Technological Advances for Ocean Surface Measurements by the Consortium for Advanced Research on Transport of Hydrocarbons in the Environment (CARTHE)

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ABSTRACT

Formed in the aftermath of the *Deepwater Horizon* event, the largest accidental marine oil spill, the Consortium for Advanced Research on Transport of Hydrocarbons in the Environment (CARTHE) focused on understanding the physical processes controlling the transport of material from a deep blowout all the way to the coast. Even though CARTHE was initially a modeling-oriented team, it progressively became more focused on observations in order to collect the data needed for model evaluation. A number of new technological advances needed to be made to collect the necessary data. This article reviews most of these, with special focus on surface sampling, where much of the oil is located during oil spills, as well as the measurement of near-field droplet size distribution.

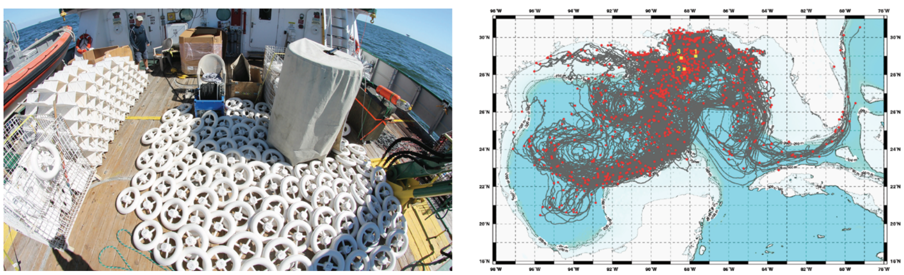
Keywords: oil spill response, ocean fronts, massive drifter sampling, marine radar, shadowgraph

Ocean Surface Sampling in the Gulf of Mexico

The Consortium for Advanced Research on Transport of Hydrocarbons in the Environment (CARTHE, http://carthe.org/) carried out several field campaigns in the northern Gulf of Mexico, with the objective of understanding processes that may influence transport of oil near the surface of the ocean, as well as evaluating the accuracy of current-generation ocean models. A variety of new instruments were created to achieve unprecedented levels of dense and overlapping data sets that span decades of spatial and temporal scales. Grand LAgrangian Deployment (GLAD) (DeSoto Canyon, Summer 2012), Surfzone Coastal Oil Pathways Experiment (SCOPE) (Destin inner shelf, Winter 2013–2014), LASER (Lagrangian Submesoscale Experiment; DeSoto Canyon, Winter 2016), and Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH) (Louisiana shelf, Spring 2017) were designed to capture transport by near-surface currents that are not well resolved. The overarching objective of these experiments was to collect data from a variety of sensors (drifting, aerial, and shipboard) to document the near-surface variability of fronts, where much of the surface oil tends to be concentrated. Two state-of-the-art models were also operated in real time during all the experiments; multiple-nested Navy Coastal Ocean Model ranging from 1 km outer nest down to 100-m horizontal resolution (Jacobs et al., 2014) as well as a coupled atmosphere-wave-ocean model (Curcic et al., 2016). The major accomplishment of the CARTHE project is the identification of the importance of so-called submesoscale flows in the northern Gulf of Mexico (Poje et al., 2014; D'Asaro et al., 2018) both during summer and winter conditions, as submesoscales are maintained year-long due to the buoyancy gradient

FIGURE 1

(Left panel) Hundreds of biodegradable CARTHE drifters being prepared for sampling the ocean. (Right panel) Trajectories of 1,000 drifters deployed in CARTHE–LASER experiment.



between the Mississippi riverine system and the interior Gulf circulation.

Advances in In-Situ Observations

Because of the high information content and high spatiotemporal variability of ocean fronts, drifters are currently the main tools that can track them in real time, as put forward by modeling in Özgökmen et al. (2012) and demonstrated in the field vividly in Poje et al. (2014) and D'Asaro et al. (2018). Approximately 2,300 drifters were released in the Gulf of Mexico under the CARTHE program. Most of these drifters are of a new design with a shallow, biodegradable hull (Novelli et al., 2017; Figure 1, left panel) to avoid plastic pollution in the ocean, a rapidly growing environmental problem as petroleum-based plastics degrade in the ocean over timescales of many hundreds of years. Our data sets contain 20 million points from drifters, in which individual trajectories usually span 4–6 months, during which time drifters traveled across the entirety of the Gulf of Mexico basin (Figure 1, right panel; Haza et al., 2018).

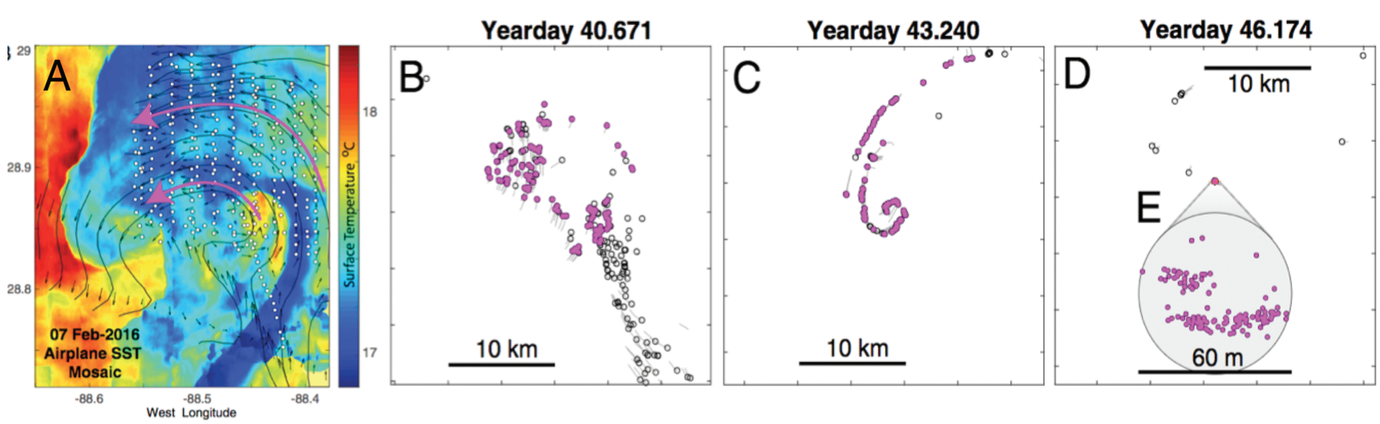
Our primary finding is that the ocean's surface is covered by convergence zones and fronts containing high vertical velocities [O(1 cm/s)]. These convergence zones are very narrow [1–100 m] and very rapidly evolving [O(1 h)]. In some cases, discovery of interesting phenomena from the data is visually obvious. For instance, a very dramatic example was captured during the LASER in winter conditions, where 300 drifters initially deployed by two ships on a frontal region over 30 km by 30 km (the size of a large city) collapsed into 30 m by 30 m (the size of a large classroom), corresponding to a contraction in area by 1 million times (D'Asaro et al., 2018; Figure 2).

The drifter technology was used in real-time response to a platform accident (Romero et al., 2016), as well as to estimate the influence of the Mississippi River outflow to an ongoing oil leak in the northern Gulf of Mexico (Androulidakis et al., 2018). The field data from CARTHE experiments was useful for NASA to evaluate a new scatterometer for ocean surface current measurements (Rodriguez et al., 2018).

The main advantage of this drifter over other designs (Lumpkin et al., 2017) is that it is extremely well calibrated in the laboratory, as well as following these extensive field campaigns in the Gulf, and that it is well

FIGURE 2

A "sink hole" identified by drifters demonstrating a collapse in area by 1 million times by the action of submesoscale processes (from D'Asaro et al., 2018). High density of drifter tracking is essential to capture such processes in the ocean, when they occur.



suited for ocean surface sampling even in very shallow waters, including coastal urban areas for pollution tracking. For these reasons, the drifter was patented and made commercially available to the oceanographic community (https://www.pacificgyre.com/carthe-drifter.aspx). The biodegradable aspect allows sampling in pristine environments, such as in the Arctic (Mensa et al., 2018).

Advances in Observations From Aerial Platforms

Because much of the oil transport takes place close to the surface of the ocean, observational platforms placed at the atmospheric side are also of interest. Satellite infrared sea surface temperature (SST) is commonly impeded by cloud cover, whereas neither the satellite microwave sensors nor altimeters have enough spatiotemporal resolution to fully capture ocean fronts. In order to extend the scale range of satellite remote sensing, to resolve the short timescales of evolution associated with fronts, as well as guiding the research vessels, innovative aerial systems were developed. Approximately 10,000 drift cards were released for ultra-high sampling density and observed from an aerostat and drones (Figure 3). By filming the motion of these cards, the motion of the ocean in the uppermost centimeter could be captured. The main concept here was to adapt a laboratory-based technique called particle image velocimetry to measure surface flows in the real ocean (Carlson et al., 2019).

An aircraft was equipped with an infrared and two visible (for sea surface roughness) cameras (Rascle et al., 2017) and operated below the cloud base. The images were fully georectified and stitched together in real time in order to provide a seamless image of the local features to the vessel (Figure 4, left panel), with a resolution of 1 m (compared to 10^3 m from MODIS, a satellite-based sensor). The typical thickness of fronts detected by both aircraft SST and surface roughness was effectively 1 m, thereby substantially and remarkably sharper than what is apparent from MODIS.

Advances in Shipboard Observations

A high-resolution marine radar was used during both LASER and SPLASH to explore its suitability for tracking features on the ocean's surface, in part to augment vessel targeting capability. A 9.4-GHz (X-band) radar was set up with an antenna that provided data with a 7.5-m resolution over a radius of 3 km around the vessel. Surface current maps were obtained by converting the sequence of radar images to Fourier space and deriving currents from wave Doppler shift. We found that this type of marine radar provided real-time images that showed frontal features effectively (Figure 4, right panel). A quantitative comparison of marine radar near-

FIGURE 3

(Left panel) Setting for the aerostat observations. (Right panel) Sample of an image from aerostats or drones, in which motion of drift cards can be used to infer surface currents.

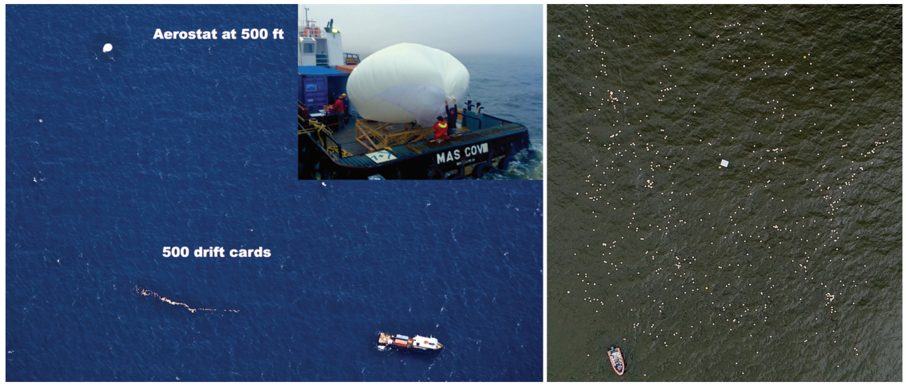
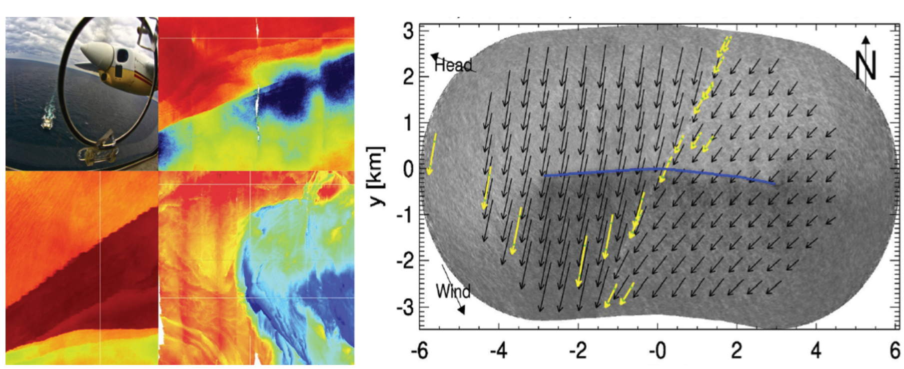


FIGURE 4

(Left panel) Sample mosaic of submesoscale features identified from aircraft SST (the scale is 10 km in diagonal direction and the color range is about 1°C). (Right panel) Velocity vectors derived from X-band marine radar as the vessel (path shown in blue) crossed a submesoscale frontal zone. Yellow arrows indicate the velocity vectors derived from nearby drifters.



surface current maps against drifter measurements was very successful (Lund et al., 2018).

The field and laboratory campaigns of CARTHE have contributed to dramatic advancements in the use of polarimetric imaging techniques for sea-surface observations. The initial deployment onboard the R/V *Walton Smith* during the GLAD experiment demonstrated the capability of the technique for making high temporal and spatial resolution measurements of the sea surface from the shipboard imaging system (Laxague et al., 2015). The polarimetric camera technology opens up a new realm of ocean sensing capability, that being the measurement of very short surface waves ranging from millimeter to meter scale (depending on the camera position and optics). These wavelengths are important for surface oil. From these measurements, it was found that gravity-capillary waves contribute the bulk of the mean-square slope of the ocean surface in steady conditions, and these length scales capture the majority of the energy transferred from wind to waves in increasing wind speed. The use of the polarimeter in the unique SUSTAIN laboratory (http://sustain.rsmas.miami.edu/) allowed for detailed exploration of the modulation of short waves by longer waves (Laxague et al., 2017), which was only possible because of the high spatiotemporal resolution of the technique. The controlled laboratory conditions also allowed CARTHE scientists to develop and calibrate (Laxague, Haus et al., 2017) a new application of polarimetric imaging to derive very near-surface currents.

The technique was validated in the ocean for the first time during the SPLASH experiment (Laxague et al., 2018), through comparison with drone-tracked drift cards, drifters, and acoustic Doppler current profilers. This technique addresses a long-standing gap in ocean sensing capabilities as no other shipboard approach can achieve continuous sampling of currents within the upper centimeter of the ocean surface. It has tremendous potential for improving understanding of surface drift velocities and remote sensing of the sea surface.

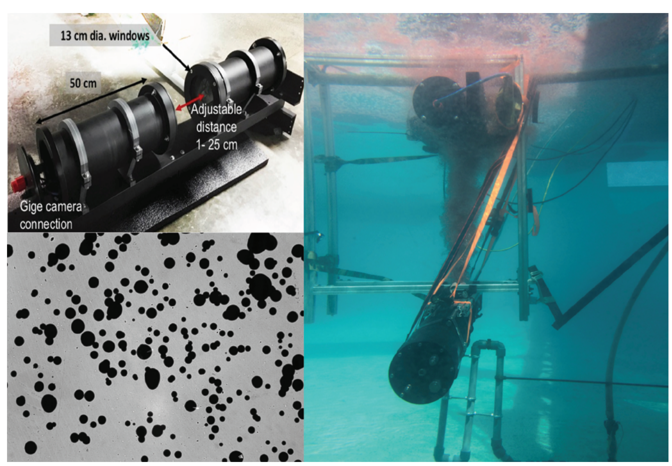
Measurement of Near-Field Droplet Size Distribution

Measurement of droplet size distribution in the near field (within a distance of a few pipe diameters) is the key to understanding and modeling how fast oil will rise in the water column in deep-sea blowouts. This measurement became particularly important due to three special aspects related to the *Deepwater Horizon* event. First, the pipe diameter in this incident was 450 mm, whereas laboratory testing typically was conducted for oil released from much smaller (1 mm) nozzles before. Second, deep-sea dispersant injection was applied during the *Deepwater Horizon* for the first time ever in order to reduce the droplet size distribution. Because this response technique is planned for future similar events, it is desirable to measure how effective it is. Finally, about 50% of the outflow during the *Deepwater Horizon* was due to gas. It is generally assumed that the gas bubbles are distributed into the oil uniformly in the riser. But, in a new theory, Boufadel et al. (2018) puts forward that the oil and gas in the Deepwater Horizon event was not well mixed, leading to so-called churn flow. This is a paradigm shift in our thinking that can also drastically change droplet size distribution, the efficacy of dispersant application, and estimates of oil discharge rates from deep blowouts.

In order to quantify these ideas, a shadowgraph, an underwater imaging system, was developed (Figure 5, upper left). This type of a device was initially designed for and very successfully used in plankton research

FIGURE 5

(Upper left) Photo of the CARTHE shadowgraph. (Right panel) Oil plume observations at the Ohmsett facility using the shadowgraph. (Lower left) Preliminary image of oil particles obtained from these experiments.



(https://www.planktonportal.org/). An extensive laboratory testing was conducted at a major oil-wave tank facility (https://www.ohmsett.com/) recently (Figure 5, right). The preliminary results (Figure 5, lower left) indicate that this technology is a promising portable method not only in a controlled laboratory setting but also in the field.

Summary and Outlook

In CARTHE, we adopted the approach of collecting massive amounts of data from multiple sensors. In order to contain the development cost and time, this was done mostly by leveraging on technologies that are spreading globally via commercial efforts, namely inexpensive GPS and other positioning devices, biodegradable materials, drones, cameras, and imaging software. Although we are providing new insights into the complexity of the ocean, new challenges have emerged. The data from such massive experimental efforts is so extensive that no single individual would be capable of digesting and making the necessary connections fast enough to provide guidance for future measurements. In order to get the most from such big data more efficiently, emerging technologies, such as new machine learning and artificial intelligence methods need to be developed or adapted.

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