Volume 33 • No. 1 • Winter 2019

The Story of Oil in the Gulf of Mexico: Where Did the Oil Go?

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- During the Deepwater Horizon (DWH) oil spill, scientists and responders needed to predict where the oil would go. The complexity of the Gulf's physical properties, a number of surprising phenomena, and the mitigating response efforts all played significant roles in the distribution and fate of the oil in the Gulf. In addition, the DWH accident was unique in that the source of the leaking oil was from a wellhead 1,500 meters below the surface. Dispersant chemicals were applied at the surface and at the wellhead, which dispersed the oil into smaller droplets.

- The spill exposed the lack of baseline data available for scientists working in the Gulf to predict the fate of oil in the marine environment and the physical processes that impact it. It is critical that sufficient baseline data continue to be collected in the many ecosystems that are at risk of being impacted by oil-related exploration and extraction activities.

- When scientists and responders were faced with the DWH oil spill, they needed to understand oil movement to determine how to remove it and minimize impacts. An associated activity engages students as environmental engineers to develop a procedure that would remove the most oil from the ocean in the event of a large-scale oil spill.

INTRODUCTION

Since the 2010 Deepwater Horizon (DWH) incident, researchers funded through the Gulf of Mexico Research Initiative (GoMRI), their collaborators, and other scientists have been working to gain a better understanding of what happens to oil after it is released into the marine environment. This research sheds light on the various processes that determined the fate of the oil, including hydrocarbon degradation, response efforts, physical processes at the surface and in the water column, and the discovery of surprising phenomenon, including a subsurface oil plume and the role of marine oil snow formation.

OIL IN THE GULF OF MEXICO

Fifty-five percent of the crude oil produced in the U.S. comes from the Gulf of Mexico region and 39% of this is from offshore drilling operations (U.S. Energy Information Administration 2015). In July 2016, there were over 54,000 oil wells and 2,500 active drilling platforms found in the Gulf (Figure 1). Offshore drilling is occurring in increasingly deeper water in order to access larger oil reserves. The risk of catastrophic accidents increases as drilling is pushed to greater depths.

THE DEEPWATER HORIZON OIL SPILL

The DWH event was an extraordinary example of an accidental release of petroleum into the marine environment. Estimating the concentrations of oil and gas released, along with the extent of the areas impacted by the accident, has proven to be a significant challenge for researchers. The chemical complexity and weathering process of oil; the intricate physical, chemical, and biological processes in the Gulf; unexpected phenomena that occurred during and after the accident; and the mitigating response effort all played a role in the fate and distribution of the oil (Passow and Hetland 2016).

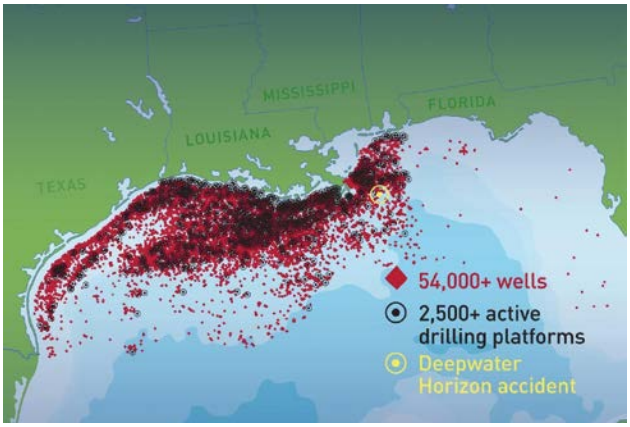

FIGURE 1. The location of all the drilling platforms and wells in the Gulf of Mexico as of July 2016, as well as the location of the Deepwater Horizon accident. Well and platform statistics obtained from Bureau of Ocean Energy Management (BOEM, https://boem.gov). Courtesy of Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG, http://ecogig.org) and mprintdesign.com

Response Efforts Affect Movement of Oil

During and after the accident, responders employed a number of measures to minimize the damage from the oil on the Gulf of Mexico's fragile ecosystems. Some of these response efforts changed the properties of the hydrocarbons present in the oil, affecting their interactions with the Gulf of Mexico's complex physical environment and altering the fate of the oil in the Gulf (Passow and Hetland 2016).

FIGURE 2. Controlled burning (left) and skimming (right) are two techniques used to remove oil from the water after an oil spill. Courtesy of National Oceanic and Atmospheric Administration (NOAA, CC by 2.0)

Some of the spilled oil was recovered through surface skimming or burned (estimates range from 2-4% through skimming and 5-6% through burning (Figure 2; Lehr et al. 2010; Passow and Hetland 2016). The heavier components of the oil sank immediately, while the lighter particles lingered in the water for months (Yan et al. 2016).

Water was released from diversionary channels of the Mississippi River in an attempt to prevent oil from reaching the Louisiana marshes. While this worked to keep the oil out of the areas where freshwater was released, it also led to the introduction of clay particles, which collected oil from the water and sank to the seafloor (Daly et al. 2016). Additionally, drilling mud was pumped into the wellhead in an unsuccessful attempt to stop the leak. The heavy mud particles quickly sank out of the water column, taking some of the oil with them (Yan et al. 2016).

Dispersants were applied at the wellhead and to the surface oil slick in order to reduce the thickness of the surface oil layer and reduce the droplet size of the oil to expedite breakdown (Figure 3; Passow and Hetland 2016). The

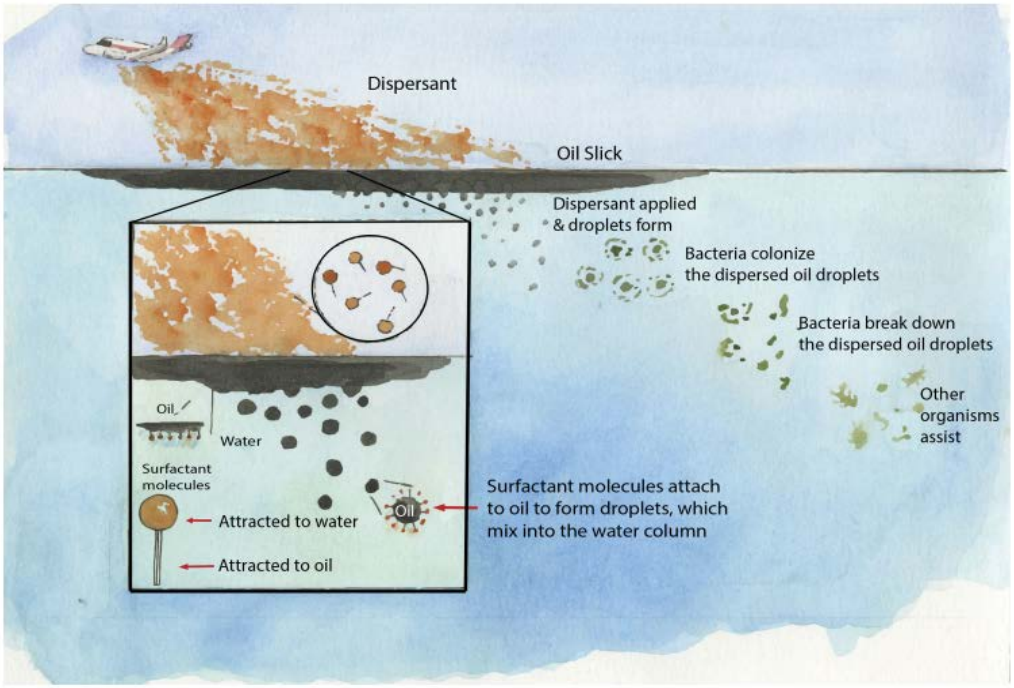

FIGURE 3. Dispersants contain molecules that have one end that is attracted to water and one end that is attracted to oil. When responders apply dispersants to an oil slick, these molecules attach to the oil, allowing the oil slick to be broken up into smaller oil droplets. These smaller droplets then mix into the water column where they are "eaten" and further broken down by microbes and other organisms. Courtesy of Graham et al. 2016, reprinted with permission from the Gulf of Mexico Sea Grant Oil Spill Science Outreach Team illustrator Anna Hinkeldey

addition of dispersants at depth worked to decrease the volume of oil collecting on the sea surface of the Gulf by approximately 21%. At the same time, dispersant addition increased the area that the oil travelled on the surface by 49% due to the smaller oil droplet sizes, increasing the region of the Gulf impacted by the oil (MacDonald et al. 2015; Joye et al. 2016).

WHERE DID THE OIL GO?

The leaking oil well can best be described as a rapid jet of hot petroleum products ejected from the wellhead into the Gulf's waters, 1,500 meters (m, almost 5,000 feet [ft]) below the surface, leading to the dispersion of the oil into small droplets (Figure 4; Joye 2015). Once released, the petroleum formed three separate, distinct features in the water, depending on the specific characteristics of the hydrocarbons (lighter weight and heavier weight compounds behaved differently): (1) a rising plume between the wellhead and the sea surface; (2) a subsurface plume at 1,100 m (3,600 ft) below the surface; and (3) an oil slick at the surface (Passow and Hetland 2016).

Identifying Oil in the Marine Environment

Hydrocarbons are molecules that contain hydrogen and carbon atoms. Natural gas is primarily made up of methane, the simplest hydrocarbon, while crude oil exists in multiple forms and can be made up of hundreds of different hydrocarbons (Maung-Douglass et al. 2016). All crude oil has a chemical signature unique to its place of origin. Scientists use laboratory equipment to identify and compare the chemical signatures of oil from a spill to oil from known origins. This process, called oil fingerprinting, can help identify the source of oil. Oil fingerprinting makes it possible to distinguish oil released during accidental spills from natural sources. Roughly, 42 million gallons of crude oil enters the Gulf of Mexico each year from the region's 900+ active natural seeps.

FIGURE 4. Artist's rendering of the multiphase plume resulting in the distribution of hydrocarbons in various directions. Courtesy of Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE, http://carthe.org)

Researchers have known for a long time that oil molecules go through physical and chemical changes that cause them to degrade or "age." This process is known as weathering and is triggered by exposure to sunlight, heat, microbes, and oxygen (Maung-Douglass et al. 2016). Warm water conditions, such as those that exist in the Gulf, can break down many of the carbon-based compounds in oil within a short time frame—on the order of weeks to one month. The weathering process changes the fingerprint and inhibits the ability to attribute oil to a specific source over time. Scientists are always striving to learn more about the compounds in oil to better understand which compounds break down more slowly. This allows scientists to accurately identify the oil source for longer periods of time.

The Rising Plume

The rising plume was made up of buoyant hydrocarbons, gas, and the dispersant that was added directly at the wellhead (Passow and Hetland 2016). As it rose, the physical conditions of the water (pressure, temperature, turbulence from currents) changed and particles in the water interacted with the hydrocarbons, changing their properties and breaking them down into smaller molecules. The plume grew horizontally as it rose, and about half of it stopped rising at 1,100 m (3,600 ft), forming a subsurface plume—an area in the Gulf with relatively higher concentrations of hydrocarbons contributed by the DWH spill. The rest continued to rise to the surface.

The Subsurface Plume

Half of the discharged petroleum remained in a subsurface plume at approximately 1,100 m (3,600 ft) deep. The buoyant hydrocarbons in the rising plume formed tiny droplets because of the rapid ejection from the wellhead and the addition of dispersant. They became neutrally buoyant and stayed trapped at this depth. This phenomenon came as a surprise to most of the researchers studying the spill.

The Gulf of Mexico is not a single homogeneous body of water. It is comprised of different depth layers that have different temperatures and densities, and there are currents that move throughout each layer like rivers. Researchers think the large jet of hot oil into the deep waters of the Gulf had an impact on the turbulent currents in the surrounding water column, which in turn played a role in trapping some of the oil in the 1,100 m layer (Figure 5; Özgökmen et al. 2016). The currents in this layer then moved the subsurface plume approximately 400 kilometers (km, 250 miles) to the southwest of the blowout site. The oil trapped in this plume was too deep to reach the shore. It eventually encountered the continental slope, penetrating the seafloor of the area to the south and south-west of the DWH site, leaving a "dirty bathtub ring" of oil contaminated sediments (Joye et al. 2016).

The Surface Oil Slick

Approximately half of the spilled oil reached the surface, creating an enormous oil slick. It is estimated that the total area impacted by the oil was approximately 112,115 km^2 (70,000 mi^2), mainly to the north and east of the DWH site (Figure 6; MacDonald et al. 2015). Up to 25% of the more volatile oil compounds evaporated in a matter of hours to days, and another 10% was skimmed or burned off, as mentioned previously (Figures 5 and 7; Passow and Hetland 2016). Using Synthetic Aperture Radar (SAR) imagery, scientists were able to determine the size and location of the remaining oil slick, revealing a footprint continuously changing as the wind and currents pushed the oil along.

The Role of Currents in the Fate of the Oil

Ocean currents carry animals, nutrients, and pollutants like oil with them as they move. The largest ocean currents in the world, such as the Gulf Stream, are very well documented (Gyory et al. 2013). Scientists can predict how fast the water in these currents will move and the direction they will go. These large, permanent currents are called mesoscale currents. The Loop Current is the primary mesoscale current in the Gulf of Mexico, moving water through and out of the Gulf, down around the tip of Florida into the Atlantic Ocean.

The smaller, temporary (lasting only a few hours to a week) currents in the ocean are called *submesoscale* currents and are poorly understood (Haza et al. 2016). Imagine mesoscale currents as highways, carrying many cars across large distances and for long periods of time (months), always going the same speed. The size and speed of these currents can be measured by satellites, allowing scientists to model them and make predictions. Submesoscale currents are like the small streets in a neighborhood. Cars use these streets every day but only for a short amount of time. They are so

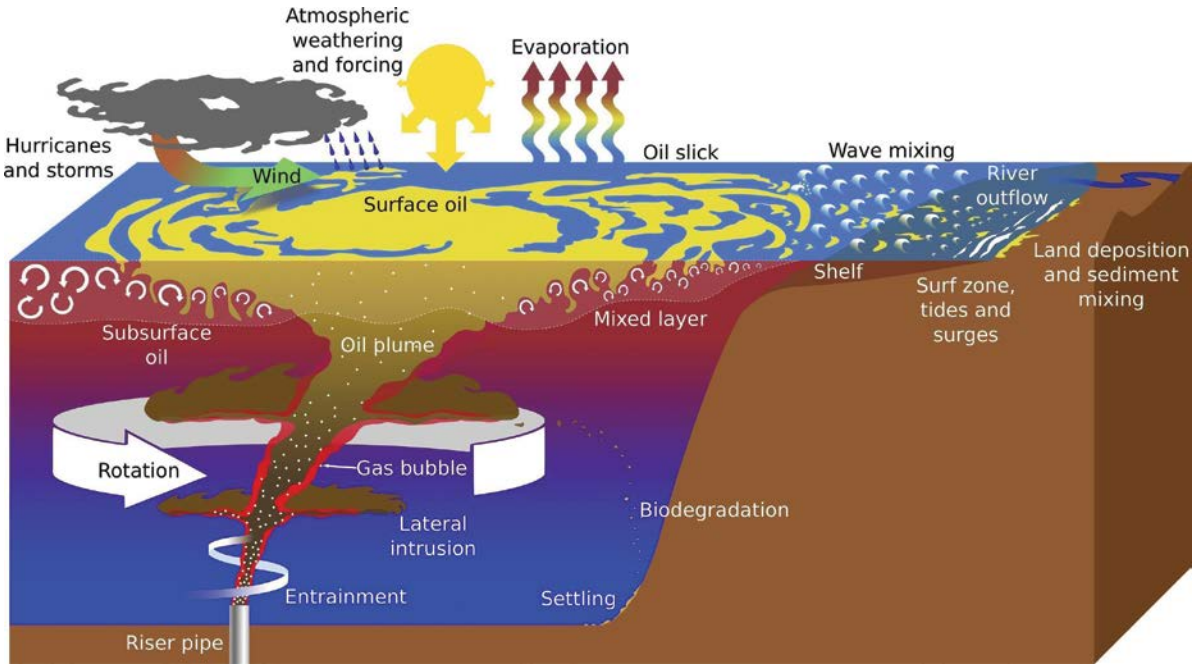

FIGURE 5. An illustration of the various processes that influence the transport of oil from a deep-water pipe to the surface and onto land. Courtesy of CARTHE; Özgökmen et al. 2016

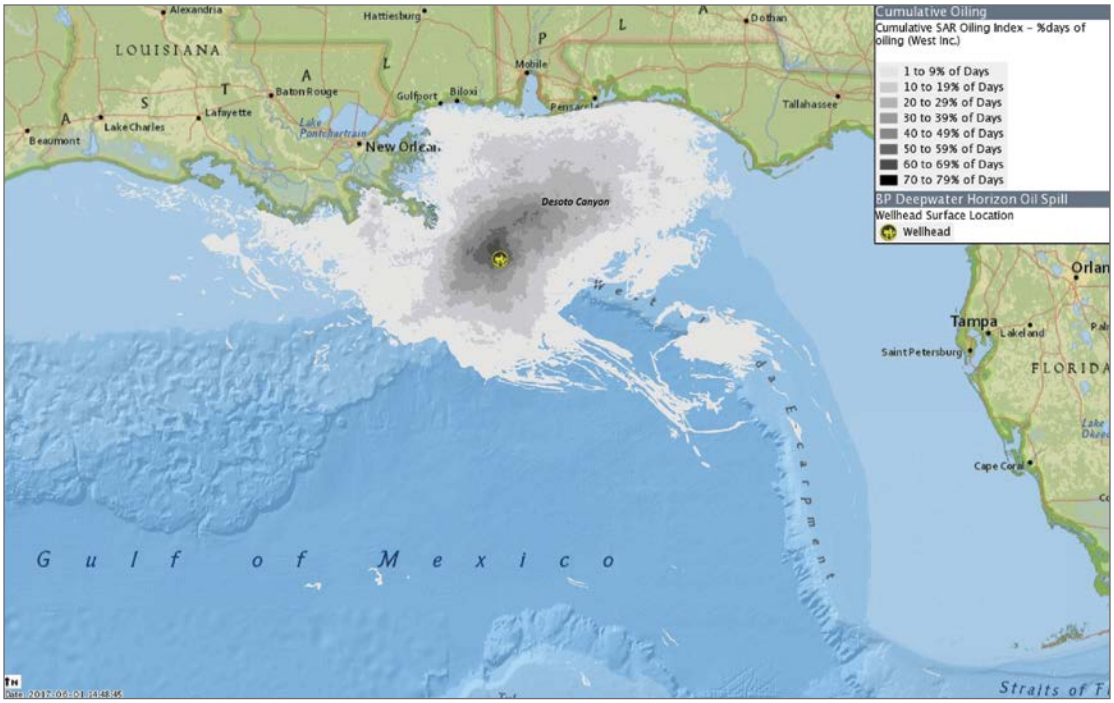

FIGURE 6. A map showing the estimated distribution of the oil on the surface of the Gulf and percentage of days of oiling by location, as measured by Synthetic Aperture Radar (SAR). Courtesy of NOAA's Environmental Response Management Application (ERMA) Deepwater Gulf Response Mapping Application (https://erma.noaa.gov/gulfofmexico/erma.html); retrieved on June 1, 2017

small and narrow that we cannot observe them by satellite. To complicate the matter, some of these roads are temporary. These submesoscale currents played an important role in the transport of surface oil from the location of the DWH accident (Poje et al. 2014).

Since the 2010 spill, much has been learned about the physical oceanography of the Gulf, providing scientists and first responders with knowledge to improve their ability to predict water movement in the event of a future incident. The knowledge and understanding of how submesoscale currents transport surface oil has been improved through a variety of different techniques including *Lagrangian* measurements (tracking a particle in the water as it moves; Lumpkin et al. 2016). A group of scientists deployed over 1,000 GPS-equipped "drifters" that float along with the currents in the Gulf. The trajectories of the drifters allow the researchers to draw maps of the diverse routes that can carry floating material like oil at the surface of the Gulf of Mexico. Over 20 million data points have been collected showing that the submesoscale currents can control how a pollutant spreads in the short term (see **Citizen Science** inset on page 12; Özgökmen et al. 2016).

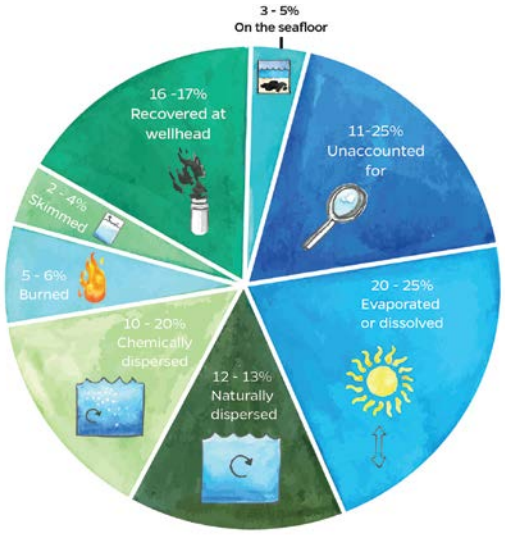

FIGURE 7. An estimate of what happened to the approximately 200 million gallons of oil from the DWH oil spill. Courtesy of Maung-Douglass et al. 2016, reprinted with permission from the Gulf of Mexico Sea Grant Oil Spill Science Outreach Team illustrator Anna Hinkeldey. Numbers are based on data from Lehr et al. 2010; Ryerson et al. 2011; Liu et al. 2012; Fingas 2013; Chanton et al. 2015; and Maung-Douglass et al. 2015.

The submesoscale currents often connect with larger currents allowing oil to move great distances; however, these smaller currents can also lead to eddies that trap the oil in the circular movement of water. During the DWH accident, spilled oil encountered an eddy, which had the fortunate effect of keeping it out of the Loop Current. The majority of the surface oil remained in the northern Gulf of Mexico, moving through eddies and currents and being pushed by the wind.

As the oil moved closer to the shore, the typical springtime gyre in coastal Louisiana brought the oil close to shore near Terrebonne and Barataria Bays. Further to the west, the currents carried oil along the shore. Winds from the north pushed oil residue offshore or further west along the coast. Onshore winds pushed oil residue into Terrebonne, Timbalier, and Barataria Bays. These opposing forces kept the oil from coming ashore in some areas, but not in others (Roth et al. 2017).

In order to assess the impact of DWH oil that reached the coastal marshes of the northern Gulf of Mexico (in comparison to the long history of coastal oil and gas development in Louisiana), scientists used dated sediment cores, a process that has long been applied to determine the history of conditions at the time of sedimentation (the process of particles settling on the seafloor) events (Parsons et al. 2006).

Sediment cores from marshes in Terrebonne and Barataria Bays were used to distinguish oiling from the DWH incident compared to historical depositions caused by oil and gas development in the area since the 1940s. Initial results indicated that the different hydrocarbons are degrading at different rates, but that the overall amount of oil is higher than it was before the DWH accident (Turner et al. 2014).

OIL ON THE SEAFLOOR

Sedimentation of the oil was another unexpected phenomenon discovered by scientists after the DWH accident (Passow and Ziervogel 2016). In September 2010, researchers observed a unique layer that carpeted the seafloor near the wellhead. Dating confirmed it was the product of a rapid sedimentation event. Researchers conservatively estimate that 3-5%, or at least 10 million gallons (Figure 7), of the oil reached the seafloor, with some estimates reaching as high as 15% (Chanton et al. 2015; Passow and Hetland 2016).

The main process responsible for transporting oil to the seafloor was the formation and settling of marine oil snow (MOS). Marine oil snow is made up of sinking detritus (dead animal and plant matter) as well as excretions of mucus-like polymers produced by marine bacteria, phytoplankton, and zooplankton. These "globs" of marine snow have a strong tendency to collect oil droplets as they form and sink, growing larger in size and providing a food source for the many bacterial species that thrive on MOS (Figure 8). As MOS travels through the water to the seafloor, it is eaten and repackaged into fecal pellets by zooplankton, degraded by bacteria, and collects new particles and more oil on its journey to the bottom. Sinking MOS can literally scrub the water column of all suspended particles and deposit them on the seafloor (Passow and Ziervogel 2016).

A significant amount of the DWH oil made its way to the seafloor as MOS. This process was not well studied prior to the spill; it was assumed that most oil compounds would float (Passow and Hetland 2016). In fact, this phenomenon was so unexpected that sedimentation rates were not measured during the accident, and the official oil budget calculations did not consider oil sedimentation (Lehr et al. 2010). Immediately following the DWH accident, rates of MOS were at least four times higher than rates measured one and two years after the spill, and significantly higher than prior years (although this was not well measured prior to the spill; Brooks et al. 2015).

Citizen Science is the collection and analysis of data by nonprofessional scientists (i.e. public citizens and students). Gulf of Mexico Research Initiative scientists have enlisted the help of citizen scientists in a variety of research projects, including the Biscayne Bay Drift Card Study, or Bay Drift. Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) teamed up with museums, schools, environmental organizations, and the local community in South Florida to conduct an experiment that collects data on how the ocean currents transport oil, marine debris, or other pollutants. The drift cards are made of untreated plywood, painted bright colors at various educational events, and released from specific locations across Biscayne Bay (near downtown Miami, Florida). Beach goers and boaters find the cards and report the location, date, and time to CARTHE staff who can piece together the mystery of how the ocean currents are moving these and other items throughout our waterways.

For more information on **Bay Drift**, including lessons featuring the real data, please visit: CARTHE.org/BayDrift.

FIGURE 8. Close-up shot of a marine oil snow particle formed in the laboratory. Courtesy of Uta Passow/ECOGIG and Aggregation and Degradation of Dispersants and Oil by Microbial Exopolymers (ADDOMEx, http://www.tamug.edu/addomex/) research consortia

The MOS from the spill settled as a 0.5-1.2 centimeter (cm) thick, low-density layer of sediment (also known as 'floc') on the seafloor (Figure 9). The estimated size of this layer ranges from 1,300 to 24,000 km^2 of the Gulf and only accounts for the sampling efforts around the vicinity of the spill site, not the cumulative area of surface oil coverage (112,115 km^2; MacDonald et al. 2015; Passow and Ziervogel 2016). Researchers have been documenting the impact of the floc on deep-sea coral communities since 2010 (Fisher et al. 2016). This research also expanded the known area of impact by identifying damage almost twice as far from the wellhead and in 50% deeper water (Fisher et al. 2014).

As the floc settled to the bottom, many animals living on and in the seafloor were suffocated or damaged. As the oily floc degraded, it changed the concentration of dissolved oxygen in the sediments (Passow and Ziervogel 2016). Cold bottom water temperatures in the Gulf and low metabolic activity of animals living in the sediment lead to extremely slow degradation rates for the oil on the seafloor. Several years post-spill, the oil footprint on the seafloor was still quite large, approximately half of its original size (Passow and Hetland 2016). Seafloor sediments preserve a record of changes that occur in the overlying water column, and Gulf sediments will forever contain an archive of the large pulse of sedimented oil from the DWH accident. Sedimentation of MOS in future marine oil spills is expected to be a main transport pathway of oil to the seafloor, which has far-reaching implications for the fragile ecosystems that exist there.

FIGURE 9. A thick, fluffy floc layer sampled from the seafloor, as observed in a sediment core taken in the Gulf of Mexico. Photo taken in September 2010. Courtesy of ECOGIG/Samantha Joye

CONCLUSIONS

The impacts of the DWH accident extended from the surface to the seafloor in the Gulf of Mexico. The complexity of the Gulf's physical oceanography, a number of surprising phenomena (formation of the subsurface plume, and formation and sedimentation of marine oil snow), and the mitigating response efforts all played significant roles in the distribution and fate of the oil in the Gulf. The spill exposed the lack of baseline data available for scientists working in the Gulf of Mexico to predict the fate of oil in the marine environment and the physical processes that impact it. Since the spill, significant scientific developments continue to be made by researchers working towards understanding the dynamic system that is the Gulf. The work being done in the Gulf by GoMRI scientists and their collaborators has important implications for future oil spills in this and other environments. It is critical that sufficient baseline data continue to be collected in the many ecosystems that are at risk of being impacted by oil-related exploration and extraction activities.

CLASSROOM ACTIVITY RESOURCES

The Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) consortium, in partnership with the Center for Education Integrating Science, Mathematics, and Computing at the Georgia Institute of Technology, developed a middle school teaching module based on ECOGIG research. In this module "7th Grade - Life Science - Experimental Design: 'Oil Spill Drill' Oil Spill Challenge," students engage as environmental engineers to develop a procedure that would remove the most oil from the ocean in the shortest time possible in the event of a large-scale oil spill. The module covers experimental design and basic concepts on how human actions impact an ecosystem. The module and two other oil spill related modules on marine oil snow and deep-sea corals are available upon request and can be found here: https://ampitup.gatech.edu/curricula/ms/science.

In addition, ECOGIG educators adapted an oil spill challenge activity appropriate for informal education settings, such as camps and classroom visits, that can be found at: http://ecogig.org/files/printablefiles/Oil_Spill_Challenge_PDF_sm.pdf.

ACKNOWLEDGMENTS

In addition to the acknowledgments for the full issue, the authors of this article would like to thank Uta Passow and Tamay Özgökmen for their review of the article; and Guillaume Novelli for contributions to the manuscript. This article was made possible by funding from GoMRI to ECOGIG, CARTHE, and CWC.

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