to extend the time series at the center of the eastern GOM where significant energy peak is found close to annual cycle. In order to address these questions, two additional years of deployment extension were proposed, approved and implemented. In order to sample not only currents but also water mass characteristics throughout the water column, additional current measurements were attempted near the interface and additional Microcats were deployed in deep water.

**DESCRIPTION:** Under the continuation funding, two additional deployments were completed. Although the detailed final configuration of the mooring differed between the two deployments, the primary objective remained the same, namely, to sample currents and temperature and salinity throughout the water column from near-surface all the way to near-bottom. Starting from the mooring configuration used in the first three deployments, additional current measurements were attempted near the interface depth and additional Microcats were deployed in deep water. Both deployments used two

ADCPs, one upward-looking set at 140 m and the other downward-looking set at 3,200 m, in order to measure currents near-surface and near-bottom, respectively, and nine Aanderaa current meters were set at 250, 350, 450, 600, 1,500, 2,000, 2,500, 3,000, and 3,186 m in order to sample the entire water column. Additional current measurements were made between 700 m and 1,200 m in order to catch the interface between the upper- and lower-layers. Specifically, Deployment 4 used four additional Aanderaa current meters set at 750, 875, 1,000, and 1,200 m, while Deployment 5 used a third ADCP set downward looking at 750 m. Compared to the previous three deployments with a total of five Microcats, significantly more detailed measurements of water mass properties (temperature and salinity) were accomplished with the use of eleven Microcats. They were set at 145 m, 351 m, 749 m, 1,000 m, 1,501, 1,800, 2,001, 2,500, 3,001, 3,187, and 3,297 m. Deployment 4 extended from May 29, 2005 to June 15, 2006 and Deployment 5 covered the period from June 17, 2006 to July 10, 2007.

**SIGNIFICANT CONCLUSIONS:** It appears that the LC and LCEs drives deep water currents in the eastern GOM. A modon pair forms underneath the LC when the LC makes northward extension prior to the formation of an LCE. However, eddy-eddy and eddy-topography interaction due to the topographic constriction in the central gulf and the limited size of the eastern basin make clear identification of “a modon pair” problematic. The observations of currents and water mass characteristics at the mooring site appear to be consistent with the Cushman-Roisin et al. (1990) mechanism for the generation of the deep anticyclone-cyclone pair beneath the LC. Another mechanism to transmit significant energy to deep water in the GOM is the barotropic oceanic response to the elevated sea surface near the center of tropical and extra-tropical storms often observed in the GOM. Simply due to the large number of those storm occurrences within GOM, this could represent another important-forcing mechanism to transmit significant energy to deep water in the GOM, thus contributing to deep water energetics and its well-mixed deep water conditions.

**STUDY RESULTS:** A total of five deployments of a deep water mooring at the center of the eastern GOM have produced the first observations of manifestations of the LC and LCEs in the eastern GOM away from the rough topographic region of the northern GOM. Most of the time, the mooring remained inside the LC. The mooring appears to be able to capture signal associated with every LCEs formed during the duration of the deployments. The observed flow field at the mooring site can be characterized as a two-layer system with the upper-layer flow dominated by the LC and LCEs the lower-layer flow dominated by smaller-scale deep water eddies. As a result, predominant time-scales of energy peak in the upper-layer are 50-120 days associated with migration of the LC in the eastern GOM, while the lower-layer showed energy peaks between 20 and 40 days. Current ellipses in deep water are more isotropic compared to those in the upper-layer, suggesting that the observed shorter-duration current variability in deep water is manifestation of smaller-scale deep water eddies. The interface between the upper- and lower-layers appears to be located between 800 m and 1,000 m. Strongest near-surface currents peaked  $> 180 \text{ cm s}^{-1}$  (3.5 knots) coinciding with the passage of the frontal jet in the LC. Upper-layer currents exhibit strong current shear reflecting the current structure within the LC. In contrast, lower-

layer currents are nearly barotropic throughout the lower layer with typical current speeds averaging  $\sim 11 \text{ cm s}^{-1}$ . However, short-duration current bursts in deep water were observed lasting a few days with maximum currents exceeding  $30\sim 40 \text{ cm s}^{-1}$ . The strongest current burst in deep water with maximum currents exceeding  $51 \text{ cm s}^{-1}$  (1 knot) was observed during Deployment 3. Throughout the five deployments, deep water currents exhibited northward drift, suggesting that on average currents at the mooring site drift northward at speeds of  $2\text{-}4 \text{ cm s}^{-1}$ . Mean upper-layer currents displayed significant year-to-year variability, reflecting changing location of the mooring relative to the LC that is dominated by the LC ring formation with significant power near several months. It appears that the mooring was located west of the LC frontal jet during Deployments 1, 2 and 5 while it was located east of the LC frontal jet during Deployments 3 and 4.

Decoupling of the upper- and lower-layer currents was typical while occasional coupling between the two layers was observed. In particular, strong northward flowing barotropic currents were observed at the time of extreme northward extension of the LC preceding the formation of LCEs. Those short-duration events lasted only a few days. However, the observed barotropic currents penetrated all the way to the bottom. The observed current variability and its associated T & S variability in deep water suggest that the idea of “a modon pair” in deep water appears to fit the observations at the mooring site, deep water currents driven by the vertical excursion of the interface between the upper- and lower-layers associated with the formation of LCEs. This appears to be the primary mechanism by which to transmit energy from the upper-layer to deep water especially below the sill depths at the Yucatan Channel (1900 m). This appears to drive smaller-scale deep water eddies. The observed smaller scales associated with deep water eddies are a result of eddy-topographic interaction as well as eddy-eddy interaction in deep water. In this respect, the presence of the topographic constriction located in the central GOM is crucial in that it prohibits free propagation of eddies from the eastern GOM toward the west, thus contributing toward cascading of eddy energy toward smaller scales.

Deployment 4 resulted in the discovery of another mechanism by which to transmit energy into deep water in the GOM. During its close encounter with Hurricane Katrina, the mooring detected significant deep water response to the passage of the hurricane. Similar response was not observed during the passage of Hurricane Rita. It appears that the observed energetic deep water response to Hurricane Katrina was the result of barotropic oceanic response to the elevated sea surface in accordance with the lower pressure distribution within the eye wall of the hurricane.

The high resolution model simulations featuring very high horizontal ( $.075^\circ$ ) and vertical (100 levels) resolution allowed more realistic representation of the bottom topography including the gentle rise and the steep escarpments. Consequently, it resulted in more realistic simulation of deep water currents in the eastern GOM, i. e., more energetic deep water and more chaotic eddy field in deep water, consistent with the observation at the mooring site. It appears that the small grid spacing in both the horizontal and vertical are necessary to resolve deep eddy interaction with the bathymetry in the GOM. The resulting eddy-eddy and eddy-topography interaction give rise to the observed

energetic and chaotic flow field deduced from the mooring data, making clear identification of “a modon pair” in deep water in the eastern GOM problematic.

**STUDY PRODUCTS:** Welsh, S.E., M. Inoue, L. J. Rouse, Jr., and E. Weeks, 2009. Observation of deep water manifestation of the loop current and the loop current rings in the eastern Gulf of Mexico. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2009-050. 119 pp.

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P.I.'s affiliation may be different than that listed for Project Manager.