TECHNICAL NOTE

Technological Advances in Drifters for Oil Transport Studies

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ABSTRACT

Advances in drifter technology applied to oil spill studies from 1970 to the present are summarized here. Initially, drifters designed for oil spill response were intended to remotely track trajectories of accidental spills and help guide responders. Most recently, inexpensive biodegradable drifters were developed for massive deployments, making it possible to significantly improve numerical transport models and to investigate, via observations, the processes leading to dispersion and accumulation of surface pollutants across multiple scales. Over the past 50 years, drifters have benefited from constant improvements in electronics for accurate and frequent location and data transmission, as well as progress in material sciences to reduce fabrication costs and minimize the environmental impact of sacrificial instruments. The large amount of in-situ data provided by drifters, covering a broad area, is crucial to validate the numerical models and remote sensing products that are becoming more important in guiding response and policy decisions.

Keywords: oil spill, drifter, ocean's surface, dispersion, transport

Introduction

The purpose of this article is to review improvements in drifter technology over the past decades with associated recent findings, which may improve future studies and impact oil transport models. In case of an accidental release of oil at sea, responders must allocate finite mitigation resources to minimize the potential damages to the environment and human health and economy. Surface oil can have severe impacts on marine life and human activity when it reaches the surface and coastal zones (Wolfe et al., 1994). How much oil is at the surface depends on the type of oil, the type of accident, and the environmental conditions. Surface oil is more easily detectable by visual observers and remote sensing techniques than subsurface oil. Avoiding landfall is usually the primary target of mitigation efforts. Therefore, accurate monitoring and prediction of the transport at the ocean surface (Where did the oil come from? Where will it go? How fast does it spread?) is crucial for preparedness. Numerical oil spill models play an increasingly significant role in predicting oil transport for risk assessment and guiding effective response (Reed et al., 1999; Spaulding, 2017).

The massive *Deepwater Horizon* event, however, posed a major and highly visible challenge for ocean prediction models and, at the same time, clearly demonstrated the need for observational programs that would provide adequate data sets, not only for fundamental quantification of ocean transport processes but also for direct model evaluation and enhanced model development.

Since 2011, in the aftermath of the *Deepwater Horizon* oil spill, the Gulf of Mexico Research Initiative (GoMRI) has enabled the investigation of the effects of oil spills on the environment and public health. The Consortium for Advanced Research on the Transport of Hydrocarbons in the Environment (CARTHE), established by GoMRI through a competitive peer-reviewed selection process, focuses on investigating the pathways and processes that drove oil from the deep Gulf of Mexico up to the coastlines. An ambitious observational program was designed to measure the ocean surface velocity field accurately and across multiple scales. The most feasible sampling strategy known was to deploy hundreds of current-following drifters (Özgökmen & Fischer, 2012; Özgökmen et al., 2011). However, back in 2012, none of the existing surface drifter designs were available in such large quantities. As a result, to satisfy the requirements of ocean sampling across multiple scales, a new drifter was developed by leveraging advances in biomaterials and in satellite positioning technology (Novelli et al., 2017).

Lumpkin et al. (2017) recently offered a comprehensive review of surface drifters with emphasis on their applications to elucidate physical and dynamical oceanic processes. Here, this article focuses on drifters developed and/or used over the past decades for the specific study of oil spill transport at sea from the first oil drifters used to monitor the position of a slick to the latest CARTHE drifter designed for massive, near-surface, and multiscales ocean sampling.

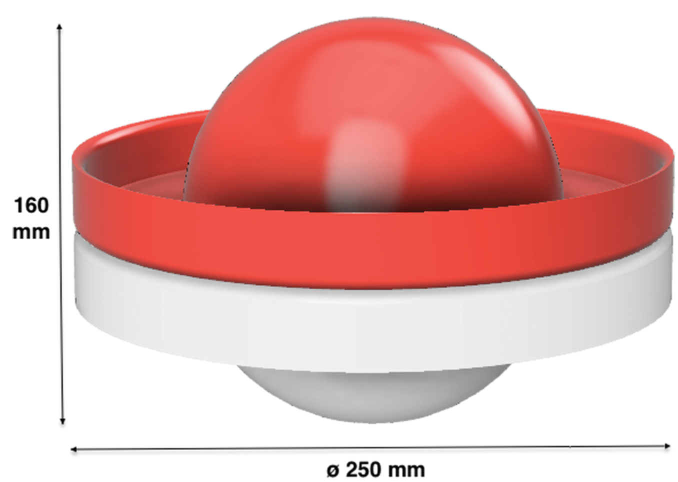
Drifters to Track Marine Oil Spills

The extent and position of an oil slick can be detected via visual observation from ships and aircrafts and by satellite remote sensing. However, such resources may not be accessible at all times. For example, many visible light observations are not available during the night and are limited to fair weather conditions or low cloud coverage. The first oil drifters, designed between the 1970s and 1990s, were intended to fill this gap; ideally, oil drifters would be deployable in an oil slick from the air or from a vessel, be carried with the oil for days, and automatically transmit their position to a remote monitoring center.

Fingas (2011) reviewed about 30 devices that had been tested for oil spill tracking by Environment Canada and the U.S. Mineral Management Service, among other groups. The tests consisted of releasing a few drifters inside small oil slicks or oil surrogates, such as cedar oil, wood chips, or cottonseed hulls. A ship would stay next to the slick for several hours to monitor it visually and estimate the distance between the drifters and the center of the slick over time. Until the 1990s, most of the oil drifter prototypes were located either visually or via triangulation of a radio signal emitted by the buoys. By the end of the 1990s, a critical improvement in terms of accuracy and remote monitoring of the position of the buoys occurred with the advent of satellite positioning systems such as ARGOS (Advanced Research and Global Observation Satellite) and GPS (Global Positioning System). ARGOS systems transmit data at a preset frequency between a platform (a buoy in this case) and low Earth orbit satellites. The location of the platform can be calculated from the position and motion of the satellites and the Doppler shift between the transmit and reception frequencies. The GPS system relies on a receiver on the platform calculating its position from the time and position of at least four (continuously transmitting) satellites of the GPS constellation in medium Earth orbit. The ARGOS systems generally use less power and can transmit data in addition to location, but they lack in location accuracy (100–1,000 m) and temporal resolution (6–28 daily passes depending on latitude). GPS systems may consume more power, as they can continuously calculate the position; they are usually accurate to 5 m or less, but they only record position. Both systems can be combined to transmit large packages of accurate geolocalized data. However, the location of the oil still needed to be mapped by *in situ* visual observers. The reported results, even though often qualitative, found that most of the drifter designs failed at following the oil slicks. The Orion buoy (Goodman et al., 1995) stood out as the design that most consistently stayed within the oil, or oil surrogate, across a variety of experiments lasting from 2 to 24 h. The Orion buoy has a diameter of about 0.25 m and is 0.16 m high (see Figure 1). A 0.03-m high ring serves as stabilizer for the buoy. The central spherical dome hosts the batteries and transmission system. Goodman et al. (1995) tested drogued and undrogued designs against oil surrogates in and offshore of Galveston Bay. Under weak tidal currents and light winds, the Orion buoy tracked the oil well for a few hours, whereas all other drifters significantly deviated from it, presumably because of near-surface current shear and wind issues. Goodman noted that experiments should last more than a few hours and that large numbers of drifters would be necessary to learn something about dispersion/spreading.

FIGURE 1

Oil spill tracking Orion buoy sketch (adapted from Goodman et al., 1995).



Reed et al. (1994) described four experimental oil releases that took place in the ocean off the Norwegian coast in 1989 and 1991. The goal was to collect data on oil slick drift and establish better trajectory modeling capabilities. Oil slicks were tracked by aerial remote sensing; wind, waves, and currents were measured, and the oil viscosity was monitored from samples taken before and during the experimental spills. Three types of drifters were released within the oil: 1-m drogued drifters referred to as "Stokes drifter"; surface thick discs 0.36 m in diameter and 0.15 m thick named "LCD" (for low cost drifter); and Argospheres, 0.30-m-diameter spherical floats. The results clearly showed that, for light winds, that is, for wind speed lower than 6–7 m/s, when no significant wave breaking occurred, the currents were significantly sheared near the surface. Thus, all the surface drifters that sampled the upper 0.30 m of the ocean did reasonably well, mimicking the drift of the oil slicks for up to 2 days. Even in the presence of a background current, the surface slicks were driven primarily by surface wind-induced currents and Stokes drift induced by short wind waves, such that the drift velocity of the slick (u) could be modeled simply, using only the wind records (W) as according to $u = 3.6\%W$, independent of the background current speed. Drifters with deeper drogues (~1 m) sampled deeper currents that were slower and tended to veer more to the right with respect to the surface, as a consequence of the Coriolis effect (also known as Ekman spiral); thus, they did not track the oil slick.

For stronger winds, above the threshold of 7 m/s in the cases reported, the drift depended on the oil properties. Light, low-viscosity oil was dispersed in very small droplets by wave-breaking action. The small droplets were entrained vertically in the water column to a depth that probably scaled with the wave height and did remain in suspension until the weather receded. Their transport was dominated by deep currents and their interaction with waves. With wave-breaking, heavy oil emulsified, which increased the viscosity of the oil-water mixture. Viscous oil broke up into larger droplets, which are more buoyant than small droplets. Thus, heavy oil was entrained less deep than light oil, making it resurface more often and subject to faster near-surface currents, which are more influenced by the wind conditions. Under strong winds, none of the drifters tested were able to track the oil, because either the slick disappeared or the deep drifters were not adequate current followers in wave conditions.

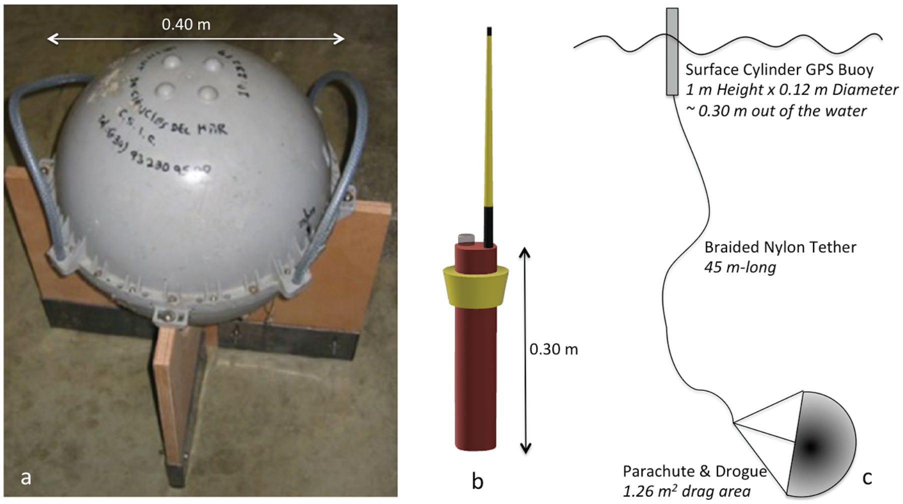
The authors concluded that, in order to predict the oil transport, one would need, at low wind speed, an accurate prediction of the wind and near-surface currents and, at high wind speed, an accurate coupled model of wind, waves, and current, as well as accounting for a variable vertical entrainment depth of oil droplets, which is a function of the nature of the oil. A variety of ocean drifters without drogues have also been used during real accidental spills (Lumpkin et al., 2017). For example, during the Prestige oil spill in Spain in 2002, eight Argospheres were deployed in slicks to track the oil and adjust oil drift models over the course of the spill (García-Ladona et al., 2016). The buoys were modified by adding wooden vertical vanes, creating a small drogue, in an attempt to reduce the windage of the sphere (see Figure 2a). A completely different ARGOS buoy was air-deployed regularly at the location of the sunken Prestige vessel (Figure 2b) to reinitialize the numerical transport models periodically (Cedre, 2006).

During the *Deepwater Horizon* spill, Horizon Marine air-deployed tens of their Far Horizon Drifters under the guidance of the National Oceanic and Atmospheric Administration's Office of Response and Restoration to monitor the oil position over the course of several months (Sharma et al., 2010). The Far Horizon Drifters are basically cylindrical buoys (0.12 m in diameter and 1 m tall), hosting batteries and GPS, tethered to a parachute that also serves as a drogue (Figure 2c). The tethers used had a length of either 4.5 m or 45 m to track currents at these depths where oil droplets could be suspended. Although the oceanographic community does not recommend the use of parachute drogues because uncertainty always remains regarding the parachute efficiency at anchoring the drifter properly (Geyer, 1988; Niiler et al., 1995), these air-deployable drifters can give a rapid synoptic map of the circulation over a broad area. The drifters transmitted their position every hour for months, showing possible pathways for oil located in and below the mixed layer.

The downside of using any of the drifters mentioned above is that the water-following characteristics of these drifters are not known and vary a lot from one design to another. Uncalibrated drifters simply cannot be used systematically to better understand the physics of surface drift and improve models. The drift characteristics of oil are not yet well known and change over time as oil ages. It is doubtful that any drifter can ever reproduce that. Nevertheless, because surface velocity data are scarce, such drifters have often been the only available

FIGURE 2

(a) Modified Argosphere drifters deployed during the Prestige oil spill in 2002. Photo credit: ©Agustí Julià (reproduced from García-Ladona et al., 2016), with permission from the author. (b) Air-deployable IESM-PTR floating ARGOS buoy sketch (adapted from Cedre, 2006). (c) Air-deployable Far Horizon Drifter with his parachute also serving as a drogue once in the water (sketch adapted from Sharma et al., 2010).



resource to get valuable information from the field. Overall, these drifters appear useful to track oil under low wind conditions, to simulate an oil spill scenario for oil spill response exercise, and for contingency planning.

Drifters to Study Oil Transport and Improve Models

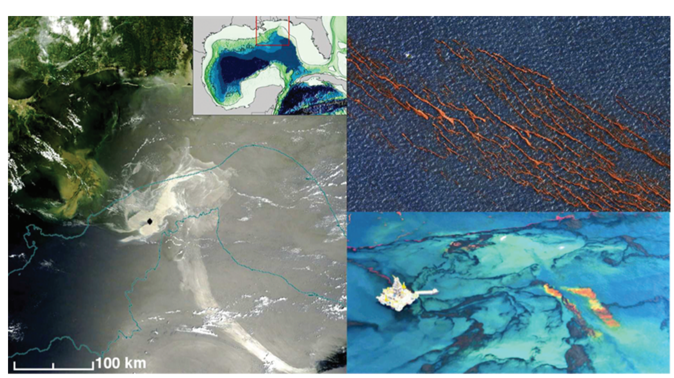
Drifters not only provide a direct visualization of the near-surface flow patterns and transport pathways but a statistical description of the turbulent flow field can also be retrieved from an ensemble of trajectories when a large number of drifters are considered. Multiple particles velocity and displacement statistics, or relative dispersion, give a measure of how a group of surface particles disperses. Note that, here, the term *dispersion* represents how and at what rate a slick can grow (or shrink) and how it may deform over time due to underlying velocity field, as opposed to the breakup of oil into small droplets as commonly used in oil literature (Boufadel et al., 2006). At the interface between the ocean and the atmosphere, the dispersion of surface oil is governed by a complex interaction of wind, waves, and currents. The processes relevant to surface oil transport, such as Langmuir turbulence (Simecek-Beatty & Lehr, 2017), mixed layer dynamics (Özgökmen et al., 2012), river plumes (Kourafalou & Androulidakis, 2013), mesoscale circulation (Olascoaga & Haller, 2012), and even extreme weather events (Curcic et al., 2016), all affect the ocean surface flow over a broad range of spatial and temporal scales (0.01–1,000 km, minutes to months; see examples illustrated in Figure 3).

Understanding, measuring, and modeling these processes is an important subject of oceanographic research. In particular, processes operating at scales below 100 km are only partially resolved by satellite altimetry and operational ocean circulation models that are used to predict oil spill trajectories.

To measure the ocean velocity field accurately and across multiple scales, the most feasible sampling strategy known is to deploy hundreds of current-following drifters. Therefore, CARTHE set up several experiments to release increasingly large numbers of drifters in the open ocean and along the coasts of the Gulf of Mexico, both in

FIGURE 3

Images of the *Deepwater Horizon* oil spill showing the oil distribution at different scales of oceanic flows. Left: Oil slick (silvery color) elongated over hundreds of kilometers by mesoscale straining result of the interaction between Loop current eddies (natural color image acquired by NASA's Terra MODIS sensor on 17 May 2010). Upper right: Oil accumulated along windrows (red) created by the interaction between wind and waves known as Langmuir circulation (NPR, 2010). Lower right: Oil (in black) accumulated along sharp fronts and cells borders (courtesy of ©Daniel Beltra).



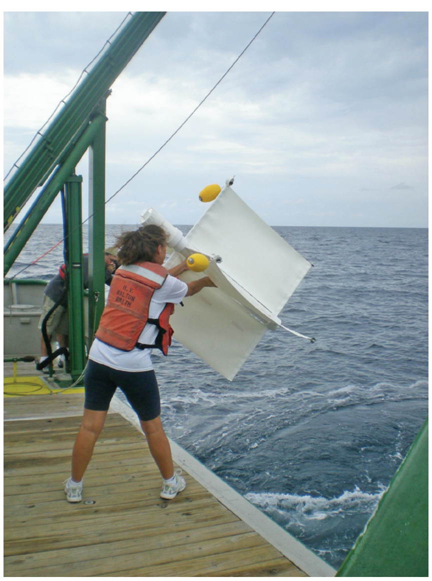
summerand in winter, between 2012 and 2017.

The CODE surface drifter design (named after the acronym of the Coastal Ocean Dynamics Experiment carried out in 1981 and 1982) was developed by Davis (1985) to track accurately the upper meter current while minimizing the wind-induced slip. The drifter consists of a meter-tall vertical pipe, containing batteries and a position system at the top, with four vanes extending from the pipe in a meter-wide cross shape (see Figure 4).

Floatation is provided by four small buoys attached by 0.30-m-long lines to the end of the vane's arms. Early designs used radio triangulation for positioning, whereas more modern ones use ARGOS and/or GPS. This design has been extensively tested in tanks and in the field, proving its capability to follow the flow in the upper meter with wind-induced slip velocity on the order of 0.2% of the wind speed at 10 m, for wind speeds below 10 m/s (Poulain et al., 2002, 2009).

FIGURE 4

CODE-type drifter deployed during the GLAD experiment.



This accurate representation of the near-surface transport has made this design the most commonly used for oceanographic studies focused on surface dynamics and for search and rescue operations (Lumpkin et al., 2017).

CARTHE's first major experiment (the Grand Lagrangian Deployment, or GLAD), in summer 2012, consisted of deploying more than 300 CODE drifters in the area of the *Deepwater Horizon* accident to quantify near-surface dispersion (Özgökmen et al., 2014). The drifters were launched in dense arrays to obtain simultaneous high-density velocity data at a range of initial separation scales between 0.1 and 10 km. The unprecedented spatial and temporal resolution of the velocity field revealed the importance of submesoscale motions in setting the dispersion rates (Poje et al., 2014). However, in a subsequent in-depth analysis of the Lagrangian statistics of the GLAD drifter trajectories, Beron-Vera and LaCasce (2016) questioned these findings and reiterated the role of mesoscale stirring in setting the dispersion rate. They suggested that the GLAD drifters undersampled the mesoscale flow and that the presence of inertial oscillations introduced a bias in the results of Poje et al. (2014). Importantly, GLAD data density allowed quantifying the effect of the unresolved physics in operational ocean models on the dispersion of surface tracer. As a result, the drifter observations could be used to significantly improve predictive models via various techniques of data assimilation (Carrier et al., 2014, 2016; Jacobs et al., 2014) and blending with satellite altimetry products (Berta et al., 2015).

The data set also served to measure the impact of tropical storms on surface transport as Hurricane Isaac passed over the GLAD drifter array in August 2012. It was found that Stokes drift was responsible for up to 20% of the average Lagrangian velocity during the passage of the storm, highlighting the importance of coupling wind, wave, and current models to represent surface transport properly (Curcic et al., 2016).

The GLAD experiment made clear that large and dense drifter arrays are an effective means of collecting multiscale velocity data. However, it also revealed that a new drifter design was needed to scale up the deployments to the 1,600 drifters planned for the Lagrangian Submesoscale Experiment (LASER) and the following Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH). Therefore, the CARTHE drifter was designed to reduce the economical and environmental cost of massive releases. The new drifter is compact and light and, therefore, easy to transport, store, and handle on research vessels. It consists of four parts only to facilitate quick assembly prior to deployment. It is mass produced by machines and therefore cost-effective, so that thousands of these drifters can be deployed in a single experiment. It uses an off-the-shelf, mass-produced GPS tracker (SPOT Trace by Globalstar) with a low-cost flat rate communication fee that makes the use of thousand units affordable, even with a time resolution as high as 5 min. Finally, it is 85% biodegradable so that long-term damage to the environment is minimized. The main material used to construct the drifter is polyhydroxyalkanoates thermoplastic that has strong mechanical properties while being nontoxic and fully biodegradable. The material is produced by engineered bacteria fed with corn sugar inside large fermentation tanks. The expected structural stability of the

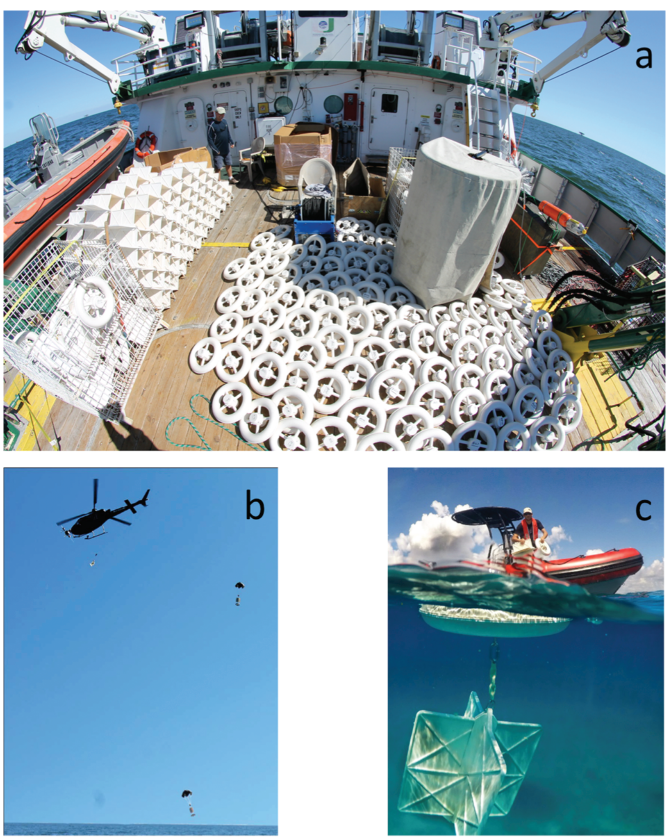
CARTHE drifters is about 1 year in the ocean and 5 years to biodegrade completely in the ocean compared to hundreds of years for petroleum-based plastic. The drifter is mass produced by injection molding and hot plate welded together in order to avoid the use of toxic glue. During its development, the drifter was extensively tested at the University of Miami's Surge Structure Atmosphere Interaction (SUSTAIN) wave tank facilities in more than 1,000 experiments (Novelli et al., 2017). The drifter consists of a floating torus (0.38 m in diameter), which houses a GPS unit with batteries, and a drogue (draft of 0.60 m), attached with a flexible connector (Figures 5a and 5c). The floater can be used without the drogue as well (draft of 0.05 m). By itself, the floater was shown to move with the speed of the Stokes drift, whereas the full drifter moves with the underlying ocean current integrated over the depth of the drogue. The drifter was designed to minimize wave rectification issues. The wind-induced slip on the full drifter was found to be less than 0.5% of the wind speed at 10 m, for wind speeds up to 23 m/s. In a series of coastal and open ocean experiments under wind speed as high as 10 m/s, there was less than 0.5% difference between the relative velocities of the CARTHE and the CODE drifters deployed together for up to 5 days. Recently, a biodegradable parachute and a parachute release system have been developed as well to facilitate air-deployments (Figure 5b).

During the LASER experiment conducted in winter 2016, a submesoscale cyclonic eddy was directly sampled by over 300 CARTHE drifters released in an approximately 20 km × 20 km array with initial drifter separation of about 1 km. After a few days, the distribution of drifter separation developed two modes: Some drifters spread over a region roughly 100 km in diameter, but at the same time over 100 drifters converged in a patch less than 60 m in diameter (D'Asaro et al., 2018). This unique observation showed clustering at scales as small as a few meters coexisting with dispersion over tens of kilometers, driven respectively by submesoscale convergence and mesoscale straining of the surface flow field. Regarding the distribution of an oil slick, being able to predict such an accumulation rate and location is important for guiding response and predicting impacts.

Another key quality of the CARTHE drifter is the extensive calibration of its drift, both with and without drogue (Novelli et al., 2017). This has made it possible to validate current measurements from a variety of remote sensing platforms. Lund et al. (2018) have been able to perform the first comprehensive validation of near-surface current maps sensed by marine X-band radar by comparing the radar measurements directly to over 4,000 drifter-derived speeds during the LASER experiment. They found an root-mean-square (RMS) error for the current speed of less than 4 cm/s and 12° for the current direction. The difference is expected as the marine radar sampled currents at greater depth than the

FIGURE 5

(a) Approximately 100 CARTHE drifters being assembled before a dense deployment. The drogues are stacked along the small red boat on the left; the floats containing the GPS are placed on the deck facing up to test the GPS transmission prior to deployment. (b) Air deployment test from helicopter of a CARTHE drifter equipped with a biodegradable parachute and parachute release system. (c) CARTHE drifter in the water deployed from a small boat.



drifters (1–5 m vs. 0.6 m) and is consistent with wave- and wind-driven currents decay and clockwise veering with increasing depth. During the subsequent SPLASH experiment, Laxague et al. (2018) had the opportunity to extract very near-surface current profiles derived from a polarimetric slope sensing technique. Such measurements were validated for the first time in the field using both drogued and undrogued CARTHE drifters. They found a current speed at 1 cm depth twice that of the average speed over the upper meter, showing the importance of resolving the near-surface layer of the ocean for the prediction of oil slick trajectories. In another study, CARTHE drifters were deployed in oil patches in the Taylor Energy site area, located off the Mississippi delta. In combination with other drifters, satellite data, drone imagery, and marine radar, they helped efficiently describe three major oil pathways in the northern Gulf of Mexico (Androulidakis et al., 2018). In Mensa et al. (2018), CARTHE drifter pairs were released in the Arctic Ocean's Beaufort Sea, where drifter pair separation statistics, second- and third-order velocity structure functions, combined with ship-based measurements of surface temperature and salinity revealed active submesoscale flows capable of enhancing the transport of sea-ice floes or surface pollutants in high-latitude ice-free conditions.

Summary

The data collected during controlled experimental oil releases at sea over the past decades indicate that, at low wind speed, surface oil tends to move downwind. In case of mild background currents (from basin to submesoscale), the surface transport may be driven primarily by wind-induced currents and wave-induced surface Stokes drift. In such conditions, drifters with small draft—on the order of 10 cm—are able to track the motion of oil, whereas drifters with deep drogue do not follow the surface oil. At high wind speeds, breaking waves break up oil slicks into droplets. The droplets can be entrained vertically in the water column for long periods of time. The location of the slick is then not well defined as resurfacing depends on the level of wave-induced turbulence and the nature of the oil, namely the droplets size and the degree of emulsification. Once below the surface, the cloud of oil is advected by deeper currents causing a differential advection varying with the depth where the droplets spend more time, according to Ekman transport theory. Whether drogued drifters can, or not, adequately represent the oil transport in these conditions is still an open question due to the difficulty in tracking suspended oil over time, particularly under bad weather conditions.

Assuredly, drifters play an important role in oil studies. They can be used during planning as oil surrogates to simulate realistic pathways and transport timescales. Thanks to the generalization of the usage of GPS for accurate remote positioning, drifters can complement remote sensing tools during a real accident by obtaining uninterrupted and real-time tracking of the thickest portions of a spill. Drifters are naturally drawn to frontal convergence zones where oil can accumulate as well, thus potentially detecting areas where response could be most effective.

Advances in biomaterial applied to sacrificial instruments now allow deploying hundreds of drifters at a time and gaining new insights into the processes of accumulation and dispersion that affect large oil spills.

New biodegradable drifters have minimal environmental impact and are now inexpensive, which help to collect dense data sets over broad areas to inform ocean models on near-surface currents for validation, assimilation, and initialization purposes.

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