Evolution of the Loop Current System During the *Deepwater Horizon* Oil Spill Event as Observed With Drifters and Satellites

Yonggang Liu,[1] Robert H. Weisberg,[1] Chuanmin Hu,[1] Charles Kovach,[2] and Rolf Riethmüller[3]

The ocean circulation patterns of the Gulf of Mexico (GOM) Loop Current (LC) system and their effects on the advection of the oil discharged during the *Deepwater Horizon* incident are described using in situ surface drifter trajectories and satellite observations from May to August 2010. These observations include altimetry-derived surface geostrophic velocities, sea surface temperature, ocean color, and surface oil locations. The elongated, northwestward penetrating LC retreated back from its northernmost position in late April 2010 and stayed farther away from the surface oil in the north during May 2010. Although the main body of the surface oil slick remained around the well site and on the Northern Gulf shelf, a small amount of the surface oil was entrained into the northern part of the LC system in mid-May 2010. An anticyclonic eddy in its formative stage then detached from the northern part of the LC in the latter part of May 2010, tending to break the direct connection between the northern Gulf with points farther south. Through interactions with smaller cyclonic eddies on either side, multiple short-lived detachment/re-attachment episodes continued for some time during the spill event, but without ever fully reestablishing a direct LC pathway from the region of the oil spill to the Florida Straits. The mean geostrophic current pattern during this time period showed a separated LC eddy in the eastern GOM. Such ocean circulation patterns helped retain the surface oil in the northeastern Gulf and kept an oil-free environment for most of Florida's coastal waters.

1. INTRODUCTION

The *Deepwater Horizon* incident occurred on the continental slope of the northern Gulf of Mexico (GOM), a transition zone between the shallow continental shelf on its northern side and the deep ocean on its southern side. The complex, time-varying ocean circulation patterns of the region [e.g., *Boicourt et al.*, 1998; *Schmitz et al.*, 2005] played an important role in advecting the oil from the spill site. On the northern side, shelf currents are generally weaker and mostly wind-driven [e.g., *He and Weisberg*, 2002, 2003a; *Morey et al.*, 2005; *Weisberg et al.*, 2003, 2005, 2009a, 2009b]; however, on the southern side, deep ocean currents, embodied by the GOM Loop Current (LC) system (the LC and its eddies) in the eastern GOM, are much stronger [e.g., *Sturges and Lugo-Fernández*, 2005]. Thus, the LC system posed a threat to the potential expansion of the *Deepwater Horizon* disaster [e.g., *Ji et al.*, this volume]. If a large amount of oil was to be entrained into the LC, it could be transported southward to the Florida Keys and further to the North Atlantic within weeks [*Weisberg*, 2011]. Thus, during the *Deepwater Horizon* spill event, a critical question was whether the oil would be entrained into the LC system.

[1]College of Marine Science, University of South Florida, St. Petersburg, Florida, USA.
[2]Florida Department of Environmental Protection, Temple Terrace, Florida, USA.
[3]Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany.

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As a part of the North Atlantic Ocean's western boundary current system, the LC is a prominent feature in the GOM. It has been the focus of many previous observational [e.g., *Sturges and Leben*, 2000; *Welsh and Inoue*, 2000; *Leben*, 2005; *Alvera-Azcárate et al.*, 2009] and modeling studies [e.g., *Oey et al.*, 2005; *Chérubin et al.*, 2006]. The position of the LC within the GOM is highly variable. The northern part of the LC can develop into a separate anticyclonic ring [e.g., *Elliott*, 1982; *Lewis and Kirwan*, 1987; *Sturges et al.*, 1993] after being pinched-off by cyclonic eddies on either or both sides of the flow [e.g., *Vukovich and Maul*, 1985; *Schmitz et al.*, 2005]. The detached eddy can either reattach to the LC or propagate westward in the Gulf [e.g., *Hamilton et al.*, 1999; *Hyun and Hogan*, 2008; *Rivas et al.*, 2008; *Alvera-Azcárate et al.*, 2009]. The LC ring shedding is believed to be quite erratic [e.g., *Sturges*, 1994; *Vukovich*, 1995; *Sturges et al.*, 2010], but with a range of some 6–17 months (over the period of satellite coverage, 1973–1999) [*Sturges and Leben*, 2000]. The frequency of eddy shedding is also found to be size dependent, with larger eddies shedding less frequently than smaller ones [*Alvera-Azcárate et al.*, 2009]. According to *Lugo-Fernández* [2007], the LC behaves as a nonlinear, damped oscillator with a very short memory. A linear (statistical) relationship was found between the LC retreat latitude and the eddy separation period [*Leben*, 2005; *Lugo-Fernández and Leben*, 2010] based on a criterion of LC location (defined by a 17 cm sea surface height anomaly contour) [*Leben*, 2005]. Given the foregoing synopsis, much remains to be learned.

Trajectories of near-surface drogued drifters were used in many previous studies to describe the circulation in the GOM [e.g., *Lugo-Fernández et al.*, 2001; *Ohlmann et al.*, 2001; *DiMarco et al.*, 2005; *Johnson*, 2005; *Ohlmann and Niiler*, 2005; *Price et al.*, 2006; *Hamilton*, 2007]. However, only a few of these drifter observations were targeted solely on the LC [e.g., *Kirwan et al.*, 1988; *Glenn and Ebbesmeyer*, 1993; *Toner et al.*, 2001; *Kuznetsov et al.*, 2002]. Satellite altimetry offered repeated sea surface height (SSH) observations, which provided very informative views of the LC system in the GOM [e.g., *Jacobs and Leben*, 1990; *Leben and Born*, 1993; *Alvera-Azcárate et al.*, 2009]. Of course, the gridded altimetric SSH products, e.g., the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) gridded product [e.g., *Pascual et al.*, 2006] have a temporal resolution of several days and spatial resolution of 1/3°. Remotely sensed sea surface temperature (SST) data have better temporal and spatial resolutions and were used in describing the GOM circulation [e.g., *Maul et al.*, 1985; *Vukovich and Maul*, 1985; *Walker et al.*, 2003; *Vukovich*, 2007]. However, SST tends to be spatially homogeneous and loses its contrast in summer. Satellite ocean color imagery provided an alternative [e.g., *Müller-Karger et al.*, 1991; *Jolliff et al.*, 2008], yet during the summer, frequent sun glint prevails in the color imagery where little information could be obtained. To overcome such a difficulty, a new color index (CI) data product was developed from Moderate Resolution Imaging Spectroradiometer (MODIS) observations, which provided nearly glint-free surface color patterns that can be used to infer major circulation patterns such as the LC system in summer [*Hu*, 2011].

Based on the above-mentioned four types of data sets (drifter, altimetry SSH, SST, and CI) plus the surface oil slicks inferred from satellite imagery [e.g., *Hu et al.*, 2003, 2009, 2011], the variation of the ocean circulation patterns in the eastern GOM is described for the period of spring–summer 2010, with a focus on the advection of the surface oil slicks, which themselves serve as a kind of passive tracer. The following questions will be examined with the data: Was the surface oil entrained in the LC system? What were the ocean circulation patterns that characterized the eastern GOM during the spill event? What are their implications for transporting hydrocarbons discharged in the northern GOM?

In an accompanying paper in this book, moored current meter records in the northern part of the LC system were analyzed for the March–June 2010 period, and the interaction of the LC and its anticyclonic eddy was studied in the context of historical altimetry data [*Hamilton et al.*, this volume]. The merger of cyclonic eddies along the LC's northern margin was described using both satellite imagery and in situ current data in another chapter [*Walker et al.*, this volume]. Near-weekly snapshots of the LC eddy were also provided with airborne expendable ocean current profilers [*Shay et al.*, this volume]. This chapter compliments these analyses by providing detailed ocean circulation patterns derived from altimetry and supported with SST, ocean CI [*Hu*, 2011], and in situ drifter observations [*Liu and Weisberg*, 2011] of the LC system during the spill event. We will focus on the entire LC system and examine its evolution during the spill event and its implications for the transport of the oil. This chapter also complements those on hydrocarbons by others in this book [e.g., *Jones et al.*, this volume; *Ryan et al.*, this volume; *Wade et al.*, this volume] and may provide useful information for future hypothesis testing.

2. DATA SETS

As a part of its response to the *Deepwater Horizon* oil spill efforts, the University of South Florida (USF) Ocean Circulation Group (OCG) deployed 18 satellite-tracked drifters in the LC region and on the West Florida Shelf during May–August 2010. Six drifters were initially deployed during a 19–24 May 2010 R/V *Bellows* cruise, a joint effort between the USF OCG, USF Optical Oceanography Laboratory, Florida Department of Environmental Protection, U.S. Coast Guard (USCG), and Florida Wildlife Research Institute (FWRI). Three drifters were subsequently deployed during a 2–14 June 2010 R/V *Weatherbird II* cruise by the USF OCG assisted by the Florida Institute of Technology (FIT). Nine more drifters were then added during a 22–25 June 2010 R/V *Weatherbird II* cruise, in a joint effort by the USF OCG, Woods Hole Oceanographic Institution (WHOI), and the Northeast Fisheries Science Center (NEFSC). The drifters, drogued at 1 m depth, transmitted data via satellite in real time. The locations of the drifter trajectories were binned at hourly time steps, plotted and archived, and made available to the public at USF OCG website (http://ocgweb.marine.usf.edu). The main purpose of the drifter deployments was to populate the region's flow field so that we could monitor the evolution of the LC, its associated eddies, and other flow field features in the eastern GOM and to help track the oil, if any was either entrained in the LC system or passed beyond Cape San Blas and onto the West Florida Shelf. This drifter data set was also used to assess the performance of a trajectory model that was employed to track the spilled oil [*Liu and Weisberg*, 2011].

Gridded sea level anomaly data from AVISO [e.g., *Pascual et al.*, 2006] were combined with a model [*Chassignet and Garraffo*, 2001] mean SSH to obtain absolute SSH in the GOM, following a procedure described in the work of *Alvera-Azcárate et al.* [2009]. Surface geostrophic currents were then calculated as the gradient of the absolute SSH, similar to that in the work of *Liu et al.* [2008]. The SSH and geostrophic current data were further interpolated in time to have daily snapshots so that they could be conveniently superimposed with other data. Note that the global AVISO product is designed for the open ocean or offshore deepwater regions. Because there are intrinsic limitations to the altimetry data in shallow seas and near coastlines [e.g., *Vignudelli et al.*, 2011], we will only focus on the deepwater area (water depth >200 m) in the GOM in this analysis.

SST data were downloaded from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) [*Stark et al.*, 2007], which uses satellite data provided by the Global Ocean Data Assimilation Experiment High Resolution SST Pilot Project [*Donlon et al.*, 2009], together with in situ observations to determine the SST. The daily Global OSTIA data have a spatial resolution of 5 km.

MODIS ocean CI was generated using MODIS land bands at 469, 555, and 645 nm with an empirical method to remove sun glint contamination and atmospheric effects [*Hu*, 2011]. It is nearly a glint-free data product to show surface color patterns, for example, to identify the LC system from the ambient flows during summer 2010. This is particularly useful when the eastern GOM becomes nearly isothermal at the surface, and the use of SST imagery is limited.

Surface oil slick data were inferred from the MODIS and the Medium Resolution Imaging Spectrometer Instrument as reported in recent literature [e.g., *Hu et al.*, 2003, 2009]. These data were collected either by a local antenna at USF or downloaded from NASA in near real time. When clouds prevailed, data from synthetic aperture radar satellite instruments were used to help delineate oil slicks [*Liu et al.*, 2000]. The satellite data interpretation was performed on a daily basis, depending on the availability of the data. Both the ocean CI and satellite oil location interpretations were archived and made available to the public at the USF Optical Oceanography Laboratory website (http://optics.marine.usf.edu/events/GOM_rigfire/). The surface oil slick data was used to update the trajectory forecast system during the *Deepwater Horizon* event [*Liu et al.*, 2011, this volume; *Weisberg*, 2011].

3. ENTRAINMENT OF SURFACE OIL INTO THE LC SYSTEM

The SST data still had good contrast in May, and they were superimposed with the surface geostrophic currents to show some snapshots of consistent surface ocean circulation patterns in the eastern GOM (Figure 1). During the initial several days of the oil spill (late April through early May of 2010), the LC had an elongated shape extending northwest (Figures 1a and 1b). The distance between the well site and the outer edge of the LC was about 150–200 km. There was an anticyclonic circulation vortex (200–300 km scale) to the northwest of the LC and to the south of the well site during late April to early May (vortex "A" in Figure 1a). The northern part of this anticyclonic vortex exhibited an eastward and southeastward flow that tended to bring surface water to the LC system (Figures 1a and 1b). The surface oil slick was in a small area located on the north side of the well site during the spill onset days. As the LC retreated to the south in early May, a cyclonic vortex (100–200 km scale) appeared on its northern edge as shown in the flow field (vortex "C" in Figure 1c). Between these two vortices, there was a stronger southward convergent flow that tended to transport the surface oil southward toward the LC system around May 12 (Figure 1d). Surface oil slicks were entrained in the LC system in mid-May (Figure 1e). The entrained surface oil slicks were not immediately transported to the southern part of the LC because they were mainly circulating around the small cyclonic eddy on the northern part of the LC system (Figure 1f). Continuous supply of surface oil to the LC system was seen from mid

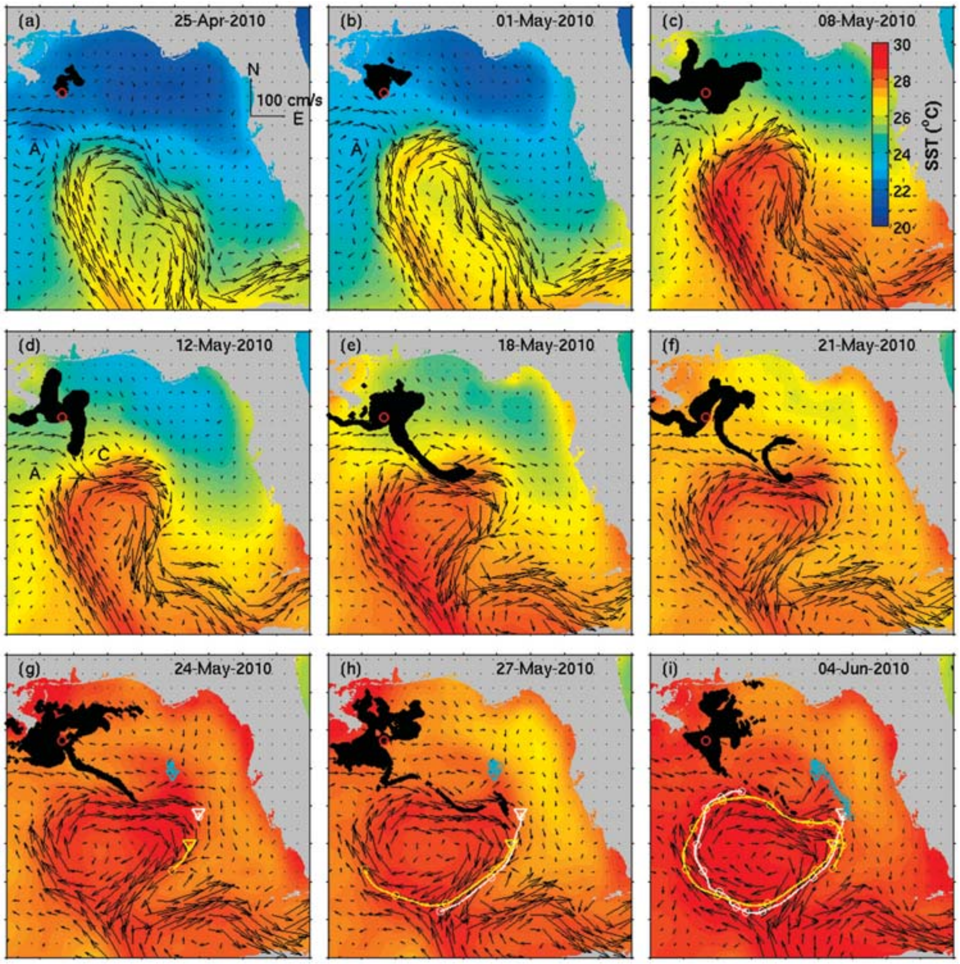

Figure 1. Entrainment of surface oil (black patches) into the Gulf of Mexico Loop Current (LC) system during 25 April 2010 to 04 June 2010. Ocean circulation snapshots in the eastern Gulf of Mexico are indicated by the surface geostrophic currents (vectors) overlaid on surface temperature. Satellite-tracked surface drifter trajectories are differentiated with various colors, with triangles designating the original release locations and open circles showing daily 0 h UTC along the trajectories. The red open circle indicates the *Deepwater Horizon* well site. Anticyclonic and cyclonic vortices are indicated by letters "A" and "C," respectively.

to late May 2010 (Figures e–1h). However, the amount of surface oil entrained into the LC system appeared to be very small relative to the total amount of discharged oil, and the majority of the surface oil slicks were found around the well site and on the shallow shelf in May 2010.

The consistency between the evolution patterns of the surface oil slicks and the surface geostrophic currents around the northern part of the LC indicates that the surface oil acted as a tracer. However, we also see that some of the surface oil disappeared with time (Figure 1) presumably by natural weathering and biological consumption. Intensive mitigation efforts, such as booming, controlled burning, and application of significant amounts of chemical dispersant, complicated the trajectories and fate determination of the surface oil as a tracer.

Surface drifters were deployed on the northeastern edge of the LC on 22 May 2010 (Figures 1g–1i) after we found the entrainment of the surface oil slick into the LC system. Starting in mid-May, the northern part of the LC was about to be pinched off by a cold eddy (Figures 1e and 1f). At that time, both the scientific community and the general public were concerned about oil being transported by the LC to the

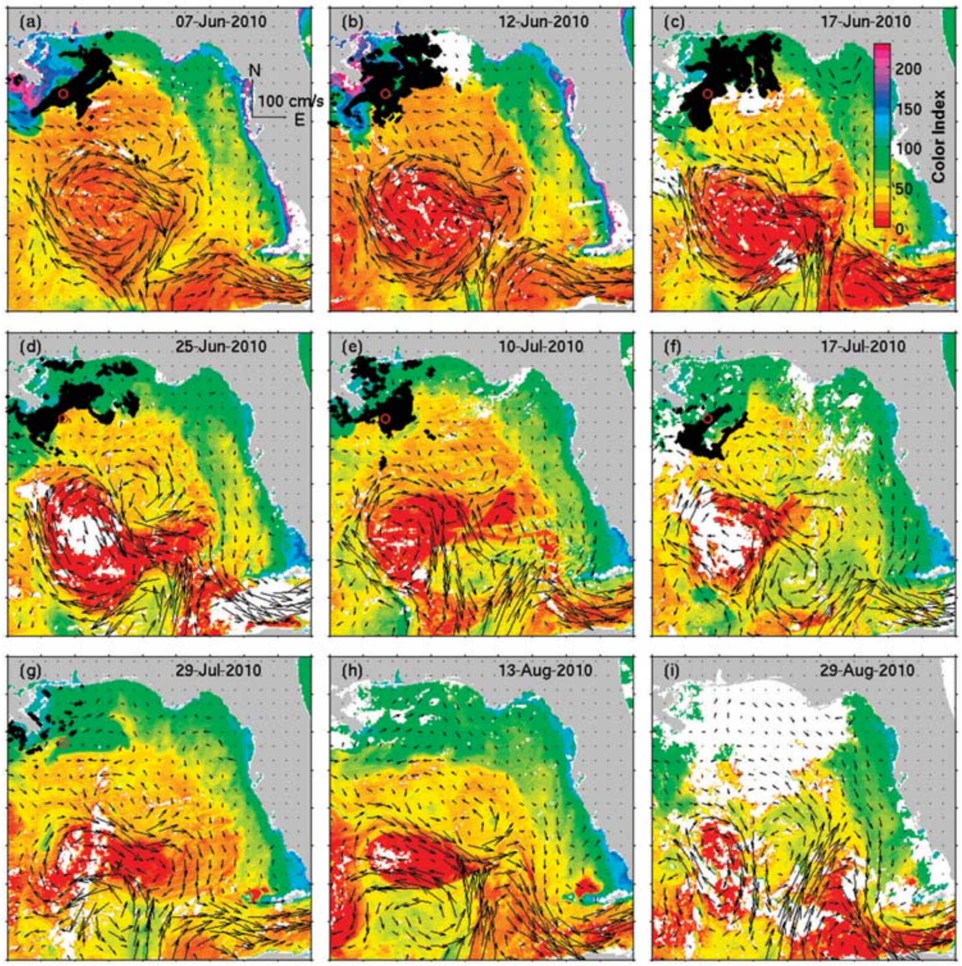

Figure 2. The Gulf of Mexico LC ring separation-reattachment-separation process during June–August 2010. Ocean circulation snapshots in the eastern Gulf of Mexico are indicated by the surface geostrophic currents (vectors) overlaid on the Moderate Resolution Imaging Spectroradiometer color index (CI) (in relative units) within 1 day. Also shown are surface oil slick (black) inferred from satellite imagery. The white blank areas denote cloud cover. Note that low CI values indicate clear waters. The red open circle indicates the *Deepwater Horizon* well site.

ecologically sensitive Florida Keys and beyond to the U.S. east coast. The drifter deployed on the east side of the cyclonic eddy in the northern LC system was advected northward for about 5 days after 22 May 2010, consistent with the northward geostrophic currents there (Figures 1g and 1h, gray drifter path). This drifter was brought to the south later by the southward currents on the outer West Florida Shelf. The other two drifters deployed on the eastern edge of the LC were circulating around the LC-shed anticyclonic eddy instead of directly entering the strong eastward LC to the southeast. It took about 10 days for the drifters to make a full circle around the anticyclonic eddy (Figure 1i). This had important implications to the transport of oil in the Gulf as further elaborated in sections 5 and 6.

4. EVOLUTION OF THE LC SYSTEM

Starting in late May to early June, the SST data tended to be spatially homogeneous due to the summer heating in the GOM region (Figures 1g–1i). Therefore, ocean CI data were used instead to track the LC and eddies in the GOM (Figure 2). For most of the time, excellent agreement was found between the CI and the geostrophic currents in representing the LC and its eddies. The ocean circulation patterns inferred by the remotely sensed ocean color and altimetry-derived data products were further corroborated by the in situ drifter trajectories (Figure 3). In order to keep the figures less cluttered, only the drifter trajectories within 10 days prior to the snapshots are shown in Figure 3.

Evolution of the LC system throughout the *Deepwater Horizon* oil spill event can be seen from the snapshots of the ocean circulation in Figures 1–3. As mentioned in the previous section, the LC shape changed from an elongated, northwestward intruded loop in late April to early May to a wider, nearly pinched-off LC eddy in mid-May. From late May through early June, the major part of the strong flow circulated around within the anticyclonic ring, even though the ring was still slightly connected to the LC to the south (Figure 1). The ring was completely detached around 7–12 June 2010 (Figures 2a and 2b) and made minor re-attachments to the LC later (Figure 2c). As the ring propagated westward, its size was reduced, and its shape became more irregular (Figures 2c–2d). The anticyclonic ring became smaller, and the current pattern became more complicated in the eastern GOM during July and August (Figures 2 and 3). This eddy stayed in the vicinity of the LC during July and August (Figures 2e–2i), and according to the analysis of *Hamilton et al.* [this volume], there were five such detachment/re-attachment cycles before the ring was finally separated in September 2010. However, unlike many such previous events, the eddy never fully reattached with the parent LC.

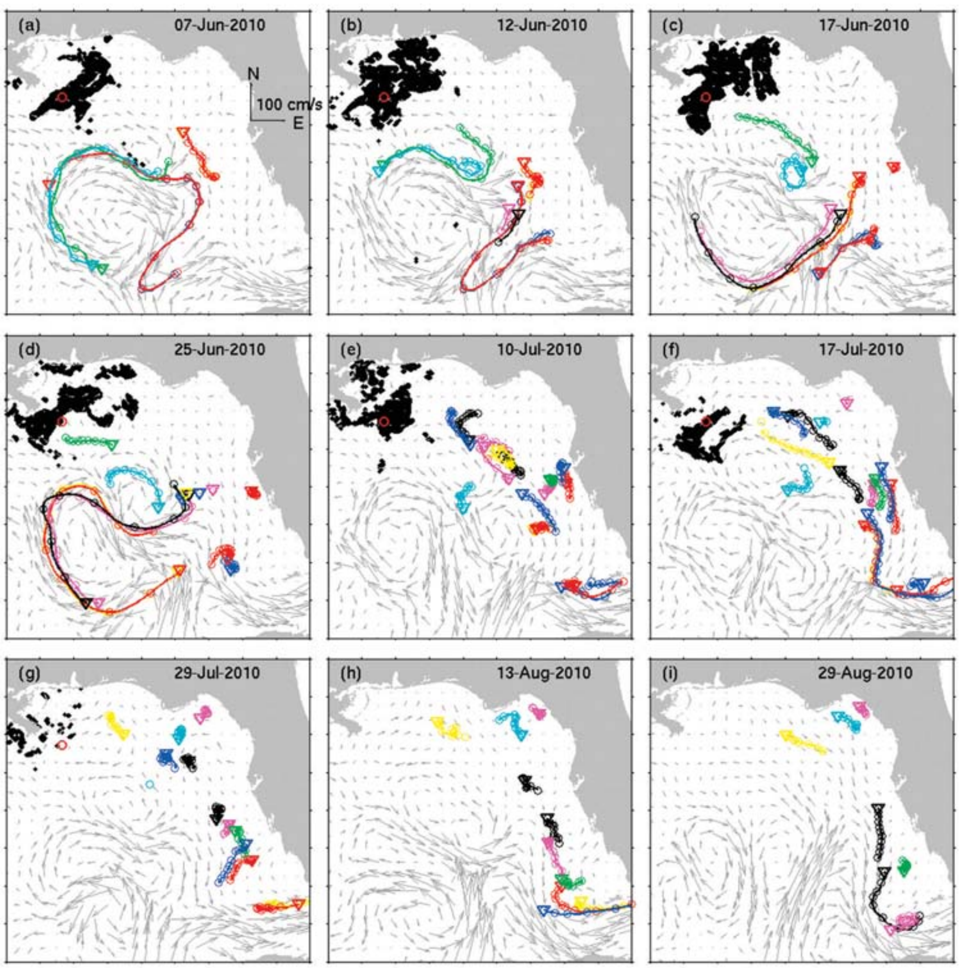

Figure 3. Same as Figure 2 but with available satellite-tracked surface drifter trajectories within 10 days prior to the snapshot dates. The drifter trajectories are differentiated with various colors. Triangles designate the starting points of the drifters up to 10 days prior to the snapshot dates. Open circles show daily 0 h UTC along the trajectories.

Interactions between the LC eddy and/or the LC itself with the outer West Florida Shelf are seen throughout the spring and summer 2010 (Figures 1 and 2). Such interactions can cause strong southward currents on the outer West Florida Shelf [e.g., *Molinari et al.*, 1977; *Huh et al.*, 1981; *Paluszkiewicz et al.*, 1983; *He and Weisberg*, 2003b] and depending on where these interactions occur then can the entire West Florida Shelf currents be set in motion [*Weisberg and He*, 2003]. Such behavior was observed during the *Deepwater Horizon* event when anomalous upwelling existed on the West Florida Shelf [*Weisberg*, 2011].

5. IMPLICATIONS FOR THE TRANSPORT OF THE OIL

Despite the complicated detachment/re-attachment process of the LC anticyclonic eddy during the *Deepwater Horizon* event, a coherent ocean circulation pattern was seen in the mean surface geostrophic currents of the eastern GOM during 1 May to 31 August 2010 (Figure 4). In the mean field, we see an anticyclonic eddy of 300–400 km diameter separated from the mean LC and a smaller cyclonic eddy located on its northeastern side. This mean cyclonic eddy was oriented with its major axis in the northwest-southeast direction. This orientation facilitated interaction with the West Florida Shelf. A composite plot of all of the USF-OCG deployed satellite-tracked surface drifter trajectories from 22 May to 31 August 2010 shows a similar coherent pattern (Figure 4). In this mean composite, we see how the separated LC eddy, together with a cyclonic eddy to its north, tended to retain oil within the Gulf, versus facilitating transport out of the Gulf through the Florida Straits.

Detailed drifter trajectories can be seen from an image animation provided by USF OCG (http://ocgweb.marine.usf.edu/~liu/drifter_USF.html). Note that most of the drifters deployed on the edge of the LC broke away from the LC either through entrainment into the cyclonic eddy on its northern margin or by intrusion onto the West Florida Shelf. Some of these drifters slowly made their way southward along the outer West Florida Shelf to the Florida Straits. This

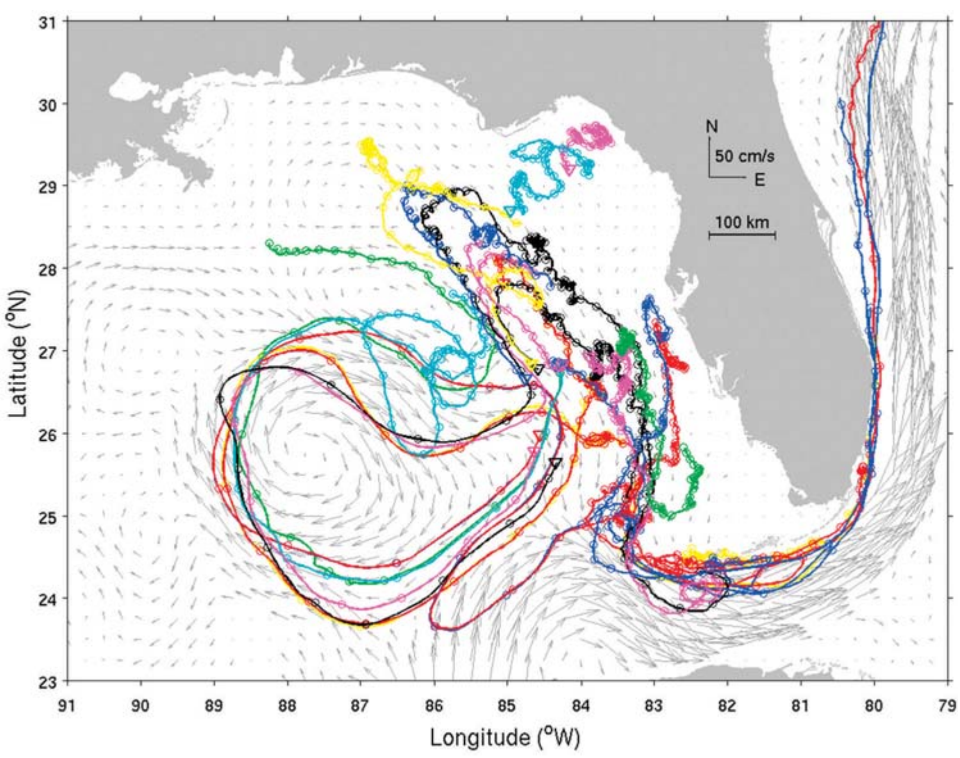

Figure 4. Mean surface geostrophic currents superimposed with satellite-tracked surface drifter trajectories in the eastern Gulf of Mexico during 1 May to 31 August 2010. The drifters were released on various dates, starting on 22 May 2010. The drifter trajectories are differentiated with various colors, with triangles designating the original release locations and open circles showing daily 0 h UTC along the trajectories.

transit took over a month because the shelf currents [e.g., *Liu and Weisberg*, 2005, 2007] tend to be an order of magnitude slower than those of the LC (i.e., 10–20 cm s^{-1} versus 100–200 cm s^{-1}). Two drifters that were deployed on the eastern edge of the LC eddy on 23 May 2010 escaped from the eddy in the south to become entrained into the LC on around 6 June 2010. These two drifters were then transported eastward and deposited on the outer West Florida Shelf where they remained for more than 2 weeks before being re-entrained into the Florida current and transported through the Florida Straits beginning near Key West around 10 July 2010 and then farther up the east coast of Florida passing the Palm Beach area around 17 July 2010. The entire journey took almost 2 months. Note that if the northern part of the LC had not separated, this journey may only have taken about 2 weeks.

6. SUMMARY

Based on in situ surface drifter trajectories, altimetry-derived surface geostrophic velocities, satellite SST, and ocean color imagery, we described the variation of the ocean circulation patterns in the eastern GOM during May–August 2010. The evolution of the LC system and its effects on the advection of the surface oil discharged from the *Deepwater Horizon* incident were examined, and the three questions posed in the Introduction were answered as follows:

Question 1: Was surface oil entrained in the LC system? Yes, some surface oil was entrained into the northern part of the LC system in mid-May 2010, even though the main body of the surface oil remained in locations around and to the north of the well site. This entrainment was caused by convergent southward flow between adjacent anticyclonic and cyclonic vortices that appeared to the northwest and north of the LC, respectively, as the LC retreated southward in early May 2010 (see http://ocgweb.marine.usf.edu/~liu/geovel.html).

Question 2: What were the ocean circulation patterns that characterized the eastern GOM during the spill event? At the onset of the spill, the LC extended northward to about the latitude of Tampa Bay, and it appeared to be progressing farther north toward the well site. However, the LC began to retreat southward in early May 2010. By mid-May, an anticyclonic LC eddy of 300–400 km diameter developed, accompanied by smaller eddies, and began to separate from the parent LC [also see *Hamilton et al.*, this volume; *Walker et al.*, this volume]. While it took some time for the anticyclonic LC eddy to fully disengage from the parent LC, the direct LC pathway from the northern GOM to the Florida Straits was essentially broken. Upon averaging from May to August 2010, we see an anticyclonic eddy separated from the LC, and a smaller, cyclonic eddy located to the northeast of the anticyclonic eddy. Interactions between the LC and the LC eddy with the West Florida Shelf tended to promote anomalous upwelling on the shelf.

Question 3: What are their implications for transporting hydrocarbons discharged in the northern GOM? Whereas historically the LC may extend as far north as the northern GOM shelf slope, throughout the *Deepwater Horizon* event, the LC remained south of where the main body of surface oil was located. Thus, only a small portion of the surface oil was entrained into the LC system. The formation of a large anticyclonic LC eddy effectively broke the direct LC connection between the northern GOM and the Florida Straits thereby helping to retain most of the surface oil in the north. Eddy shedding is a regular feature of the LC's cycle of northward penetration and subsequent retreat back to the south, which occurs over intervals of roughly every 6–17 months [e.g., *Sturges and Leben*, 2000]. Examination of the historical satellite altimetry record shows that more times than not, a shed LC eddy re-attaches with the parent LC, after which the LC may extend to the well site or even as far west of the longitude of Texas before it once again sheds an eddy and retreats back to the south [e.g., *Alvera-Azcárate et al.*, 2009]. Thus, the behavior of the LC during the *Deepwater Horizon* event may be considered as being more the exception than the rule.

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C. Hu, Y. Liu, and R. H. Weisberg, College of Marine Science, University of South Florida, St. Petersburg, FL 33701, USA. (yliu@marine.usf.edu)

C. Kovach, Florida Department of Environmental Protection, Temple Terrace, FL 33637, USA.

R. Riethmüller, Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, D-21502 Geesthacht, Germany.