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When Mother Nature Smiles – Multi-year Analysis of Currents at the Macondo Well Site

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Abstract

Contrary to popular belief, the *Deepwater Horizon* (*DWH*) blowout and oil spill could have been far more environmentally and economically catastrophic. Relatively benign metocean conditions persisted in the Gulf of Mexico during the spill response efforts at the Macondo site. Statistical evidence indicates that metocean conditions could have been far worse, making the response efforts significantly more challenging and the economical repercussions orders of magnitude greater. Analysis of historical data and statistical trends over the past 26 years enumerates 22 separate incursions of the Loop Current or Loop Current Eddy into northern Mississippi Canyon. Such conditions can vastly complicate the scale of response efforts. Here we are presenting the possible impacts of worst-case environmental scenarios on response efforts at the Macondo site and the potential repercussions of strong Loop Current events during the oil spill. This study will help outline effective metocean risk management strategies for deepwater operators to mitigate the effects of oil spills in the future.

Introduction

The activities of the offshore oil & gas industry in the Gulf of Mexico (GOM) have intensified and extended farther offshore in recent decades, creating new challenges for marine resource and environmental management. The occurrence of oil spills in such an environment is fundamentally a matter of probability. Although not the first, the *Deepwater Horizon* oil spill has proved to be the largest and most catastrophic in U.S. waters. The semi-submersible offshore drilling rig was operating in 1500m of water when it experienced a fatal explosion on 20 April 2010. The explosion resulted in the prolonged expulsion of oil from the sea floor and the broken riser before the well was finally capped on 15 July. Final estimates of the oil released into the water column range from 798,000 gallons/day (USGS, 2010) to 4 million gallons/day (BP maximum estimate, 20 June 2010). Early reports on 23 April indicated that the oil spill had already formed a surface slick 1.6 km wide by 8 km long. By 25 April aerial surveys reported sheen spreading over a surface area of 32 km² (NOAA 2010). Within two days, the edge of this slick approached within 40 km of coastal Louisiana. Response efforts to contain, collect, disperse, or burn the surface oil slick and landed oil fraction involved the efforts of some 48,000 people over the Gulf coast region, with the majority along the coastlines and shelf waters of Louisiana, Mississippi, and Alabama and the northwestern coast of Florida. Damage assessment and recovery effort continue to this day.

Efforts to coordinate and deploy assets for spill mitigation in an offshore shelf and deepwater environment are greatly impacted by oceanographic and meteorological processes at multiple scales. At basin scales, the ocean circulation in the GOM is dominated by the Loop Current. The Loop Current exhibits two remarkable processes that are extensively studied: the extensive northward migration into the northeastern GOM continental shelf and the associated shedding of mesoscale anticyclonic eddies. The Loop Current extends northward from the Yucatan Channel to variable latitude forming, at times, a direct connection to the Florida Straits. At other times, it extends well north over the upper continental slope and the Texas-Louisiana shelf-break before retroflecting to the southeast and exiting the Gulf through the Florida Straits. Large warm-core eddies episodically separate from the Loop Current at intervals from 3-18 months (Forristall, et al., 1992, Leben et al., 2005, Sturges et al., 2005). Although mainly confined to the upper 1000 m, the Loop Current (LC) and the Loop Current Eddies (LCE) exhibit velocity surface currents in excess of 2 m/s (3.75 knots). Over the northeastern GOM continental shelf in water depth < 500 m, the circulation is complex, comprised of currents driven by wind and buoyancy forcing from large volumes of freshwater and the amplified tidal currents found over the inner shelf (Walker, 1996). Where the shelf break merges into the upper northern GOM (NGOM) slope, the increasing influence of the Loop Current and its energetic eddies lead to a highly dynamic current regime that consists (at times) of many small eddies, both cyclonic and anticyclonic. The Loop Current or a LCE in close proximity to the NGOM slope region plays a significant role in driving circulation over the shelf rise and upper slope (Hamilton, 2000, Wang et al., 2003; Ohlmann, et al., 2001).

Monitoring oil dispersion and transport over the NGOM shelf and slope represents a significant challenge in this dynamic region. Given the Macondo well site location on the NGOM slope, a prolonged spill beyond several weeks elevated the threat of oil-entrainment into the Loop Current and subsequently extensive spreading to the interior Gulf, the West Florida Shelf, and the Straits of Florida. Analysis of historical data and statistical trends over the past 26 years enumerates 22 separate incursions of the Loop Current or LCE into northern Mississippi Canyon (MC). Such close proximity of the Loop Current to the MC252 spill site would have vastly increased the likelihood of offshore entrainment and complicated the scale of response efforts. Here we review the historical record of the Loop Current's impact in northern MC and the implications for past and future spill-response efforts over the NGOM slope.

Horizon Marine, Inc. (HMI), an operational oceanographic monitoring and forecasting company, has been actively monitoring the GOM circulation and reporting on the location, strength, and evolution of the Loop Current and associated eddies since 1984. In this paper we review archived historical data to ascertain the prevailing metocean conditions typically encountered in northern MC and the MC252 lease block. A comprehensive analysis of all the meteorological and oceanographic data available in public and private archives is beyond the scope of this paper. This discovery process aims to reveal how frequently the sites located on the upper NGOM slope have been directly impacted by either a major invasion of the Loop Current or a LCE. This paper highlights the energetic and rapidly changing nature of circulation within the deepwater oil and gas producing regions.

Data Sources and Validation Methodology

The supporting data are acquired from remote sensing satellites, vessels observations, meteorological data, and a network of satellite-tracked drifting buoys and point current meters. Over 2700 Far Horizon Drifters (FHD) drifters have been air deployed from fixed-wing aircraft into the GOM over the past 26 years as part of a Loop Current monitoring program. The primary source of data regarding currents is a low-cost, air-deployable drifting buoy that was first deployed in 1984. Each drifter is equipped with a GPS receiver that produces a position retrieval every hour and a typical lifetime ranging from 120-180 days. Drogued to remain with the current and having negligible windage, the drifter yields valuable information on Loop Current frontal location and the evolution and propagation of LCEs. Remotely sensed data include satellite sea surface temperature (SST) images, sea surface height (SSH) altimetry, Airborne eXpendable BathyThermographs (AXBTs), MODIS ocean color images, Acoustic Doppler Current Profiler (ADCP) measurements from platforms and survey vessels, and water property profile data from autonomous gliders. These data are used to identify and analyze the strength of both the Loop Current and its eddies. Over the 26-year history of the program, advances in remote sensing, geographic information systems, and satellite telemetry have been regularly incorporated into the analysis. The collected data and reports produced during this period result from one of the longest continuing surveillance efforts in modern oceanography.

Historical LC Impact on Upper NGOM Slope

Eddy/Loop Incursions to MC252

We examined the complete archives of Eddy Watch charts from 1984 to 2010 for instances where the frontal signature of the Loop Current was located within the boundaries of northern MC. Several thousand Eddy Watch charts were available for this study. The central chart feature is a line delineating the Loop Current front. Over the years the chart format varied in geographic extent, as did the line styles and markers used to locate and label the oceanographic information. The frontal position is located by a blend of available data but is heavily weighted by surface data. Previous studies have shown that the main body of the Loop Current is generally correlated with the surface front location. For example, when the Loop Current approaches the NGOM slope, the isotherms defining the warm Loop Current waters curve gradually seaward with depth such that the subsurface frontal boundary at 200 m may be found some distance seaward of the surface front. The positional difference in the surface and subsurface frontal positions can approach 15-25 km (Oey et al., 2005). This positional uncertainty must be accepted given the available data at the time.

Figures 1 and **2** are two charts showing the configuration of the "mature" phase of the Loop Current and a LCE, respectively. In the first chart (**Figure 1**), the Loop Current was delineated as a continuous feature extending well northward in eastern MC in July 1989. The Loop Current shed Nelson Eddy in February 1998 but reconnected and remained intact until late August 1989 (by convention the eddy retains its name throughout the period of reconnection). The northern front of Loop Current/Nelson Eddy extended to 29°20' N into the Destin Dome lease area. Drifter currents circulating around the eddy exceeded 2 knots throughout July-August 1989. In the second chart, the frontal boundary outlines both the Loop Current and the closed anticyclonically rotating eddy (Eddy Zapp) in April 1995. The center of the Eddy Zapp was situated in Atwater Valley and the eddy peripheries extended well into Green Canyon (GC) and as far north as 28°36'N in MC. Ancillary information collected from research vessels and drifters routinely indicated maximum currents along the northern front in excess of 2 knots. A maximum current of 3.2 knots was measured during a survey of this front.

In **Table 1** we list the 22 similar events found in Eddy Watch charts where the frontal boundary of a mature Loop Current or a LCE occupied MC. These events were qualitatively classified as "major" or "minor" according to the magnitude of the currents observed along the northern boundary, the duration of the occupation, or the eddy size identified by surveillance. Major events, often the result of longer duration occupations by the Loop Current and/or a LCE also reflect the size of an eddy or the large circumference of the Loop Current at the time. Unnamed eddies are quite common on the upper NGOM slope and in DeSoto Canyon (DC) (Hamilton, 2000, Ohlman et al., 2001). A review of the charts and data records shows that even the minor Loop Current events in **Table 1** were often accompanied by currents over 2 knots reported by a single drifter or a ship of opportunity. Taking into account both major and minor events implies that MC is occupied by either the Loop Current or a LCE once every 1.2 years. This implies a return period of slightly more than once each year. The Loop Current eddy shedding interval is irregular but lies in the range of 6-11 months (Sturges and Leban, 2000, Leben et al., 2005). The Loop Current itself, however, may surge northward and into MC prior to completing the eddy shedding process.

Table 1. Loop Current and LCE Events in northern MC from1984 to 2010.

Year	***Eddy or Loop Current Event***	***Impact***
2007	Zorro/Loop Current	major
2005	Vortex	
2004	Ulysses	
2003	Sargassum	
2001	Odessa	minor
2000	Lazy	minor
1999	Juggernaut	
1999	Unnamed WE	minor
1998	Gyre	
1997	Deviant	minor
1996	Unnamed WE	minor
1995	Unnamed WE	minor
1995	Zapp	major
1994	Yucatan	
1993	Loop Current	
1993	Vagabond	
1992	Unnamed WE	minor
1990	Loop Current	
1989	Nelson	
1987	Little Jupiter	minor
1985	Elusive	minor
1984	Unnamed WE	minor
TOTAL:	22 events	

Northward surges of the Loop Current have taken it close to the Mississippi Delta (Vukovich et al., 1979) as well as into deep canyons east and west of the delta (Huh and Schaudt, 1990). One prime example was the prolonged invasion of the Loop Current in 2007 prior to the complete shedding of Eddy Zorro.

Eddy Zorro was formed in early 2007, but the period of its complete detachment from the Loop Current was short lived. The eddy separated and reattached to the Loop three times over a period of nearly four months. It was also the only major eddy known to be totally re-absorbed by the Loop Current (**Figure 3**). In March of 2007, the LC/LCE advanced rapidly north across active lease blocks at a rate of 94 nmi in only three weeks, or nearly 4.5 nmi/day. This rate is nearly triple the typical progression rate of eddies observed over the past several decades. The coupled LC/LCE also extended farther north than any previously observed eddy, ultimately impacting shallow shelf operations in South Pass (SP) off the Mississippi Delta. The LCE (Eddy Zorro) exhibited maximum currents as high as 4.3 knots even after separating from the Loop Current. While approaching its maximum northward extension, 2 knot currents were reported on 02 June in shallow shelf water in the SP lease area. The LC/LCE continued to push north and, by 11 June, reached 29°37'N. The LC/LCE remained north of 29°00'N for 10 days until 14 June when it retreated south out of Viosca Knoll (VK). The Loop Current front was last placed in northern MC on 28 August 2007.

Drifter Observations

From 1985 until 2002 standard Argos positioning was used to track Horizon's FHDs. The Argos positioning in the GOM often had gaps for 8 to 10 hours between groups of position retrievals. In 2002 the FHD transmitters were upgraded and a GPS receiver was installed. This upgrade allowed for GPS position retrievals every hour. On average each buoy returns approximately 20 positions per day. Over 2700 drifters have been air deployed into the GOM. The 26 year record of drifter data is weighted toward the last 15 years as more drifters were utilized for surveillance. The expanding program enabled increased spatial/temporal sampling over the entire GOM. The retrieved data are interpolated to every two hours prior to analysis, and simple first differencing is used to calculate velocity. Thus, drifters provide an efficient an accurate way of capturing synoptic-scale currents in the GOM. Certain unavoidable sampling biases should be noted. Drifters deployed into a frontal region may not experience the maximum existing current because of horizontal (or vertical) displacement from the main core of the stream. Secondly, drifters expelled from a Loop Current or LCE frontal region are seldom replaced immediately.

The archive of drifter trajectories is used to investigate the spatial distribution of currents associated with advance and retreat of the Loop Current and LCEs into the GOM. The steady influence of the Loop Current variability on currents located throughout the northern GOM slope region can be seen in the percentage of time that sites experience surface currents in excess of 1 knot (**Figure 4**). Highest percentages (>60%) are found east of 87°00' W and south of 26°00' N. This region is often occupied by the Loop Current and LCEs. The lowest percentages are found over the shelf and slope in the northwestern GOM and the Texas-Louisiana shelf. There is a greater than 20% chance that drifters passing through northern MC traveled at speeds in excess of 1 knot.

The maximum speeds observed by drifters were calculated on a 0.1° by 0.1° grid located throughout the GOM north of 22°00' N. The largest drifter speeds are associated with the strongest currents located within the peripheral fronts of the Loop Current and LCEs, although the drifter may not be anchored within the strongest currents found across the frontal region. It must be cautioned that despite the large number of drifters circulating in the GOM over 26 years, the records of drifter speed are irregularly distributed in time and space. The resulting map of maximum surface current shown in **Figure 5a** shows an extensive area stretching broadly from 23°00' N to 28°30' N and from 93°00' W to 84°00' W where currents in excess of 2.5 knots have been recorded. Many locations over the NGOM slope, including all the other lease areas, have experienced currents approaching 2 knots at least once in the last 26 years. This expanded area can be considered the Loop Current and LCE "zone of influence". On average, the centers of circulating LCEs travel generally west-southwest after separating from the Loop Current (Forristall, et al., 2010). We have observed several instances where eddies exhibited large radial extents or followed a curvilinear path that resulted in their peripheries extending well to the northwest and over the slope. The MC252 site, located just north of 28°48' N, has clearly experienced strong currents in excess of 3 knots at least once (**Figure 5b**).

Elevated drifter speeds in northern MC and near MC252 are most often, but not always, associated with the close proximity of the Loop Current or a LCE. As a measure of the frontal proximity, we use the minimum linear distance from MC252 to either a LCE or Loop Current front. This metric is readily calculated from the Eddy Watch charts which have been available in digital form since 2007. We then plot the maximum daily drifter current observed near MC252 as a function of the distance from the site location to the front (**Figure 6**). This reveals several interesting features. When the Loop Current or LCE front is located in excess of >175 nmi distant currents are generally <1 knot. This statistic likely includes a measurement bias since drifters are less frequently placed in the northern MC when the Loop Current is located south of 26° 00' N in its "young" phase. At the other extreme, when the Loop Current or a LCE has moved into northern MC and is within 25 nmi of MC252, the drifter currents will often approach or exceed 2+ knots. This peak is associated with Eddy Zorro's prolonged impact throughout northern MC in 2007. Lying between the two extremes of frontal range are several episodes where currents exceed 1.5 knots while the nearest front is located between 25 to 150 nmi. Of these three episodes, one is clearly ascribed to the passage of Hurricane Gustav in September 2008 while the second is associated with the nearby presence of Eddy Darwin in January-February 2009. The source of elevated drifter currents (>2+ knots observed during June-July 2010) is unclear and may reflect vigorous but poorly resolved mesoscale circulation on the NGOM slope (Hamilton, 2000).

Tropical Storms Within 100 nmi of MC252

The National Hurricane Center (NHC) maintains a record of all Atlantic tropical cyclones since 1851. Storm tracks were obtained from NOAA's National Hurricane Center's "Extended Best Track" file from 1985-2010. There are a total of 127 tropical storms and hurricanes with storm-center trajectories passing through the greater GOM region. Storms generally pass through the GOM within a few days' time. We have identified a total of 23 storms passing within 100 nmi of the MC252 site. Storm trajectories are shown in **Figure 7.**

Table 2. Tropical storms and hurricanes within 100 nmi of MC252 from 1985-2010. Columns contain storm metrics recorded within the 100 nmi radius including maximum wind speed, minimum central pressure, radius of maximum wind speed, hurricane category, and the minimum distance of the central low.

Name	*Date*	*Year*	*MaxWind (knots)*	*MinPress (mb)*	*RadiusMax (nmi)*	*Category (at MC252)*	*MinRange (nmi)*
ELENA	9/02	1985	105	957	-99	3	75
JUAN	10/31	1985	60	978	-99		52
BERYL	8/09	1988	45	1001	-99		52
FLORENCE	9/10	1988	70	983	-99		50
ANDREW	8/25	1992	125	941	15	4	86
ALBERTO	7/03	1994	50	997	25		83
BERYL	8/14	1994	25	1012	50		62
OPAL	10/04	1995	130	919	25	4	39
DANNY	7/19	1997	70	984	15		64
EARL	9/03	1998	80	985	50	1	25
GEORGES	9/28	1998	95	961	30	2	5
HELENE	9/22	2000	60	996	30		65
BERTHA	8/05	2002	35	1008	35		18
HANNA	9/14	2002	50	1001	90		39
HENRI	9/04	2003	25	1009	50		69
BONNIE	8/12	2004	45	1008	25		64
IVAN	9/16	2004	110	931	20	3	13
ARLENE	6/11	2005	55	990	50		63
KATRINA	8/29	2005	125	913	20	4	73
EDOUARD	8/04	2008	45	1002	20		39
GUSTAV	9/01	2008	95	954	25	2	60
IDA	11/09	2009	60	991			21
BONNIE	7/24	2010	25	1011			43

Eight hurricanes have passed within 100 nmi of MC252. Five of these storms were classified as Category 3 or higher, exhibiting central air pressures below 965 mb and wind speeds above 95 knots. There have been 8 years since 1985 when two major storms impacted the site, often within a one-month period and most often during August and September. Two hurricanes occurred within a one month period in 1998 - Hurricane Earl and Hurricane Georges (category 1 and 2, respectively). Several of these major storms would be categorized as direct strikes where the central low passed within 25 nmi of MC252 (Earl 1998, Georges 1998, Ivan 2004).

Hurricanes with trajectories outside the 25 nmi range can still generate significantly strong surface currents in the northern MC region. Hurricane Katrina passed through the GOM in August 2005 and encountered the Loop Current, Eddy Walker, and Eddy Vortex. Hurricane Katrina ranks as the sixth most intense Atlantic hurricane and among the most intense category 5 hurricane observed in the GOM with a minimum pressure of 902 mbar and maximum sustained winds of 78 m/s (~175 mph). Katrina weakened as it crossed the tip of Florida then intensified rapidly over the Loop Current. At this time the Loop Current was extended very far north and west into the Gulf just prior to shedding a Loop Current eddy (Eddy Vortex). Model simulations have shown that the strongest hurricane-induced currents were located to the right of Katrina's track. The strongest total currents (hurricane and Loop/eddy) were along the eastern limb of the anticyclonic eddy-shaped Loop Current (prior to shedding Eddy Vortex) and also along the eastern edge of the main southward flowing Loop Current (Frolov, 2010). The absolute maximum current reaches 2.56 m/s (~5 knots) in the northern part of the eddy. A more typical maximum current seen along the majority of the main front is 2.2 m/s. No drifters were located within northern MC near site MC252, but a drifter located to the north in South Pass reported currents in excess of 2 knots during the storm (**Figure 8**).

The Events of 2010

The events of April-August 2010 highlight the impact of large-scale, deep ocean circulation on the NGOM slope. Given the location of the Macondo well site, a prolonged spill beyond several weeks elevated the threat of oil entrainment into the Loop Current and subsequent extensive spreading to the interior Gulf, the West Florida Shelf, and the Straits of Florida. Satellite observations indicated offshore extension of the oil patch in two separate episodes in May and June. Direct observations confirm the episodic existence of export pathways between the main spill site and distant regions of the GOM. Drifter trajectories indicate that significant portions of the transport can occur as cross-slope fluxes in both the on- and off-slope direction.

FHD #2521was deployed on 22 April south of the Macondo site (**Figure 9**). The Loop Current was in a mature phase at the time, having pushed north into the Gulf over the NGOM slope (north of 27°30'N). To the south and west of the Mississippi Delta region, a weak anticyclonic eddy (ACE) was present, possibly a result of a recent peak in freshwater influx from the Mississippi River that peaks in mid April (Walker, et al., 1996). A large, cyclonic frontal eddy (CE) was present just north of the main Loop Current front, following the merger of two smaller cyclones during early May. The counterclockwise circulation associated with this large cyclone, together with the anticyclonic flow in the ACE to the west, created a mechanism of counter-rotating vortices that accelerated flow to the southeast. Drifter #2521 was dragged into this flow and became entrained along the northern edge of the Loop Current on 16 May. Velocities >1.0 ms^{-1} were sustained from 18 to 21 May as the drifter was dragged into the strong current and then recirculated around the large CE to the north of the front. Satellite-derived maps of surface oil distribution from NOAA NESDIS indicated the progressive entrainment of surface oil in the same direction over similar time scales.

A second event in mid June suggested that entrainment and cross-shelf transport pathways from the well site were reestablished episodically. The offshore circulation was again dominated by the influence of closely spaced counter-rotating mesoscale eddies: the anticyclonic Loop Current eddy centered at 25°10.2'N, 86°55.2'W and a large elliptical CE to the southeast centered at 26°45'N, 85°55.8'W over the lower slope of the West Florida Shelf. A group of drifters deployed on 13 June directly south of the Macondo site and near high concentrations of surface oil indicated by NOAA NESDIS maps (**Figure 10**) were eventually entrained by currents arising from the nearby eddies by 19 June. Although these drifters were deployed within several hours of one another, the spatial variation in flow caused drifters to separate at ~10 km/day, leading to the dispersion of the drifter group as they entered the high velocity region. The region of strongest surface velocity (and velocity gradient) was at the confluence of the two eddies. Drifters #2562 and #2564 accelerated to >1 ms^{-1} in the juncture region as early as 20 June. Drifter #2561 entered the same region (speeds >1 ms^{-1}) a day later on 22 June while drifter #2565 lagged behind and transited the region on 25 June. The drifters passed one after the other between the two eddies over a 5-day period, their trajectories funneled through a narrow region <19 km wide near 26°18'N, 86°42'W. After leaving this narrow confluence, three drifters experienced a general counterclockwise motion around the CE to the north and, by 21 July, were distributed north of 27°30'N and west of 86°00'W. Drifter #2561, on the other hand, entered the confluence region a day behind the first two drifters, but three days ahead of the last drifter, and was expelled to the east over the West Florida Shelf and drifted slowly south until it became entrained by the Loop Current and exited the Gulf by 14 July.

Several hundred drifting buoys were deployed between April and August to track oil and circulation patterns. **Figure 11** illustrates the trajectories of a subset of drifters passing within 60 nmi of the Macondo spill site (1° in latitude). Two features are notable in this diagram. First, numerous trajectories include episodes of both along slope and cross-slope movement. Several drifters deployed over the NGOM slope were entrained into the deepwater eddy field and subsequently expelled and moved back onto the shelf. Likewise, drifters deployed into the eddy field moved up slope and into waters <500 m deep. Lastly, several drifters entrained off the slope and into the convoluted eddy and then back on the shelf completed their excursions in less time than drifters arriving at similar locations by along-slope advection.

Discussion

A comprehensive study of all available oceanographic and meteorological data collected in the vicinity of all the NGOM lease areas is beyond the scope of this paper. This effort is limited mainly to records available in Horizon Marine's archive collected over 26 years of continuing surveillance of the GOM circulation. The focus of this study has been further narrowed to the general area of northern MC and, more specifically, to the MC252 lease block. In reviewing even these limited data, the routine impact of Loop Current dynamics on circulation over the NGOM slope and cross-slope advection of material becomes clear.

We have identified 22 events within a 26-year span in which the charted location of the Loop Current or LCE places the leading fronts of these features within northern MC. A portion of these events are relegated to minor status because of limited duration, or the currents reported by drifting buoys or other in-situ data were not considered especially remarkable at the time. Many so-called minor events reflect the influence of mesoscale eddy activity on the upper NGOM slope which remains poorly resolved and difficult to predict even today. Eddy Zorro, a major LCE and a prime example of prolonged impact, was situated within northern MC from 09 May to 28 Aug 2007, or upward of 111 days. Over the last several decades, there are few years in which northern MC has escaped the influence or direct impact of the Loop Current cycle of invasion and eddy shedding.

Strategic and tactical drifter deployments from 1985 to the present day provide a valuable source of information on Lagrangian circulation patterns. The surface currents obtained over 26 years (heavily weighted toward the last 15 years) indicate that very little of the deepwater lease areas on the NGOM slope have escaped the impact of strong currents approaching 2 knots. There is literally “no place to hide” from currents of this strength, given sufficient time for nature to run its course. Elevated surface currents are often, but not exclusively, associated with the Loop Current or LCEs. Fronts within <25 nmi of any site vastly increase the likelihood that currents will soon be in excess of 2 knots, if not more. Hurricane impacts also remain a recognizable threat due to their rapid translation speeds. There are many instances, however, where drifter currents in northern MC exceeding 2 knots are ambiguously associated with mesoscale circulation feature or shelf flow.

In light of these findings, one might argue that the recent 2010 metocean conditions encountered on the upper NGOM slope were benign relative to most years.

- The maximum latitude of the Loop Current was 28°13.8’N achieved on 14 May 2010. This, however, was located far to the east of the site and thus not considered a threat.
- A persistent CE was located along the northeast edge of the Loop Current and acted to forestall Loop Current rotation and incursion up the NGOM slope. (This feature also formed an extensive area of combined flow between counter-rotating eddies).
- Currents in excess of 1.5 knots were virtually absent near MC252 and nearby mobile offshore drilling units equipped with sensors.
- The upper slope circulation appeared to consist mainly of weak mesoscale eddies at the head of DeSoto Canyon and along-shelf flows.
- No major hurricanes passed near MC252 (except for 1 weak tropical storm).

Acquiring rapid, accurate, and usably synoptic maps of circulation is critical to forecasting oil movement, fate, and landfall. Drifter observations were crucial for validating satellite images showing connectivity between the shelf and the Loop Current (and associated eddies), for identifying zones of convergence, and revealing active transport pathways between the oil spill and other locations within the Gulf and beyond. In two separate episodes in May and June, drifter observations showed the extensive spreading and entrainment of surface oil into the Loop Current. We also observed evidence of active transport pathways between the main spill site and distant regions of the GOM. Although the entrainment of drifter #2561 into the Loop Current and its subsequent trajectory indicated an alarming potential for direct oil transport to the West Florida shelf, to our knowledge (with the exception of the extreme northwestern coast of Florida) oil slicks were never sighted on this part of the shelf.

Monitoring oil dispersion and transport throughout the shelf, slope, and deepwater regions of the GOM represents a significant challenge. The DWH oil spill remains unique because of the spill’s deepwater expulsion, prolonged duration and magnitude, its location on the continental slope, and the extensive impact on coastal and oceanic regions. As an added complication, the spill occurred in the part of the open ocean subjected to strong and highly variable currents capable of transporting oil to remote locations. Furthermore, dispersant applied to the oil resulted in large quantities of oil spreading throughout the mixed layer and within the water column. These observations illustrate the complexities associated with spill response planning in an environment where basin-scale circulation episodically exercises a strong influence on material transport and fate. Environmental resource locations closest to the spill sites have the greatest risk of contact. Material entrainment by active deepwater circulation features near the NGOM slope can vastly increase the geographic range of transport. With increased travel time, the complex patterns of wind and ocean currents produce multiple opportunities for a spill to make contact with any given environmental resource or shoreline segment. Under these conditions, the total length of coastline threatened by potential oil landfall increases dramatically.

Entrainment of oil off the slope and its subsequent dispersion over large areas may have positive impact as well. Off shelf transport leads to increased weathering and evaporation of surface oil in contact with warm tropical waters, thus decreasing the total volume of oil available to threaten sensitive marshes, bays, and other important habitats. However, as we have demonstrated here, the entrainment of material off one portion of the NGOM slope can also result in accelerated transport through the convoluted pathways threaded around the offshore mesoscale circulation to another, perhaps more ecologically or demographically sensitive, coastline.

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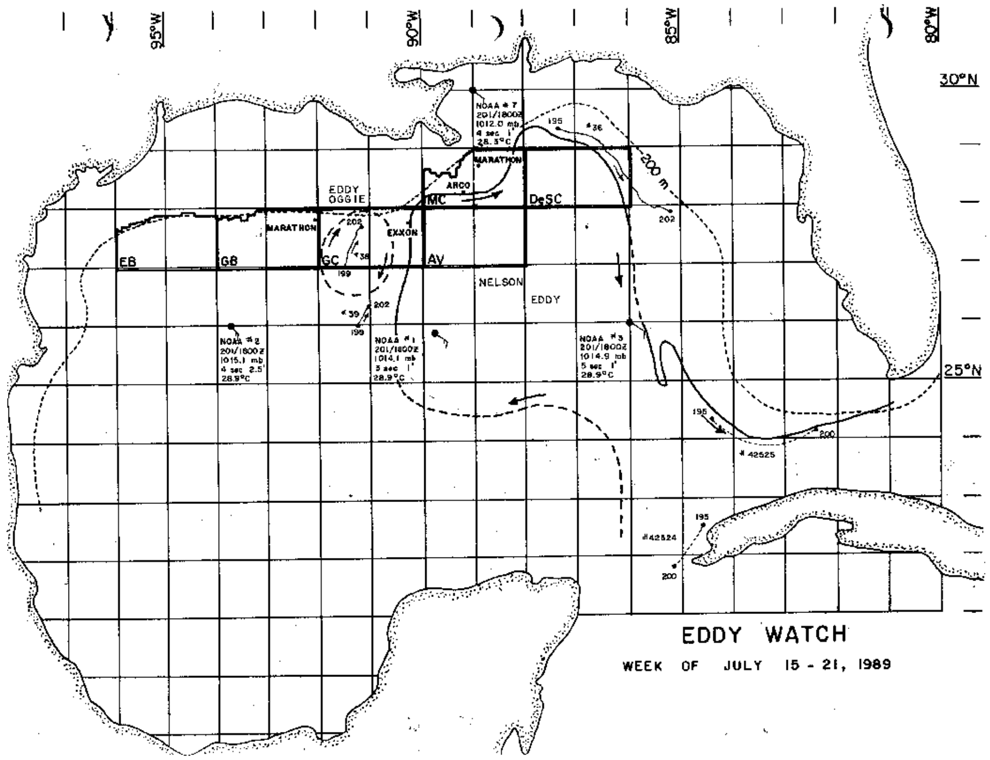

Figure 1. The mature phase of the Loop Current July 1989, prior to the separation of Nelson Eddy.

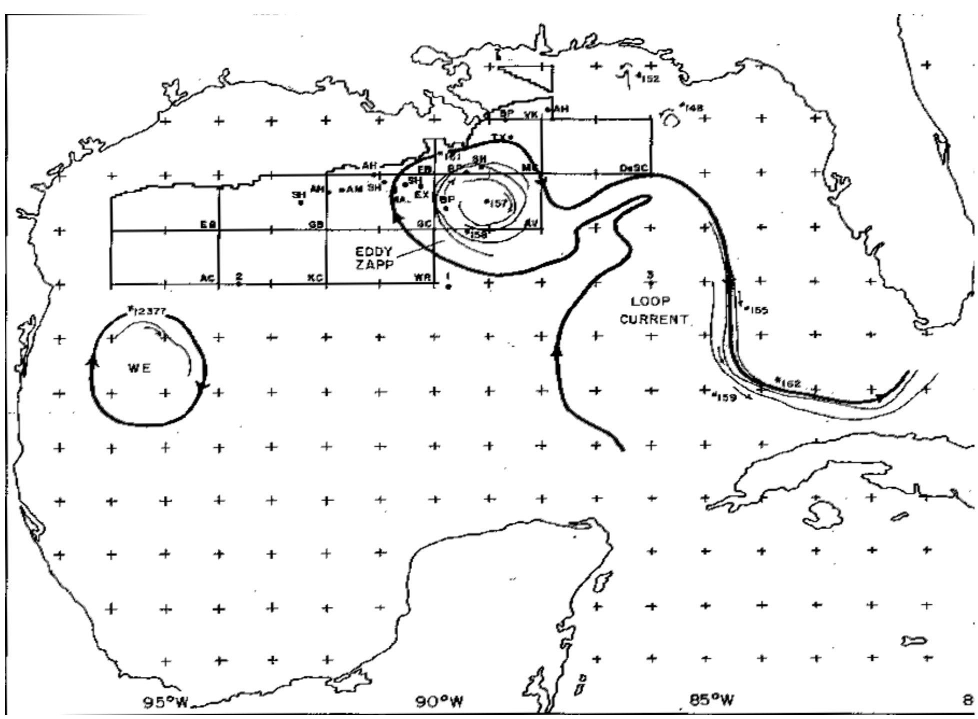

Figure 2. Occupation of MC by Eddy Zapp as depicted in the 28 April 1995 Eddy Watch chart.

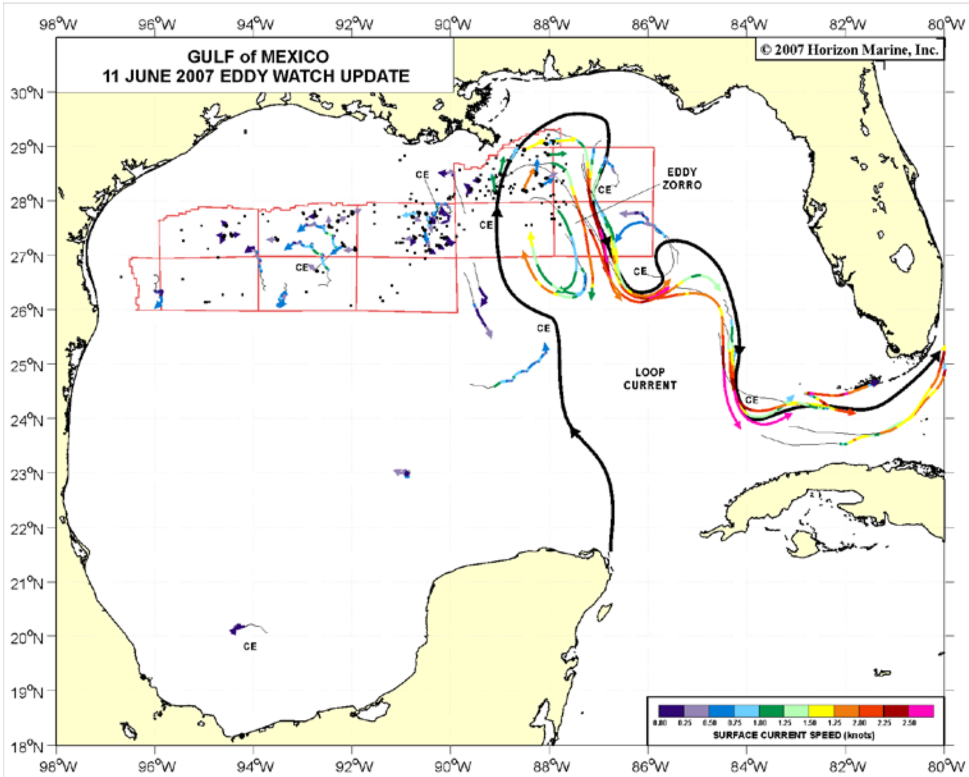

Figure 3. Incursion of the Loop Current and Eddy Zorro into the northern Gulf of Mexico as far as 29°37'N in 2007.

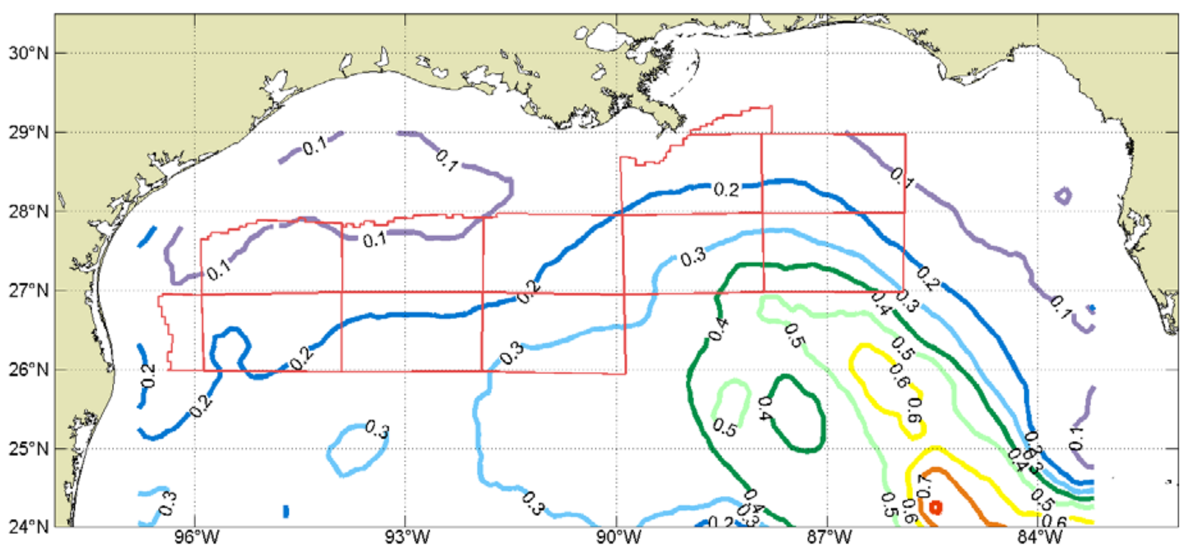

Figure 4. Percentage of time that drifters reported current speeds in excess of 1 knot 1985-2010.

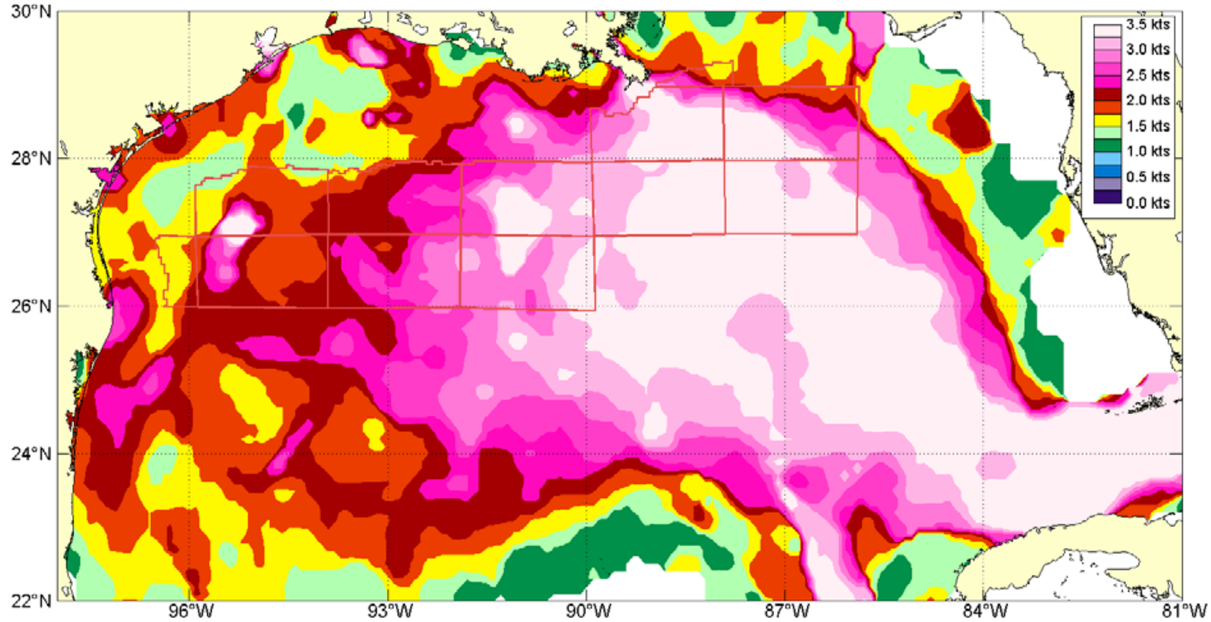

Figure 5a. Contours of the maximum current speed recorded in NGOM by >2,600 drifters deployed between 1985-2010.

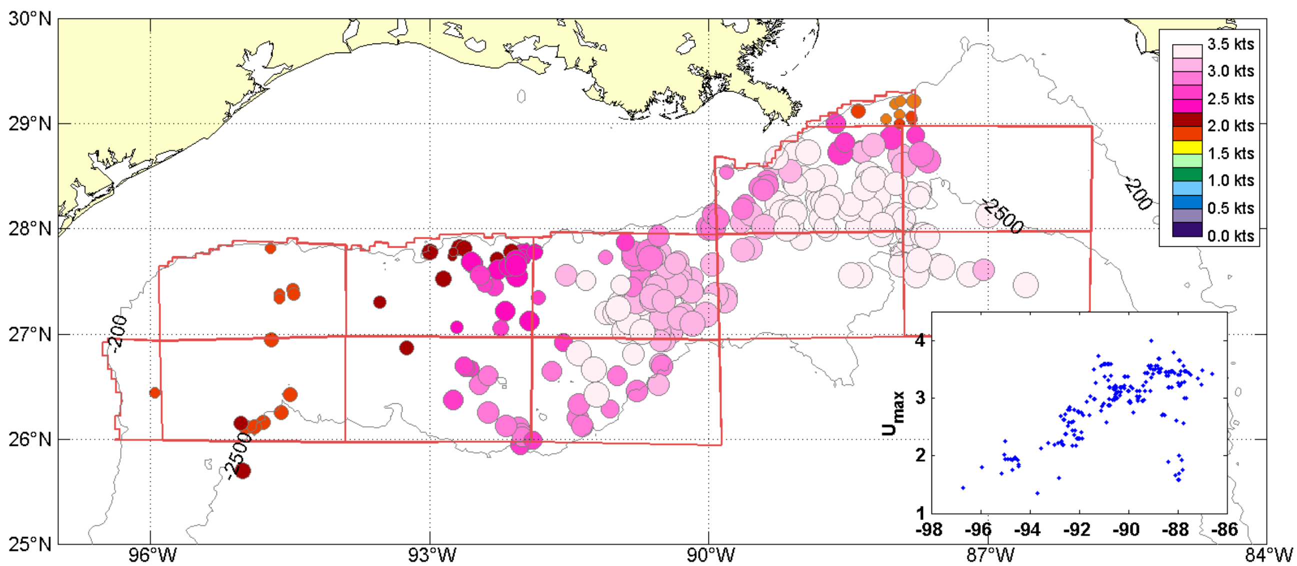

Figure 5b. Maximum historical current reported by drifters at active sites on the NGOM slope. Inset figure (lower right) shows the general dependence of maximum current speed on longitude.

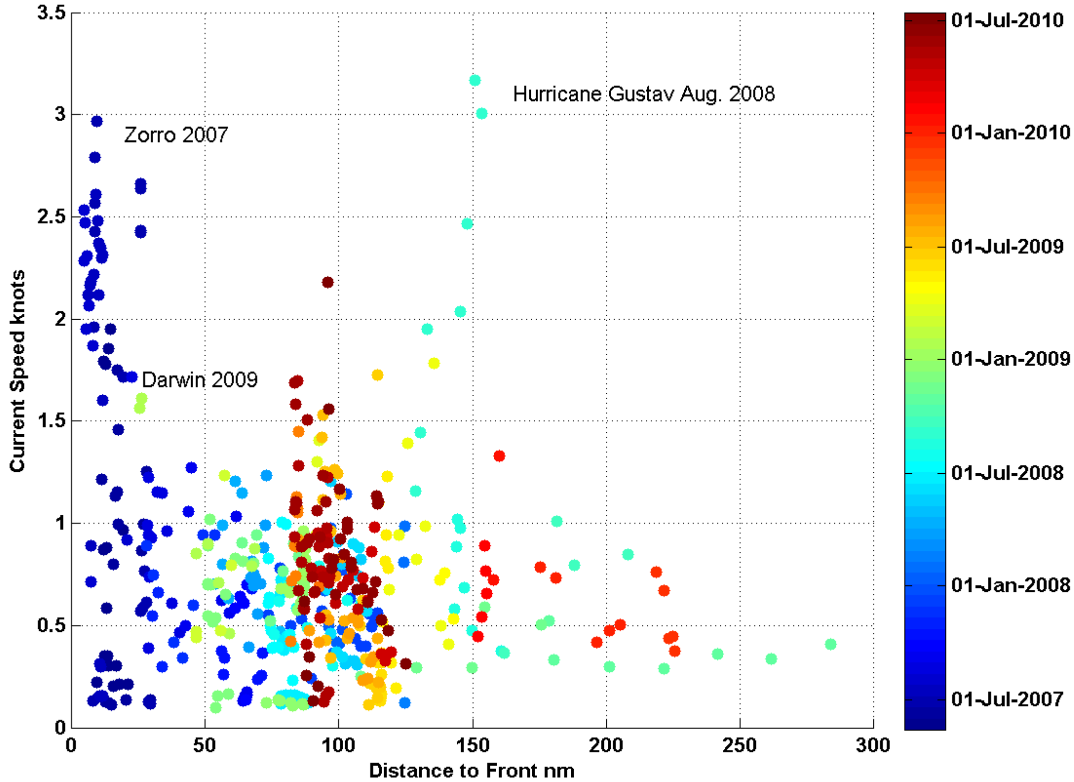

Figure 6. Drifter speed within 20 nmi of the DWH located in MC252 as a function of linear distance between the DWH site and the closest Loop Current or LCE front identified in Eddy Watch charts from 14 May 2007 to 14 July 2010. The color scale corresponds to the date.

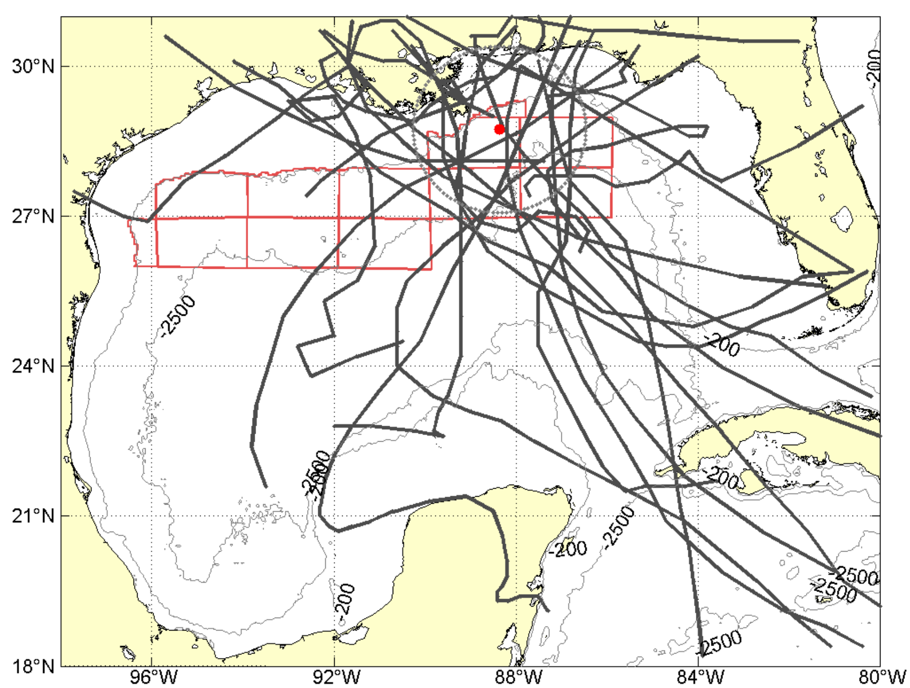

Figure 7. Trajectories of hurricanes and tropical storms from 1985-2010 passing within 100 nmi of the MC252 lease block. The red dot is the location of the Macondo well in MC252. The range ring diameter is 100 nmi.

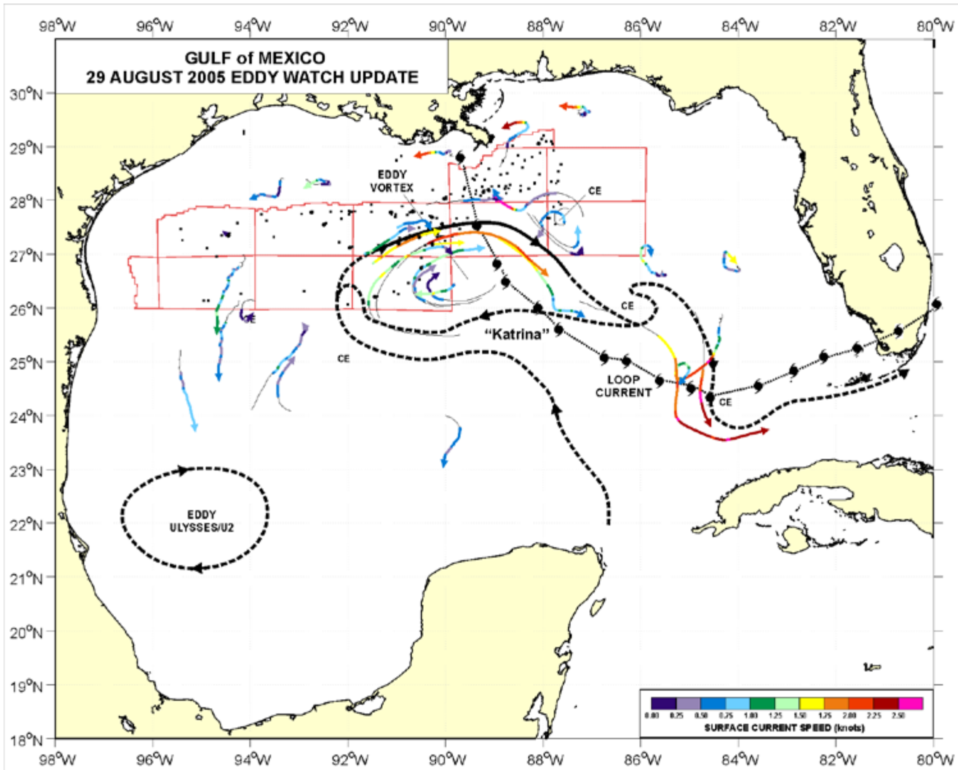

Figure 8. Track of Hurricane Katrina layered with the frontal analysis chart for 29 August 2005. Drifter trajectories are layered over the Loop Current and Loop Current eddy fronts. Drifter speeds are color-coded in knots. Note elevated currents (>2.0 knots) observed by a single drifter to the north of South Pass.

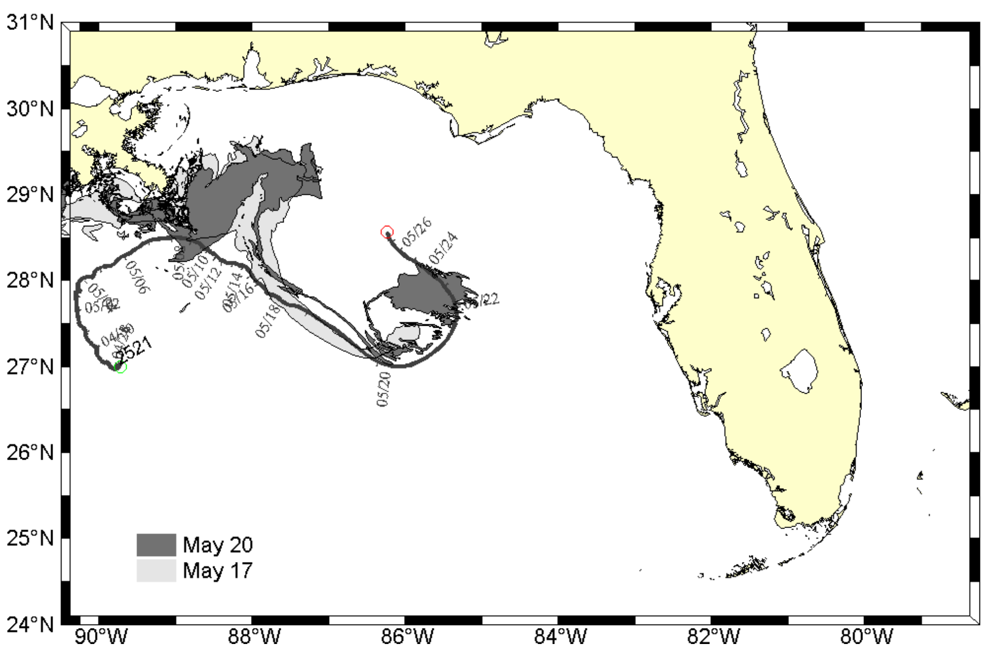

Figure 9. Trajectory of FHD #2521 overlaid on NOAA NESDIS oil distribution maps from 17 May and 20 May 2010. Green (red) circles indicate the start (end) of the drifter trajectory.

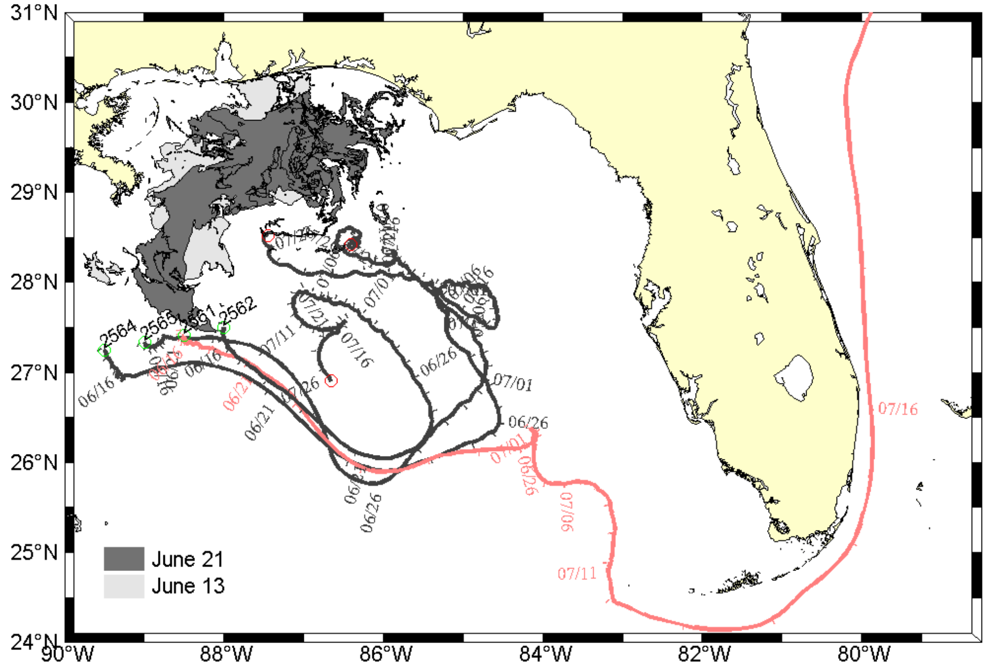

Figure 10. Trajectories of the drifter group #s 2561, 2562, 2564, and 2565 from 13 June 2010 overlaid on oil distribution maps from NOAA NESDIS for 13 June and 21 June. Green (red) circles indicate the start (end) of the drifter trajectories.

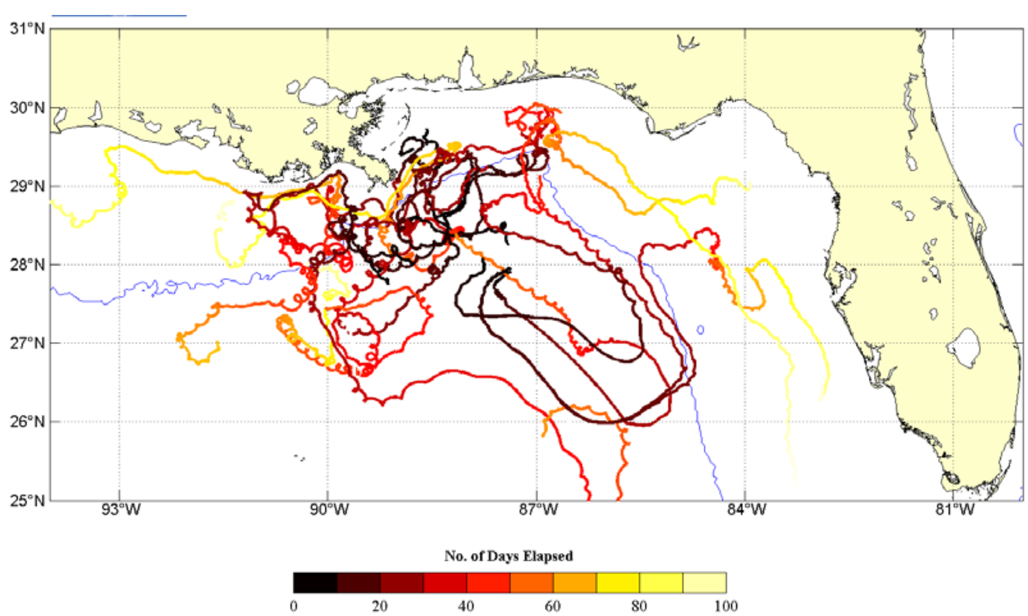

Figure 11. Selected drifter trajectories passing within 60 nmi of MC252 between April and August 2010. The color indicates cumulative travel time in days after leaving this range.