MEASURING OIL RESIDENCE TIME WITH GPS-DRIFTERS, SATELLITES, AND UNMMANED AERIAL SYSTEMS (UAS).

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Abstract

As oil production worldwide continues to increase, particularly in the Gulf of Mexico, marine oil spill preparedness relies on deeper understanding of surface oil spill transport science. This paper describes experiments carried out on a chronic release of crude oil and aims to understand the residence time of oil slicks using a combination of remote sensing platforms and GPS tracked drifters. From April 2017 to August 2018, we performed multiple synchronized deployments of drogued and un-drogued drifters to monitor the life time (residence time) of the surface oil slicks originated from the MC20 spill site, located close to the Mississippi Delta. The hydrodynamic design of the two types of drifters allowed us to compare their performance differences. We found the un-drogued drifter to be more appropriate to measure the speed of oil transport. Drifter deployments under various wind conditions show that stronger winds lead to reduce the length of the slick, presumably because of an increase in the evaporation rate and entrainment of oil in the water produced by wave action. We have calculated the residence time of oil slicks at MC20 site to be between 4 to 28 hours, with average wind amplitude between 3.8 to 8.8 m/s. These results demonstrate an inverse linear relationship between wind strength and residence time of the oil, and the average residence time of the oil from MC20 is 14.9 hours.

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1. Introduction

During an oil spill, one of the key response operations consists of monitoring the trajectory of floating oil and the projection of its possible pathways (*Street*, 2011). Particularly, when an oil spill occurs in close proximity to a shoreline, it is of major importance to evaluate the real-time and near-future conditions that may determine the oil spreading and pathways in order to plan and design the containment operations accordingly (*Owens*, 2000; *Nixon* 2016; *Garcia-Pineda et-al*, 2017). For this task, oil spill response operations rely largely on remote sensing and oil spill modeling that help identify the location, magnitude (and size), and possible fate of the spill. Information about the location and size of the spill in combination with meteorological and oceanographic data are then used to project and calculate not only the potential trajectories of the oil (*Hole et-al*, 2019), but also the estimated time that hydrocarbons would take to approach environmentally sensitive areas.

The trajectories of the floating oil are mainly dependent on two factors: *wind* and *surface currents* (*Röhrs* et al., 2012, *Walker et al., 2011*). The direction and magnitude of each one of these factors could have independent effects on the spreading of the floating oil. Oil spill trajectory models rely heavily on the analysis and forecasting of these two factors to determine the potential pathways of hydrocarbons (*Broström et al.*,2011, *Le Hénaff et al., 2012, Röhrs* et al., 2015). These models incorporate not only the oceanographic and meteorological conditions, but the specific composition and type of the oil that affect its evaporation and dispersion processes *(North et al., 2011)*.

The time it takes for the oil to be transported from a point A to a point B is based on the speed of the oil transport (driven by the combination of the wind and surface currents). However, the life time of the oil, which is the time that oil would last floating on the surface before getting evaporated or dispersed (also known as the residence time) has been studied on limited cases *(Reed et al 1994, Liu et al, 2013)*. This is an important factor because even when one can calculate the time that it would take oil to travel a given distance based on the meteorological and oceanographic prevailing conditions, we need to know if oil would actually last that much time at the surface after being exposed to multiple sea surface processes like emulsification, evaporation, oxidation, dissolution, and natural dispersion (entrainment) by breaking waves.

Studies on the residence time of an oil spill are difficult because they depend on the continuous observation of the oil horizontal displacement (*Reed et al.* 1994, *Liu et al.* 2013). These studies require controlled releases in the ocean which are difficult to be permitted for obvious environmental repercussions. In this study, we overcome these difficulties by using a recurring oil spill located at the MC20 lease block on the Gulf of Mexico (GoM), also known as the Taylor Energy Oil Spill (*Warren et al*., 2014). This spill site produces a chronic release of oil which is caused by the destruction of the production platform since Hurricane Ivan in 2004 (MacDonald et al., 2015). The vicinity of the site to the Mississippi Delta also introduces the effects of the river plume dynamics (river currents and associated density fronts), which control the region's local circulation patterns (*Schiller et al.*, 2011; *Androulidakis et al*., 2015) and moreover the oil pathways (*Kourafalou and Androulidakis,* 2013; *Androulidakis et al.,* 2018). From April 2017 to August 2018, we performed multiple synchronized deployments of GPS-tracked drifters in the vicinity of this site to study the life time of the oil slick produced by the Taylor Energy oil leak. These deployments were closely monitored by Unmanned Aerial Systems (UAS) and satellite observations. The objective of this study is to perform an analysis of the drifter trajectories monitored by a remote sensing multiplatform (aerial and satellite) to evaluate the residence time of the oil slick at this site.

1.1 Background

Oil spill monitoring with aerial and satellite remote sensing is a common practice (*Svejkovsky et al.*, 2012; *Leifer et al.*, 2012; *Garcia-Pineda et al.*, 2015). Remote sensing images capture the presence of floating oil on a snapshot basis, so that, when looking at any satellite or aerial imagery of the oil slick, two unanswered questions arise: 1) How long has that oil been there?, and 2) for how long will that floating oil last? Several studies aimed to understand the residence time (or life time) of the floating oil on the ocean surface using different modeling approaches (*Daneshgar et al.*, 2016; *MacDonald et al.*, 2015). One alternative way to measure the life time of the floating oil is to monitor its displacement as it is being transported by surface currents to see how long it lasts on the surface. In order to do this, we used drifters, which are GPS tracking devices developed specifically to track oil spills under the effects of winds and surface currents (*Reed et al.,* 1994; *Novelli et al.*, 2017). These instruments have been used in the past to understand the processes related to the transport of floating oil on the ocean. *Igor et al.* (2012) and *Rohrs et al.* (2012) used results obtained from in-situ observations and drifter deployments to improve the performance of oil transport models. *Jones et al.* (2016) reported how they used drifters to monitor and follow oil released on a controlled experiment in the North Sea. In other related studies, *Reed et al.* (1994) used drifter experiments to study the role of wind and emulsification in 3D oil spill modeling. P*ayne et al.,* (2007, 2008); and *French McCay et al.,* (2007, 2008) conducted a series of drifter/drogue/fluorescein dye dispersion experiments to calibrate an oil transport model by hindcasting advective drogue movement and dye dispersion under different environmental conditions.

In this study we used the MC20 site as a natural laboratory to understand the possible hydrocarbon pathways under different environmental conditions (Figure 1). The origin of the oil release on this site is situated on the seafloor at approximately 150m depth, therefore oil traveling through the water column and at the sea surface requires closely monitoring to understand the transport processes and its residence time. Initial results of this observational campaign were recently presented by *Androulidakis et al*. (2018), who reported the significant effects of river induced fronts on the transport of the floating oil detected at MC20 site[1]. These results highlighted the outstanding capability of the drifters to follow the oil pathways, and motivated us to use the same types of drifters to measure the residence time that floating oil could last on the surface; therefore, we complemented our drifter experiments with additional deployments, for a total of 6 drifter campaign experiments under different oceanographic and meteorological conditions using multiple drifters.

[1] see video https://www.youtube.com/watch?v=T6X2HAsYPu8

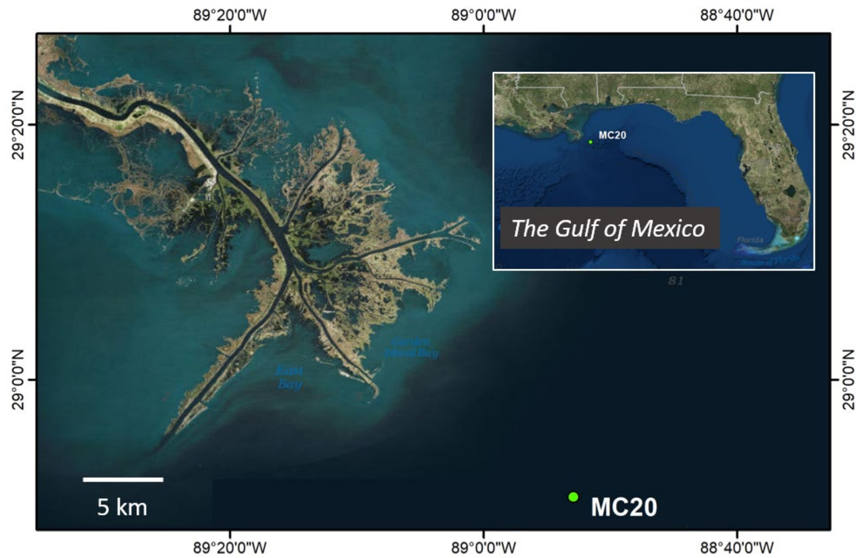


Figure 1. Study site MC20 (Taylor oil spill) located 20 km southeast from the tip of the Lousiana Peninsula. The release origin of the oil is situated on the seafloor at aproximately 450ft water depth.

2. Materials and Methods

In total, we deployed 16 GPS-tracked drifters from research vessels at the MC20 site study area (at 88.978ºW, 28.938ºN) on 6 different deployment dates (Table 1). The analysis of the oil life time is based on satellite imagery collections within the 6 campaigns. Drifter displacement was monitored by a real time UAS system that allowed us to observe the location of the drifters in reference to the oil slick. The multirotor UAS was equipped with high-resolution cameras that broadcasted the video signal in real time to a pilot's controller and to a screen mounted inside the monitoring vessel (Figure 2). This system allowed us to see the location and progression of displacement of the drifters and the vessel from an aerial perspective with reference to the oil slick.

Table 1. Array of drifters and satellite images used during the six deployment dates

Deployment Case	Drifter Type				Satellite/Aerial Images
	CARTHE (Un-drogued)	CARTHE (Drogued)	I-SPHERE MetOcean (Un-drogued)	CODE MetOcean (Drogued)	
18 to 20-Apr-17	2	2	1		RADARSAT-2,
25-Apr-17	1	1			RADARSAT-2, ASTER, WorldView-2,
26-Apr-17	1	1	1	1	TerraSAR-X,
16-Aug-17	1	1	1	2	CosmoSKY-MED, SENTINEL-1A, WorldView-2
29-Apr-18	1				LANDSAT-8, Sentinel-2A,
16-Aug-18	1				UAS

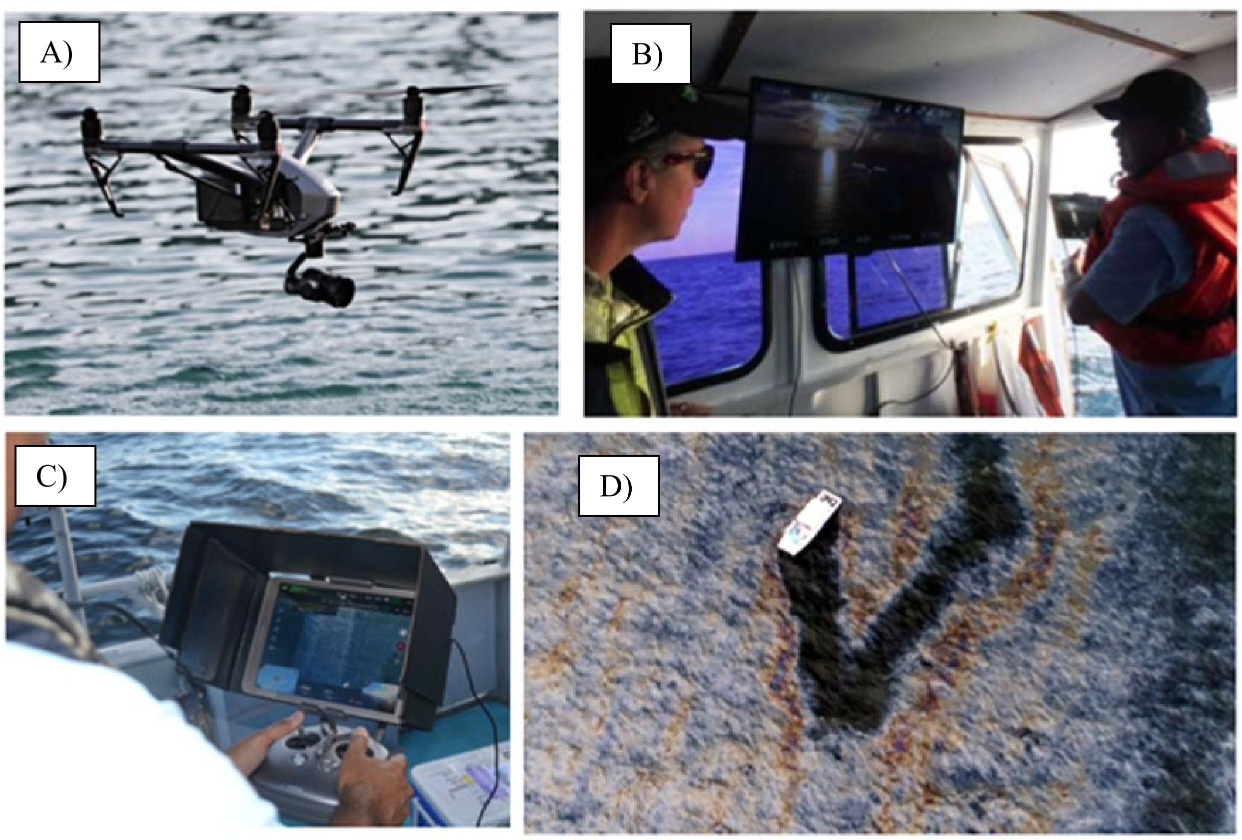


Figure 2. Multi-rotor UAS aircraft (A) was used to monitor the location of drifter from (B) inside and (C) outside the vessel in real time. (D) This system allowed us to see the location of the drifters and vessel within the oil slick.

Drifter deployments were planned in synchronization with multiple satellite collections. These planned satellite collections were acquired in coordination with MDA Corporation, National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA). Satellites tasked to image the area of the slick and drifter trajectories included Synthetic Aperture Radar (SAR) satellites (RADARSAT-2, TerraSAR-X, CosmoSKY-MED, and SENTINEL-1) and optical satellites (ASTER, WorldView2, SENTINEL-2, and MODIS). Prior knowledge of the satellite schedule was used to monitor the oil slick and the weather conditions before, during, and after all of the drifter deployments. Each of these satellites have different configurations and capabilities to detect oil under a wide range of conditions (*Garcia-Pineda et al.,* 2019), however during all 6 days of deployments the viewing conditions were optimal for the detection of the floating oil.

We employed un-drogued and drogued drifters in order to follow the surface oil pathways and distinguish it from possible subsurface (0.5 m below surface) material pathways (like oil droplets suspended in the upper mixed layer), respectively. By using these two types of drifters, we were able to examine the difference on the displacement of the drifters influenced by subsurface (drogued) and merely by surface (un-drogued) currents and winds.

2.1 Drifters types

For the un-drogued drifter, we used the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE; https://www.pacificgyre.com/carthe-drifter.aspx) drifter, which is a low cost, biodegradable instrument that tracks oil by transmitting its position every 5 minutes (Novelli et al., 2017). Figure 3A shows the CARTHE undrogued drifter being deployed by Yannis Androulidakis at the same time with a UAS flight over the slick source at MC20 site (6 drifters; Table 1). By adding 2 perpendicular panels attached by a small chain, this drifter can be then configured as a drogued drifter, as shown on Figure 3B (4 drifters; Table 1). These plates make the drifter respond to subsurface currents (approximately 0.5 meter below surface), in contrast to the undrogued drifter that is displaced by the surface currents, while also affected by direct wind effect. In addition, the un-drogued I-SPHERE drifter (Figure 3C) was also deployed at MC20 site on three different occasions (Table 1); this is an expendable, low cost, bi-directional spherical drifting buoy, provided by the Norwegian Meteorological Institute (https://www.metocean.com/product/isphere/). Besides the GPS positional data, the I-SPHERE drifter also provided real-time sea surface temperature. The CODE/DAVIS drifter is shown on Figure 3D as being deployed by Matthieu Le Hénaff (Figure 3E). This drifter is also provided by Met-Ocean (https://www.metocean.com/product/codedavis-drifter/). This instrument has been designed and tested to meet the performance criteria of the Coastal Ocean Dynamics Experiment (CODE) drifter developed by Dr. Russ Davis of Scripps Institution of Oceanography (SIO). We also used and deployed this drifter at the MC20 slick source site on three different occasions (Table 1). The CODE/DAVIS drifter is designed to measure coastal and estuarine water currents within a meter of the water surface, performing as a drogued drifter.

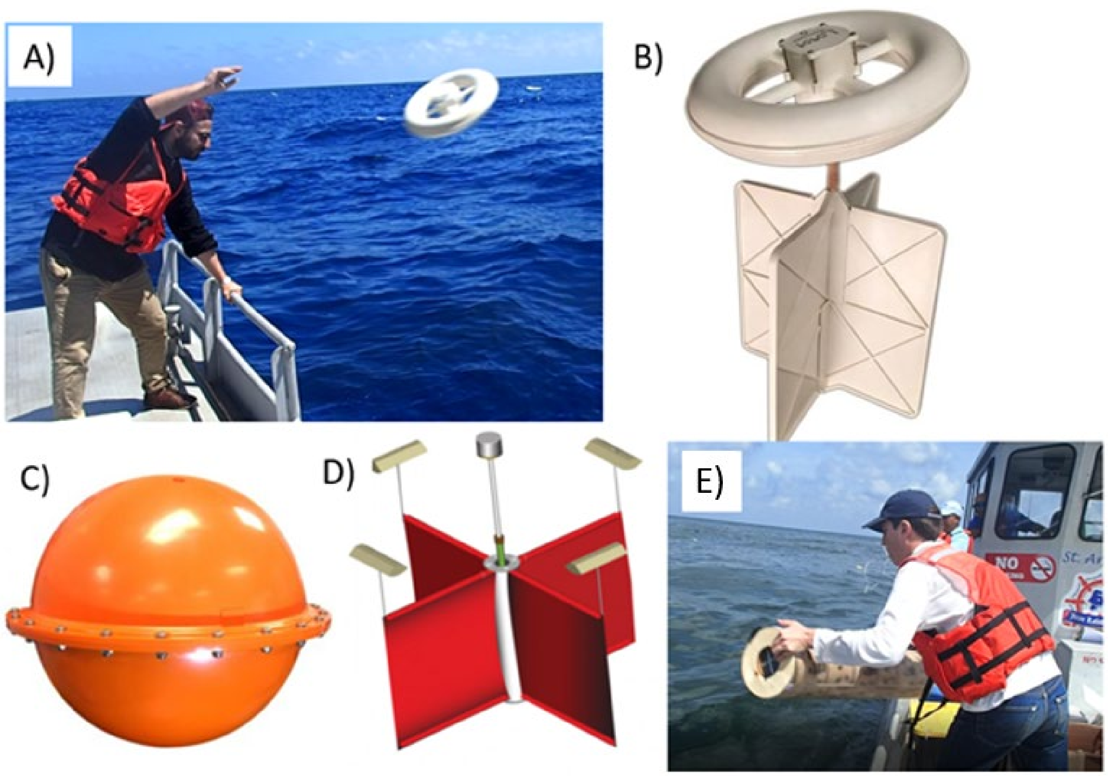


Figure 3 (A) Deployment of a CARTHE un-drogued drifter, (B) a CARTHE drogued drifter, (B) (C) an I-SPHERE drifter, (D) a CODE drifter and (E) deployment of a CODE drifter packed in a cardboard box.

2.2 Measuring Oil Residence Time with Drifters: Experiment design

The experiments consisted of deploying different types of drifters at approximately the same place and time. We used an UAS to position the boat right at the source of the oil slick (the location where oil reaches the surface also called Oil Slick Origin, or OSO) at MC20 and then we performed the deployments while the UAS monitored the position of the vessel, the drifters, and the floating oil (Figure 4). These deployments were scheduled to coincide with planned acquisitions of a variety of satellite images (Table 1). The objective was to track the drifters to measure how long it takes to be transported over the same distance as the oil slick length. We planned these missions at the MC20 site, monitoring forecast weather and ocean models that allowed us to capture the surface currents under different conditions, in particular the river plume extension. Drifters used in this experiment were left on the ocean with the objective of monitoring a multi-day drifting pattern and were not recovered (*Androulidakis et al*. 2018). Table 1 is a summary of days in which we analyzed the satellite images and the drifter trajectories used during this experiment.

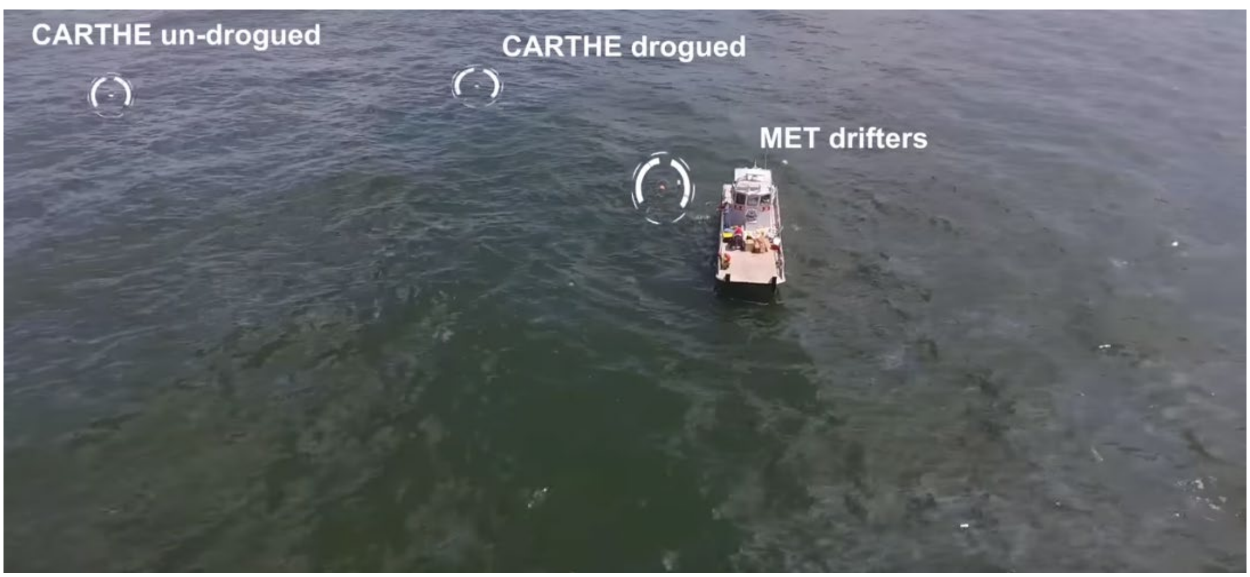


Figure 4. Aerial (UAS) view of oil, research vessel and drifters after being deployed right at the source of the MC20 site.

Androulidakis et al (2018) showed that the Mississippi river plume depth (around 5 m) is deeper than the drogue depth and, therefore, the drogued drifters are also influenced by the plume dynamics and the associated density fronts. It is important to point out that we use un-drogued drifters in this study for measuring the speed of the oil displacement, while drogued drifters are used to estimate how subsurface current differ from the surface ones. The hydrodynamic design of the un-drogued CARTHE drifter makes this type of drifter behave more appropriately to follow the oil speed, because the floating oil is only a thin layer of few micrometers suspended on the surface of ocean water. This drifter configuration is the 'thinnest' having the least drag and the smaller sail among the drifters we used.

2.3 Ocean and oil spill models

The 2017 simulation, used in the study, was based on the implementation of the Hybrid Coordinate Ocean Model (HYCOM) in the GoM with high horizontal resolution (1/50°, ~1.8 km), 32 hybrid vertical levels and data assimilation (GoM-HYCOM 1/50; Le Hénaff and Kourafalou, 2016). Information about HYCOM can be found in the model's manual (https://www.hycom.org/). This HYCOM implementation is forced by the 3-hourly winds, thermal forcing and precipitation on the spatial resolution of 0.125° produced by European Centre for Medium-Range Weather Forecasts (ECMWF; https://www.ecmwf.int/). The open boundary conditions are provided from the operational GLoBal HYCOM (GLB-HYCOM 1/12° resolution; Chassignet et al. 2009; https://www.nrl.navy.mil/). An important aspect of GoM-HYCOM 1/50 simulation is the special treatment for daily river discharges along the Gulf's coastline. The 2017 simulated archives employed here are part of a long-term simulation system that provides daily forecast ocean fields of the GoM in a weekly basis, operated by the Coastal and Shelf Modeling Group at the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami (http://coastalmodeling.rsmas.miami.edu/). More details and validation of the GoM-HYCOM 1/50 simulation can be found in Le Hénaff and Kourafalou (2016), Androulidakis et al. (2019a, 2019b). The surface salinity and currents derived from the simulation were used to describe the local circulation and river plume evolution around the Delta during April and August 2017. Oil spill simulations presented here were carried out by the Lagrangian open source code OpenDrift (Dagestad et al., 2018. https://github.com/OpenDrift/opendrift/).

2.4 Wind Data

Wind measurements by a National Data Buoy Center (NDBC; https://www.ndbc.noaa.gov) are used to describe the wind conditions around the Mississippi Delta during the field experiments. Buoy 42040 (time step every 10 minutes) is located east of the Delta (29.208^{o}N, 88.226^{o}W).

3. Results

3.1 Case 1. Drifters deployment from April 18-20, 2017

Three drifters were deployed during the first day of that field experiment (Figure 4) on April 18, 2017 at approximately 16:41 (UTC). Additionally, two more drifters were deployed on April 20 at 12:48 (UTC). The satellite image shown on Figure 5 shows the length of the oil slick and the trajectory of the drifters. During the 2nd deployment on April 20, drifters were influenced by easterly wind-induced surface currents and revealed trajectories along the Mississippi River front, formed by the downstream current toward the west (Androulidakis et al., 2018). The prevailing southeasterly winds between April 20 and 22, 2017 (Figure 6) determined this pathway, driving the surface waters along the outer river plume front and finally toward the coast, west of the Louisiana Peninsula. It is noted that all drifters deployed on 20 April initially propagated westward along the front and their fate was largely determined by the extension of the plume and thus the front's location under the effect of strong easterly winds. The total length of the slick, derived from the satellite image, was 24.5 km (Figure 5). The time it took the un-drogued drifters to cover the same distance was approximately 10 hours (Table 2).

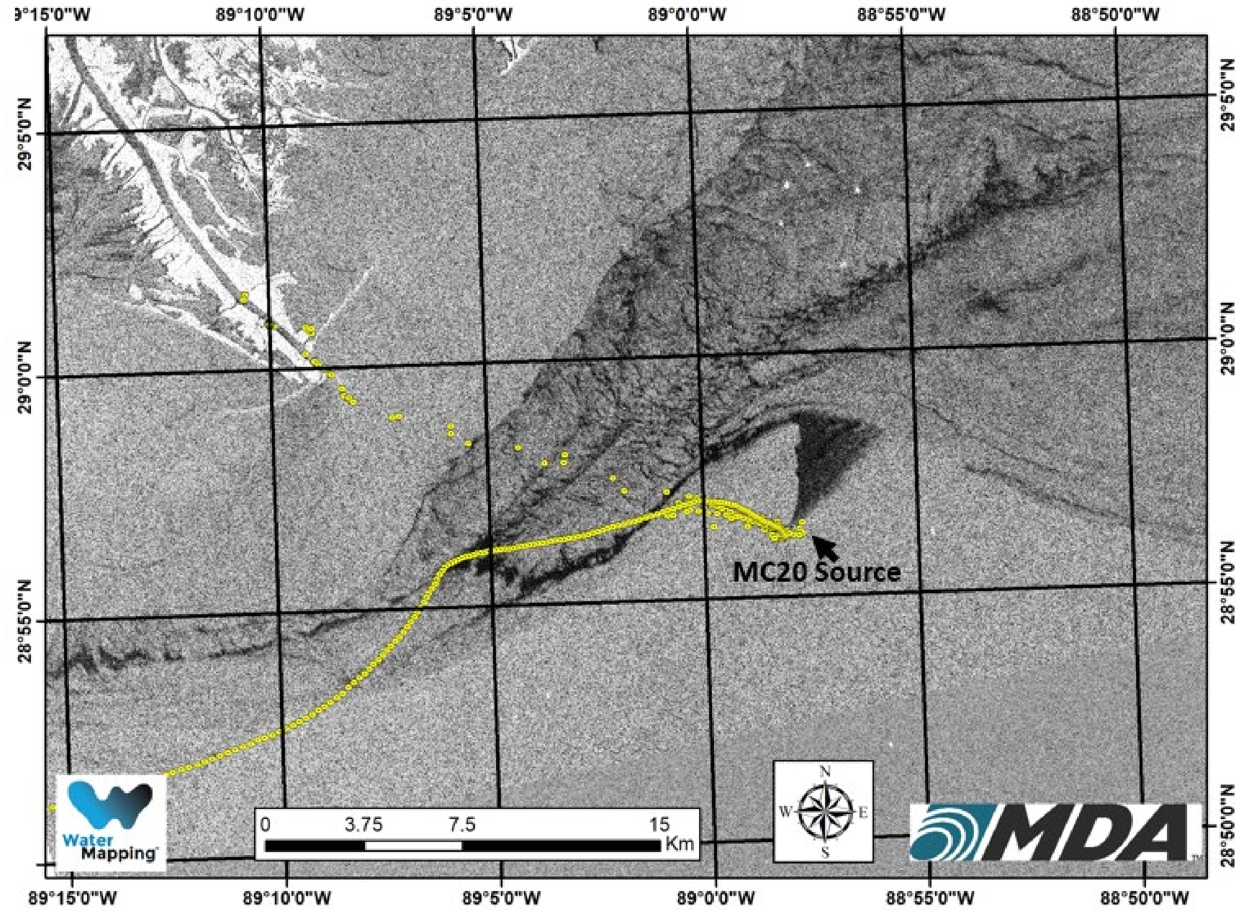


Figure 5. Satellite image obtained by SAR satellite RADARSAT-2 just few minutes before the deployment of the drifters on 20 April 2017 (Case 1). The yellow dots represent the un-drogued drifter positions every 5 minutes. Spaced dots (shown from inside the river towards the MC20 source) occurred before deployment. The solid-dark shaded feature (in contact with the MC20 Source) is the oil slick from MC20 as seen on the SAR data.

We would like to stress the fact that the satellite image occurs in a snapshot, while the trajectory of the drifters is captured over a long period of time (several hours). In our analysis, we use the satellite image as a guide to estimate the length of the slick, and then we use the records from the drifters to estimate the time it took for the oil to travel over the same distance. It is expected that the shape of the slick captured on the satellite image will not match perfectly the trajectory of the drifters, but it should follow a similar directional pattern. For example, the RADARSAT-2 satellite image of April 20 (Figure 5), captured approximately 1 hour before the deployment, shows the oil traveling almost straight northward. However, almost immediately after the deployment, the oil and drifters shifted towards the west along the river front. It is critical to monitor the wind conditions before, during, and after the deployment, in tandem with the position of the river plume front, to analyze potential changes in oil or drifter trajectories.

Table 2. Summary of the drifter deployments and observations.

Case	Satellite	Image Time (UTC)	Drifter deployment time (UTC)	Oil displacement (Length of the Slick in km)	Drifter Time (hrs)	Wind average	Oil/Drifter speed (m/s)
20-Apr-17	RST2	23:57:00	16:17:00	27	10.5	6.91	0.71
25-Apr-17	ASTER	16:49:00	two days before	13.5	28	4.22	0.13
26-Apr-17	TerraSAR-X	23:49:00	20:45:00	8.9	4	8.8	0.65
16-Aug-17	CosmoSKY Sentinel-2A	11:10 & 16:29	12:13:00	54	19	3.8	0.79
29-Apr-18	Landsat	16:45:00	13:35:00	34	14	5.7	0.67
18-Aug-18	N/A	N/A	13:52:11	11	14	4.6	0.46

Figure 6 presents records from meteorological station NDBC 42012 nearby the MC20 site showing the direction and magnitude of the wind during the various study cases. The average wind speed for the 10 hours prior to the RADARSAT-2 (RST2) image was 6 m/s. Few hours after the image there were calm wind conditions that allowed the oil to remain on the surface for a longer period of time. As shown on Figure 6, the wind changed slightly its direction from the time of the RADARSAT-2 image to the time of the drifter deployment; initially winds were blowing to the east, then they changed to the north-east. The wind conditions before, during, and after each satellite snapshot are the main factor driving and evaporating the oil slick as it appears on the satellite image.

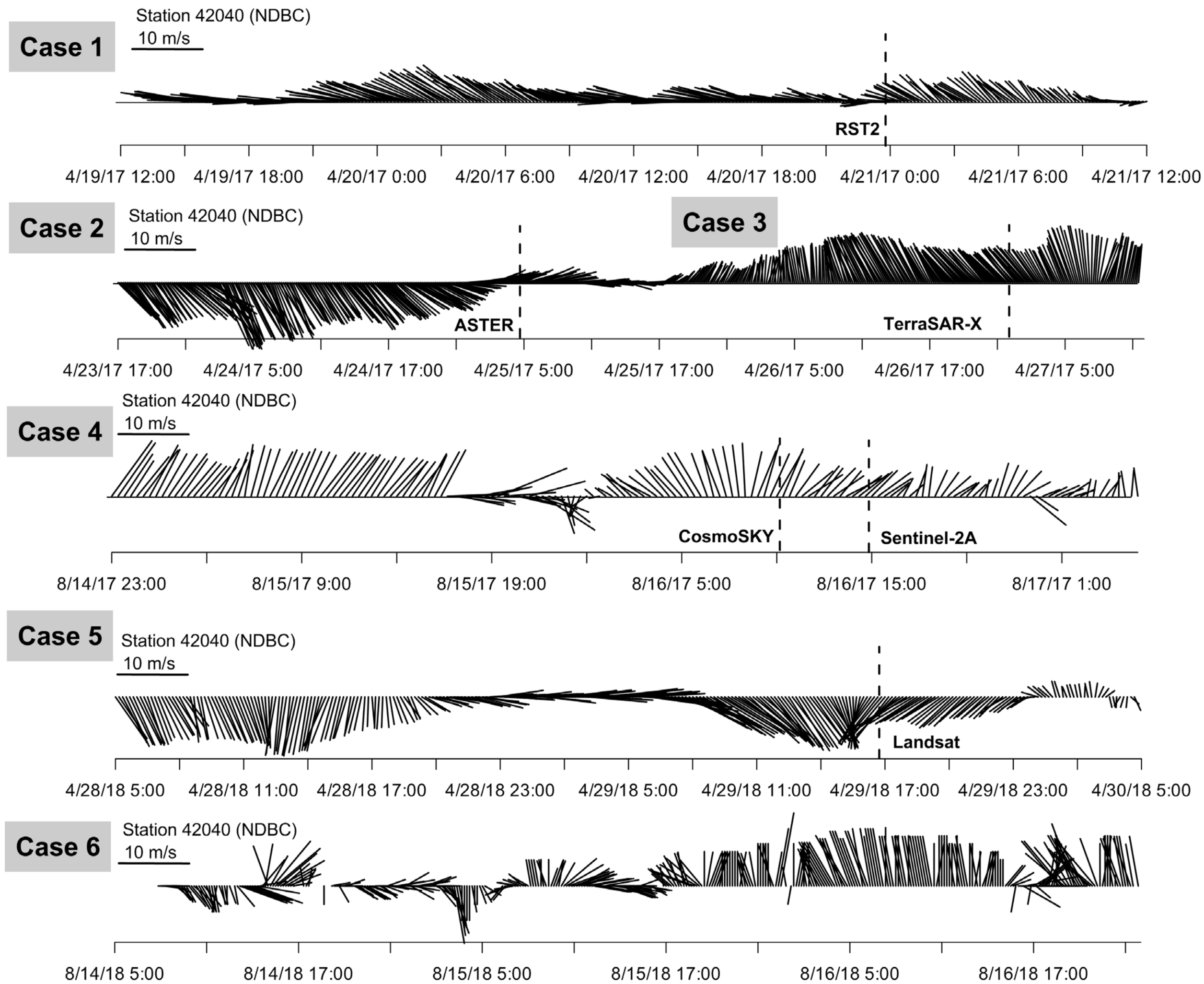


Figure 6. Summary of wind history observations on each of satellite observations derived from 42040 NDBC station. The six study cases and the time of each satellite snapshot (dashed line) are also marked.

The simulated surface conditions (salinity and currents) over the study region during Case 1, derived from the GoM-HYCOM 1/50 model simulation, are presented in Figure 7a. It is a high-resolution (2 km) simulation of the full Gulf of Mexico, with realistic river-induced dynamics and assimilation of observations to ensure realistic ocean condition representation. The strong downstream current of the river plume (westward) is strongly related to the prevailing easterly winds. Moreover, the location of the MC20 site (with a depth of approximately 150m) in the vicinity of the river front on 20 April 2017 contributed to the evolution of the westward pathway of both drifters and oil; easterly winds enhance this type of river plume spreading while, on the contrary, the upstream (northeastward) river plume currents are more related to westerly and southerly winds (Walker et al., 2005; Schiller et al., 2011; Androulidakis and Kourafalou, 2013; Androulidakis et al., 2018). The simulated river plume thickness along the river fronts ranges between 5 to 10 m (not shown) in agreement with observations collected by Androulidakis et al. (2018).

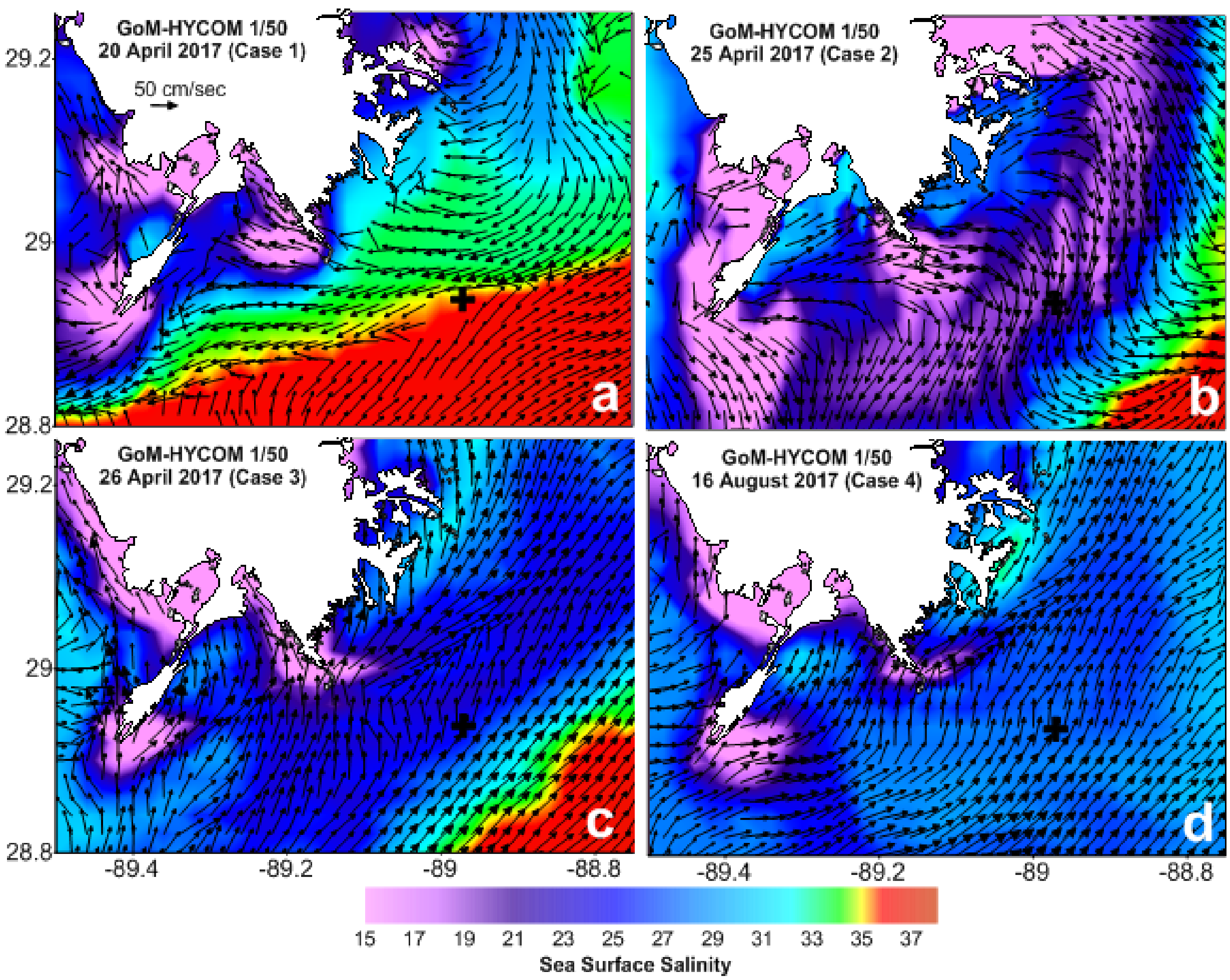


Figure 7. Sea surface salinity and currents as derived from GoM-HYCOM simulations on a) 20 April 2017 (Case 1), b) 25 April 2017 (Case 2), c) 26 April 2017 (Case 3) and d) 16 August 2017 (Case 4).

3.2 Case 2. April 25, 2017

On two different locations (separated approximately by 20 km), two drifters were deployed on April 25, 2017 and the same day an image by satellite ASTER was collected at 16:49 (UTC).

The two drifters initially propagated eastward and then southward (Figure 8), following the dominant direction of the winds (northwesterlies; Figure 6). Figure 8 is a false composite color image is used to display the close location of the main river plume with the oil slick. The length of the slick was 13.5 km and the time that took the drifters to travel that distance was 28 hours (Table 2). The average wind speeds during that period of time was 4.22 m/s.

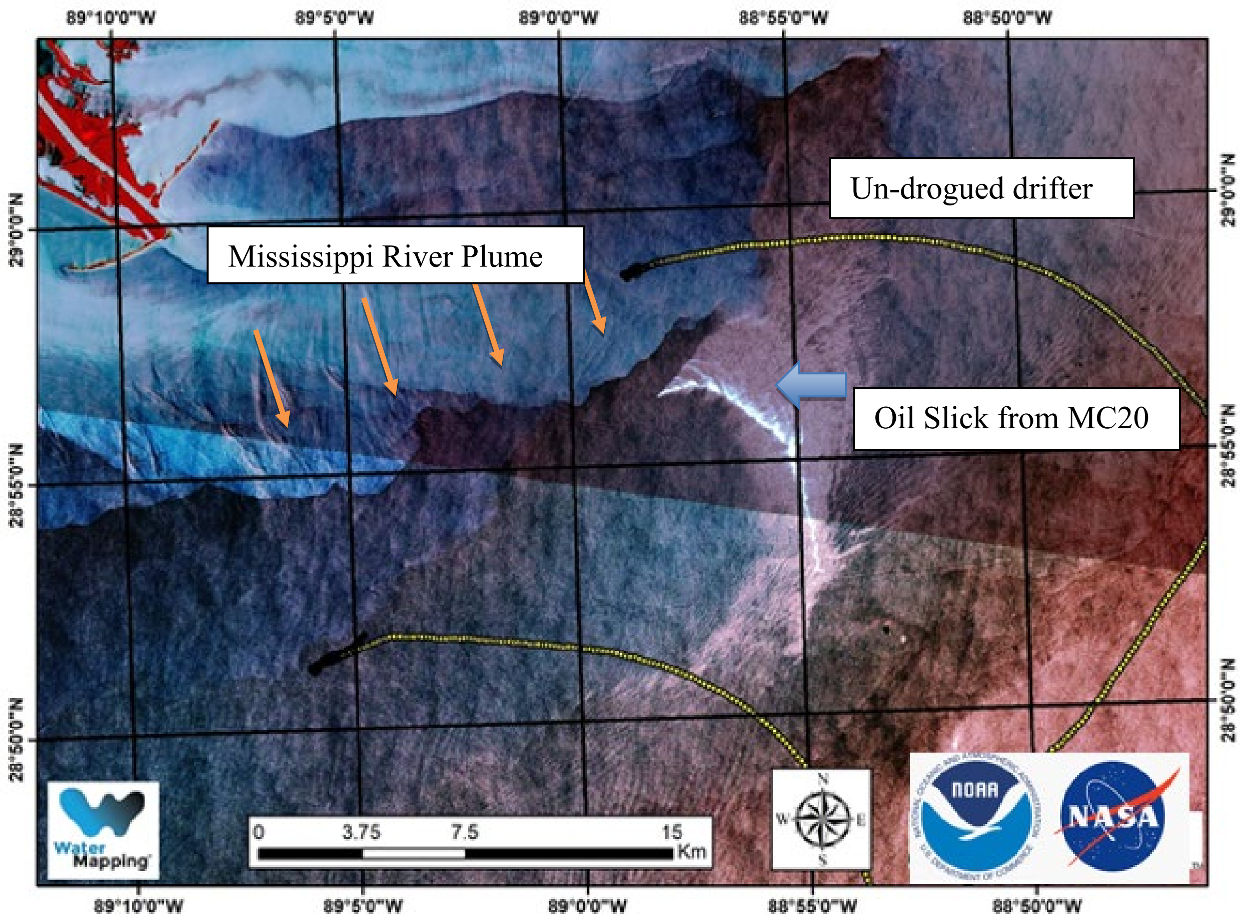


Figure 8. Satellite image collected by ASTER satellite on April 25 at UTC 16:49 with drifter deployments on April 25 (Case 2). The green dot marks the location of the MC20 site. The southernmost exit of the Mississippi Delta can be seen on the upper left corner of the map.

A comparison of observations made by three different satellites is shown on Figure9. These satellite images were used to extract the oil thickness classification of the slick with high agreement among the different satellite platforms (Garcia-Pineda et al., 2019). The thickest classification of the oil associated with thicker emulsified oil (dark spots shown on RADARSAT-2 Quadpol Entropy image; Figure 9B) and thicker un-emulsified oil (bright feature shown on ASTER image; Figure 9C) shows a similar general direction as the drifter trajectory displayed on Figure 8. These quasi synoptic observations show not only the distribution of the oil, but the location of the thickest oil layers within the slick. It is important to point out that the presence of the thickest layer of oil matches the direction of the drifter deployed the same day of the satellite snapshot.

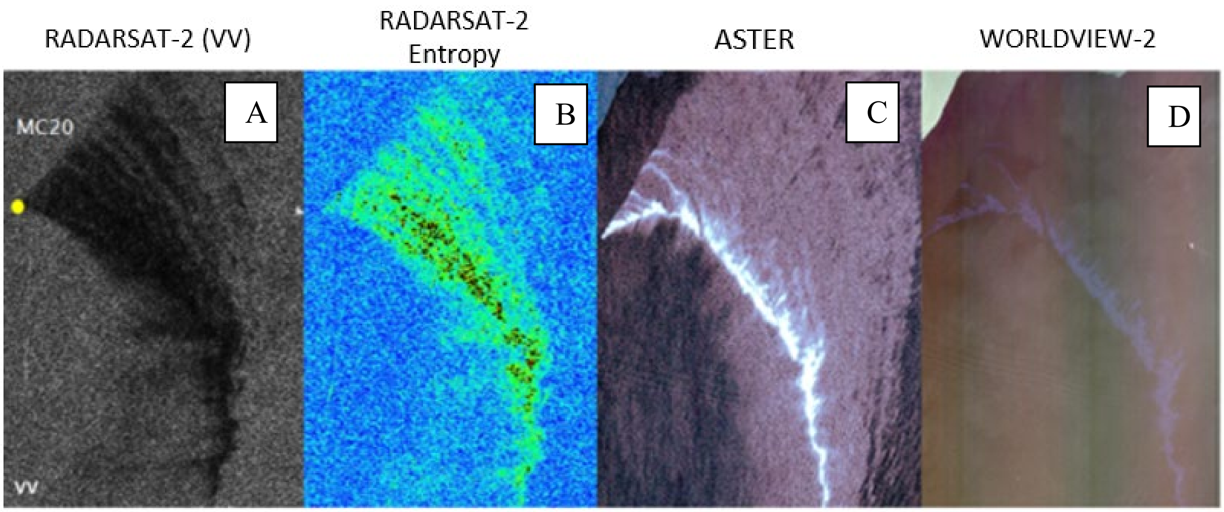


Figure 9. Comparison of synoptic imagery and by products from satellite images obtained on April 25, 2017 from: A) RADARSAT-2 VV, B) A byproduct of the RADARST-2 image called Entropy that classifies thick emulsions from thin oil, C) ASTER and D) WorldView-2.

3.3 Case 3: April 26, 2017

Deployments on April 26, 2017 presented a unique opportunity due to the strong southerly winds (Figure 6) that occurred that day and enhanced the northeastward upstream currents over the MC20 site (Figure 7c). We will refer to this case as the "Strong Wind Case." Four drifter deployments occurred at the same time right at the location of the oil slick source. A satellite image collected by TerraSAR-X shows the displacement of the drifters in reference to the slick (Figure 10). In this case (stronger winds), drifters followed the same direction from the initial hours and then started to separate. The winds were mostly from the South and the fronts of the river plume created a predominant barrier to the displacement of both drifters and oil, guiding them towards the North-East. Southerly winds enhanced the northeastward extension of the Mississippi river plume (upstream currents) toward the northeastern shelves of the Gulf (Schiller et al., 2011; Androulidakis et al., 2015; Androulidakis et al., 2018). This case demonstrates the influence of the river plume on the trajectory of the oil slick towards the North East.

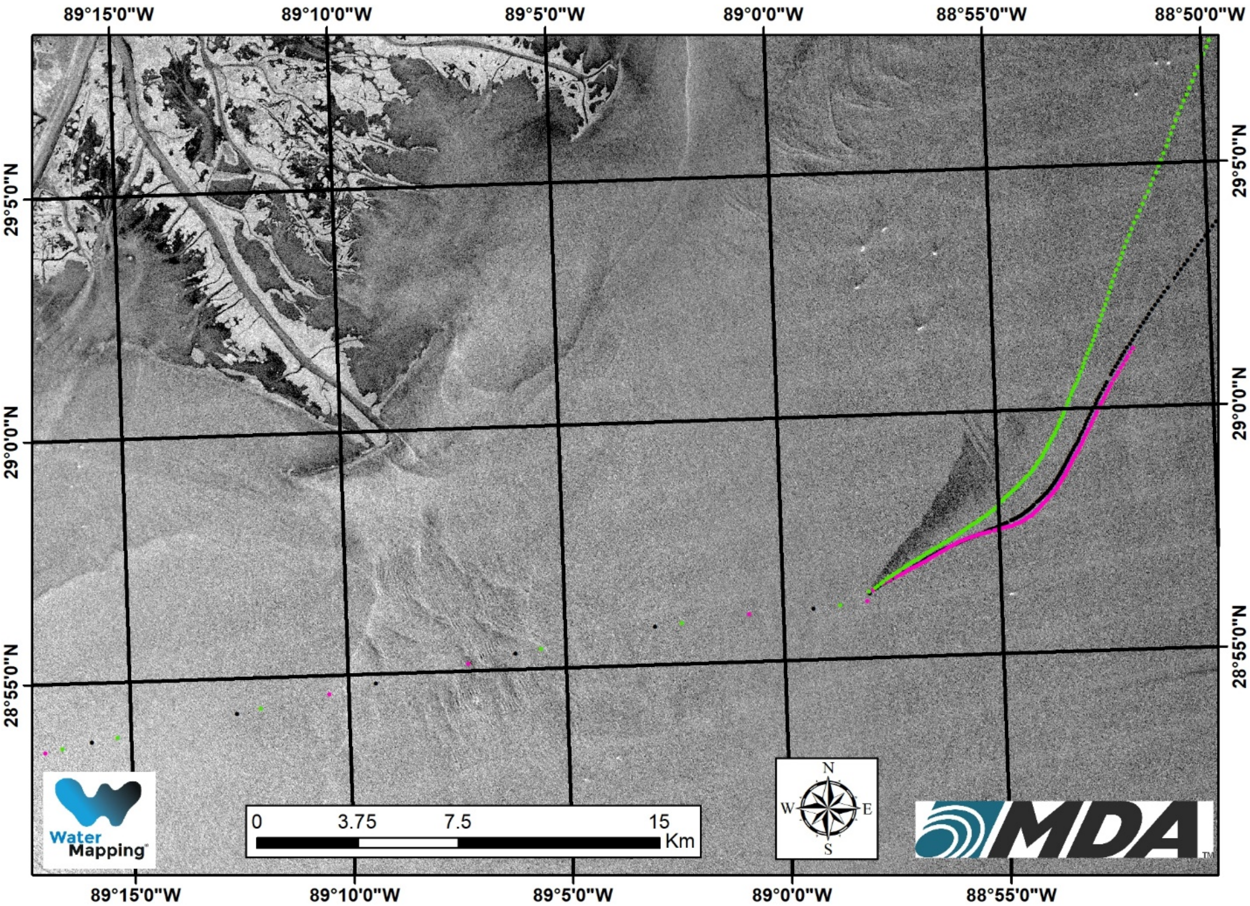


Figure 10. Case 3 is shown with a SAR satellite image collected by TerraSAR-X on 26 April 2017 at 23:49 (UTC). The trajectory of the drifters is shown as green and black (drogued) and magenta (un-drogued).

In this case, due to the strong wind conditions, a much smaller slick is shown compared to any of the previous cases. This once again confirms the inverse relationship between the wind speed and the oil slick size. High wind conditions will favor not only the evaporation but also other processes like re-entrapment of the oil, which is a process driven by an increase in the wave action in which oil is re-introduced into the water (from the surface downward), before it gets mixed and dissolved in the water column. Strong winds also affect the circulation and strength of the surface currents. In this case we could observe a larger separation between the drogued and un-drogued drifters than in any of the other cases. The length of the slick was 8.9 km and the time that the un-drogued drifter took to be displaced by this distance was 3 hours (Table 2). The average wind conditions during that period were 8.8 m/s (with gusts of up to 11m/s). By the time the un-drogued drifter reached the length of the slick the drogued drifter was approximately 3 km behind, so that the drogued drifter is approximately 33% slower.

3.4 Case 4. August 17, 2017

In contrast to the previous case, on August 17, 2017 we experienced very calm wind conditions for a long period of time (Figure 6) resulting in similar northeastward currents but with lowest magnitude (Figure 7d) combined with the wind. This is the “Calm Wind Case”. In this case we deployed 5 drifters at approximately 12:30 (UTC). Figure 11 shows an UAS aerial view that capture the 5 drifters with the monitoring vessel. We used two CODE drifters, one I-Sphere, one CARTHE drogued, and one CARTHE un-drogue.

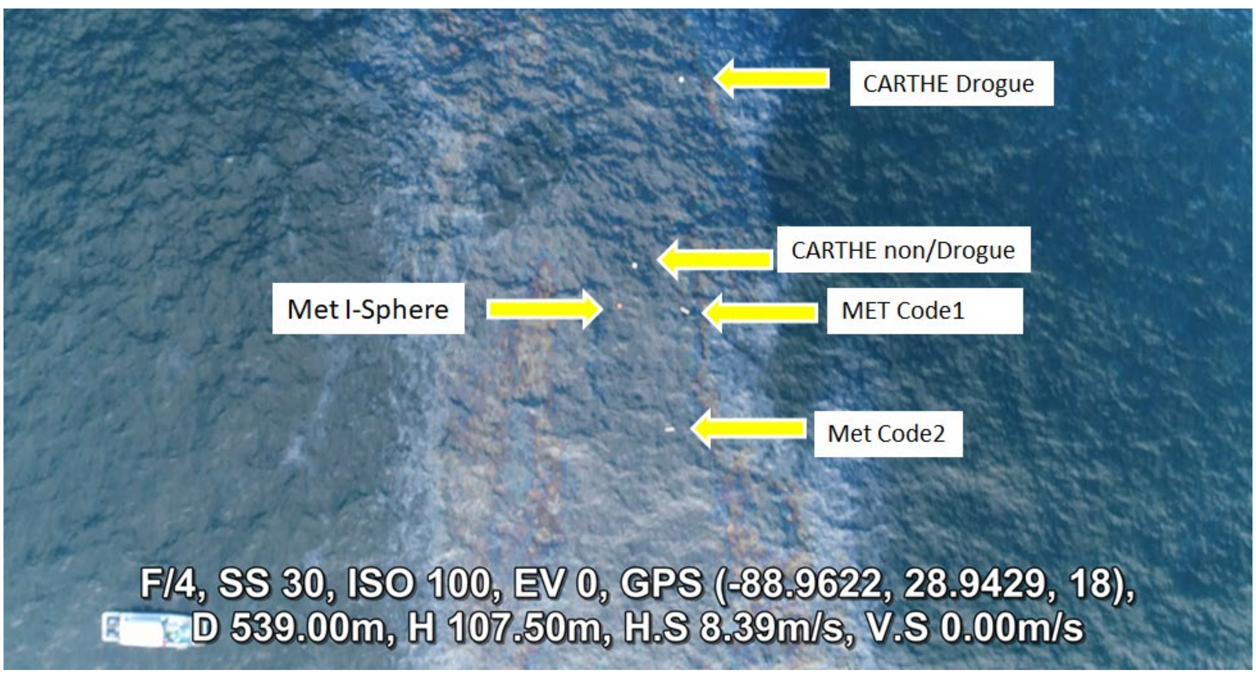


Figure 11. Bottom left of this image shows the 42ft monitoring vessel, on the center (inside rainbow-sheen the oil slick) can be seen the 5 different drifters. This UAS snapshot was collected approximately 30 minutes after the simultaneous deployment of the drifters at the source of the oil slick.

High resolution imagery obtained by the UAS (2 cm resolution) allowed us to confirm that the drifters followed the path along the thicker oil within the slick. Figure 12 shows an orthographic map created by the UAS image captures, and it shows the location and path of the drifters within the thicker (metallic) oil.

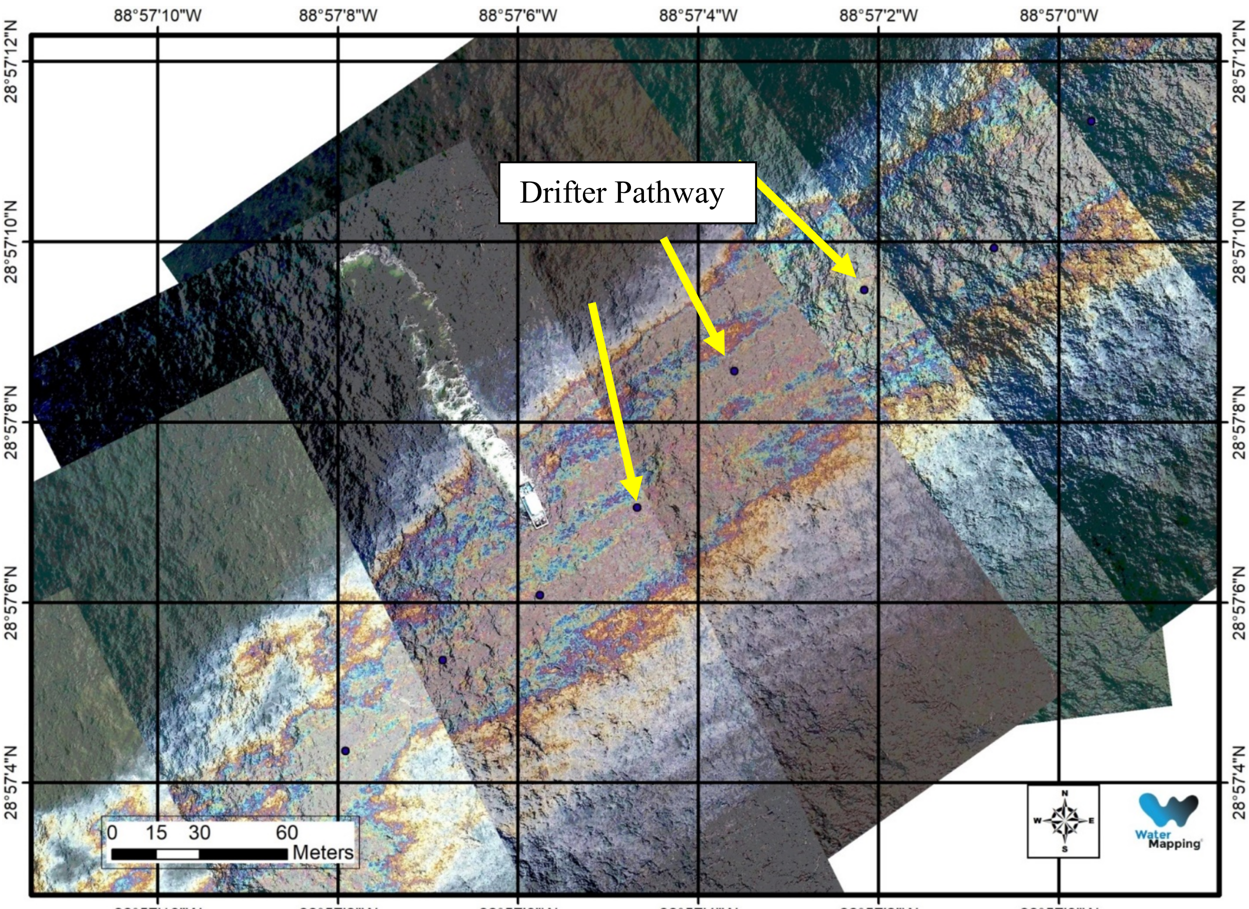


Figure 12. High resolution UAS orthomosaic image of the oil captures the drifter pathway inside the thicker oil within the slick. The location of this snapshot is approximately 2 miles northeast from the oil slick origin.

A Worldview-2 satellite image (1m resolution) was collected on August 17, 2017 at 16:56 UTC. Figure 13 shows a map where an orthographic UAS is projected over the Worldview-2 image. This map shows the pathway of the drifters on the UAS projected stills. The displacement of the slick captured by the UAS with respect to its location on the WorldView-2 image was approximately 0.3 km north. In this case the UAS and the WorldView-s images are able to confirm the effectiveness of the undrogued CARTHE drifters following the oil trajectory.

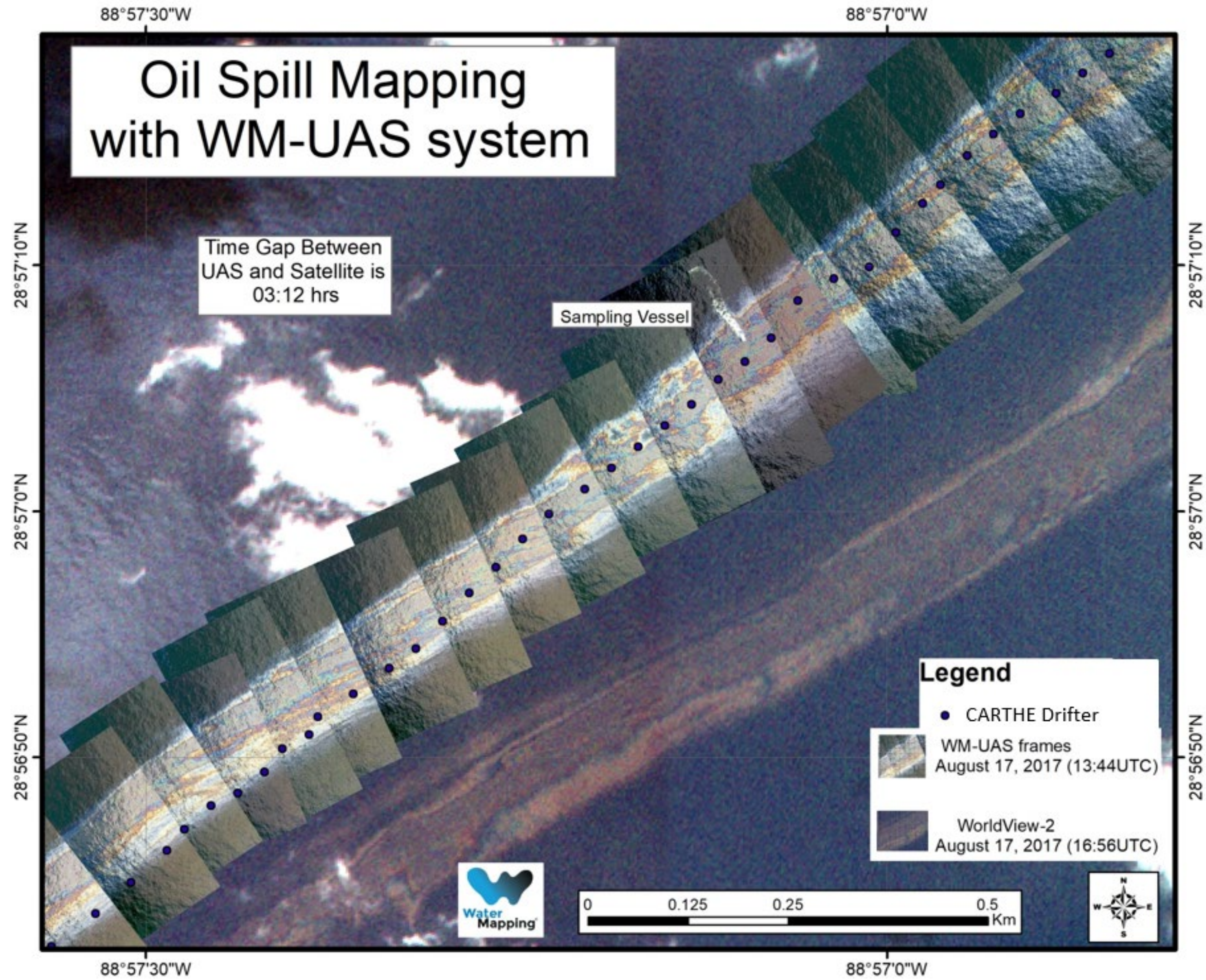


Figure 13. A UAS ortographic map of the oil slick from UAS together with the Worldview-2 image collected on August 17, 2017 at 16:56 (UTC) on the background.

The length of the slick was of 54 km (Figure 14), the time that un-drogued drifters took to travel that distance was 19 hours and the average wind speed was of 3.8 m/s during that period. Despite the calm wind conditions, we observed very strong upstream (northeastward) currents (Figure 7d) within the extended river plume.

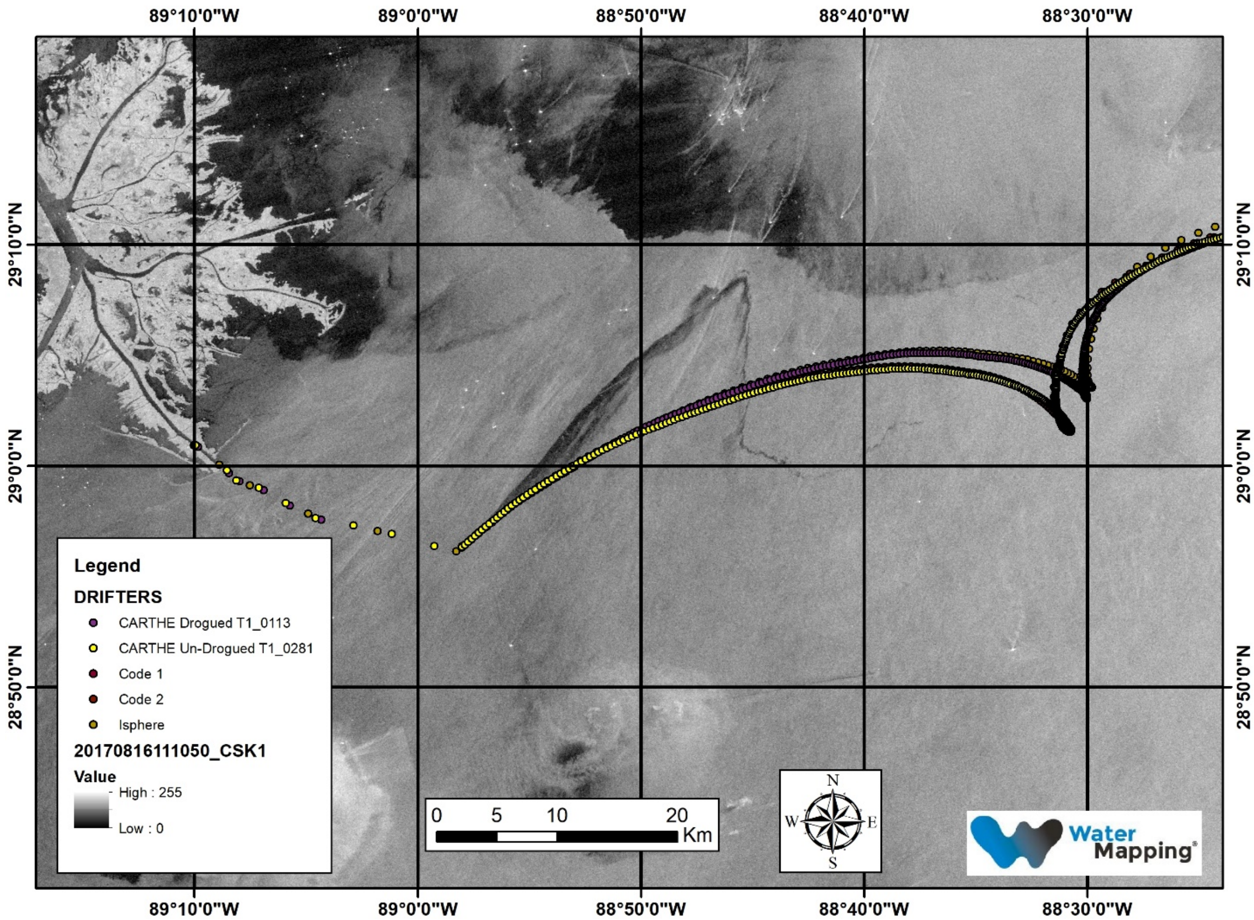


Figure 14. Image collected by the satellite CosmoSkymed on 16 August 2017 (Case 4) showing a slick of 54 km and the drifter trajectories. A UAS video of the conditions of the slick observed this day can be seen here: https://youtu.be/0Ly0ktQbtCw. This video describes in high detail how we monitored closely the drifters using the UAS.

Over the first 19 hours of drifting, we could observe that the I-SPHERE and the CARTHE un-drogued drifters maintained a close distance of less than 800 meters of separation between them, which represents less than 2% difference compared to the 54 km length of the slick. The three drogued drifters (CODE-1, CODE-2, and CARTHE drogued) maintained a close distance among them of less than 400 meters. However, during the same period of time, the two groups of drogued and un-drogued drifters got separated by a maximum distance of 3.5 km (which is less than 7% of the overall distance of the slick). This case helped to confirm the displacement of the 4 different types of drifters and suggests that the difference between them is less pronounced during calm conditions than with strong winds. The difference between the shape of the slick and the trajectory of the drifters in Figure 14 is due to the fact that drifter locations (yellow dots) show a progressive sequence of displacement over time, whereas the satellite is only one snapshot taken in a fraction of a second. The changes in the drifter location helps to understand how the slick would have moved as time passed. The drifter position better matched the orientation of the slick close to the release time.

3.5 Case 5. April 29, 2018

A fifth deployment of a CARTHE un-drogued drifter was carried out on 29 April 2018 (Case 5). We used again the UAS to confirm that the drifter not only followed the oil pathway, but stayed within the thick patch of oil (red dots on Figure 15).

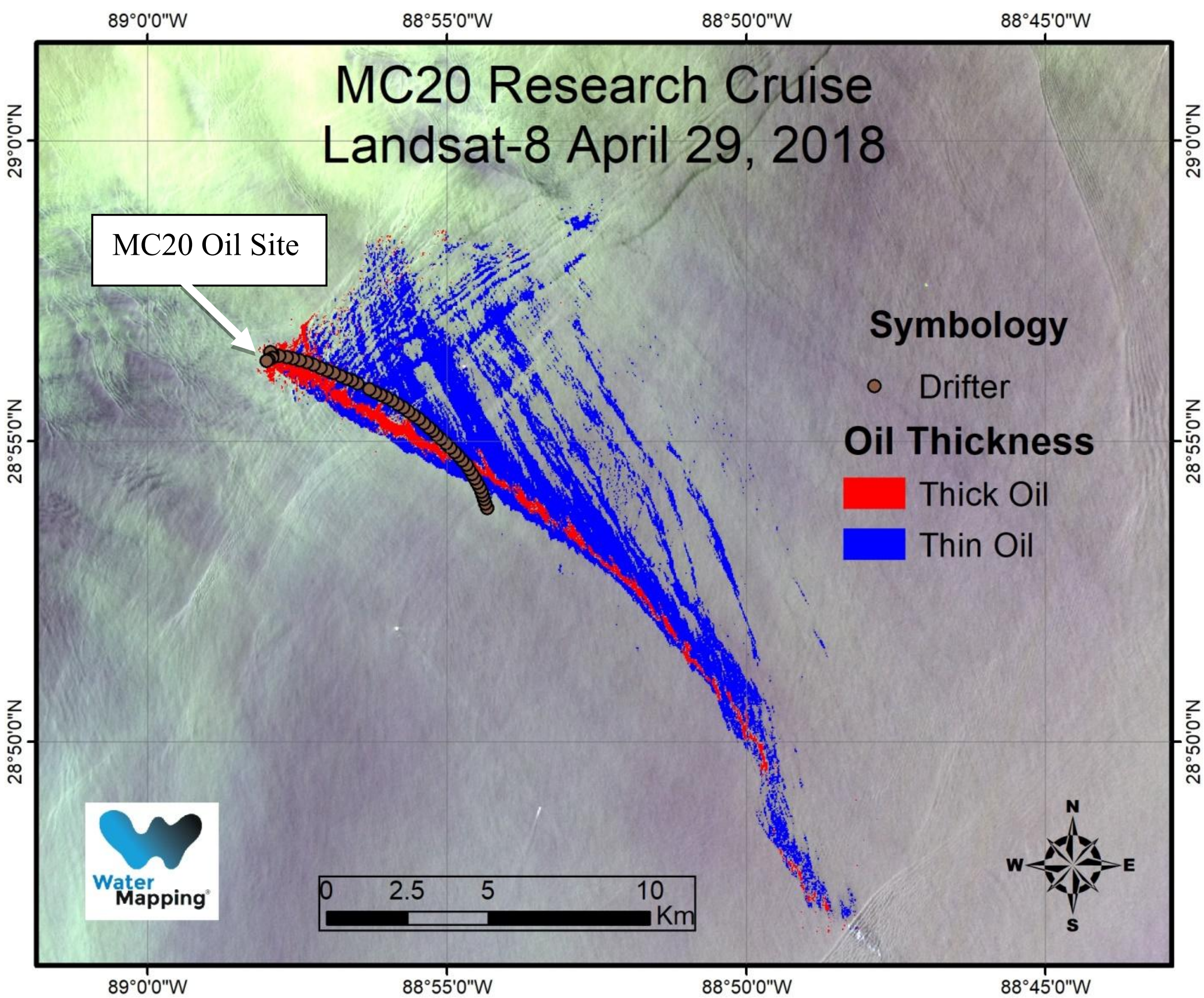


Figure 15. Case 5 of drifter deployments with oil thickness classification. Landsat-8 image collected on April 29, 2018 at 16:45 (UTC).

A high-resolution image collected by Sentinel-2A is shown on Figure 16. This image was collected within 5 minutes from the Landsat shown on Figure 15. On Figure 16, the drifter is located inside the thick oil, which is shown as a bright feature within the darker slick.

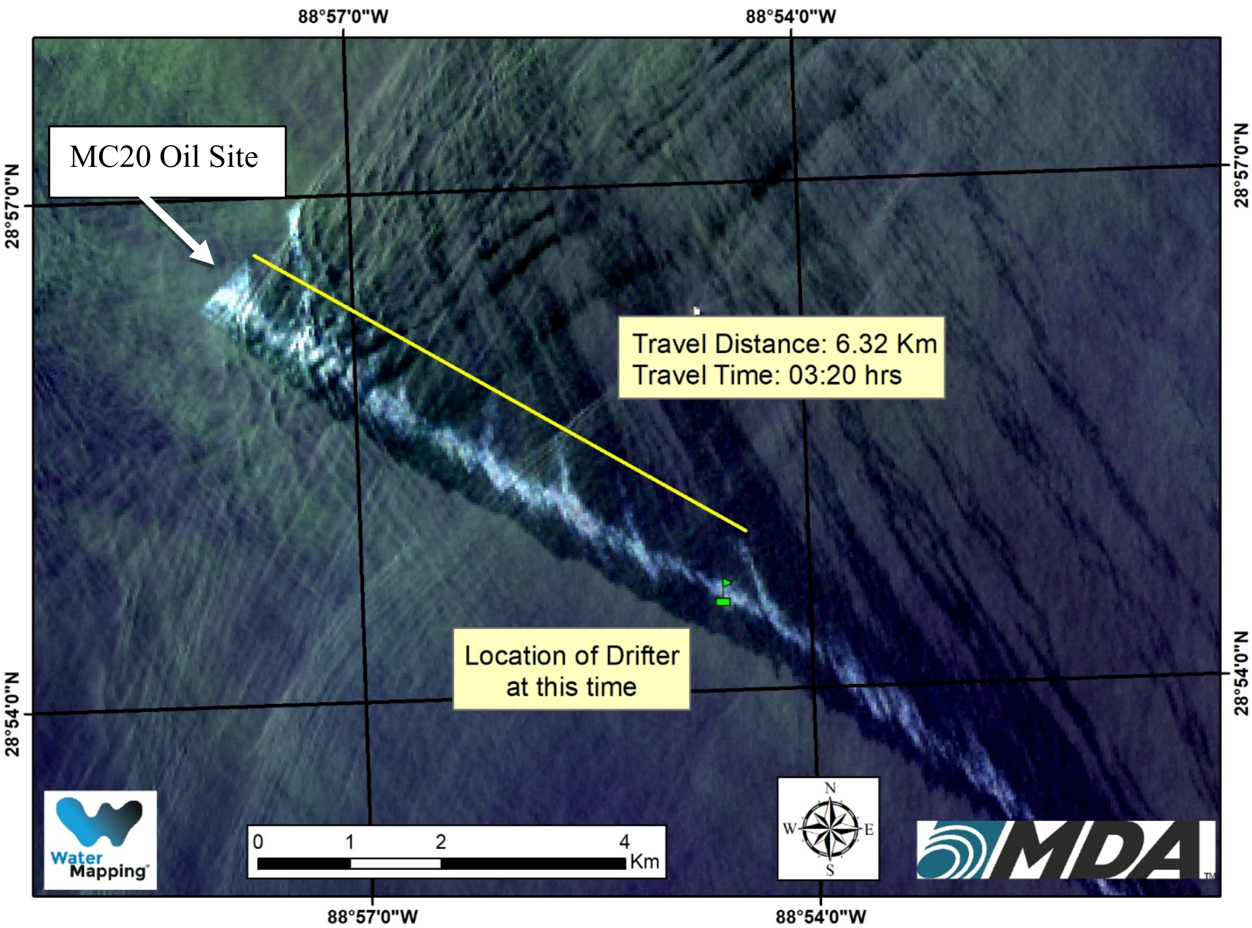


Figure 16. Subset from Sentinel-2A image that shows the position of the drifter after 3:20 hrs from its deployment at the source. The darker pixels in the shape of striking lines correspond to the oil slick and the bright stripe inside the dark area corresponds to the thicker oil. The separation of these oil slick lines suggests a slight change in the wind direction.

On Figure 16, the drifter is located at 6.32 km from the oil origin and it took 03:20 hrs to travel this distance. However, the total length of the slick for this case was 17 km and the time that the drifter took to travel such a distance was 15 hours. The average wind speed during that time was thus 3.9 m/s.

3.6 Case 6. August 18, 2018

The last deployment of an un-drogued CARTHE drifter was carried out from the United States Coast Guard (USCG) vessel 'Brant' at 08:11 hrs on August 18, 2018 (Figure 17). The drifter was deployed from this vessel and then a smaller inflatable sampling boat from the Brant was deployed to monitor the drifter more closely. Figure 17 shows the USCG Brant (bottom) and the smaller sampling boat (upper left) around the oil slick sourced from the MC20 site.

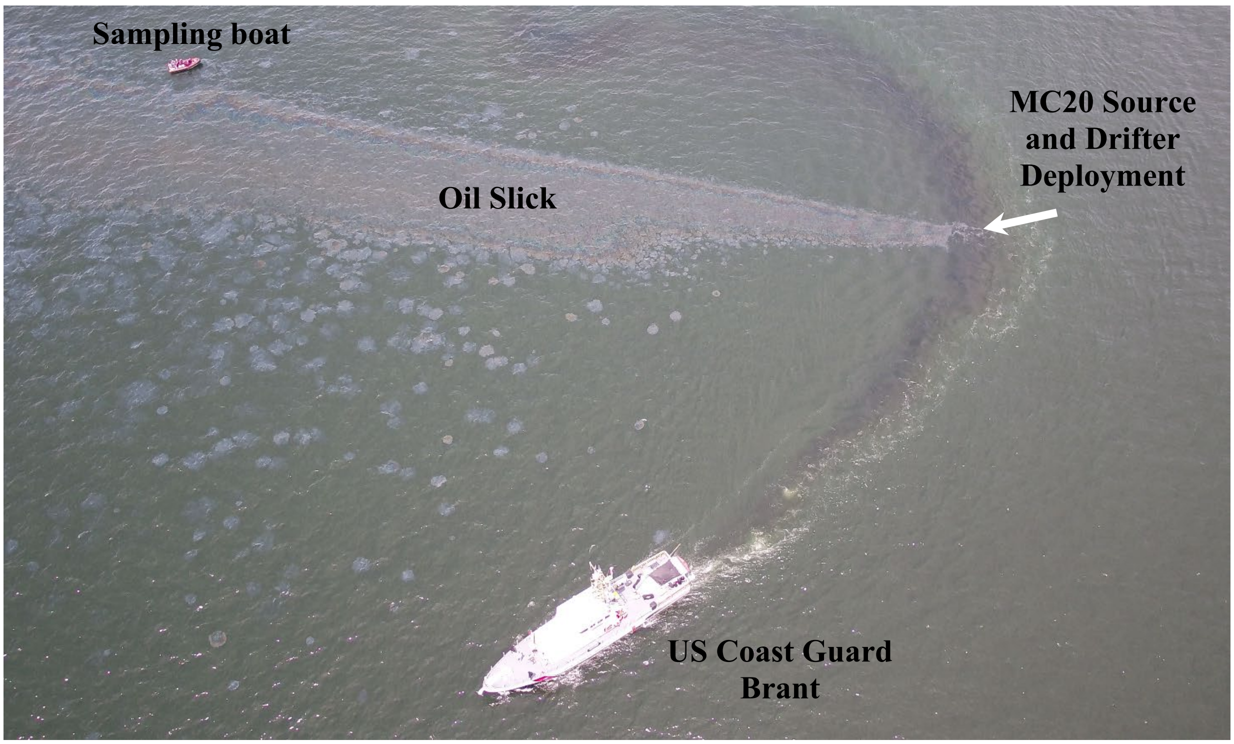


Figure 17. The USCG Brant monitoring around the oil source at MC20 (drifter deployment) guided by the UAS real time video system on 18 August 2018. The extension of the oil slick and the location of the sampling boat are also shown.

We were able to follow the drifter for 9 continuous hours. During that time, we experienced thunderstorms and wind shear of 180 degrees. Notwithstanding the rain, thunderstorms, and wind change in direction, the oil always remained on the surface and the drifter stayed within the oil. In this case, because of the cloud cover, we could not use a satellite to image the oil, however Figure 18 shows two aerial snapshots taken by the UAS before and after the storm.

Figure 18. Direct UAS monitoring of the drifter within the oil before (top) and after (bottom) the thunderstorms on 18 August 2018.

By tracking its position, we retrieved the drifter on the next morning (August 19, 2018), and using the UAS we were able to confirm that oil was totally absent, as it had fully evaporated and dissipated. This case was very valuable, as it demonstrated the performance of the drifter under stormy conditions and wind shear, during which the drifter remained inside the narrow oil slick at all times despite the rough conditions. This confirmation was achieved by maintaining constant sight of the drifter from the USCG vessel and from the UAS.

Table 3 shows a summary of the 6 cases (with different weather conditions) where CARTHE un-drogued drifters were deployed at the origin of the MC20. Slick length was measured using satellite images, and the time that the GPS-tracked drifters took to be displaced over the same distance was also recorded. This study allowed us to estimate the speed of the oil transport by having a reference of the drifter times.

Table 3. Summary of the drifter deployments and observations.

Case	Satellite	Image Time (UTC)	Drifter deployment time (UTC)	Oil displacement (Length of the Slick in km)	Drifter Time (hrs)	Wind average	Oil/Drifter speed (m/s)
20-Apr-17	RST2	23:57:00	16:17:00	27	10.5	6.91	0.71
25-Apr-17	ASTER	16:49:00	two days before	13.5	28	4.22	0.13
26-Apr-17	TerraSAR-X	23:49:00	20:45:00	8.9	4	8.8	0.65
16-Aug-17	CosmoSKY Sentinel-2A	11:10 & 16:29	12:13:00	54	19	3.8	0.79
29-Apr-18	Landsat	16:45:00	13:35:00	34	14	5.7	0.67
18-Aug-18	N/A	N/A	13:52:11	11	14	4.6	0.46

The oil slick length ranged between 8.9 km to 54 km (average value of 24.7 km), within a time range from 4 to 28 hours (average 14.9 hours) and wind amplitude between 3.8 to 8.8 m/s.

4. Discussion

By sorting the residence times estimated with drifters in an ascending order, and plotting these times against the average wind speed, we can observe that there is a strong inverse correlation between these two variables (Figure 19). The strongest wind conditions of 8.9 m/s (dot on the upper left of the plot) produced a residence time of approximately 4 hours while low wind conditions of 3.8 and 4.22 m/s produced residence times of approximately 19 and 28 hours respectively. This inverse correlation appears linear, at least within this range of observed wind conditions. For this analysis we are considering that the oil residence time corresponds to the same time that each drifter took to be displaced by a distance equal to the length of slick under the various wind conditions.

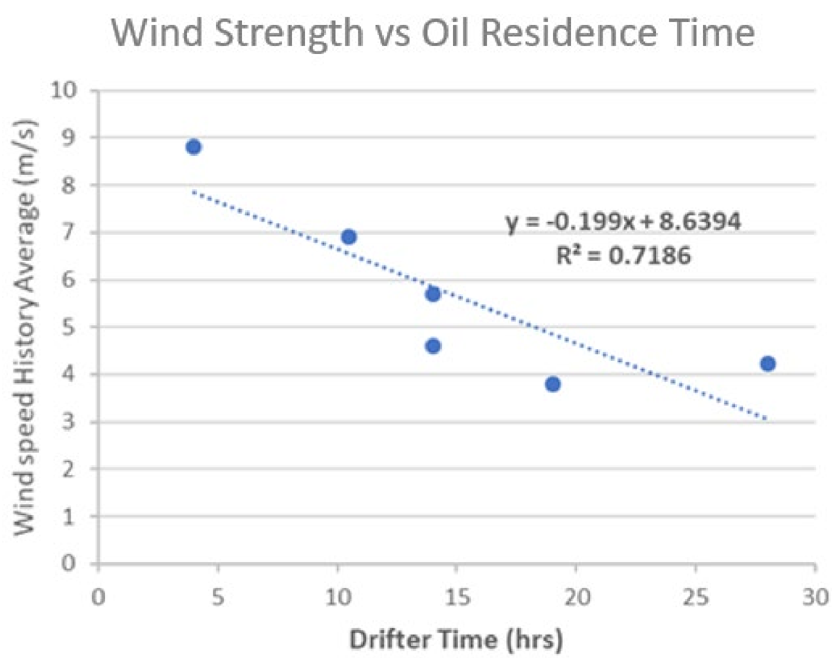


Figure 19. Relationship between the wind speed and the oil residence time. From 8.8 to 3.8 m/s winds there is an inverse correlation with the duration of the residence time of the floating oil.

These six cases confirm that the wind is the main driving factor for the duration and transport of the oil on the surface. Not only will the wind guide the direction and influence the speed of transport, but more importantly, the strength of the wind will influence the evaporation and dissipation rates. The "Calm Wind Case" (Figure 14) confirms that oil can travel for a much longer time if the wind is calm enough to let the oil prevail on the surface. These calm wind conditions, in combination with the sustained northeastward upstream currents related to the Mississippi River plume, displaced the oil over approximately 54 km in only 19 hours. In contrast, the 'Strong Wind Case' (Figure 11) confirmed that under strong winds (wind gusts above 11m/s) the re-entrainment (re-immersion of the oil) and evaporation effects will increase drastically, as the plume lasted for approximately 4 hours only.

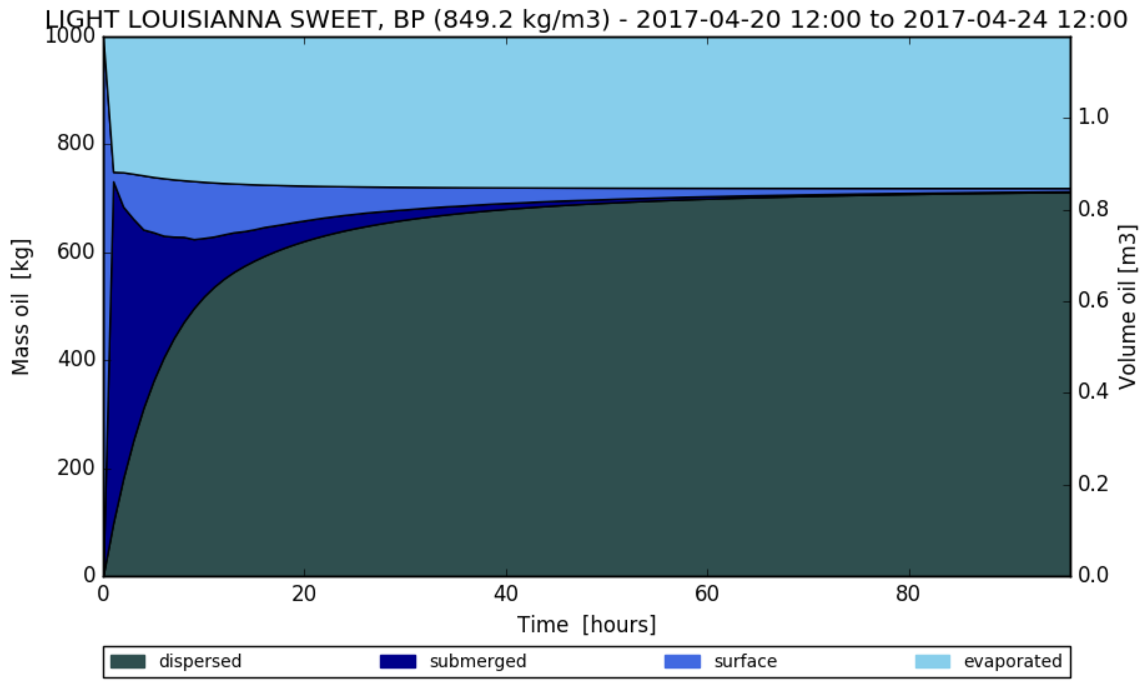
A summary of the wind conditions and the timing with the satellite images was presented in Figure 6. Case 1 was the simplest to analyze in terms of wind direction and displacement. For that case, wind persisted in the same direction (northwestward) for more than 48 hours, showing only alterations in amplitude. Those conditions allowed the drifters to be pushed persistently on the general same direction. The slick captured by RADARSAT-2 (Figure 5) was 27 km and the un-drogued drifter took 10.5 hours to cover the same distance. In contrast, wind conditions for Case 2 were more complicated, as the direction of the wind turned around (130°) in less than 12 hours, and this effect was captured by the ASTER satellite (Figure 8), and also confirmed by the simulated surface currents (Figure 7). The wind history for cases 3,4 and 5 suggest less changing conditions. These observations quantify, for the first time to our knowledge, how wind strength is inversely correlated to the residence time of the oil, as strong winds will generate shorter lifetime of the oil slick and calmer winds will produce a longer life time of the oil. This is explained by the direct effect of the re-entrapment and evaporation ratio produced by the wind.

For chronic or persistent releases of oil (natural or accidental), calculation of the residence time of an oil spill is important because this can help estimate the flux or volume of oil discharge over a given period of time. We have calculated this residence time to be between 4 to 28 hours within the measured wind conditions between 8.8 to 3.9 m/s, respectively. However, we can expect the residence time to be shorter if the wind is stronger, or longer if the wind speed is lower or if there is no wind at all for longer periods of time.

The residence time will be affected by the dosage or flux of oil. It is expected that a larger amount of oil will produce more emulsification and oil will last longer. For example, a natural seep in the Gulf of Mexico that produces a persistent thin slick (with a small dosage of oil) will produce a shorter (in time) slick than a spill where the discharge happens more rapidly and allows the oil to be aggregated on the surface with higher volumes, such as the Deepwater Horizon oil spill in 2010. The thinner an oil slick, the more rapid it will evaporate. Also, as larger oil spills are forced into windrows, the oil can aggregate into thicker or emulsified (water-in-oil) mousse which is slow to evaporate and difficult to entrain into the water column.

The residence times estimated here are particular for the MC20 (Sweet Louisiana) crude oil which physical-chemical properties have not been considered in this analysis. There are probably hundreds or maybe thousands of types of oil that can be classified into a general four main classes of crudes (Very Light, Light, Medium, Heavy fuel). Within the heavy fuel crude oils, marine hydrocarbons are the most viscous and least volatile. Further investigation will be required to analyze the residence times from this oil compared to others.

In most oil spill simulation models available today, the thickness of the oil slick is not considered, with few exceptions (e.g. SIMAP model that includes spreading, weathering, emulsification, and oil thicknesses). Most oil drift models in use today are Lagrangian where the oil is represented by a number of independent particles. This means that each particle will have its own mass balance, and the surface residence time will be independent of the amount of oil released. Fig. 20 top panel shows an example of a mass balance simulation carried out with the OpenDrift (Dagestad et al, 2018) oil drift model with a constant wind of 10 m/s. Currents are taken from the GoM Hycom 1/50 high resolution ocean model (Androulidakis et al., 2018), and the simulation starts at April 20th 2017. 1000 kg of oil is released instantaneously, and we see that more than 20% evaporates soon after release. After 48 hours just a few percent remain at the surface. However, for lower wind speeds the calculated residence time (using OpenDrift) is much longer than the residence time actually observed in this study (Fig. 20, lower panel). One main reason for this could be that the observed oil slick is very thin in this case and more



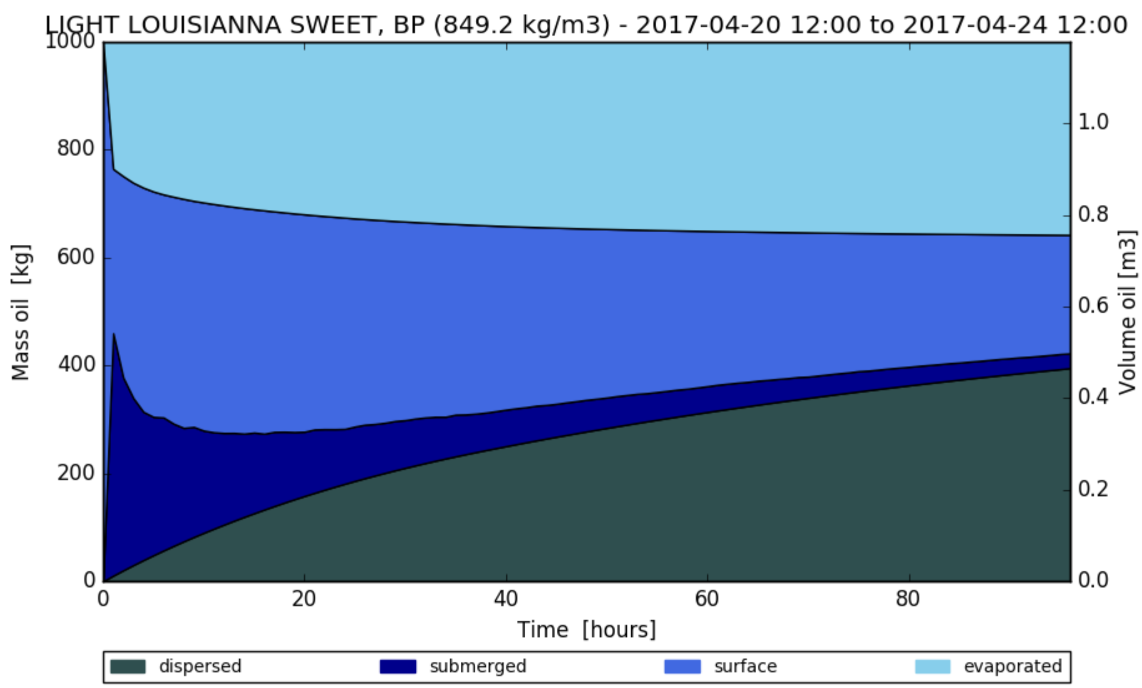


Fig. 20. Mass balance of 1000kg oil released in 20 April at 12:00 hrs as simulated by the OpenDrift oil drift model. Simulation with 10 m/s wind at top and 6 m/s wind at bottom.

Results obtained by this study are important input for oil spill modeling. The contrast between observations and modeling enhance the importance of incorporating oil thicknesses into oil models to improve their performance.

5. Conclusions

Drogued and un-drogued drifters were used to monitor the residence time of the oil from MC-20. The hydrodynamic design of the two types of drifters allows us to compare the performance difference between them. The un-drogued drifter is more adequate to measure the oil transport speed because its hydrodynamic design, having a shallow drag and short sail, it mimics better the thin layer of oil, contrary to the drogued drifter which has a deeper drag and behaves closer to the subsurface currents (~ 50cm deep). Although it is not yet possible to know the exact speed of the oil, using these two types of drifters allow us to provide a lower and an upper bound for the oil residence time estimate. We found a difference of 0.1 m/s between the drogued and the un-drogued drifter during the first 12 hours after deployment. This means that during the first 12 hours of displacement there would be about 17% difference on the distance that both drifters are displaced. Results shown on Table 2 are obtained from un-drogued drifters, therefore this should be considered as the maximum speed of transport of the oil. The strongest wind conditions were observed on April 26, 2017 with an average wind speed of 10.2 m/s (figure 10). It took less than four hours for the drifters to travel the distance of the slick observed by TerraSAR-X. In contrast, the calmest wind conditions occurred on August 16, 2017 before the CosmoSky-MED image (Figure 14) and it took up to 28 hours for drifters to travel that same distance. For the six cases under analysis, the average resident time of the oil slick was 14.9 hours with an average wind of 5.67 m/s. However, we can expect the residence time to be shorter if the wind is stronger, or longer if the wind is lower. These results can be used to understand the flux flow (rate of discharge) of the MC20 site over time or any other persistent source of oil in the ocean (e.g. natural seeps, leaking pipelines). By estimating the oil volume on the surface (oil slick extent by thickness classes) it will be possible to normalize the residence time by the wind conditions to calculate the oil dosage over time.

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