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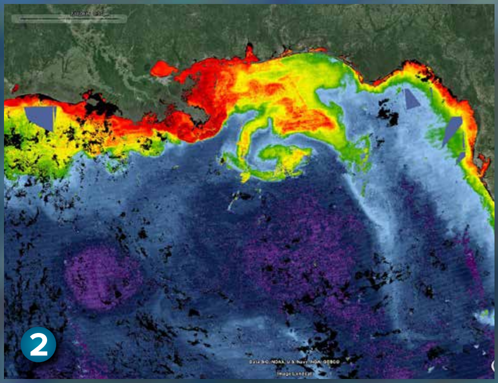

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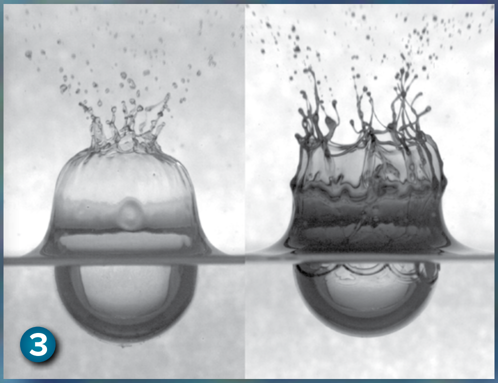

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Synthesis and Crosscutting Topics

By John W. Farrington, Kathryn A. Burns, and Margaret S. Leinen

ABSTRACT. In recent years, there have been significant advances in fluid dynamics/physical oceanography, microbiology, weathering, remote sensing, and analytical chemistry as they pertain to the fate and effects of oil spills. Effects of the Deepwater Horizon oil spill on water column organisms and ecosystems have been difficult to ascertain. Laboratory experiments have expanded understanding of oil effects on phytoplankton and zooplankton. “Marine oil snow” has been identified as a significant factor in the fate of oil chemicals and their deposition with sediments. Oil chemicals and their effects on 24 km^2 of mud-benthic communities surrounding the well site, and in a few other areas, have lasted several years. Some deep-sea corals have also been affected for several years, and oil chemicals and their effects in heavily oiled marsh areas are projected to last a decade or longer. Lightly oiled marsh areas have recovered or are recovering. Research about use of dispersants highlights the need to update the 2005 National Research Council study of dispersant use on oil spills. Ongoing research should provide some closure for the issues of long-term effects on fisheries and marine mammals, and impacts on human health. Practical uses of this new knowledge are discussed briefly.

INTRODUCTION

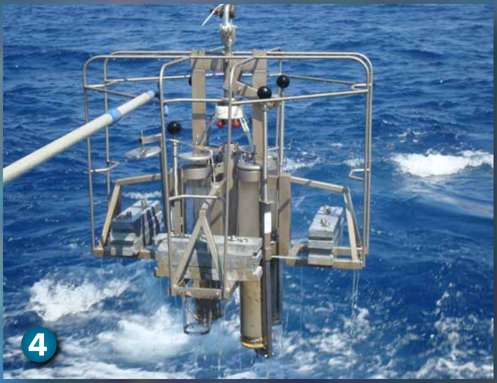
This article highlights important advances of Deepwater Horizon (DWH) oil spill research to date, major questions yet to be answered, and new questions posed. We caution that this is a mid-course summary assessment. We cannot do justice to all the research summarized in articles in this issue of *Oceanography*. Research and debates about aspects of the fates and effects that have been published are ongoing, consistent with the scientific process. Box 1 reminds us of the difficult challenge being addressed.

Mainly, papers in this issue (highlighted in orange here) report on research conducted with funding from the Gulf of Mexico Research Initiative (GoMRI; Shepherd et al.). This effort is founded in decades of research focused on oil pollution in the marine environment. For example, by the mid-1970s, the majority of processes governing the fate of oil were known qualitatively (e.g., see Figure S1 in the online supplementary material). Similarly, the types of effects to be expected were known in a general sense (NRC, 1975, 1985, 2003; Table S2). Most importantly, over the years, we have learned that each oil spill has unique characteristics (NRC, 1975, 1985, 2003, among others).

KEY ADVANCES IN UNDERSTANDING FATES AND EFFECTS OF OIL IN THE MARINE ENVIRONMENT

Complexity of Chemical Composition of DWH Petroleum (Oil and Gas)

Overton et al. provide a synopsis of the complexity of the chemical composition of petroleum (gas and oil). The vast majority of discrete oil and/or gas samples or hydrocarbons from air, water, particulate matter, sediments, and organisms were analyzed using methods that evolved from analytical chemistry advances of two to three decades ago and based on the current requirements of the Natural Resources Damage Assessment (NRDA) processes. These methods are considered the “routine” or standard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PHOTOS. (1) A team from the Maritime Magnet Program at South Broward High School participated in a student drifter competition that is part of an effort to improve predictions of how oil moves through coastal waters and onto shores. *Photo provided by the Consortium for Advanced Research on Transport of Hydrocarbons in the Environment* (2) The Gulf of Mexico as seen in this July 11, 2015, satellite-derived chlorophyll-*a* image showing a plume originating from the Mississippi River. *Image provided by Ryan Vandermeulen* (3) Splashes resulting from impact of a raindrop on a 30 micrometer oil slick (left) and a 400 micrometer oil slick (right). Splash behavior changes with increasing oil layer thickness, and more droplets are ejected as aerosol for the thicker oil slick. *Image credit: David W. Murphy* (4) Sediment samples collected from the seafloor using a multi-corer are being subjected to a full suite of hydrocarbon and isotopic analyses. *Photo credit: Deep-C Consortium* (5) Example of the commensal ophiuroid *Asteroschema clavigerum* (brittle star) on a coral impacted by the DWH oil spill. Note the hydroids (brown, hairy-looking material) that have settled on dead parts of the coral. *Photo courtesy of C. Fisher and the Ocean Exploration Trust* (6) Marine technicians Jennifer Hemphill, Matthew Metcalf and Sara Kerner set fyke nets (traps used to collect marsh-associated finfish and shellfish) near Point-aux-Pins, Alabama. *Photo credit: Ryan M. Moody* (background photo) Oil sampling location during research cruise off Louisiana coast on May 26, 2010. *SkyTruth photo, public access by NOAA*

methods of analyses for oil spill samples. The numbers of samples analyzed from the DWH oil spill numbered in the tens of thousands, with an array of concentration data for upward of 100 or more individual hydrocarbons per sample (e.g., Wade et al., 2016). This very large data set has yet to be fully interpreted in detail, although the process has begun (e.g., Boehm et al., 2015; Murawski et al.; Wade et al., 2016).

Detection and Analysis of Gas and Oil In Situ

White et al. summarize the combined arrays of longer-standing technologies, for example, conductivity-temperature-depth (CTD) instruments; GO-FLO sampling bottle rosette arrays; and sediment traps, as well as the latest technologies such as autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs). These vehicles were instrumented with optical sensors for detecting oil droplets, particles, and plankton, and AUV *Sentry* also carried an in situ membrane inlet mass spectrometer that was deployed during and after the DWH oil spill (see White et al. Figure 1). "Satellite, aircraft, buoy, glider, profiler, and surface vessel platforms" were used to assess surface ocean oil.

The ocean research and technology and the oil spill response communities can take advantage of the experience of and lessons learned from deploying these technologies. Such an evaluation should lead to development and procurement of an optimum array of instruments and systems to be used by oil spill response agencies and entities worldwide, as well as development of plans that will better inform appropriate responses to oil spills.

Advances in Analyzing Petroleum and Transformation Products

Exciting advances in analytical chemistry have extended analytical power beyond the more standard, routine methods discussed above. Advances include the evolution of two-dimensional gas chromatography (GC×GC; e.g., Gaines et al., 1999; Frysinger and Gaines, 2002) and its coupling to high-resolution mass spectrometry. These techniques were applied with great success to expand our understanding of the fate of oil chemicals in smaller regional oil spills (e.g., Reddy et al., 2002). As a result, the techniques were robust and ready for use in analyzing several hundred DWH samples.

Another exciting development has been the interfacing of gas chromatography to Fourier transform-ion cyclotron resonances-mass spectrometry (GC-FT-ICR-MS), which has been used to analyze DWH oil and selected samples from the environment (White et al.; Tarr et al.). This methodology helps unravel the composition of the higher molecular weight asphaltenes and resins in crude oil, chemicals that have largely been ignored in prior oil spill studies. The methodology also provides critical insights about the type and molecular weight range of chemicals found in environmental samples that result from photochemical reactions and microbial degradation of oil.

These new analytical capabilities augment traditional GC-MS methods and provide more quantitative understanding of how much oil is in the environment and where it goes (Boehm et al., 2015).

Box 1. The Challenge

Take a complex mixture of hundreds to thousands of chemicals (crude oil), inject it as a mixture of gas and oil into the complexity of the Gulf of Mexico ecosystems, subject it to physical dynamic processes (evaporation, dissolution, photochemical reactions) on scales from microns to 1,000 km, as well as dynamic biological and chemical processes (microbial degradation, metabolism of oil by some marine animals who take up oil chemicals and excrete the metabolites, sorption/desorption on particulate matter, deposition and resuspension), and then address the fates of the oil and microbial degradation, metabolites, and photochemical reaction products on time scales of minutes to decades in multiple components of the ecosystems. Furthermore, and even more challenging: What are the effects on biological scales from subcellular to whole ecosystems over that span of time? Stir in some dispersant, and the situation enters another level of complexity!

Fluid Dynamics and Physical Oceanographic Processes

Socolofsky et al. and **Özgökmen et al.** summarize achievements in applying fluid dynamics, field observations, experiments, and modeling of physical oceanographic processes in the Gulf of Mexico to the DWH well blowout and subsequent fate of the spilled gas and oil.

Nearfield modeling workshops, the model intercomparison workshop, and related research by several groups led to significant advances in our understanding of what happens during and immediately after a DWH-type event. **Socolofsky et al.** describe the physics and fluid dynamics of injection of high-pressure gas (including formation of gas hydrates) and oil at the seabed, the subsequent formation of a plume or multiple plumes (depending on conditions) at intermediate water depths, and the resulting plume dynamics, including gas bubbles and oil droplets. Hind-cast modeling provides useful comparisons with field observations and brings attention to the importance of spatial and temporal scales for the processes governing the fate of the oil and gas (**Socolofsky et al.** Figure 6).

Özgökmen et al. provide a schematic depiction (their Figure 2) of the transport processes important to the fate of DWH gas and oil. They note the importance of the remote-sensing tools deployed on satellites and aircraft, especially synthetic aperture radar (SAR), in providing assessment of the locations and spreading of oil slicks after a spill has begun and/or reached the surface.

Complex interactions of motions at different scales, from the Loop Current to the mesoscale and submesoscales, are important for predicting the spreading of the oil. The lack of sufficient observations to unravel these interactions on multiple scales was addressed post-spill by a Grand Lagrangian Deployment (GLAD) experiment (**Özgökmen et al.**). In addition, an experiment was conducted to measure inner shelf and surf zone processes—Surf zone Coastal Oil Pathway Experiment (SCOPE)—“the last mile” to the coast and in the surf zone. The results of natural basin-scale dispersion processes in the deep Gulf of Mexico were assessed by an inert tracer release experiment. Figure 5 in **Özgökmen et al.** depicts the 12-month post-tracer release results and provides one boundary condition for expectations for dilution and transport in the deep Gulf of Mexico. This article also summarizes the various ways this new knowledge can inform operational oil spill models.

Weathering of Oil

The physical-chemical processes of evaporation and dissolution acting on spilled oil at the ocean’s surface have long been studied both in the laboratory and in the environment (e.g., see Figure S1). Schwarzenbach et al. (2003) discuss in detail the underlying physical-chemistry processes.

Tarr et al. summarize research about weathering processes and how they apply to the DWH oil spill. The chemical analyses of diverse sample types coupled with studies of ocean surface, subsurface, and coastal-nearshore processes are significant contributions from DWH spill research.

Advances in analytical chemistry provide greater resolution of changes in the chemical composition of oil that result from weathering processes (**Tarr et al.** Figure 4). As mentioned above, the newer methods of GC-FT-ICR-MS expand the analytical chemistry “window” to studies of weathering of the higher molecular weight components of some crude oils—the asphaltenes and resins (**Overton et al.**)—and to reaction products of photochemistry and microbial degradation (Figures 2 and 4 of **Tarr et al.**).

Microbiological Degradation of Gas and Oil and Microbial Ecology

Advances in molecular biology (i.e., genomics, metagenomics, proteomics, metaproteomics, metabolomics) led to the development of computational modeling techniques that predict the response of microbial communities to gas and oil inputs from the DWH spill (**Joye et al.**). Collectively, this research is a major step forward in understanding microbial degradation of gas and oil inputs to the marine environment, particularly deepwater environments.

It is known that microbial degradation of oil is influenced by the physical state of the oil, for example, whether it is dissolved/dispersed in the water column, sorbed to particulate matter, or buried in beach sand or in nearshore or marsh sediments. The continuing presence over months to years of partially biodegraded oil in nearshore sediments, beach sands, and marshes is evidence that complete degradation of the higher molecular weight cycloalkanes, and polycyclic aromatic hydrocarbons (PAHs) will take years to decades in some places (Joye et al.; Rabalais and Turner).

A new aspect of the DWH spill research was the study of microbial populations and their activity in the oil-laden deepwater plume at ~1,000 m to 1,200 m depth. Open-ocean and deep-ocean measurements in this type of environment had previously been rare to nonexistent. The results of this research provide new knowledge of the effects of gas and oil on microbial populations and communities, and the resulting microbial degradation of some individual chemicals in the oil and gas. Relatively few experiments have examined the influence of the deep ocean's high pressures on microbial degradation of hydrocarbons (Joye at al.).

Particulate Matter and "Marine Snow"

An important discovery about the fate of DWH oil in Gulf of Mexico continental margin and deep-sea environments concerns the contributions of marine snow/oil interactions to the short- and long-term fate of the DWH oil chemicals.

It has been known for decades that sorption (both absorption and adsorption) of medium to higher molecular weight hydrocarbons to particulate matter, such as mineral particles, organic-material-coated mineral particles, and fecal pellets, is an important process in the fate of oil chemicals (Figure S1). Passow and Hetland provide a synopsis of vertical transport and sedimentation of particulate matter through the water column (see their Figure 2). The resulting delivery of oil chemicals to the benthos and surface sediments is important to the fate of oil in marine ecosystems and its effects on benthic organisms, as discussed below.

It may be speculated that marine snow, also well known in biogeochemical cycles for a few decades, is involved somehow in the biogeochemical cycle of petroleum hydrocarbons. In fact, pioneering research connected with the DWH spill demonstrates that marine snow participates in the fate and effects of medium to higher molecular weight hydrocarbons and perhaps to the products of photochemical and biodegradation reactions. Passow and Hetland and Passow and Ziervogel explore and summarize the various interactions between phytoplankton, microbial processes, and oil chemicals—with and without dispersant added to the mix. The term for marine snow interacting with oil chemicals is MOSSFA, for marine oil snow sedimentation and flocculent accumulation. Much follow-on research related to these phenomena has evolved from initial discoveries and workshops organized to explore the findings and discuss needed experiments and observations (e.g., GoMRI, 2015). Oil-mineral aggregates (OMA) are also discussed as potentially important. The DWH experience strongly indicates that MOSSFA events need to be factored into fate-and-effect models for future spills and targeted for field measurements during response assessments and research.

Passow and Hetland note an additional important hypothesis and associated field observations: DWH oil chemicals entrained in the subsurface plume at ~1,100 m depth horizontally intersected the surface sediments of the continental slope, resulting in incorporation of oil chemicals into surface sediments that resemble a "bathtub ring."

Initial deposition of MOSSFA material was followed by resuspension and transport that resulted in lateral redistribution (Passow and Hetland). The amount of DWH oil deposited to surface sediments was estimated by a few studies, summarized by Passow and Ziervogel, as roughly between 2% and 15% of the total released oil. Box 1 in their article provides an important comparison of contoured areas of between 1,500 km^2 and 24,000 km^2 receiving deposited oil according to five different studies. Four years after the spill, the DWH oil footprint on the seafloor was still quite extensive, at about half of its original size.

Fate of Oil: Beaches and Coastal Wetlands

Despite best efforts at preventing oil from reaching shore—dispersants, containment booms, sorbent booms, oil skimmers on oil slicks at sea, burning of herded oil, release of freshwater from Caernarvon diversion of the Mississippi, and use of booms to protect shorelines in key areas—over 1,700 km of beaches and wetlands (marshes and mangroves) were oiled out of 7,058 km of shoreline surveyed along the Gulf Coast of Louisiana, Mississippi, Alabama, and some parts of the Florida Panhandle (Michel et al., 2013; Rabalais and Turner). As with oil spills in the past, oiling of beaches and the wetlands was uneven, resulting in some heavily oiled areas and some lightly oiled areas as defined by appearance and/or measurement of petroleum hydrocarbons. Much of the oil coming ashore was in the form of an oil-water emulsion that has been termed "mousse."

Beaches

The majority of the heavily oiled and moderately oiled beaches were cleaned according to response protocols (BP, 2014). However, some of the oil was incorporated into nearshore submerged mats of oil and sand, and other oiled sand was buried in beaches. The dynamic environment of storm-impacted nearshore and beach areas resulted in reemergence of buried oiled sand and re-oiling of some beaches by the nearshore oiled-sand mats. Several multiyear studies have tracked the fate of residual oil-tar patties or residual oil-tar balls on beaches, documenting compositional changes due to weathering and microbial processes (Rabalais and Turner; Tarr et al.). There is now a wealth of information concerning the fate of oil coming ashore to beaches to inform responses to future spills.

Marshes

The majority of the oiled marsh areas were in the Louisiana coastal area. There was time for several scientists to get background samples prior to the oil coming ashore, and some of these areas were already the subject of long-term marsh ecology studies. In addition, some areas had already been subjected to inputs of petroleum hydrocarbons from various small spills and chronic sources over the years (Rabalais and Turner). Earlier marsh studies provided critical assessment of the status of these coastal areas prior to the DWH oil coming ashore.

Oiling was patchy in location and intensity. Oil was found not only at the edge of marshes but also up to 100 m into the marshes in some locations and at depths of several centimeters in marsh sediments. Oil arrived at the marshes with varying degrees of weathering. The oil chemicals persisted in some places through June 2013, and fresh oil that was still evident in some marshes in 2015 may have been "sequestered inside fiddler crab burrows" (Rabalais and Turner). For some heavily oiled marsh locations, it will take a decade or longer for PAHs to reach background, pre-DWH spill concentrations.

The patchiness of the oiling and the heterogeneity of the spatial and temporal aspects of return to background concentrations, or nondetectable concentrations for petroleum hydrocarbon in the marsh sediments, is consistent with results of studies of previous spills that oiled marshes or mangroves (e.g., Teal et al., 1978; Burns and Teal, 1979; NRC, 1985, 2003; Baca et al., 1987; Burns et al., 1993, 1994; Reddy et al., 2002; Bejarano and Michel, 2010).

BIOLOGICAL EFFECTS

Beaches and Wetlands

Beaches

Studies of microbial community compositions were conducted in concert with studies of weathering and biodegradation of DWH oil in beach areas. However, there has been a paucity of studies of the effects of oil on beach fauna that were oiled by the DWH spill and subjected to various cleanup operations (Rabalais and Turner). In one beach environment in Mobile Bay, Alabama, nematodes seemed to be adversely impacted for a short period of time (months). During this same time period, fungi flourished (Murawski et al.).

Marshes

Rabalais and Turner summarize field studies that used carefully documented heavily oiled marsh areas, lightly oiled marsh areas, and control plots; laboratory experiments; and mesocosm experiments. Adverse effects were identified at various levels of organization within marsh ecosystems in comparisons of heavily oiled sites with sites with low oil concentration and with controls. Recovery began within one year in marsh areas with low oil concentrations. Marsh areas covered with heavier doses of oil, mainly in the area surrounding Barataria Bay in Louisiana, are still recovering and may take a decade or longer to fully recover. Increased marsh erosion rates have been documented at heavily oiled sites after two years (Rabalais and Turner). All of the preceding observations are consistent with what has been learned from previous studies of marshes and mangroves.

Clearly, continuity of studies of the oiled and control marshes in Barataria Bay for an extended period of one or two decades is warranted.

Nearshore, Continental Shelf, and Open-Ocean Plankton

Temporal and spatial heterogeneity of natural driving functions of phytoplankton and zooplankton populations, such as riverine inputs of freshwater, nutrients, and particulate matter; storms; and variability in populations over time due to climate change and other human factors including chronic pollution inputs and fishing pressure, make it difficult to ascribe any observed population changes to the DWH oil spill over a large area for periods of weeks or longer (Buskey et al.; Murawski et al.; Fisher et al.).

The complex interactions of physical, chemical, and biological processes with oil chemicals and dispersants under the actual DWH event conditions make it challenging to unravel the importance of any given process to the fates and effects of the petroleum chemicals. Thus, it has been and continues to be appropriate to conduct laboratory and mesocosm experiments that simplify the interacting factors. Buskey et al. review numerous laboratory experiments that have added significantly to our knowledge. When designing such laboratory and mesocosm experiments, it is challenging to decide what concentrations of oil, stages of weathering/biodegradation, and dosing/mixing protocols to use to best represent conditions in the field—immediate post-spill near the site of the spill or far afield weeks or months later. After that time, oil concentrations in the water column decreased as a result of a combination of deposition to sediments, microbial degradation, dilution with surrounding water, and exchange to the atmosphere at the air-sea interface of any remaining volatile oil chemicals.

A greater understanding of the biology/ecology of the pelagic and mesopelagic zone should be pursued with studies of such subjects as the important roles phytoplankton, zooplankton, and the microbial loop play in the food web; exudation/production and packaging of marine snow; and the role of marine oil snow in removing oil from the water column.

Fisheries and Fish

Murawski et al. note the complications in unraveling the effects of DWH oil on fisheries, given all the other factors that influence stocks of fish, for example, fishing pressure, other chronic pollution inputs, ecological perturbations due to fluctuations/timing of freshwater inputs, and climate change.

Fish landings were adversely impacted for several months because of closure of DWH-associated fishing areas to protect public health (i.e., reduce the risk to public health of eating DWH oil contaminated species). Fish landings rebounded once it was determined, after the DWH well was sealed, that only a few areas remained where contaminated fish might pose a threat to public health.

Areas and volumes of Gulf seawater where DWH oil concentrations in the water column were elevated above background were compared to usual temporal and spatial extents of spawning and larval fish distributions. The results suggest exposures were low to modest for fish populations as a whole. One exception may be tilefish (a burrowing fish species) living in areas containing oil-contaminated sediments.

Overall, the fisheries in the Gulf recovered to pre-spill population levels within a year or two after a short-term decline. Some longer-lived species such as bluefin tuna and red snapper may suffer longer-term declines if there has been impairment in growth rates or year-class strengths (Murawski et al.).

In summary, there were some short-term effects of the DWH spill on fisheries and on specific fish species stocks, and future assessments will provide information about whether there is any significant detectable long-term impact.

Nearshore and Continental Shelf Benthos

Thus far, there is a limited amount of published data on any effects of DWH oil or oil/dispersant mix on the soft bottom benthic community in this geographic zone. Murawski et al. cite studies of macrofauna (Cooksey et al.; 2014) and of meiofauna (Landers et al.; 2014) conducted soon after the spill that did not reveal strong effects, and sediment PAH concentrations were not elevated above pre-spill background in their sampling sites. However, the sampling area was along the northeastern Gulf of Mexico coast and not in the area of soft bottom sediment with elevated DWH hydrocarbon concentrations identified by Murawski et al. west of the Mississippi Delta.

DWH oil and/or dispersants may have adversely affected shallow water communities, but it was difficult to be definitive because of apparent ongoing "natural or anthropogenic stressors associated with life on the shallower shelf" (Fisher et al.). Observations of an area of pinnacle reefs at the edge of the continental shelf demonstrated that they were adversely affected by the spill (Murawski et al.).

Open Ocean and Deep Sea

The lack of adequate baseline or benchmark data hampered efforts to discern adverse effects on both mesopelagic and bathypelagic fauna. Ongoing efforts, some about to be concluded, may rectify this situation (Fisher et al.).

The existence of active petroleum seeps is a reasonably understood natural phenomenon of the deep Gulf seafloor. In areas near the seeps, benthic fauna utilize seep carbon either via a food web based in microbes that use the oil as a carbon source, or by being a host for symbiotic bacteria. Despite the presence of natural seep ecosystems, which might be thought to precondition organisms and ecosystems to the addition of DWH oil chemicals, DWH oil deposited on the seafloor has adversely affected some areas of the benthos (Fisher et al.). This observation suggests that some or most preconditioning processes related to the presence of natural oil seeps are localized near the seeps.

In two sites, about 70 km and 130 km northeast of the DWH well at 1,143 m and 1,043 m depth, respectively, analyses of carefully obtained multicore sediment samples showed that there was an 80%–93% decline in benthic foraminifera in surface sediments sampled in December 2010, seven months after the accident. A year later, one site closest to the well site showed evidence of recovery, while the other site continued to show a decline in benthic foraminifera (Schwing et al., 2015). Further assessments at these sites are in progress.

Areas within 3 km of the DWH wellhead displayed "a severe relative reduction of benthic macro- and meiofaunal diversity…(–54% and –38%, respectively)…over an area of about 24 km^2" (Fisher et al.). Moderate impacts extended up to 17 km toward the southwest and 8.5 km toward the northeast over an area of 148 km^2, and the effects were correlated to petroleum hydrocarbon and barium concentrations. Because of geographic location, the elevated concentrations were not attributable to natural hydrocarbon seepage (Figure 2 in Fisher et al.). According to these authors, macrofauna and meiofauna diversity had not recovered after four years. Once again, longer-term assessment is in order.

DWH oil chemicals deposited to the benthos had observable adverse impacts on deep-sea coral communities in selected areas of the hard bottom seafloor, and there is compelling observational and chemical evidence that the adversely impacted deep-sea corals were covered with marine oil snow as a result of a MOFFSA event (Fisher et al.). As with the adversely affected soft-bottom benthic communities, follow-up assessment is warranted.

Assessment of the effects the DWH spill had on cetacean populations is hampered by the low precision of the estimates of abundance in given locations. There were 140 reported mortalities attributable to the spill, but mortalities may have been as much as 50 times higher because of lack of carcass recovery (Fisher et al.). Ongoing GoMRI research will provide further insights about the long-term impacts on cetaceans, especially sperm whales (*Physter microcephalus*).

DISPERSANTS

Dispersant application is an important potential response to spilled oil within the context of Net Environmental Benefit Analysis (NEBA; API, 2016; IOGP-IPIECA, 2016; IPIECA, 2016; ITOPF, 2016). Thus, it is important to learn as much as practicable about the fate and effects of dispersant use during the DWH spill to inform future decisions about using dispersants.

John et al. provide a synopsis of how dispersants interact with oil and seawater. They also summarize the use of the Corexit class of dispersants, specifically

Corexit EC9500A (commonly referred to as Corexit 9500), for the DWH spill and provide a concise description of the chemistry and physical chemistry of dispersants. **John et al.** also summarize the considerable research on options other than Corexit and the improvements to currently available dispersants that have been undertaken during the past few years.

As widely reported, the DWH spill was the first time dispersants were introduced into an escaping gas and oil plume at the depth of release. Corexit 9500 was also sprayed on surface oil slicks by aircraft. The results of field observations and laboratory experimentation involving DWH oil, other oils, dispersants, and oil-dispersant mixtures provided some important results that have stimulated ongoing research.

Analytical methods have been developed to detect the surfactant components of Corexit 9500 in various types of samples and at low concentrations. In the DWH spill studies, one component of Corexit 9500, dioctylsodium sulfosuccinate (DOSS), was detected in various parts of the Gulf's ecosystems, including in the subsurface oil plume, in deep-sea sediments and corals, and in samples of residual oil mats and tarballs in beach sands (**John et al.**).

Other research has focused on the interactions of dispersants with the formation and fate of marine snow and marine oil snow. The research thus far indicates complexity in these interactions (**John et al.**) that will require more experiments to clarify the roles of various processes. The same can be stated for the interaction of Corexit 9500 with microbial populations and the ability of such populations to biodegrade components of oil.

Some studies demonstrate that Corexit 9500 has some adverse effects on selected species of bacteria, thereby altering the microbial ecosystem. How Corexit impacts microbial degradation of oil compounds in situ under field conditions has yet to be clarified. **John et al.** note the importance of undertaking laboratory research in a manner that allows for extrapolation to concentrations of dispersant-oil mixtures that have been, or will be, found in the environment under actual oil spill response conditions.

After the use of dispersants at the DWH spill, there have been intense debates at oil pollution focused scientific meetings surrounding such experiments or extrapolations to field conditions, given the complex set of interactions suggested from field observations. Prince (2015) provides a thoughtful review and outlines several of the questions remaining to be answered.

It has been a decade since the 2005 review of use of dispersants in response to oil spills by the US National Research Council. Given the importance of the topic and the results published in the literature since 2005, especially since the DWH spill, it is time for the US National Research Council, or a similar authoritative organization, to conduct another review.

HUMAN HEALTH ISSUES

Risks from Exposure to DWH Oil-Contaminated Beach Sand and Seafood

Overall, both short-term and long-term risks to human health from exposures to DWH oil-contaminated seafood and beach environments were not considered unacceptable according to guidelines developed by state and federal public health authorities (**Dickey and Huettel**). However, fisheries were closed for 74 days in areas impacted by the spill, and, as noted by **Dickey and Huettel** and explained in detail in Wickliffe et al. (2014), the risks associated with eating oil-contaminated seafood are based on a limited number of specific PAHs that could be measured accurately in the past and for which it was feasible to estimate risks. More could be and should be done to update risk assessments of the complex mixture of PAHs (and other crude oil chemicals) that are known to be present in seafood contaminated by crude oils. The assessments should include chemical compositions of an extended range of medium to higher molecular weight PAHs such as found in the DWH crude oil.

Singer and Sempier summarize the ongoing research that addresses the important complex issues of the interrelationships between the DWH oil spill and socioeconomic, sociological, and stress factors, and the health of the diverse populations of people in the Gulf.

EDUCATION AND OUTREACH

GoMRI Graduate Students and Postdoctoral Researchers

The GoMRI research synthesized and summarized in this article has benefited substantively from the research efforts of graduate students, postdoctoral scientists, and engineers. **Benoit et al.** note that graduate education, advising, and mentoring have been woven into GoMRI-supported research from the beginning of the program. Master's and doctoral degree students and postdoctoral researchers have had the opportunity to pursue research that contributes to advancing fundamental new knowledge in ocean sciences; physical, chemical, geological and biological sciences; and/or engineering, while simultaneously addressing immediate or near-term oil pollution challenges and solutions. It is interesting that the GoMRI graduate education, advising, and mentoring efforts have been ongoing for several years and incorporate many of the valued-added (our words) aspects of graduate education in ocean sciences described or called for by authors of several articles in the March 2016 special issue of *Oceanography* focused on graduate education in the ocean sciences (http://tos.org/oceanography/issue/volume-29-issue-01). This GoMRI cadre of early career scientists and engineers are, or soon will be, poised to pursue a diverse range of rewarding careers across a variety of sectors (e.g., academia, business and industry, government agencies, nonprofit entities) to help solve immediate or near-term problems, to advance fundamental knowledge, or both.

Informing Stakeholders

Shepherd et al. show that hundreds of peer-reviewed articles that include results of GoMRI-supported research have been published in scientific journals, informing one stakeholder group—the international scientific and engineering community. Importantly, this credible science and engineering effort underpins an impressive array of education and public outreach activities described by Benoit et al. These efforts are engaging a much broader spectrum of stakeholder groups—the general public, commercial and sports fishers, recreation and tourism, various industries, elected and appointed officials, and local, state, and national agencies—and are currently being assessed.

CROSSCUT OF MAJOR FINDINGS AND PROCESSES

Where Did All the Oil Go?

Figure 1 summarizes our current understanding of the processes controlling the fate of the DWH oil and gas input. While much progress has been made on the physical dynamics, as summarized earlier, at best we have only qualitative or semi-quantitative understanding of the amounts and rates of movement along other biogeochemical process pathways and for only a small proportion of all the chemicals involved. Passow and Hetland in their Figure 3 outline the challenge of documenting "Where did all the oil go?" That question is important, but the answer will incorporate what happens as the processes proceed and the composition of the oil changes. Perhaps, as research continues and more NRDA data and other data are interpreted fully and published, a better answer than we have at present will be forthcoming.

Figure 2a–c depict three of the major crosscutting issues that have emerged. Figure 2a highlights in simple terms the complexity of understanding the fates and effects of spilled oil (see Box 1). Progress has been modest in exploring and understanding the interactions of photochemical reactions and microbial degradation as they influence toxicity of oil chemicals to marine organisms and the fates of oil chemicals, especially when considering the addition of dispersant to the mix. A continuing challenge is how to extrapolate quantitatively from sublethal effects at the subcellular, cellular, and organism level to effects at the population level.

Figure 2b is a significant simplification of the complexity of understanding the effects of oil on marine organisms. It has taken a combination of field observations, laboratory experiments, and mesocosm experiments coupled with modeling to make progress on this topic. Now that NRDA field data from the early days and months of the spill are available for water columns in nearshore, continental margin, and deep-sea regions, it is possible to place some of the laboratory and mesocosm experiments in a more quantitative framework of actual field exposures. However, despite the large size of the data set relative to some other spills in the past, the spatial and temporal coverage is limited compared to what we believe was the actual exposure field and

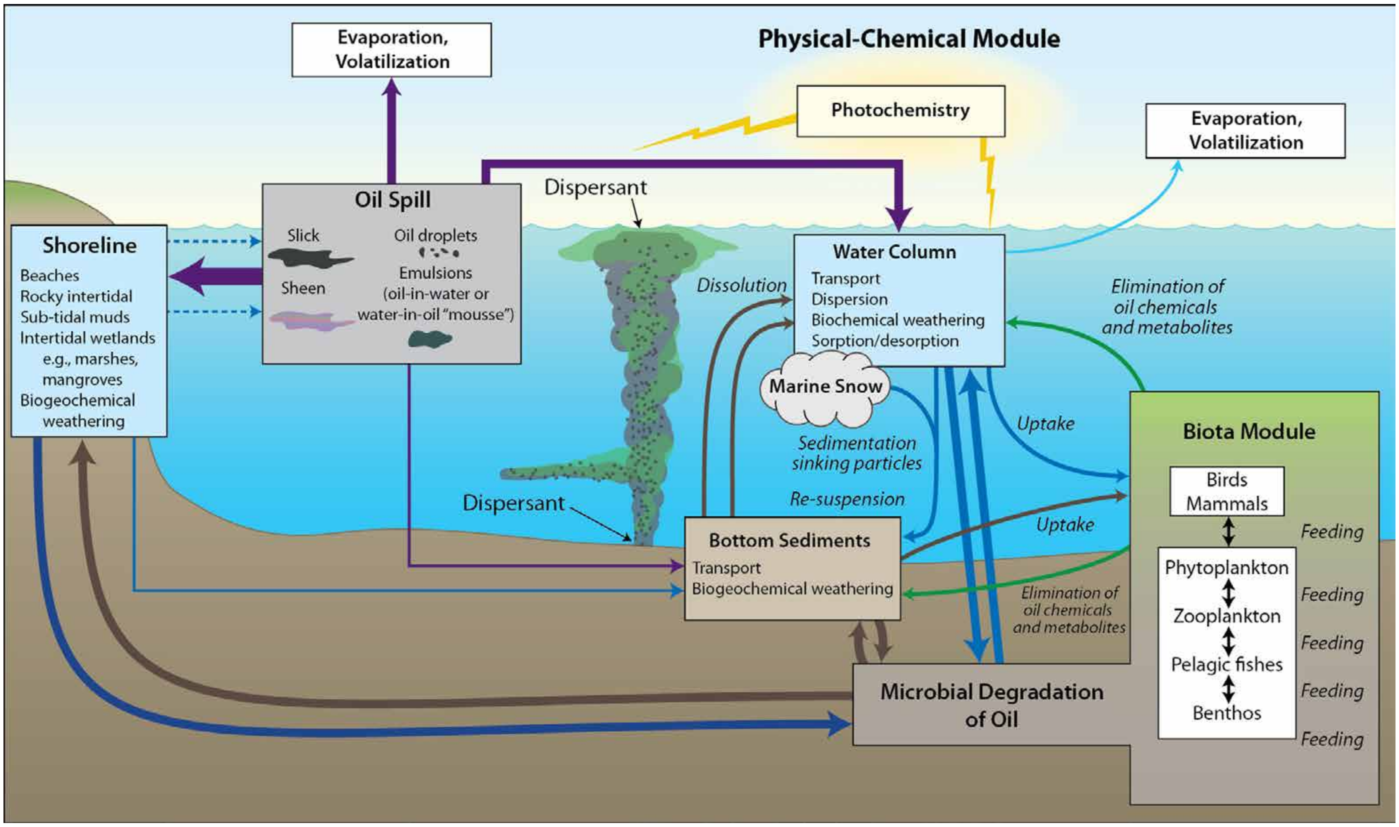


FIGURE 1. Schematic summarizing the fate of Deepwater Horizon gas and oil, including physical-chemical and biological modules with relevant processes.

variability given the physical dynamics and biogeochemical processes summarized in this special issue.

Figure 2c provides a pictorial summary of the importance of knowledge gained about MOSSFA. Although simplistic, it highlights the fact that many more experiments are needed to pin down exactly what happens when oil chemicals, bacteria, phytoplankton, and normal marine snow interact. Add dispersants to that mix as another challenge!

CONCLUDING THOUGHTS

NRDA-Related Research and Assessments

Now that the legal aspects of the NRDA case have been settled and approved by the courts, there is a concern among some scientists involved in the DWH oil spill assessment and research that adequate funding to fully interpret and publish those interpretations in peer-reviewed papers will not be available. However, some papers are appearing in the scientific literature (e.g., Stout et al., 2016). Hopefully, some funding process will be put in place without delay to avoid the loss of such valuable interpretations and knowledge. Otherwise, it will be a significant lost opportunity that most likely will be regretted when the next large oil spill occurs.

Translating Knowledge to Operational Response

The results of research described in this special issue are of obvious relevance to operational oil spill response no matter where a spill happens in the world. It seems appropriate and timely to recommend that one or more workshops be devoted specifically to translating knowledge gained to operational response capabilities (NOAA, 2016): workshops in which the operational response people set the agenda in a collaborative manner with research scientists.

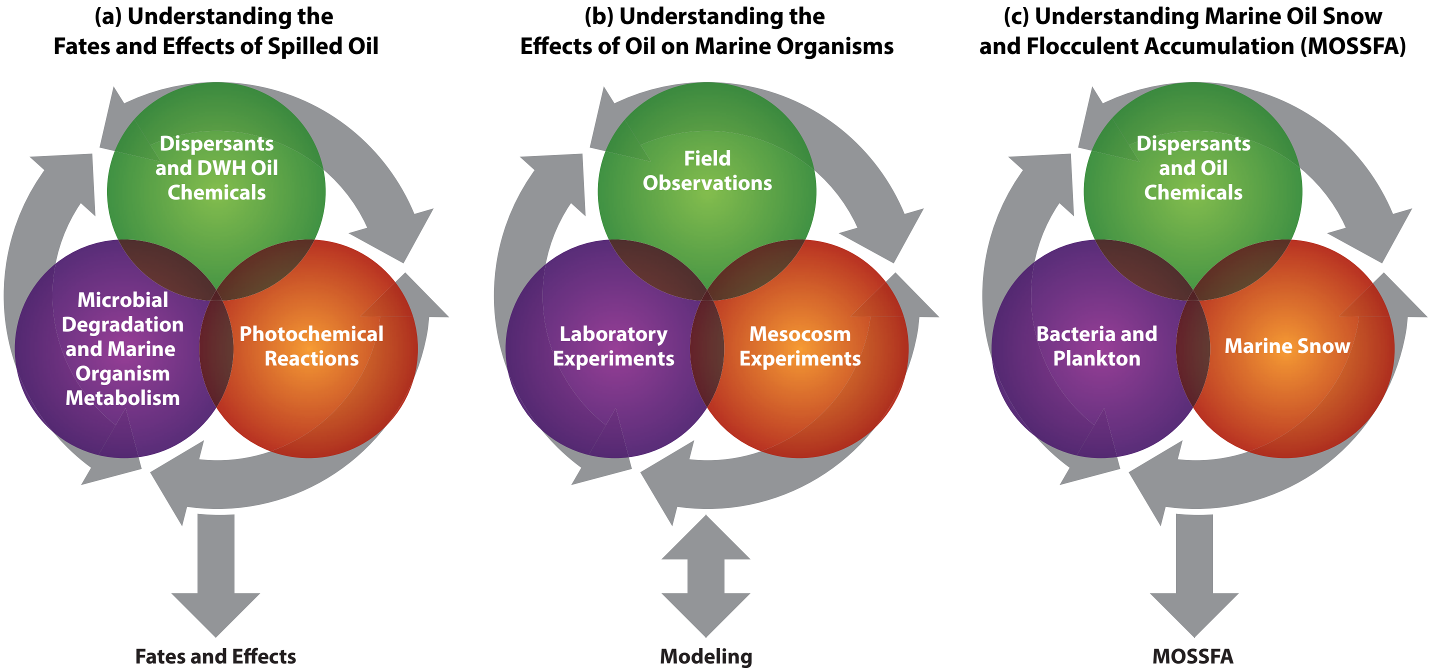
Baselines

Several of the papers in this special issue of *Oceanography* call for obtaining adequate "baselines" for the Gulf of Mexico in the event of another DWH type event. Despite US agency support of several programs to collect such information, the "baseline knowledge" vis-à-vis the DWH spill proved inadequate, especially for deepwater biogeochemical, biological, and ecological knowledge, as noted in several papers in this issue.

As soon as practicable, the scientific community, informed by the DWH experience, should agree to and provide a comprehensive description of the needs for collecting an adequate baseline of knowledge to appropriate agencies and entities involved in offshore gas and oil activities. This information would inform environmental policy and managers who oversee those activities and should lead to a better understanding of the fate and effects of spilled oil on Gulf of Mexico ecosystems. In addition, such an effort could stimulate preparation or updating of baselines of knowledge for other continental margin ecosystems. The importance of maintaining and augmenting ocean observing systems that collect information on physical, chemical, geological, and biological processes should be part of the comprehensive needs description for "baselines."

SUMMARY

Much has been learned thus far about the fate and effects of the DHW release of oil and gas into the Gulf of Mexico as summarized in the papers of this special issue and in the literature cited in them. Simultaneously, fundamental knowledge


(a) Understanding the Fates and Effects of Spilled Oil

(b) Understanding the Effects of Oil on Marine Organisms

(c) Understanding Marine Oil Snow and Flocculent Accumulation (MOSSFA)

FIGURE 2. Crosscut of some important issues from Deepwater Horizon oil spill research thus far.

important to understanding the functioning of coastal, continental shelf, and deep Gulf of Mexico ecosystems has also been gained. More knowledge will be obtained through ongoing research funded by GoMRI, slated to extend to 2020. If activities associated with other oil spills such as the *Exxon Valdez* are any indication (e.g., Peterson et al., 2003; Wiens, 2013), research and interpretations will be forthcoming for a few decades. This is especially the case for the GomRI research and environmental assessments concerning the DWH spill because of the significant, important data archiving requirements and data retrieval systems built into GomRI from the beginning as described by **Gibeaut**.

SUPPLEMENTAL MATERIAL

The supplemental figure and tables are available at http://dx.doi.org/10.5670/oceanog.2016.84.

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