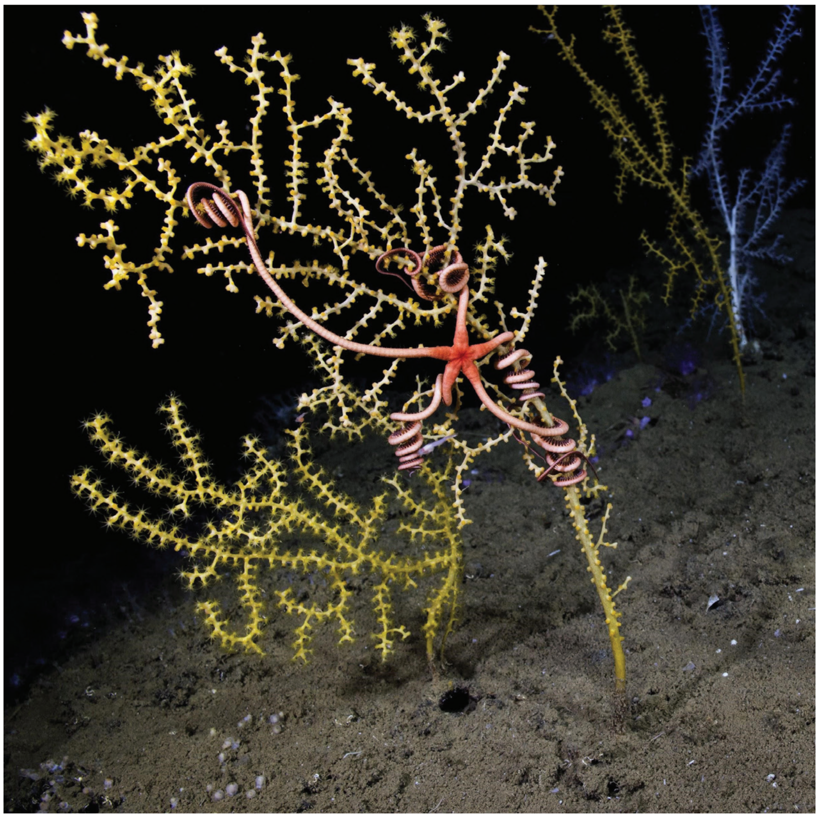
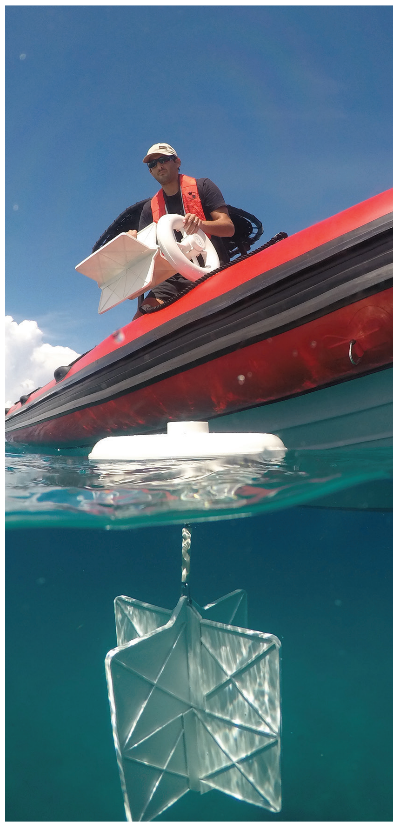
current

THE JOURNAL OF MARINE EDUCATION

Volume 33 • Number 1 • Winter 2019



❖ Special Issue Featuring the Gulf of Mexico Research Initiative ❖

Research Resulting from the 2010 Deepwater Horizon Oil Spill

GULF OF MEXICO RESEARCH INITIATIVE

NATIONAL MARINE EDUCATORS ASSOCIATION

"... to make known the world of water, both fresh and salt."

THE NATIONAL MARINE EDUCATORS ASSOCIATION brings together those interested in the study and enjoyment of the world of water. Affiliated with the National Science Teachers Association, NMEA includes professionals with backgrounds in education, science, business, government, museums, aquariums, and marine research, among others. Members receive *Current: The Journal of Marine Education*, NMEA News Online, and discounts at annual conferences. Membership information is available from: NMEA National Office/Attention: Jeannette Connors, 4321 Hartwick Road, Suite 300, College Park, MD 20740, or visit our website online at www.marine-ed.org/. Phone: 844-OUR-NMEA (844-687-6632); Email: nmea@marine-ed.org.

current

THE JOURNAL OF MARINE EDUCATION

Volume 33 • No. 1 • Winter 2019

Jessica Kastler, Ph.D., Katie Fillingham, Sara Beresford, and Teresa Greely, Issue Editors

Lisa M. Tooker, Managing Editor

Eric Cline, Designer

Current is published up to four times a year for members of the National Marine Educators Association. Library subscriptions to Current are available for $50 a year. Individual issues are available from the editors for $15.

Editorial and advertising offices: NMEA, c/o Jeannette Connors, 4321 Hartwick Road, Suite 300; College Park MD 20740

Front Cover: Courtesy of *from left to right*: (top left) ECOGIG and Ocean Exploration Trust; (top middle) CONCORDE; (top right) LADC-GEMM; (bottom right) Gabriel Kasozi; (bottom middle) CARTHE/Cedric Guigand; and (bottom left) RECOVER

current

THE JOURNAL OF MARINE EDUCATION

Volume 33 • No. 1 • Winter 2019

CURRENT LOG I would like to welcome you to this special issue of Current: The Journal of Marine Education *featuring research and educational activities resulting from science funded by the Gulf of Mexico Research Initiative (GoMRI).*

GoMRI is a 10-year (2010-2020) research program that was established through a $500 million financial commitment by BP after the Deepwater Horizon oil spill. Led by a 20-member Research Board, GoMRI's goal is to improve society's ability to understand, respond to, and mitigate the impacts of petroleum pollution and related stressors on the marine and coastal ecosystems, with an emphasis on conditions found in the Gulf of Mexico. Knowledge accrued from this program is being applied to restoration and to improving the long-term environmental health of the Gulf of Mexico. The GoMRI Research Board, for which I serve as chair, oversees operations of the program and ensures the intellectual quality, effectiveness, and academic independence of the research.

Since its inception, the GoMRI Research Board has placed a high value on and has prioritized communicating GoMRI-funded research with audiences beyond the scientific community. It has dedicated significant funds to education and outreach efforts at the GoMRI program level, as well as to GoMRI's funded consortia, research projects, and external partners. This special issue has been produced by the outreach coordinators of GoMRI consortia. Their goal is to share some insights of GoMRI-funded research and education resources with you, so that you may incorporate the science and associated activities into your curriculum. I thank all of the GoMRI outreach coordinators for their dedicated efforts to share GoMRI-funded science, and for their efforts to produce this special issue, especially Jessie Kastler, Katie Fillingham, Sara Beresford, and Teresa Greely, who served as editors. I hope you enjoy it.

Sincerely,

Dr. Rita Colwell
Chair of the Gulf of Mexico Research Initiative Research Board

GULF OF MEXICO RESEARCH INITIATIVE

This special issue of *Current* was sponsored by the Gulf of Mexico Research Initiative (GoMRI). The editors thank the GoMRI outreach coordinators for contributions and appreciate reviews by Debi Benoit, Steve Sempier, Chuck Wilson, and two anonymous peer reviewers whose comments greatly improved the manuscripts.

CONTENTS

Introduction to the GoMRI Special Issue on Research Resulting from the 2010 Deepwater Horizon Oil Spill

On April 20, 2010, the Deepwater Horizon oil rig exploded in the Gulf of Mexico, releasing 210 million gallons (780,000 cubic meters or m^3) of oil and gas into the surrounding ecosystem; the flow persisted for 87 days before the well was capped. Sadly, 11 workers died. As responders began efforts to stop the flow and collect spilled oil, officials worked to minimize threats to human health and economies, and environmental scientists jumped into action to learn as much as possible about the spill and its effect on the Gulf of Mexico.

High school teachers process plankton samples aboard the R/V *Point Sur* in the Gulf of Mexico during Consortium for Oil Spill Exposure Pathways in Coastal-River-Dominated Ecosystems (CONCORDE's) AUV Jubilee Workshop Cruise in July 2015. Courtesy of Jessie Kastler

Researchers quickly realized that the lack of baseline data on the Gulf of Mexico ecosystems would make it difficult to know how the Gulf and the organisms living there would be impacted. Furthermore, the complex interactions and linkages between the ecosystems in the Gulf required scientists with a wide variety of backgrounds to work together to answer challenging questions. Where would the oil end up? How would it impact the animals living in the Gulf? How would the spill affect the local communities? Fish ecologists needed toxicologists, field scientists needed modelers, and geochemists needed physicists to assemble a complete understanding of the effect of the spilled oil and dispersant.

One month into the spill, BP made a commitment to provide $500 million for 10 years to fund a research program on the impact of the spill and to prepare for future spills. BP worked with the Gulf State governors through the Gulf of Mexico Alliance to create a program that would publish scientific results totally independent of BP. That program, the Gulf of Mexico Research Initiative (GoMRI), which is governed by a Master Research Agreement with BP, has provided an unprecedented opportunity to bring together over 2,500 scientists with the common goal of understanding the impacts of oil spills and improving response and mitigation capabilities for the future. GoMRI-funded researchers are comprehensively studying the Gulf ecosystem, and research is funded under five major research themes: physical distribution of petroleum and dispersants in the ocean; chemical and biological evolution and degradation of petroleum and dispersants; environmental effects of petroleum and dispersants throughout the water column and the surrounding ecosystem; technology developments; and public health impacts. A full listing of the GoMRI Research Themes is available here: http://research.gulfresearchinitiative.org/research-about/.

Research sponsored by GoMRI is selected through a peer-review process modeled after National Science Board standards, and results are published in peer-reviewed journals. GoMRI requires that data generated through these research efforts be made publicly available through the

Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC). Nine years into the 10-year program, GoMRI-funded research has produced more than 1,000 peer-reviewed journal publications and over 2,100 publicly available datasets. The program is also training the next generation of young researchers who are professionally at home in the Gulf of Mexico and, in many cases, contributing to the development of baseline data Gulf-wide. From this single event, and through the GoMRI program, a huge body of scientific knowledge has grown. Strong scientific collaborations have unfolded that have enabled researchers to address complicated questions across disciplinary boundaries about the impacts of the Deepwater Horizon and other oil spills.

Since its inception, GoMRI valued and prioritized efforts to communicate and share GoMRI-funded research with the public. The GoMRI program itself generates and disseminates information through website stories, newsletters, webinars, and social media. GoMRI provides funding for research consortia to carry out public outreach efforts in ways that are relevant to each consortium's research activities and local communities. GoMRI has also established partnerships with Smithsonian Ocean Portal, the Gulf of Mexico Sea Grant Oil Spill Science Outreach Program, and Screenscope Films. The Ocean Portal publishes articles and blog posts featuring GoMRI-funded researchers and their science. The Gulf of Mexico Sea Grant Oil Spill Science Outreach team delivers oil-spill related products and services to specific target audiences in the Gulf region and the nation, including accessible publications of use to educators. GoMRI's partnership with Screenscope Films has resulted in the *Dispatches from the Gulf* series, which includes two documentary films and 75 short videos sharing stories about GoMRI science and the GoMRI community. More information about the GoMRI-funded consortia and these partner-produced products is included in this issue and can be found online at http://gulfresearchinitiative.org/.

Through this special issue, we hope to convey elements of the process of science by exploring how GoMRI researchers have addressed the GoMRI research themes. Starting with a single event in 2010, successive observations and results have quickly grown into a body of knowledge that is building our understanding of oil spill and dispersant impacts on the Gulf of Mexico. This asking and answering of questions is how science moves forward.

Researchers and graduate students associated with The Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) work with teenage girls to process fish samples during the summer Oceanography Camp for Girls' research cruise aboard the R/V *Weatherbird II* in the Gulf. Courtesy of Teresa Greely

GoMRI-funded oil spill research offers a unique opportunity to teach students the three dimensions of the *Next Generation Science Standards* (NGSS, https://www.nextgenscience.org/): disciplinary core ideas (content), scientific and engineering practices, and cross-cutting concepts. Specifically, this research captures how we practice science and engineering, and demonstrates their application in the real world. To assist in sharing this content, each article is accompanied by a selection of resources that can be incorporated into classroom teaching. Additionally, each article begins with a few bullets which highlight the main points of the article, summarize how it addresses a key research question and relates to the scientific process, and provides a brief description of the associated activity, if applicable.

There are five articles in this issue. Three address some of the overarching questions about the Deepwater Horizon oil spill and how GoMRI science is working to answer them. *The Story of Oil in the Gulf of Mexico* asks, "Where did the oil go?" From a physical oceanography standpoint, how do we know where the oil went in the Gulf of Mexico, and what new science has emerged to help scientists answer this question? *Deepwater Horizon Oil Spill Impacts on Organisms and Habitats* asks, "What happened to the ecosystem as a result of the oil?" From an ecological perspective, what impacts did the oil have on the wildlife and ecosystems in the Gulf? *Technological Advances in Ocean Sciences Resulting from the Deepwater Horizon Oil Spill* discusses new technologies that have been developed to better understand impacts from the oil spill and some citizen science projects that have resulted.

Two additional features introduce the curious phenomenon of marine oil snow (MOS) and GoMRI's data sharing policies. In *An Underwater Blizzard of Marine Oil Snow*, research into the formation and sedimentation of MOS illustrates how scientists with diverse research interests uncovered a process with unexpected significance in moving released oil to the floor of the ocean. The final article, *The Gulf of Mexico Research Initiative Information and Data Cooperative: Data Transparency and Data Sharing* describes GoMRI's requirement to make all data produced through GoMRI funding publicly available for sharing with the broader scientific community, and highlights the importance of data transparency.

These articles represent only a snapshot of the vast amount of research being produced by GoMRI-funded scientists. The GoMRI program will conclude in 2020. An effort is now underway to synthesize the knowledge accrued through 10 years of dedicated research effort, to make the scientific advancements available to the research, response, and user communities in responding to future spills. Of course, the state of the knowledge is always changing; it is GoMRI's hope that the legacy of the program will serve to inform new scientific discoveries in oil spill science for many years to come. Links to additional resources, websites, and information are provided throughout the issue. We also invite you to utilize GoMRI's Special Issue of *Oceanography*, "GoMRI: Deepwater Horizon Oil Spill and Ecosystem Science": tos.org/oceanography/issue/volume-29-issue-03. We hope you enjoy this special issue and find it to be a useful resource in your classroom.

CO-EDITORS: JESSIE KASTLER, KATIE FILLINGHAM, SARA BERESFORD, AND TERESA GREELY

JESSIE KASTLER is the Outreach Coordinator of the Consortium for Oil Spill Exposure Pathways in Coastal River-Dominated Ecosystems (CONCORDE), and the Coordinator of Program Development for the Marine Education Center of the University of Southern Mississippi, Gulf Coast Research Laboratory in Ocean Springs, Mississippi.

KATIE FILLINGHAM is a Program Specialist with the Gulf of Mexico Research Initiative (GoMRI) at the Consortium for Ocean Leadership in Washington, District of Columbia.

SARA BERESFORD is the Communications and Outreach Lead for the Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) research consortium at the University of Georgia Department of Marine Sciences in Athens, Georgia.

TERESA GREELY co-leads the Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) Outreach Team, and serves as the Director of Education and Outreach and a teaching faculty at the University of South Florida's College of Marine Science in St. Petersburg, Florida.

This special issue of Current *was sponsored by the Gulf of Mexico Research Initiative (GoMRI). The editors thank the GoMRI outreach coordinators for contributions and appreciate reviews by Debi Benoit, Steve Sempier, Chuck Wilson, and two anonymous peer reviewers whose comments greatly improved the manuscripts.*

Outreach Specialists working with science consortia funded by GoMRI met in February 2017. They include (front, left to right) Murt Conover, Teresa Greely, Angela Lodge, Elizabeth Thornton, Lalitha Asirvadam, Jessie Kastler, Tina Miller-Way; (back, left to right) Rachel McDonald, Laura Bracken, Katie Fillingham, Sara Beresford, Sara Heimlich, David Mellinger, Emily Davenport, Dan DiNicola, and Ben Prueitt. Courtesy of Katie Fillingham

GOMRI-FUNDED CONSORTIUM DESCRIPTIONS

The Gulf of Mexico Research Initiative (GoMRI) has funded both research consortia and individual investigators through multiple rounds of Requests for Proposals. Each of the 17 GoMRI-funded consortia has its own education and outreach program, which has produced a variety of resources that may be useful to educators. A brief description of each consortium follows, with a link to its website; throughout this issue, they will be referred to by their acronyms. GoMRI has also partnered with the Gulf of Mexico Sea Grant Oil Spill Science Outreach Program, the Smithsonian Ocean Portal, and Screenscope Films. These partnerships have leveraged the outreach efforts of the consortia and produced a variety of unique education and outreach products. Their websites are also provided.

GOMRI-FUNDED CONSORTIA

The Alabama Center for Ecological Resilience **(ACER)** studies the role biological diversity (genetic, taxonomic, and functional) plays in determining the resilience of northern Gulf of Mexico ecosystems to impacts of oiling and dispersants. ACER investigates resilience across many groups of organisms and at several organizational scales to help predict the impacts of different forms of disturbance on critical coastal ecosystems. http://acer.disl.org/

The Aggregation and Degradation of Dispersants and Oil by Microbial Exopolymers consortium **(ADDOMEx)** investigates the impacts of spilled oil and dispersants on microbes that produce extracellular polymeric substances (EPS). When EPS and oil combine, they ultimately sink back to the seafloor. As dispersants can enhance or impede microbial activity depending on environmental conditions, ADDOMEx research may inform clean-up efforts after future oil spills. http://www.tamug.edu/addomex/

The Consortium for Advanced Research on Marine Mammal Health Assessment **(CARMMHA)** investigates the effects of oil exposure on Gulf of Mexico marine mammals, including dolphins. This is a new consortium funded by GoMRI started in 2018. https://www.carmmha.org/

The Consortium for Advanced Research on Transport of Hydrocarbon in the Environment **(CARTHE)** focuses on the physical distribution, dispersion, and dilution of petroleum and associated contaminants subject to currents, air-sea interactions, and tropical storms. CARTHE's main goal is to predict the fate of oil released into the environment to guide response and minimize damage to human health, the economy, and the environment. http://carthe.org/

The Center for the Integrated Modeling and Analysis of the Gulf Ecosystem **(C-IMAGE)** explores the impacts of oil spills on the Gulf of Mexico by comparing two Gulf oil spills, the Ixtoc and the Deepwater Horizon, to advance understanding of the processes, mechanisms, and environmental consequences of marine oil blowouts. http://www.marine.usf.edu/c-image/

The Consortium for the Molecular Engineering of Dispersant Systems **(C-MEDS)** studies dispersants, an essential aspect in the response to large oil releases in deep ocean environments. http://dispersant.tulane.edu/

The Consortium for Oil Spill Exposure Pathways in Coastal River-Dominated Ecosystems **(CONCORDE)** improves prediction of future oil spill impacts in shallow waters where freshwater flow and irregular coastlines complicate currents and associated plankton movements. http://www.con-corde.org/

The Consortium for Resilient Gulf Communities **(CRGC)** focuses on helping the Gulf of Mexico region understand and overcome stress brought on by events such as the Deepwater Horizon oil spill. CRGC's goal is to increase community resilience by strategic planning and risk communication with local stakeholder groups, and provide guidance to policymakers for future disasters. http://www.resilientgulf.org/

The Consortium for Simulation of Oil-Microbial Interactions in the Ocean **(CSOMIO)** synthesizes model developments and results to advance understanding of how microbial biodegradation influences accumulation of oil in the water column, in marine sediments of the deep ocean, and on the shelf. CSOMIO also investigates the impacts of potential future oil spills under different conditions to understand how they will influence biodegradation. This is a new consortium funded by GoMRI that started in 2018. https://csomio.org/

The Coastal Waters Consortium **(CWC)** assesses how oil and dispersant change, break down, and impact Gulf of Mexico coastal ecosystems. Specifically, CWC studies food web structure, shifts in populations, individual and ecosystem function during recovery, and the interaction of oil with other stresses on the ecosystem. http://cwc.lumcon.edu/

The Deep Sea to Coast Connectivity in the Eastern Gulf of Mexico consortium **(Deep-C)** studies deep sea to coast connectivity in the northeastern Gulf of Mexico and investigates the environmental consequences of the release of oil and dispersants on living marine resources and ecosystem health in the deep Gulf. http://deep-c.org/

The Deep Pelagic Nekton Dynamics of the Gulf of Mexico consortium **(DEEPEND)** investigates deepwater communities on short-term and long-term timescales to assess their recovery following the Deepwater Horizon oil spill using an integrated net system to collect animals from the surface to 1500 meters deep. http://www.deependconsortium.org/

The Dispersion Research on Oil: Physics and Plankton Studies consortium **(DROPPS)** investigates the breakup of oil patches into droplets in various physical conditions (e.g. breaking waves) when dispersant and bacteria are present. DROPPS also explores oil movement and its interaction with oil-degrading bacteria, phytoplankton, and zooplankton. https://sites.cns.utexas.edu/utmsi.dropps

The Ecosystem Impacts of Oil and Gas Inputs to the Gulf consortium **(ECOGIG)** investigates the ecological impacts of natural and human-caused oil and gas inputs on deepwater ecosystems in the Gulf of Mexico. ECOGIG quantifies the impacts, fates, and dynamics of hydrocarbons in the Gulf and evaluates specific biological responses and adaptations to hydrocarbon exposure, both natural and human-caused. http://ecogig.org/

The Gulf of Mexico Integrated Spill Response consortium **(GISR)** conducts field and laboratory experiments to improve understanding of the physical, chemical, and biological behavior of petroleum fluids as they transit the Gulf from a deep oil spill to the beaches, marshes, estuaries, or atmosphere. http://gulfresearchinitiative.org/tag/gisr/

The Littoral Acoustic Demonstration Center - Gulf Ecological Monitoring and Modeling consortium **(LADC-GEMM)** conducts acoustic surveys to assess regional cetacean populations (sperm whales, beaked whales, and dolphins) and provide recommendations for actions to improve stock recovery for these species. http://www.ladcgemm.org/

The Relationships of Effects of Cardiac Outcomes in Fish for Validation of Ecological Risk consortium **(RECOVER)** examines the effects of oil on two ecologically and economically important species of fish in the Gulf of Mexico: Mahi-Mahi and Red Drum. http://recoverconsortium.org

PARTNERS

Gulf of Mexico Sea Grant Oil Spill Science Outreach Program: https://gulfseagrant.org/oilspilloutreach

The Smithsonian Ocean Portal: https://ocean.si.edu/conservation/gulf-oil-spill

Screenscope Films' *Dispatches from the Gulf* Documentary Series: http://dispatchesfromthegulf.com/

ADDITIONAL INFORMATION AND RESOURCES

For more information about GoMRI's education and outreach products and resources, including those produced by the GoMRI-funded consortia, please visit: http://education.gulfresearchinitiative.org.

For more information about GoMRI-funded research programs and individual investigators, please visit: http://research.gulfresearchinitiative.org/.

Volume 33 • No. 1 • Winter 2019

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

BY EMILY DAVENPORT, LAURA BRACKEN, SARA BERESFORD, AND MURT CONOVER

- 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).

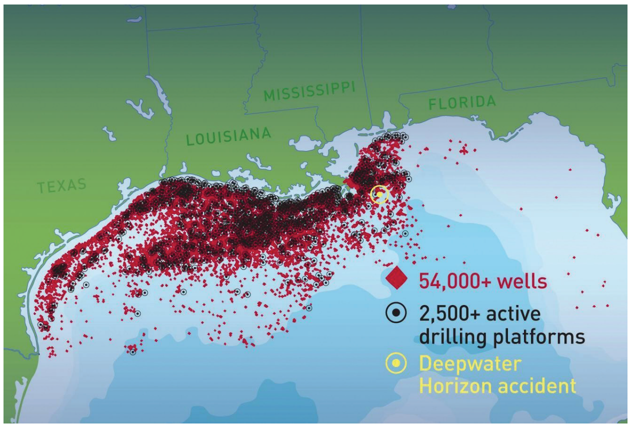


FIGURE 1. The location of all the drilling platforms and wells in the Gulf of Mexico as of July 2016, as well as the location of the Deepwater Horizon accident. Well and platform statistics obtained from Bureau of Ocean Energy Management (BOEM, https://boem.gov). Courtesy of Ecosystem Impacts of Oil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

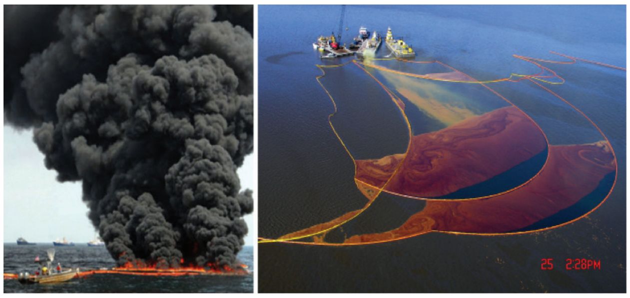


FIGURE 2. Controlled burning (left) and skimming (right) are two techniques used to remove oil from the water after an oil spill. Courtesy of National Oceanic and Atmospheric Administration (NOAA, Creative Commons Attribution 2.0)

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

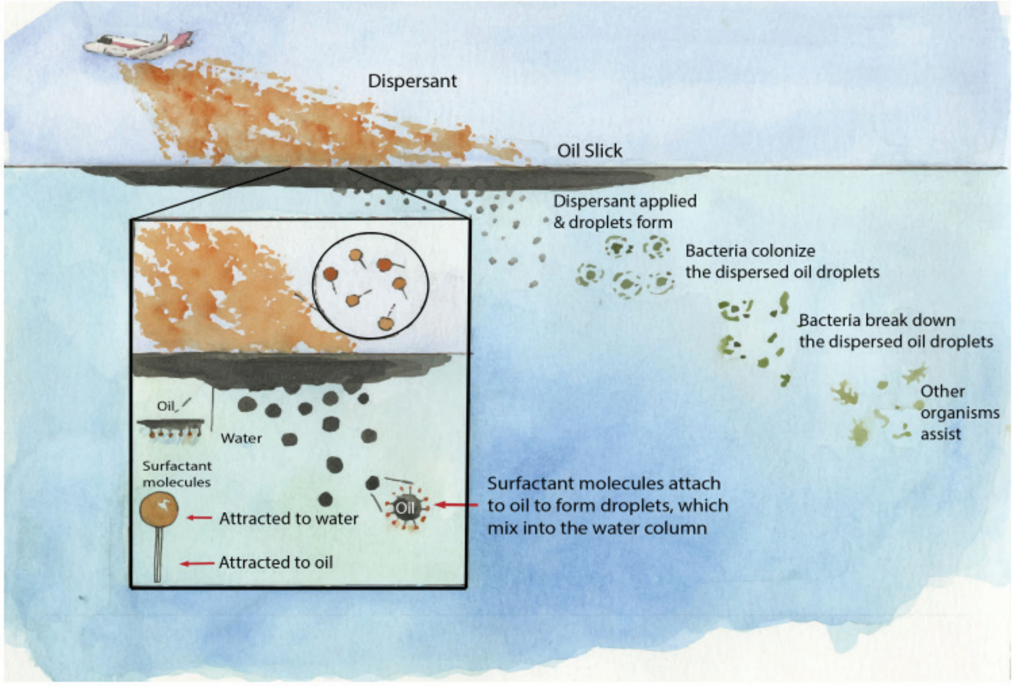


FIGURE 3. Dispersants contain molecules that have one end that is attracted to water and one end that is attracted to oil. When responders apply dispersants to an oil slick, these molecules attach to the oil, allowing the oil slick to be broken up into smaller oil droplets. These smaller droplets then 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

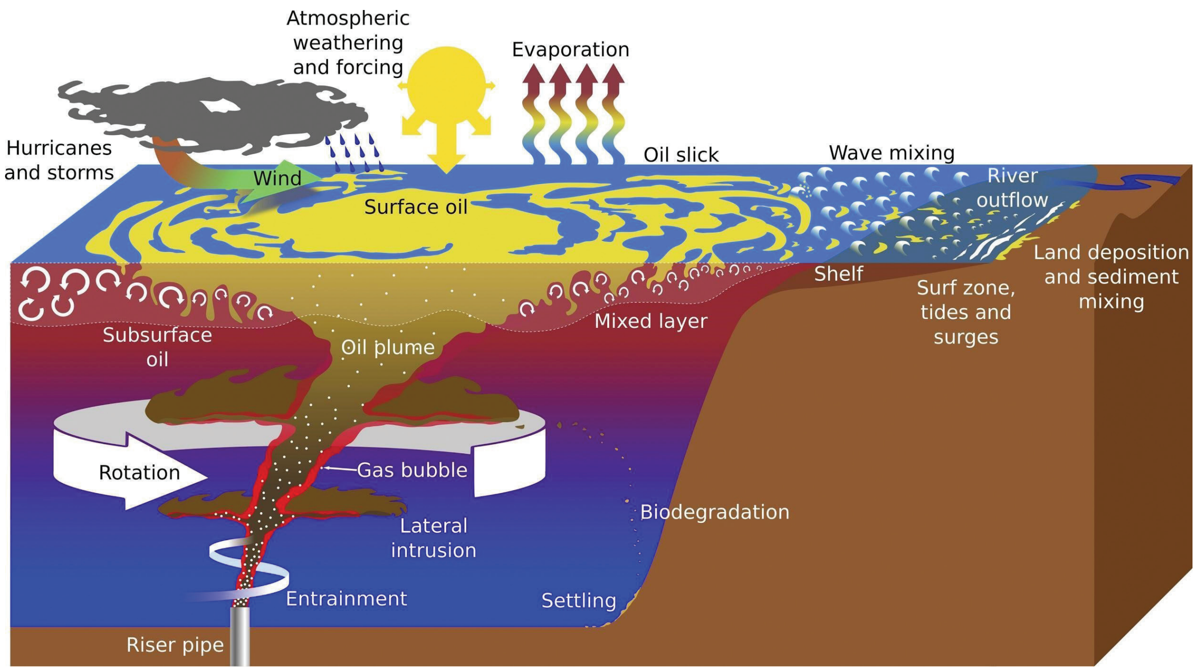


FIGURE 5. An illustration of the various processes that influence the transport of oil from a deep-water pipe to the surface and onto land. Courtesy of CARTHE; Özgökmen et al. 2016

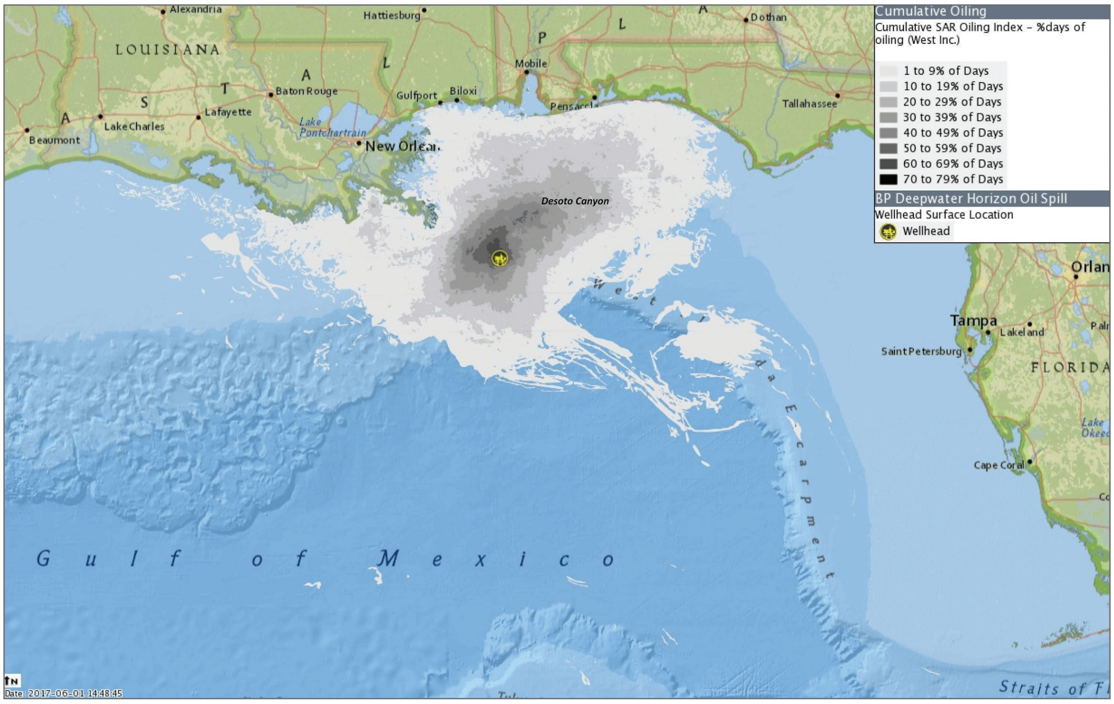


FIGURE 6. A map showing the estimated distribution of the oil on the surface of the Gulf and percentage of days of oiling by location, as measured by Synthetic Aperture Radar (SAR). Courtesy of NOAA's Environmental Response Management Application (ERMA) Deepwater Gulf Response Mapping Application (https://erma.noaa.gov/gulfofmexico/erma.html);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

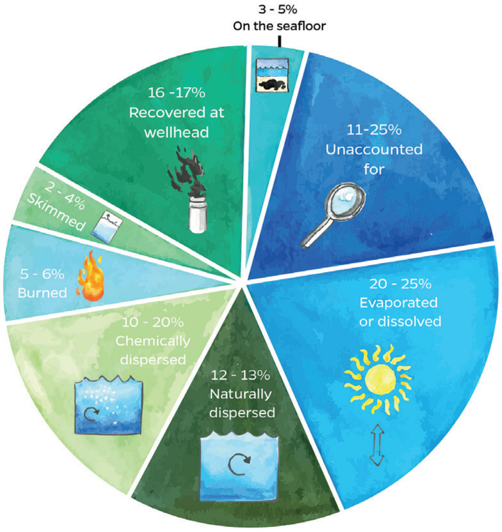


FIGURE 7. An estimate of what happened to the approximately 200 million gallons of oil from the DWH oil spill. Courtesy of Maung-Douglass et al. 2016, reprinted with permission from the Gulf of Mexico Sea Grant Oil Spill Science Outreach Team illustrator Anna Hinkeldey. Numbers are based on data from 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).

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.

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).

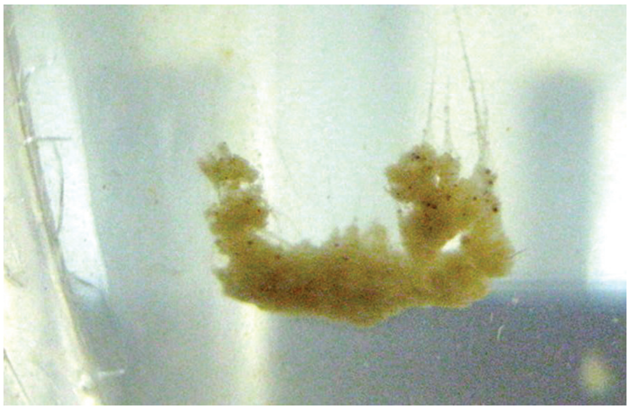


FIGURE 8. Close-up shot of a marine oil snow particle formed in the laboratory. Courtesy of Uta Passow/ECOGIG and Aggregation and Degradation of Dispersants and Oil by Microbial Exopolymers (ADDOMEx, http://www.tamug.edu/addomex/) research consortia

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.

erma.noaa.gov/gulfofmexico/erma.html

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.

REFERENCES
Brooks G.R., R.A. Larson, P.T. Schwing, I. Romero, C. Moore, G. Reichart, T. Jilpert, J.P. Chanton, D.W. Hastings, W.A. Overholt, K.P. Marks, J.E Kostka, C.W. Holmes, and D. Hollander. (**2015**.) Sedimentation pulse in the NE Gulf of Mexico following the 2010 DWH blowout. *PLoS ONE*,10(7): e0132341. doi.org/10.1371/journal.pone.0132341.

Chanton, J., T. Zhao, B.E. Rosenheim, S.B. Joye, S. Bosman, C. Brunner, K.M. Yeager, A.R. Diercks, and D. Hollander. (**2015**.) Using natural abundance radiocarbon to trace the flux of petrocarbon to the seafloor following the Deepwater Horizon oil spill. *Environmental Science & Technology*, 49(2): 847-854. doi.org/10.1021/es5046524.

Daly, K.L., U. Passow, J.P. Chanton, and D. Hollander. (**2016.**) Assessing the impacts of oil-associated marine snow formation and sedimentation during and after the Deepwater Horizon oil spill. *Anthropocene*, 13: 18-33. doi.org/10.1016/j.ancene.2016.01.006.

ERMA. (**2015.**) Web application: *Gulf of Mexico Environmental Response Management Application, National Oceanic and Atmospheric Administration*. Retrieved June 1, 2017 from erma.noaa.gov/gulfofmexico/erma.html.

Fingas, M. (**2013.**) MACONDO well blowout mass balance: A chemical view. *Proceedings of Arctic and Marine Oil Spill Program Technical Seminar*, 75-102.

Fisher, C.R., P. Hsing, C.L. Kaiser, D.R. Yoerger, H.H. Roberts, W.W. Shedd, E.E. Cordes, T.M. Shank, S.P. Berlet, M.G. Saunders, E.A. Larcom, and J.M. Brooks. (**2014.**) Footprint of Deepwater Horizon blowout impact to deep-water coral communities. *Proceedings of the National Academy of Sciences*, 111(32): 11744-11749. doi.org/10.1073/pnas.1403492111.

Fisher, C.R., P.A. Montagna, and T.T. Sutton. (**2016.**) How did the Deepwater Horizon oil spill impact deep-sea ecosystems? *Oceanography*, 29(3): 182-195. doi.org/10.5670/oceanog.2016.82.

Graham, L., C. Hale, E. Maung-Douglass, S. Sempier, L. Swann, and M. Wilson. (**2016.**) Oil spill science: Chemical dispersants and their role in oil spill response. *MASGP*, 15-015. masgc.org/oilscience/oil-spill-science-dispersant-bkgrnd.pdf.

Gyory, J., A.J. Mariano, and E.H. Ryan. (**2013.**) "The Gulf Stream." *Ocean Surface Currents*. University of Miami. Retrieved 28 March 2017 from oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html.

Haza, A.C., T.M. Özgökmen, and P. Hogan. (**2016.**) Impact of submesoscales on surface material distribution in a Gulf of Mexico mesoscale eddy. *Ocean Modelling*, 107: 28-47. doi.org/10.1016/j.ocemod.2016.10.002.

Joye, S.B. (**2015.**) Deepwater Horizon, 5 years on. *Science*, 349: 592-593. doi.org/10.1126/science.aab4133.

Joye, S.B., A. Bracco, T.M. Özgökmen, J.P. Chanton, M. Grosell, I.R. MacDonald, E.E. Cordes, J.P. Montoya, and U. Passow. (**2016.**) The Gulf of Mexico ecosystem, six years after the Macondo oil well blowout. *Deep-Sea Research II*, 129: 4-19. doi.org/10.1016/j.dsr2.2016.04.018.

Lehr, W., S. Bristol, and A. Possola. (**2010.**) *Oil Budget Calculator Deepwater Horizon*. Retrieved September 2018 from Federal Interagency Solutions Group, Oil budget calculator science and engineering team. restorethegulf.gov/sites/default/files/documents/pdf/OilBudgetCalc_Full_HQ-Print_111110.pdf.

Liu, Z., J. Liu, Q. Zhu, and W. Wu. (**2012.**) The weathering of oil after the Deepwater Horizon oil spill: Insights from the chemical composition of the oil from the sea surface, salt marshes, and sediments. *Environmental Research Letters*, 7(3): 035302. doi.org/10.1088/1748-9326/7/3/035302.

Lumpkin, R., T.M. Özgökmen, and L. Centurioni. (**2016.**) Advances in the application of surface drifters. *Annual Review of Marine Science*, 9(1): 59-81. doi.org/10.1146/annurev-marine-010816-060641.

MacDonald, I. R., O. Garcia-Pineda, A. Beet, S. Daneshgar Asl, L. Feng, G. Graettinger, D. French-McCay, J. Holmes, C. Hu, F. Huffer, I. Leifer, F. Muller-Karger, A. Solow, M. Silva, and G. Swayze. (**2015.**) Natural and unnatural oil slicks in the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, 120(2): 8364-8380. doi.org/10.1002/2015JC011062.

Maung-Douglass, E., M. Wilson, L. Graham, C. Hale, S. Sempier, and L. Swann. (**2015.**) Oil spill science: Top 5 frequently asked questions about Deepwater Horizon oil spill. *GOMSG-G-15-002*. masgc.org/oilscience/oil-spill-science-FAQ.pdf.

Maung-Douglass, E., L. Graham, C. Hale, S. Sempier, T. Skelton, L. Swann, and M. Wilson. (**2016.**) Oil spill science: Frequently asked questions—oil edition. *GOMSG-G-16-004*. masgc.org/oilscience/oil-spill-science-oil-FAQ.pdf.

Özgökmen, T.M., E.P. Chassignet, C.N. Dawson, D. Dukhovskoy, G. Jacobs, J. Ledwell, O. Garcia-Pineda, I.R. MacDonald, S.L. Morey, M. Josefina Olascoaga, A.C. Poje, M. Reed, and J. Skancke. (**2016.**) Over what area did the oil and gas spread during the 2010 Deepwater Horizon oil spill? *Oceanography*, 29(3): 96-107. doi.org/10.5670/oceanog.2016.74.

Parsons, M.L., Q. Dortch, R.E. Turner, and N.N. Rabalais. (**2006.**) Reconstructing the development of eutrophication in Louisiana salt marshes. *Limnology and Oceanography*, 51(1, part 2): 534-544. doi/pdf/10.4319/lo.2006.51.1_part_2.0534.

Passow, U., and R.D. Hetland. (**2016.**) What happened to all of the oil? *Oceanography*, 29(3): 88-95. doi.org/10.5670/oceanog.2016.73.

Passow, U., and K. Ziervogel. (**2016.**) Marine snow sedimented oil released during the Deepwater Horizon spill. *Oceanography*, 29(3): 118-125. doi.org/10.5670/oceanog.2016.76.

Poje, A.C., T.M. Özgökmen, B.L. Lipphardt, Jr., B.K. Haus, E.H. Ryan, A.C. Haza, G.A. Jacobs, A.J.H.M. Reniers, M.J. Olascoaga, G. Novelli, A. Griffa, F.J. Beron-Vera, S.S. Chen, E. Coelho, P. J. Hogan, A.D. Kirwan, Jr., H.S. Huntley, and A.J. Mariano. (**2014.**) Submesoscale dispersion in the vicinity of the Deepwater Horizon spill. *Proceedings of the National Academy of Sciences*, 111(35): 12693-12698. doi.org/10.1073/pnas.1402452111.

Roth, M., J. MacMahan, A. Reniers, T.M. Özgökmen, K. Woodall, and B. Haus. (**2017.**) Observations of inner shelf cross-shore surface material transport adjacent to a coastal inlet in the Northern Gulf of Mexico, *Continental Shelf Research*, 137(4): 142-153. doi.org/10.1016/j.csr.2016.12.017.

Ryerson, T.B., K.C. Aikin, W.M. Angevine, E.L. Atlas, D.R. Blake, C.A. Brock, F.C. Fehsenfeld, R.S. Gao, J.A. de Gouw, D.W. Fahey, J.S. Holloway, D.A. Lack, R.A. Lueb, S. Meinardi, A.M. Middlebrook, D.M. Murphy, J.A. Neuman,J.B. Nowak, D.D. Parrish, J. Peischl, A.E. Perring, I.B. Pollack, A.R. Ravishankara, J.M. Roberts, J.P. Schwarz, J.R. Spackman, H. Stark, C. Warneke, and L.A. Watts. (**2011.**) Atmospheric emissions from the Deepwater Horizon spill constrain air-water partitioning, hydrocarbon fate, and leak rate. *Geophysical Research Letters*, 38(7.) doi.org/10.1029/2011GL046726.

Turner, R.E. (**2014.**) *Sediment Core Oil Age Dating*. Unpublished raw data.

Turner, R.E., E.B. Overton, B.M. Meyer, M.S. Miles, and L. Hooper-Bui. (**2014.**) Changes in the concentration and relative abundance of alkanes and PAHs from the Deepwater Horizon oiling of coastal marshes. *Marine Pollution Bulletin*, 86:291-297. doi.org/10.1016/j.marpolbul.2014.07.003.

U.S. Energy Information Administration. (**2015.**) *Petroleum & Other liquids–Crude Oil Production*. Retrieved August 2018 from eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm.

Yan, B., U. Passow, J.P Chanton, E. Nothig, V. Asper, J. Sweet, M. Pitiranggon, A. Diercks, and D. Pak. (**2016.**) Sustained deposition of contaminants from the Deepwater Horizon spill. *Proceedings of the National Academy of Sciences*, 113(24): E3332-E3340. doi.org/10.1073/pnas.1513156113.

EMILY DAVENPORT is the Education and Outreach Coordinator for the Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) research consortium at the University of Georgia Department of Marine Sciences in Athens, Georgia.

LAURA BRACKEN is the Outreach Manager and Program Manager for the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE), based at the University of Miami's Rosenstiel School of Marine and Atmospheric Science in Miami, Florida.

SARA BERESFORD is the Communications and Outreach Lead for the Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) research consortium at the University of Georgia Department of Marine Sciences in Athens, Georgia.

JENNIFER (MURT) CONOVER is the Associate Director of Education and Outreach at the Louisiana Universities Marine Consortium (LUMCON) and the Coastal Waters Consortium (CWC) Education and Outreach Coordinator in Cocodrie, Louisiana.

JOIN NMEA

We invite you to join us and share your ideas, resources, expertise, and inspiration with like-minded professionals.

Networking and building a sense of 'family' is a key benefit of our organization—however, members receive many other benefits as well: discounts at conferences, opportunities for scholarship and leadership, and many others. See http://www.marine-ed.org/?page=mbr_benefits for a complete list of benefits.

We have exciting initiatives happening both locally and globally and would love to collaborate with you!

You have many ways to get involved with this wonderful organization—join committees at http://www.marine-ed.org/ (*click on Groups, then Committees*), share your ideas, help with strategic initiatives, plan implementation, collaborate with other NMEA colleagues, and bring in new members (*contact membership committee chair Lynn Whitley at lwhitley@usc.edu*).

Go to the NMEA website at www.marine-ed.org and click on the "Join Us" link to choose your membership category and start the sign-up process.

Volume 33 • No. 1 • Winter 2019

An Underwater Blizzard of Marine Oil Snow

BY TERESA GREELY, JESSIE KASTLER, SARA BERESFORD, AND KATIE FILLINGHAM

- The Deepwater Horizon oil spill illustrates how science works in a catastrophe. Starting with observations of a previously documented underwater phenomenon known as marine snow, a broad collaboration of researchers each applied their disciplinary skills to improve our understanding of this phenomenon.
- Marine snow is an aggregation of mineral and organic particles held together by mucus from organisms. When marine snow incorporates oil while it settles through the water column, it is called marine oil snow. Unexpectedly, marine oil snow carried a significant amount of spilled oil to the seafloor during the Deepwater Horizon spill.
- While marine snow formation is an ongoing natural process, the story of marine oil snow will continue to develop as part of the Gulf of Mexico Research Initiative (GoMRI) legacy.

In April 2010 the R/V *Pelican* was at sea conducting research in the Gulf of Mexico when its crew learned of the spill resulting from the Deepwater Horizon (DWH) oil rig explosion. Recognizing the opportunity to collect valuable data from the initial stages of the event, members of the crew changed course and headed toward the spill site. There they saw oil at the surface, but it was not concentrated in one area as an oil slick. Rather, it was distributed over a large area in blobs and strands with the consistency of glue. In the months during and after the spill as other researchers began collecting data, they made more observations. Thick layers of fuzzy, oily blobs were seen in images collected by subsurface cameras and in sediment traps between the surface and the seafloor. Other scientists found unexpected accumulations in sediment cores collected from the seafloor shortly after the spill (Figure 1).

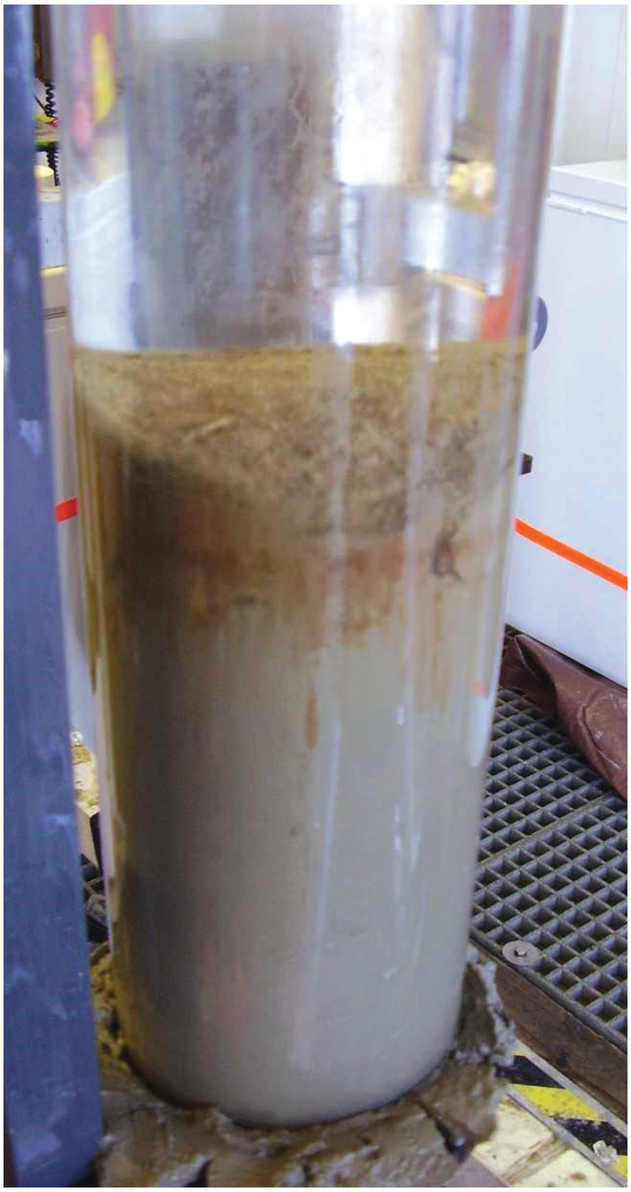


FIGURE 1. A layer of marine oil snow covering seafloor sediments in a core sample collected during a November 2010 cruise at a site 175 kilometers (km) east, northeast of the DWH wellhead in 400 meters (m) water depth (site MC04). Courtesy of Patrick Schwing, University of South Florida, College of Marine Science

Typically, oil floats above seawater because it is less dense. So why were scientists finding it on the seafloor and how did it get there?

A previous article in this issue highlights many of the physical processes contributing to the movement of the oil in the Gulf. Another article in this issue describes the spill's impacts on different organisms. These physical and biological processes

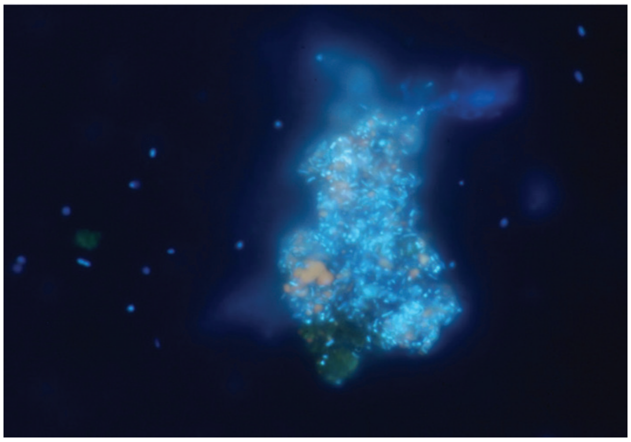


FIGURE 2. A fluorescent picture of marine oil snow (MOS). The orange spots are droplets of oil, while all the blue is the bacteria present in the sample. Courtesy of Emily Whitaker, Texas A&M University

FIGURE 3. Dispersed oil droplets bound to marine detritus and plankton collected in northern Gulf of Mexico waters during Deepwater Horizon (2010). Courtesy of David Liittschwager

cannot be considered separately. The sea story of marine oil snow (MOS) connects physical and biological processes, the transport of oil from the surface to the seafloor and back again, and the multidisciplinary efforts of scientists with very different areas of expertise. Geochemists, sedimentologists, ecologists, and physical oceanographers considered these observations from their own perspectives, which contributed to a new understanding of the phenomenon of marine oil snow formation. Combining their expertise, researchers supported by the Gulf of Mexico Research Initiative (GoMRI) collaborated after the oil spill to improve our understanding of this unusual phenomenon.

Marine snow is a naturally occurring mixture of organic and inorganic particles that range in size from 0.5 mm to >10 cm. Each aggregate is composed of bacteria, plankton, fecal pellets, and mineral particles released by organisms or carried from land (Alldredge and Silver 1988). Marine snow initially forms when zooplankton, phytoplankton, and bacteria near the surface of the ocean excrete a mucus-like exopolymeric substance (EPS) (Quigg 2016). This EPS, known informally as 'sea snot,' is made primarily of carbohydrates with some protein. It is sticky and can protect an organism from toxins. When planktonic organisms die and begin to settle to the bottom of the water column, the mucus they produce attracts minerals and other organic particles to make larger aggregates. The aggregates, or marine snow, are denser than the organic particles, so they fall more rapidly than the individual particles. Sinking marine snow 'flakes' are repackaged as they stick to other flakes, or by zooplankton grazing or bacterial decomposition (Figure 2). They play a role in the food web during their settling because they are an important source of nutrients to organisms that live in seawater deeper than 200 meters (m) where little to no sunlight penetrates and thus no photosynthesis occurs.

Recognizing similarities between the blobs they observed in the sediments near the Deepwater Horizon wellhead and marine snow, GoMRI-funded scientists considered the possibility that the strange accumulations could have resulted from a similar process. They hypothesized that incorporation of oil into marine snow was a significant mechanism by which oil reached the seafloor. In fact, scientists ultimately concluded that during the DWH event, a 'different kind of snow' was generated. This 'new' snow was a combination of high concentrations of oil and oil-containing sea snot called marine oil snow, abbreviated MOS. The MOS aggregates near the wellhead during the DWH spill were observed to be much larger than unpolluted marine snow aggregates, causing scientists to suspect that the presence of oil and the dispersant used in the oil spill response was impacting the way marine snow forms (Passow and Ziervogel 2016).

There were several ways oil from the spill was incorporated into marine snow during the DWH event. Many planktonic organisms died, triggering deposition of the dead plankton on the seafloor (Passow and Ziervogel 2016). Nutrient inputs from the Mississippi River and from the oil stimulated greater than usual production of phytoplankton (Daly et al. 2016; Passow and Ziervogel 2016). This abundance of phytoplankton incorporated large quantities of oil into MOS. Zooplankton then consumed MOS particles, concentrating it in larger particles such as fecal pellets that were released back into the water column (Passow and Ziervogel 2016). The addition of

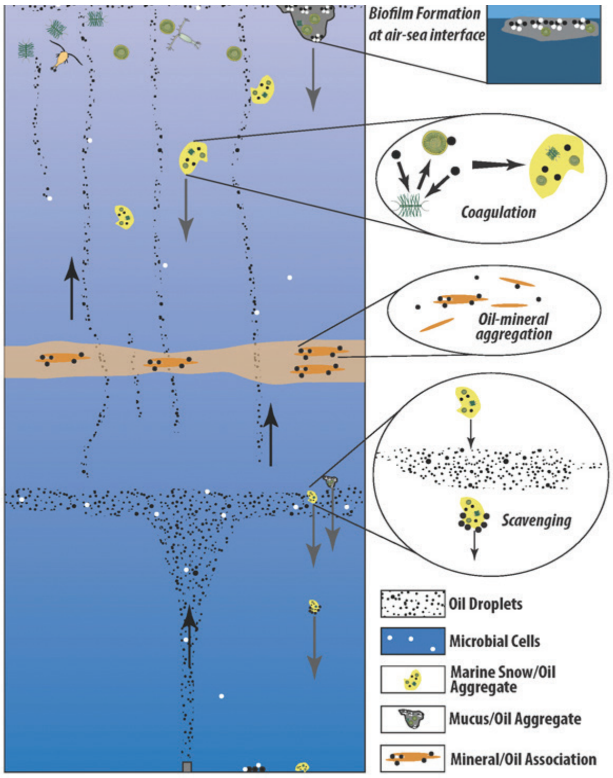


FIGURE 4. A schematic depicting the interactions between oil, mineral particles, and marine snow in the water column. Oil droplets in the water column can create aggregates with mineral particles and marine snow. These large particles rapidly sink through the water column carrying the oil with them, creating a process that transports oil from the surface to the deep ocean. Sinking particles that pass through subsurface oil layers can accumulate and carry even more oil to the ocean floor. Meanwhile, oil that reaches the surface can form large mucus-oil aggregates which can also subsequently sink to theocean floor. Courtesy of Adrian Burd, University of Georgia and University of Maryland Center for Environment Integration and Application Network, http://ian.umces.edu/

chemical dispersant stimulated phytoplankton and bacteria to produce large amounts of mucus, mixing water into the oil, increasing its surface area, and making it easier to consume (Figure 3; Passow and Ziervogel 2016). Bacteria also formed additional MOS as they congregated at the edges of oil slicks to consume the oil (Passow et al. 2012).

Marine snow can concentrate at any depth and takes months or years to settle on the seafloor (Figure 4). During the DWH event, the production of marine snow increased and combined with oil and dispersants to generate an underwater blizzard of marine oil snow that accumulated on the seafloor over four to five months (Brooks et al. 2015). Pulses of deposition began with the death of 40-70 trillion planktonic organisms and led to the accumulation of approximately one centimeter of MOS on deep-sea coral (Passow and Ziervogel 2016). It has been estimated that 2-15% of spilled oil landed on the seafloor, most as a result of MOS sedimentation (Daly et al. 2016; Brooks et al. 2015).

Because marine snow provides food for many benthic invertebrates such as amphipods, isopods, some fish species that live primarily on the seafloor (i.e. tilefish and king snake eel), and fishes that visit the bottom (i.e. red snapper), there is concern that the incorporation of oil into marine snow could lead to the bioaccumulation of oil within the food web (Daly 2016). With the potential for a long residence time, there is also concern that the damaging effects of MOS on benthic organisms will be prolonged (Montagna et al. 2013; Daly et al. 2016). Researchers have reviewed records of past oil spills to see if marine oil snow was significant in oil transport in those events. While limited data collection on the seafloor near these past spills did not allow scientists to draw many conclusions, there is evidence of MOS sedimentation in some other spills, including the 1979 Ixtoc spill in the Gulf of Mexico near Campeche, Mexico (Vonk et al. 2015).

The story of marine oil snow and the underwater blizzard caused by the DWH spill exemplifies science at work. Scientists aboard the R/V *Pelican* observed a previously described phenomenon in a new setting: marine snow incorporating oil into large aggregates at the sea surface. Other scientists aboard the R/V *Weatherbird II* found additional evidence of the same process while conducting their own post-spill investigations on the seafloor. Scientists studying MOS have referred to the phenomenon in calls for enhanced testing of dispersants to explore its behavior in realistic field conditions with variable temperature and nutrient characteristics (van Eenennaam 2016). They further declare a need for improved benthic assessments including pre-drilling baseline data collection and early post-spill sampling (Vonk et al. 2015; Daly et al. 2016). The research effort made possible by GoMRI facilitated collaborations to help connect the dots. Observations are coming together to form significant conclusions and contribute a multidisciplinary description of an unexpected phenomenon caused by the oil spill. The end of this story is not yet written. As with all subjects of scientific study, there will always be another observation to make and other questions to ask.

ACKNOWLEDGMENTS
In addition to the acknowledgments for the full issue, the authors of this article would like to thank Kendra Daly and Antonietta Quigg for their contribution to the manuscript. This article was made possible by funding from GoMRI to CONCORDE, C-IMAGE, the Consortium for Ocean Leadership, and ECOGIG.

REFERENCES

Alldredge, A.L., and M.W. Silver. (1988.) Characteristics, dynamics and significance of marine snow. *Progress in Oceanography*, 20(1): 41-82. doi.org/10.1016/0079-6611(88)90053-5.

Brooks, G.R., R.A. Larson, P.T. Schwing, I. Romero, C. Moore, G.-J. Reichart, T. Jilbert, J.P Chanton, D.W. Hastings, W.W.A. Overholt, K.P. Marks, J.E. Kostka, C.W. Holmes, and D. Hollander. (2015.) Sedimentation pulse in the NE Gulf of Mexico following the 2010 DWH blowout. *PLoS ONE*, 10(7): e0132341. doi.org/10.1371/journal.pone.0132341.

Daly, K.L., U. Passow, J. Chanton, and D. Hollander. (2016.) Assessing the impacts of oil-associated marine snow formation and sedimentation during and after the Deepwater Horizon oil spill. *Anthropocene*, 13(18): 18-33. doi.org/10.1016/j.ancene.2016.01.006.

Montagna, P.A., J.G. Baguley, C. Cooksey, I. Hartwell, L.J. Hyde, J.L. Hyland, R.D. Kalke, L.M. Kracker, M. Reuscher, and A.C.E. Rhodes. (2013.) Deep-sea benthic footprint of the Deepwater Horizon blowout. *PLoS ONE*, 8(8): e70540. doi.org/10.1371/journal.pone.0070540.

Passow, U., K. Ziervogel, V. Asper, and A. Diercks. (2012.) Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico. *Environmental Research Letters*, 7(3): 035031. doi.org/10.1088/1748-9326/7/3/035301.

Passow, U., and K. Ziervogel. (2016.) Marine snow sedimented oil released during the Deepwater Horizon spill. *Oceanography*, 29(3): 118-125. doi.org/10.5670/oceanog.2016.76.

Quigg, A., U. Passow, W-C. Chin, C. Xu, S. Doyle, L. Bretherton, M. Kamalanathan, A. Williams, J. Sylvan, Z. Finkel, A. Knap, K. Schwehr, S. Zhang, L. Sun, T. Wade, W. Obeid, P. Hatcher, and P. Santschi. (2016.) The role of microbial exopolymers in determining the fate of oil and chemical dispersants in the ocean. *Limnology and Oceanography Letters*, 1: 3-26. doi.org/10.1002/lol2.10030.

van Eenennaam, J.S., Y.Y. Wei, K.C.F. Grolle, E.M. Foekema, and A.T.J. Murk. (2016.) Oil spill dispersants induce formation of marine snow by phytoplankton-associated bacteria. *Marine Pollution Bulletin*, 104(1-2): 294-302. doi.org/10.1016/j.marpolbul.2016.01.005.

Vonk, S.M., D.J. Hollander, and A.J. Murk. (2015.) Was the extreme and widespread marine oil-snow sedimentation and flocculent accumulation (MOSSFA) event during the Deepwater Horizon blow-out unique? *Marine Pollution Bulletin*, 100(1): 5-12. doi.org/10.1016/j.marpolbul.2015.08.023.

TERESA GREELY co-leads the Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) Outreach Team, and serves as the Director of Education and Outreach and a teaching faculty at the University of South Florida's College of Marine Science in St. Petersburg, Florida.

JESSIE KASTLER is the Outreach Coordinator of Consortium for Oil Spill Exposure Pathways in Coastal River-Dominated Ecosystems (CONCORDE) and the Coordinator of Program Development for the Marine Education Center at the University of Southern Mississippi, Gulf Coast Research Laboratory in Ocean Springs, Mississippi.

SARA BERESFORD See bio on page 16.

KATIE FILLINGHAM is a Program Specialist with the Gulf of Mexico Research Initiative (GoMRI) at the Consortium for Ocean Leadership in Washington, District of Columbia.

Volume 33 • No. 1 • Winter 2019

Deepwater Horizon Oil Spill Impacts on Organisms and Habitats

BY SARA BERESFORD, JESSIE KASTLER, RACHEL MCDONALD, DAN DINICOLA, AND KATIE FILLINGHAM

- Conclusive statements about how organisms and biological communities fared after the Deepwater Horizon accident are still difficult to make nearly a decade after the spill. Much of the work on organisms and their habitats will continue for years to come, and some of the impacts will only be apparent with long-term study.

- Scientists have learned, and will continue to learn, important lessons by studying the impacts of the largest accidental oil spill in history on marine habitats and life in the Gulf of Mexico, such as impacts on large vertebrates (fish, cetaceans, birds), deep-sea organisms, phytoplankton and other marine microbes, coastal and pelagic fishes, and marsh plants and animals. Gulf of Mexico Research Initiative (GoMRI) researchers are finding that sublethal impacts (those that do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, and/or reproduction) are important, and understanding them provides critical insight about longer-term, population-level impacts of the spill on marine life.

- One of the most valuable lessons from this accident has been that it is critically important to collect baseline data for ecosystems, in particular those which are most at risk of impact by industrial activities, and GoMRI researchers are helping to contribute to this body of knowledge.

- Researchers developed innovative ways to investigate the impacts of oil on many different organisms and habitats. An associated activity provides students the opportunity to conduct their own virtual experiment on two species of fish, assessing changes in swim behavior and vision after oil exposure with "fish treadmills."

INTRODUCTION

What happened to marine organisms in the months and years following the Deepwater Horizon (DWH) oil spill in the Gulf of Mexico? Almost a decade after the spill, the answer to that question is still not completely clear. There is no single condition report for all of the animals affected by the spill. Some species, like gulls and wading birds, were gravely injured. Others did not appear to be greatly affected, like some species of estuarine fish (Haney et al. 2014b; Able et al. 2015; McCann et al. 2017). Many individual organisms, including dolphins, were killed immediately, while some, such as mahi-mahi fish, suffered sublethal impacts that affected the way they feed, navigate, or reproduce (NOAA(c); Incardona et al. 2014). In many cases we don't know and may never know. Scientists participating in the Gulf of Mexico Research Initiative (GoMRI) have been working to understand and determine impacts of the oil and dispersant (see box on page 28) on organisms, and here we highlight some of their research efforts. Moving from deep sea to coastal habitats, we focus on a few groups of organisms.

SPECIALIZED DEEP-SEA COMMUNITIES

How Did Oil Enter the Deep-sea Food Web?

Cold seeps play an important role in the deep Gulf of Mexico ecosystem (Fisher 2007). Cold seeps are areas where hydrogen sulfide, brine, methane, and other hydrocarbon-rich fluids naturally 'seep' out of the ocean floor. Mussels and tubeworms dominate the cold seep communities and provide structure and habitat for diverse associations of benthic or bottom-dwelling animals such as shrimp, crabs, polychaete worms, and eventually deep-sea coral. The hydrocarbon seepage at cold seeps requires that microorganisms living in the vicinity be able to degrade, or at least tolerate, hydrocarbon exposure (Joye et al. 2014; 2016).

While sunlight fuels the food web in the shallower, sunlit waters of the Gulf, microbes near cold seeps are capable of converting oil and methane into energy, which is then carried into higher trophic levels by microplankton-like protists. The microbial response to the DWH spill likely transferred significant amounts of oil- and gas-derived carbon into the planktonic-microbial food web (Fernandez-Carrera et al. 2016). Researchers detected oil in the food web as early as late summer 2010 using isotopes to trace DWH carbon to zooplankton (Graham et al. 2010; Chanton et al. 2012). This hydrocarbon was still being recycled through the food web for two years after the end of the spill (Fernandez-Carrera et al. 2016).

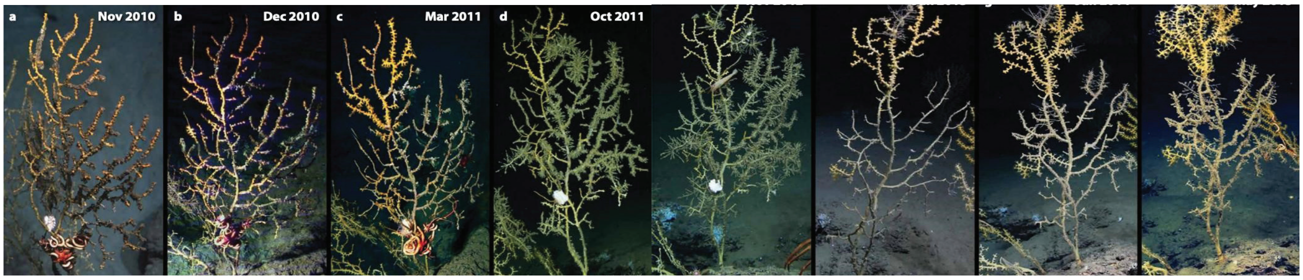


FIGURE 1. Photo time series demonstrating oil spill impact on a deep-sea coral community over time. Coral is partially covered by oily flocculent material in 2010, and by 2011 many branches of the coral have died and become covered by hydroids. The brittle star and anemone living on the coral were gone by 2013. Courtesy of F. Girard; Figure 3 from Fisher et al. 2016

Microbes also played an important role in transporting oil to the deep sea. Marine snow is formed when a sticky mucus excreted by zooplankton, phytoplankton, and bacteria combines with organic and inorganic particles already in the water. Settling of these particles is an important mechanism for transporting nutrients to the deep sea. Scientists were surprised to learn after the DWH spill that this process also transported a significant amount of oil and dispersant to the bottom and ultimately into the marine food web (Joye et al. 2014).

Documenting Damage to Deep-sea Corals

Deep-sea colonial corals are slow-growing and known to live for hundreds to thousands of years (Fisher et al. 2014a; Fisher et al. 2016). In the deep Gulf, they colonize the hardground substrate resulting from microbial activity at cold seeps and serve as an important foundation species within deep-sea benthic communities. Their complex structures provide habitat, energy, and organic matter for a variety of organisms, including fishes, sponges, clams, oysters, crabs, brittle stars, barnacles, and krill. They are diverse, sessile (fixed in place), sensitive to damage, and slow to recover.

Damage to deep-sea corals from the DWH accident was documented in an area 13 kilometers (km) to the southwest of the accident site in November 2010 (White et al. 2012; Fisher et al. 2016; Fisher et al. 2014b; Hsing et al. 2013). This site was known to be in the path of a well-documented, mid-depth plume of neutrally buoyant water enriched with petroleum hydrocarbons from the spill. Scientists observed numerous coral colonies at this location showing widespread signs of stress, including tissue loss, deformation of calcite hard parts, excess mucus, death of associated animals, and covered by a layer of aggregated oil, dispersant, mineral, and organic material known as “floc.”

Since 2010, several additional sites with damaged deep-sea coral colonies have been discovered as far as 22 km away from the Macondo wellhead (Fisher et al. 2014b; Fisher et al. 2016). Other research groups have found damage they attributed to this spill on mesophotic coral reefs (found at 30-150 meter [m] depths) as far away as 109 km north-east of the spill site (Silva et al. 2016; Etnoyer et al. 2016). Researchers have developed innovative sampling methods and data analyses for documenting impacts. High-resolution camera equipment mounted on submersibles was used to collect images of the corals, the analysis of which enabled researchers to quantify changes over time (Figure 1). Since 2010, over 350 spill-impacted coral colonies have been visited and photographed annually. Some corals have shown signs of recovery; others are not expected to survive the spill’s impacts. Corals in the deep sea grow very slowly and, ultimately, die slowly. The ultimate fate of the deep-sea corals is still unknown.

Lessons from the Coral Research

Spill Footprint and Role of Marine Snow: Studies of deep-sea corals after the DWH spill have allowed researchers not only to investigate impacts on the corals themselves, but also to draw conclusions about movement of DWH oil after the spill and the extent of the spill’s footprint on the seafloor, including estimating the extent of affected seafloor and depths at which impact was observed. In particular, the coral studies have improved understanding of the movement of the subsurface oil plume and the importance of marine oil snow (Fisher et al. 2014b; Fisher et al. 2016).

Role of Ophiuroids (Brittle Stars): A recent study uncovered new information about the role that ophiuroids (i.e. brittle stars) may have played in the extent of impact and recovery of a species of deep-sea coral (*Paramuricea*) after the spill (Girard et al. 2016). Ophiuroids, amongst other invertebrates, are known to associate with some deep-sea corals (Figure 2). Previous studies suggested that ophiuroids benefit from this association by getting better access to zooplankton and other suspended particles for nutrition. Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG, http://ecogig.org) researchers found that corals also benefit from the ophiuroids. In this symbiotic relationship, ophiuroids not only help protect their coral hosts from deposition of material, but they also have a positive effect on recovery. This study is important not only in the context of the oil spill, but also when considering other impacts corals might be exposed to, such as natural or anthropogenic sedimentation events.

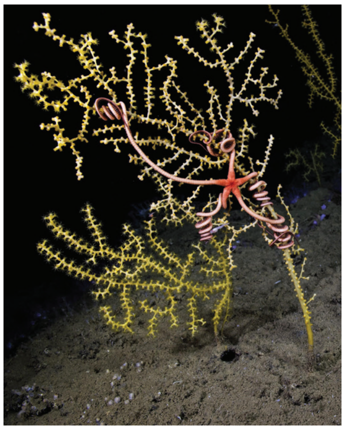


FIGURE 2. Brittle star (ophiuroid) living on deep-sea coral in the Gulf of Mexico. Courtesy of ECOGIG and Ocean Exploration Trust

FISH

Gulf fishes live in a variety of locations, from deep to shallow water. They may be bottom dwellers or surface feeders. They may travel broadly, linking separate parts of the ocean through the food web. Research since the oil spill has focused on assessing effects on individual fishes as a way of establishing damage that might affect full populations and on assessing actual damage to full populations. Research has included both field observations in affected areas and a variety of laboratory investigations.

Mortality Versus Sublethal Effects

Beginning with research following the *Exxon Valdez* oil spill in 1989 and continuing with research on the DWH oil spill, researchers have found that sublethal impacts (those that do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, and/or reproduction) of oil and dispersant are important and, in some cases, can be significant (Peterson et al. 2003; Buskey et al. 2016). Understanding sublethal impacts provides critical insight about longer-term, population-level impacts of the spill on marine life. Several different types of sublethal effects are described here for fishes, and in later sections for other organisms.

Fishes exposed to high concentrations of oil frequently die, but lower concentrations of oil can cause injury, or sublethal effects (Peterson et al. 2003). For example, during the months after the DWH oil spill, fishermen across the northern Gulf reported seeing fish, such as red snapper, with skin lesions. The number of lesions observed was greatly reduced in subsequent years, which limited the scientists' ability to confirm the link between oil contamination and lesions (Murawski et al. 2014). If exposure to oil did cause the lesions, it would be an example of a sublethal effect of the contamination. Rather than dying immediately, injured fish are more susceptible to death by predation, less efficient feeding, and reduced immunity to diseases. They may also have reduced ability to successfully reproduce. In addition, young fish (embryos, larvae, and juveniles) are extremely susceptible to sublethal impacts.

Relationships of Effects of Cardiac Outcomes in Fish for Validation of Ecological Risk (RECOVER, http://recoverconsortium.org) scientists used laboratory experiments to study sublethal effects of oil on juvenile mahi-mahi. They explored the consequences of oil exposure using a swim tunnel (Incardona 2014). Cardiac function tests showed oil-exposed fish could not swim as fast or as long as healthy individuals. In vision experiments, oil-exposed fish became disoriented when following a moving target. The deficiencies resulting from oil exposure did not cause immediate death to the juvenile fish. However, affected fish were less able to evade predators, acquire food, spawn, migrate, and avoid oil (Figure 3; Mager et al. 2014; Stieglitz et al. 2016). All of these results reduce a fish's prospects for survival.

Population-level Impacts

Laboratory studies on individual organisms have consistently documented negative effects of oil (Fodrie et al. 2014). Researchers also anticipated a reduction in fish populations, which they inferred from surveys of species density (Fodrie et al. 2014). Post-spill studies in estuarine species of fish consistently showed damage to individuals, including sublethal abnormalities in development of individuals such as those described earlier for open water fishes (Dubansky et al. 2013). However, population-level damage had not

FIGURE 3. A mahi is loaded into a recovery tank after tagging. Courtesy of RECOVER

materialized by 2011 (Fodrie and Heck 2011). Coastal Waters Consortium (CWC, http://cwc.lumcon.edu) investigators explored this contradiction by reviewing past studies of oil spill impacts on coastal and estuarine Gulf fishes. They found that some factors conceal population-level responses while others reduce it (Fodrie et al. 2014). For example, closing an area to fishing might lead to an increase in survival of speckled trout that masks mortality related to the oil spill (Fodrie et al. 2014). On the other hand, flatfish swimming away from oil unharmed could make it appear that there are reduced population levels (Fodrie et al. 2014). From these results, researchers recommended that future research link population-level surveys with lab and field studies of individual animals (Fodrie et al. 2014).

OTHER LARGE MARINE VERTEBRATES

The body of literature documenting the toxicity and impacts of oil and, in some cases, chemical dispersant is large. In addition to GoMRI research publications, there are many resources to consult, the most comprehensive of which is the Natural Resources Damage Assessment document (NRDA 2016). The information presented here on birds, sea turtles, and marine mammals, less studied in the GoMRI program, is a subset of that body of work which summarizes results of hundreds of studies documenting specific impacts to as many habitats, organisms, and processes as possible following the DWH oil spill. The NRDA report was produced as a comprehensive description of oil spill impacts for the purpose of assessing a financial penalty to the responsible parties. Similarly, the Gulf of Mexico Sea Grant Oil Spill Science Outreach publications (see https://gulfseagrant.org/oilspilloutreach/) provide excellent sources of information about the impacts of the spill on a variety of species of interest.

Birds

In the northern Gulf of Mexico, birds live in a variety of habitats, including open water, island waterbird colonies, barrier islands, beaches, bays, and marshes (NRDA, 4-461). They were exposed to DWH oil in a variety of ways, including physical coating of their feathers and bodies, ingestion of contaminated prey, ingestion due to preening oiled feathers, and inhalation of oil vapors (NRDA, 4-461; 4-471). Emergency response activities to control and clean up the DWH spill may also have negatively impacted birds. Some clean-up activities disturbed birds while nesting or foraging, crushed nests and young birds, and in some cases intentionally scared birds away from heavily oiled areas using propane cannons and other methods (NRDA, 4-504). Burning and skimming operations may have fatally exposed birds to smoke (NRDA, 4-505) or fumes (NRDA, 4-471). Oiled booms retained oil on the water against bird colonies for several days and likely increased their exposure to oil (NRDA, 4-506).

Birds experienced a variety of adverse health impacts. A bird with oil-coated feathers loses its insulation as well as its ability to swim or float, causing the bird to expend more energy to swim or dive (NRDA, 4-471). Oil-coated feathers also impact a bird's ability to fly. The impacts of ingesting or inhaling oil are devastating to birds. Laboratory studies indicated a variety of problems from oil ingestion, including anemia, weight loss, hypothermia, heart and liver abnormalities, reproductive disruption (such as delayed egg laying, decreased eggshell thickness, etc.), gastrointestinal dysfunction, and death (NRDA, 4-461; 4-471).

More than 93 species of birds across all five Gulf states in a variety of habitat types were exposed to the oil (NRDA, 4-509). More than 8,500 dead and oil-impacted birds were collected after the DWH spill (NRDA, 4-479). Estimates of total bird loss vary widely and include not only bird deaths, but also birds not born as a result of the spill (NRDA, 4-509). Conservatively, it was estimated that 56,100 to 102,400 birds were lost in the first year after the spill (NRDA, 4-509); however, total injury is likely substantially higher, not only due to longer-term health effects, but also an acknowledgment that a significant amount of bird injury and loss in the first year after the spill was unquantified (NRDA, 4-509). Research models concluded that 800,000 coastal and 200,000 offshore birds died (Haney et al. 2014a, b). These numbers corresponded to losses estimated at 12% and 32% of the pre-spill populations of brown pelican and laughing gull, respectively (Haney et al. 2014b). Extensive restoration of bird habitat across the Gulf is a critical part of recovering from the spill.

Sea Turtles

Five of the world's seven sea turtle species live in the Gulf (Kemp's ridleys, loggerheads, hawksbills, leatherbacks, and green turtles), all of which are listed as threatened or endangered under the United States Endangered Species Act (NRDA, 4-516). All of the habitat types they occupy in the northern Gulf were impacted by the DWH spill, including open ocean, nearshore, and coastal areas. Turtles spend time at the water's surface to breathe, bask, rest, and feed, which put them at particular risk of exposure to DWH surface oil (NRDA, 4-517). Response activities were particularly disruptive for the turtles, including boat traffic, dredging, and clean-up activities on the beaches. Response personnel and vehicles on the beaches, equipment, and increased lighting disrupted nesting behavior and the nests themselves. Scientists estimate that almost 35,000 hatchlings were injured by response activities (NRDA, 4-518).

FIGURE 4. Dr. Brian Stacy, veterinarian with the National Oceanic and Atmospheric Administration (NOAA), prepares to clean an oiled Kemp's ridley turtle during the Deepwater Horizon oil spill. Courtesy of NOAA and Georgia Department of Natural Resources (Creative Commons Attribution 2.0)

FIGURE 5. Striped dolphins (*Stenella coeruleoalba*) observed in emulsified oil on April 29, 2010. Courtesy of NOAA (Creative Commons Attribution 2.0)

Sea turtles were exposed to oil by breathing oil droplets and oil vapors, ingesting oil-contaminated water and prey, and becoming coated in surface oil (Figure 4; NRDA, 4-516). Scientists concluded that the most acute adverse effects to turtles resulted from becoming coated in oil and getting bogged down or stuck in the surface oil (NRDA, 4-541). Turtles that became mired in the surface oil suffered from decreased mobility, exhaustion, dehydration, and overheating, all of which decreased their ability to feed and evade predators and, in many cases, the result was turtle death.

Due to the size of the surface oil slick, turtle surveys only covered less than 10% of the surface oil slick and did not include areas near the wellhead nor surveys conducted throughout the entire 87 days of the spill (NRDA, 4-517). Using knowledge of turtle behavior and statistical methods, scientists estimate that between 4,900 and 7,600 adult and large juveniles and between 55,000 and 160,000 small juvenile sea turtles were killed by the spill (NRDA, 4-518). These losses and reductions in reproduction potential cause challenges to recovery for turtle populations. Because turtles migrate around the world, damage to sea turtle populations is potentially global (Hale et al. 2017).

Marine Mammals: Dolphins

There are 22 species of marine mammals, including dolphins, whales, and the West Indian manatee, in the northern Gulf inhabiting open water, nearshore, and estuarine habitats (NRDA, 4-585). All of these habitat types were contaminated by DWH oil (NRDA, 4-598), and tens of thousands of marine mammals were exposed to the surface oil through inhalation, aspiration, ingestion, absorption, or skin exposure (NRDA, 4-584). The oil damaged their tissues and organs, which resulted in reproductive failure, adrenal disease, lung disease, liver failure, anemia, and in many cases, death. Marine mammals were also impacted by oil spill response activities, such as oil removal, dispersant use, and boat traffic, which exposed them to smoke and chemical dispersant, blocked access to habitats, increased vessel traffic, and noise from boats and response operations (NRDA, 4-606).

The DWH oil spill occurred after the start of an Unusual Mortality Event (UME). An UME is defined by the Marine Mammal Protection Act as an unusually large, unexpected marine mammal stranding event (NOAA[a]). Deaths attributed to the spill contributed to the largest and longest-lasting UME ever recorded for the Gulf (NRDA, 4-584). Between 2010 and 2014, 1141 mammals, mostly bottlenose dolphins, stranded along the northern Gulf shoreline, 95% of them dead. Of these, 89 stranded before the spill began (NOAA[b]). Dolphins that stranded in the Gulf had disease conditions consistent with oil exposure, unlike animals that stranded elsewhere (Venn-Watson 2015). Although the DWH spill began after the beginning of the UME, researchers concluded the spill was responsible for the persistent increase in deaths (NOAA[b]).

Amongst the best studied marine mammal populations were the stocks of bottlenose dolphins in Barataria Bay and Mississippi Sound (NRDA, 4-585). Scientists projected their populations were reduced by 51% and 62%, respectively

Volume 33 • No. 1 • Winter 2019

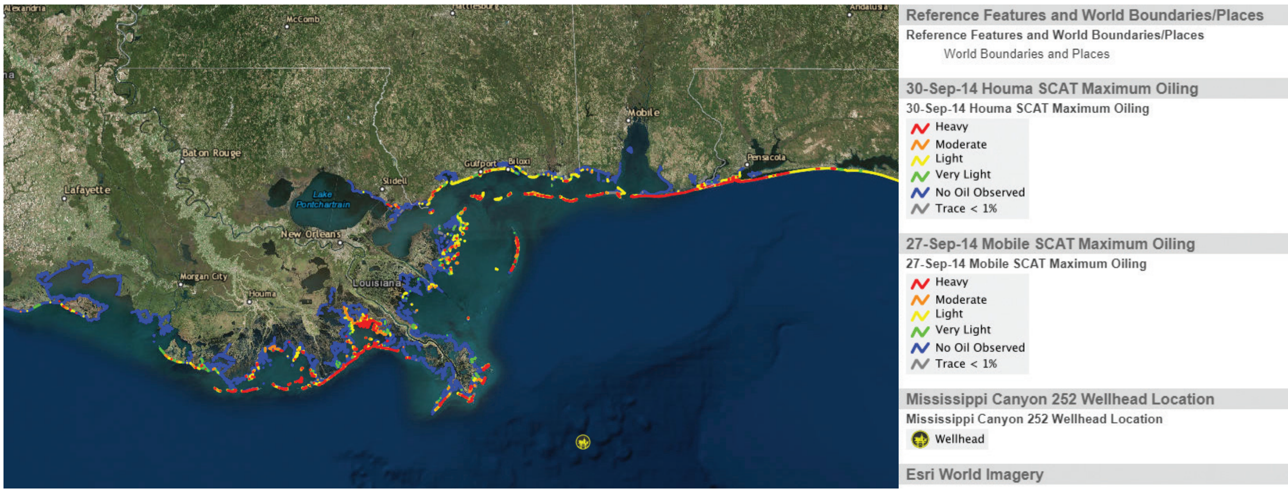


FIGURE 6. This figure shows areas where the shoreline was assessed for oil between the beginning of the spill and the end of September 2010. Red and orange marks show heavy and moderate oiling, respectively. Yellow, green, and blue marks represent areas where oiling was light, very light, or not observed. The oil well is located southeast of the mouth of the Mississippi River delta, shown here in yellow. Courtesy of NOAA's Environmental Response Management Application (ERMA), 2015

(NRDA, 4-585). Adrenal glands help an animal respond to environmental stress; in stranded and dead bottlenose dolphins from heavily oiled Barataria Bay, adrenal glands were unusually small (Schwacke et al. 2014; Venn-Watson et al. 2015; NRDA, 4-135). These dolphins experienced a relatively higher death rate and lower reproductive success (Lane et al. 2015). Only 20% of pregnant dolphins bore viable calves, compared to the 80% birth rate reported elsewhere.

Marine mammal populations in the Gulf have been declining in recent years due to a variety of human activities (NRDA, 4-585). In heavily oiled habitats after the DWH spill, the effects on marine mammals were devastating (Figure 5). With no recovery efforts, scientists predict that it would take Barataria and Mississippi Bay bottlenose dolphin stocks 40 to 50 years to fully recover (NRDA, 4-585). Whales and dolphins are long lived and slow to reach reproductive age; they only give birth to offspring every three to five years (NRDA, 4-637). Restoration efforts will include monitoring, analysis, and a scientifically-based management approach (NRDA, 4-637).

Understanding the effects of the oil spill on different animals is important; in particular, consumers at the higher trophic levels of the food web, such as birds, turtles, and marine mammals, can serve as good indicators of overall ecosystem health. During the spill, many animals perished immediately through direct contact when they swallowed or swam in oil or dispersant (Hale et al. 2017). Air-breathing animals like whales, sea turtles, and birds were also susceptible to inhalation of DWH vapors and smoke (NRDA, 4-67). Indirect impacts from oil and dispersant also caused damage to individuals and populations through loss or degradation of habitat, and through disruption of social behaviors such as reproduction and rearing of young (Peterson et al. 2003). Many animals suffered sublethal effects of chemical exposure that caused them to be more susceptible to infection, organ and brain damage, and reproductive failure (NOAA[d]).

Oil spill response efforts themselves impacted some animals; turtle nesting activity, for example, was impacted by response activities on the beaches during and after the spill (NRDA, 4-516). Recovery efforts will focus on long-term population monitoring and habitat restoration for these important animals.

COASTAL HABITATS

Mats of weathered oil mixed with seawater reached the coastlines of all five of the Gulf states, impacting over 2,000 km of coastline, with Louisiana receiving the heaviest amount of oiling (Figure 6; Nixon et al. 2016). Just over half of the oiled shoreline was marshes.

Beaches

On sandy shorelines, oil mats that washed onto beaches or into shallow water were buried in sediment by wind, tide, and waves (Graham et al. 2015). Mats 100 km long and nearly 20 centimeters (cm) thick were found south of Louisiana beaches (Michel et al. 2013). These mats were exposed and reburied, with parts breaking off and remaining on the beaches (Figure 7). The patchy distribution of the mats and the cycle of burial and exposure made it difficult to find and remove oil. Efforts to remove oil continued into 2013 in Mississippi, Alabama, and Florida, while a few miles of Louisiana beach were still subject to removal efforts into 2015 (Graham et al. 2015). As of 2014, oil saturated sand aggregates were still present on Alabama beaches, leaving researchers to predict beaches will continue to have oil aggregates beyond background, pre-spill levels for the foreseeable future (Hayworth et al. 2015). A new technique was developed to allow shoreline monitors to distinguish oil from the DWH spill from other anthropogenic sources and natural seeps (Han and Clement 2018).

FIGURE 7. Layers of weathered oil are seen in the cross section of this sediment sampling trench that researchers dug on Pensacola Beach shortly after the DWH oil spill. Courtesy of Deep-C and Markus Huettel

Marshes

Marsh vegetation was completely lost up to 15 m from the edge of some of the most heavily oiled marshes, resulting in accelerated erosion (Michel et al. 2013). Marsh impact was directly related to the extent of oiling of the substrate (soil); heavily oiled marshes were devastated, and moderately oiled marshes were less impacted (Lin and Mendelssohn 2012). Some recovery of vegetation was documented during the first years after the spill (Lin and Mendelssohn 2012; Zengel et al. 2015; Silliman et al. 2012). However, the extent of marsh recovery as documented in different studies is variable (Rabalais and Turner 2016).

Scientists from the Alabama Center for Ecological Resilience (ACER, http://acer.disl.org) considered whether plant diversity may influence the effects of oil exposure on coastal vegetation. Some marsh plant species are resistant to the negative effects of oiling (Pezeshki et al. 2000). In post-spill lab experiments that considered black mangrove and smooth cordgrass separately, both species were harmed by oil. However, damage was reduced when both species were present together. Therefore, researchers conclude that greater species diversity may mitigate some of the negative effects of an oil impact (Hughes et al. 2018).

In both field observations and lab experiments, smooth cordgrass was less impacted and recovered to a greater extent than black needlerush (Lin and Mendelssohn 2012). The mixed black needlerush-smooth cordgrass community had shifted to a primarily smooth cordgrass marsh after two to three years, a loss of marsh plant diversity that may increase its vulnerability to future oiling (Figure 8).

Populations of some marsh invertebrates declined after marshes were oiled. Salt marsh periwinkle snail numbers were significantly reduced in marshes that were heavily oiled

FIGURE 8. Students Jessica Diller (bottom) and Kamala Earl (top) prepare enclosed treatment plots in oiled marshes of Barataria Bay, Louisiana. Courtesy of Gabriel Kasozi

(Zengel et al. 2016). Greatly reduced numbers of sub-adult snails in 2011, in both heavily and less severely impacted marshes, were attributed to reproductive failure and adult mortality resulting from the oil (Pennings et al. 2016). The recovery of the snail population is expected to depend on the extent of recovery of marsh vegetation (Zengel et al. 2016).

The Gulf marshes exist in a delta where they are already experiencing a combination of human and natural processes, such as subsidence (compaction of sediments), canal dredging, and sea level rise. Coastal Louisiana marshes were eroding at high rates before the oil spill; nearly 4,833 square kilometers (1,900 square miles) of marsh was lost between 1932 and 2016 (Couvillion et al. 2017). Heavy oiling of these marshes due to the DWH spill increased erosion rates and limited recovery of marsh vegetation (Silliman 2012; Turner et al. 2016).

As with the rest of the Gulf, coastal habitats experienced diverse impacts. Sandy beaches have been cleared of visible oil. However, oil from DWH and other sources remains in the environment where it may be exposed by a future storm. Already vulnerable marshes have been subject to vegetation loss and increased rates of erosion that may result in permanent loss of marshes and their residents.

CONCLUSIONS

Nearly a decade after the DWH oil spill, conclusive statements about how organisms and habitats fared are still difficult to make. This is how science works. It is slow and challenging, and sometimes it is inconclusive. Much of the work described in this paper will continue for years to come, as some of the impacts—and trajectories of recovery of impacted organisms—will be apparent only with long-term study. However, scientists are learning important lessons by studying the impacts of the largest accidental oil spill in history on marine life in the Gulf.

The oil spill enabled scientists to **further understand the unique deep-sea ecosystems** in the Gulf; in particular, cold seep communities and their microbial inhabitants, who were already conditioned to living in the presence of small amounts of seep hydrocarbons. Research into the impacts of the DWH spill on deep-sea corals provided not only information about impacts and recovery of these sentinel creatures, but also shed light on oil movement and the extent of the spill's footprint on the seafloor.

Microbes played a previously less-understood, yet important role in transferring oil and gas deeper into the water column and into the marine food web. While much of the oil and gas movement during and after the spill was driven by physical processes, scientists found that microbially-mediated **marine oil snow formation** was an important factor that transferred oil from the surface waters and subsurface plume deeper in the water column. Scientists also learned that microbial response to the spill was an important mechanism for transferring oil- and gas-derived carbon into the marine food web.

The immediate and lethal impacts of the spill on individual, large vertebrates were reported extensively by the media. Quantifying **long-term impacts on animals with broad ranges**, like whales, dolphins, and turtles, has been logistically challenging. Further questions about long-term impacts have taken longer to answer or have yet to be determined.

Sublethal impacts are important, and understanding them provides critical insight about longer-term, population-level impacts of the spill on marine life. Sublethal impacts do not immediately kill the animal, but affect its feeding habits, navigation, gene expression, development, and/or reproduction. Understanding sublethal impacts through data collection

DISPERSANTS

During the response efforts following the Deepwater Horizon (DWH) oil spill, commercial-grade dispersants called Corexit™ 9527A and Corexit™ 9500A (Corexit™) were applied to the surface oil slick, and for the first time, at the wellhead nearly 1500 meters below the sea surface (Lubchenco 2012). Approximately 1.8 million gallons of Corexit™ was used, 0.77 million gallons of which were injected directly into the wellhead on the seafloor (NRDA, 2-10). Dispersants are applied to oil spills to break the oil up into smaller droplets, similar to how liquid dish soap disperses grease. This process makes it easier for oil-degrading bacteria and organisms to break it down in the environment.

Dispersant is just one tool in the oil spill responders' toolbox that can be used as a resource in clean-up efforts. The Gulf of Mexico Research Initiative has funded many research projects aimed at understanding what impact the use of dispersant had during the DWH accident, and scientists are still learning where the dispersant ended up in the Gulf and how it affected the surrounding ecosystem and human health.

Understanding the impact of dispersants on ecosystems, coastlines, and local communities is essential. Therefore, it is important that scientists continue to study them so that if they are used again in response efforts, their use can be based on the best available science. Research into dispersants and how oil breaks down in the environment is helping scientists discover new technologies and techniques that can be added to the toolbox in responding to future oil spills.

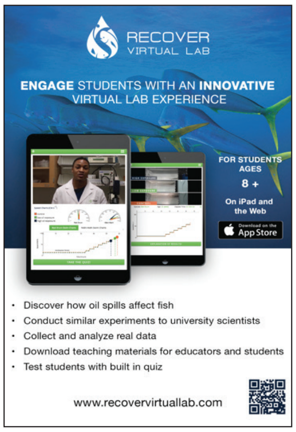
and/or modeling allows scientists to figure out the mechanism by which the spill impacts the organisms and estimate how that impact is reflected in the **population-level impact** and trajectory of recovery.

Coastal marshes were already experiencing changes and stress from human and natural processes prior to 2010. The DWH spill added insult to injury; marshes continue to erode from the edges inward, damaging their diverse associations of unique marsh vegetation, animals, and microbes.

Several scientists have pointed out that understanding the spill's impacts was impeded by **lack of baseline data**. Without sufficient baseline data, it is impossible to quantify and assign ecological importance to impacts resulting from the spill. One of the most valuable lessons from this accident has been that it is critically important to collect baseline data for ecosystems; in particular, those which are most at risk to be impacted by industrial activities. GoMRI research has contributed to establishing a baseline to inform future research and response efforts.

CLASSROOM ACTIVITY RESOURCE

The RECOVER Virtual Lab is available as a web application (http://recovervirtuallab.com) or a free app from the Apple App Store by searching for "Recover Virtual Lab." The RECOVER Virtual Lab takes teachers and students through a series of videos and simulations similar to laboratory-based experiments conducted by scientists to study oil impacts on mahi-mahi and red drum. The simulations include a description of RECOVER's "fish treadmills" or swim tunnels. Students and educators can visualize the data, repeat experiments, and discuss findings. The Virtual Lab also includes transcripts, a teacher workbook that can serve as a classroom lesson guide, and a brief quiz to test users on what they've learned.



ACKNOWLEDGMENTS

In addition to the acknowledgments for the full issue, the authors of this article would like to thank Steve Sempier of the Mississippi-Alabama Sea Grant Consortium and the Gulf of Mexico Sea Grant Oil Spill Science Outreach Program, Samantha Joye, and Nancy Rabalais for their contributions to the manuscript. This article was made possible by funding from GoMRI to the Consortium for Ocean Leadership and the following research consortia: ECOGIG, CONCORDE, ACER, and RECOVER.

REFERENCES

Able, K.W., P.C. López-Duarte, F.J. Fodrie, O.P. Jensen, C.W. Martin, B.J. Roberts, J. Valenti, K. O'Connor, and S.C. Halbert. (**2015.**) Fish assemblages in Louisiana salt marshes: Effects of the Macondo oil spill. *Estuaries and Coasts*, 38: 1385-1398. doi.org/10.1007/s12237-014-9890-6.

Buskey, E.J., H.K. White, and A.J. Esbaugh. (**2016.**) Impact of oil spills on marine life in the Gulf of Mexico: Effects on plankton, nekton, and deep-sea benthos. *Oceanography*, 29(3): 174-181. doi.org/10.5670/oceanog.2016.81.

Chanton, J.P., J. Cherrier, R.M. Wilson, J. Sarkodee-Adoo, S. Bosman, A. Mickle, and W.M. Graham. (**2012.**) Radiocarbon evidence that carbon from the Deepwater Horizon spill entered the planktonic food web of the Gulf of Mexico. *Environmental Research Letters*, 7(4). doi.org/10.1088/1748-9326/7/4/045303.

Couvillion, B., H. Beck, D. Schoolmaster, and M. Fischer. (**2017.**) Land area change in coastal Louisiana (1932 to 2016): U.S. Geological Survey Scientific Investigations Map 3381. *U.S. Geological Survey Pamphlet*. ISSN 2329-1311. doi.org/10.3133/sim3381.

Dubansky, B., A. Whitehead, J.T. Miller, C.D. Rice, and F. Galvez. (**2013.**) Multitissue molecular, genomic, and developmental effects of the Deepwater Horizon oil spill on resident Gulf killifish (*Fundulus grandis*). *Environmental Science and Technology*, 47(10): 5074-5082. https://pubs.acs.org/doi/abs/10.1021/es400458p.

ERMA. (**2015.**) Web Application: *Gulf of Mexico Environmental Response Management Application*, National Oceanic and Atmospheric Administration. Retrieved November 15, 2018 from erma.noaa.gov/gulfofmexico.

Etnoyer, P.J., L.N. Wickes, M. Silva, J.D. Dubick, L. Balthis, E. Salgado, and I. MacDonald. (**2016.**) Decline in condition of gorgonian octocorals on mesophotic reefs in the northern Gulf of Mexico: Before and after the Deepwater Horizon oil spill. *Coral Reefs*, 35(1): 77-90. doi.org/10.1007/s00338-015-1363-2.

Fernández-Carrera, A., K.L. Rogers, S.C. Weber, J.P. Chanton, and J.P. Montoya. (**2016.**) Deep Water Horizon oil and methane carbon entered the food web in the Gulf of Mexico. *Limnology and Oceanography*, 61: S387-S400. doi.org/10.1002/lno.10440.

Fisher, C.R., H.H. Roberts, E.E. Cordes, and B. Bernard. (**2007.**) Cold seeps and associated communities of the Gulf of Mexico. *Oceanography*, 20(4): 118-129. doi.org/10.5670/oceanog.2007.12.

Fisher, C., A. Demopoulos, E. Cordes, I. Baums, H. White, and J. Bourque. (**2014a.**) Coral communities as indicators of ecosystem-level impacts of the Deepwater Horizon spill. *BioScience*, 64: 796-807. doi.org/10.1093/biosci/biu129.

Fisher, C.R., P-Y. Hsing, C.L. Kaiser, D.R. Yoerger, H.H. Roberts, W.W. Shedd, E.E. Cordes, T.M. Shank, S.P. Berlet, M.G Saunders, E.A. Larcom, and J.M. Brooks. (**2014b.**) Footprint of Deepwater Horizon blowout impact to deep-water coral communities. *Proceedings of the National Academy of Sciences of the United States of America*, 111(32): 744-749. doi.org/10.1073/pnas.1403492111.

Fisher, C.R., P.A. Montagna, and T.T. Sutton. (**2016.**) How did the Deepwater Horizon oil spill impact deep-sea ecosystems? *Oceanography*, 29(3): 182-195. doi.org/10.5670/oceanog.2016.82.

Fodrie, F.J., K.W. Able, F. Galvez, K.L. Heck, Jr., O.P. Jensen, P.C. López-Duarte, C.W. Martin, R.E. Turner, and A. Whitehead. (**2014.**) Integrating organismal and population responses of estuarine fishes in Macondo spill research. *BioScience*, 64(9): 778-788. doi.org/10.1093/biosci/biu123.

Fodrie, F.J., and K.L. Heck. (**2011.**) Response of coastal fishes to the Gulf of Mexico oil disaster. *PLOS ONE*, 6(7): e21609. doi.org/10.1371/pone.0021609.

Girard, F., B. Fu, and C.R. Fisher. (**2016.**) Mutualistic symbiosis with ophiuroids limited the impact of the Deepwater Horizon oil spill on deep-sea octocorals. *Marine Ecology Progress Series*, 549: 89-98. doi.org/10.3354/meps11697.

Graham, W.M., R.H. Condon, R.H. Carmichael, I. D'Ambra, H.K. Patterson, L.J. Linn, and F.J. Hernandez, Jr. (**2010.**) Oil carbon entered the coastal planktonic food web during the Deepwater Horizon oil spill. *Environmental Research Letters*, 5(4). doi.org/10.1088/1748-9326/5/4/045301.

Graham, L., C. Hale, E. Maung-Douglass, S. Sempier, L. Swann, and M. Wilson. (**2015.**) Navigating shifting sands: Oil on our beaches. *MASGP-15-025*. masgc.org/oilscience/oil-spill-science-beaches.pdf.

Hale, C., L. Graham, E. Maung-Douglass, S. Sempier, T. Skelton, L. Swann, and M. Wilson. (**2017.**) Oil spill science: Sea turtles and the Deepwater Horizon oil spill. *TAMU-SG-17-501*. masgc.org/oilscience/oil-spill-science-sea-turtles.pdf.

Han, Y., and T.P. Clement. (**2018.**) Development of a field testing protocol for identifying Deepwater Horizon oil spill residues trapped near Gulf of Mexico beaches. *PLoS ONE*, 13(1): e0190508. doi.org/10.1371/journal.pone.0190508.

Haney, J.C., H.J. Geiger, and J.W. Short. (**2014a.**) Bird mortality from the Deepwater Horizon oil spill. I. Exposure probability in the offshore Gulf of Mexico. *Marine Ecology Progress Series*, 513: 225-237. doi.org/10.3354/meps10991.

Haney, J.C., H.J. Geiger, and J.W. Short. (**2014b.**) Bird mortality from the Deepwater Horizon oil spill. II. Carcass sampling and exposure probability in the coastal Gulf of Mexico. *Marine Ecology Progress Series*, 513: 239-252. doi.org/10.3354/meps10839.

Hayworth, J.S., T.P. Clement, G.F. John, and F. Yin. (**2015.**) Fate of Deepwater Horizon oil in Alabama's beach system: Understanding physical evolution processes based on observational data. *Marine Pollution Bulletin*, 90(1): 95-105. doi.org/10.1016/j.marpolbul.2014.11.016.

Hsing, P.-Y., B. Fu, E.A. Larcom, S.P. Berlet, T.M. Shank, A. Frese Govindarajan, A.J. Lukasiewicz, P.M. Dixon, and C.R. Fisher. (**2013.**) Evidence of lasting impact of the Deepwater Horizon oil spill on a deep Gulf of Mexico coral community. *Elementa: Science of the Anthropocene*, 1:12. doi.org/10.12952/journal.elementa.000012.

Hughes, A. R., J. Cebrian, K. Heck, J. Goff, T.C. Hanley, W. Scheffel, and R.A. Zerebecki. (**2018.**) Effects of oil exposure, plant species composition, and plant genotypic diversity on salt marsh and mangrove assemblages. *Ecosphere*, 9(4). doi.org/10.1002/ecs2.2207.

Incardona, J.P., L.D. Gardner, T.L. Linbo, T.L. Brown, A.J. Esbaugh, E.M. Mager, J.D. Stieglitz, B.L. French, J.S. Labenia, C.A. Laetz, M. Tagal, C.A. Sloan, A. Elizur, D.D.

Benetti, M. Grosell, B.A. Block, and N.A. Scholz. (2014.) Deepwater Horizon crude oil impacts the developing hearts of large predatory pelagic fish. *Proceedings of the National Academy of Science of the USA*, 111: E1510-E1518. doi.org/10.1073/pnas.1320950111.

Joye, S.B., J.E. Kostka, and A.P. Teske. (2014.) Microbial dynamics following the Macondo oil well blowout across Gulf of Mexico environments. *BioScience*, 64(9): 766-777. doi.org/10.1093/biosci/biu121.

Joye, S.B., S. Kleindienst, J.A. Gilbert, K.M. Handley, P. Weisenhorn, W.A. Overholt, and J.E. Kostka. (2016.) Responses of microbial communities to hydrocarbon exposures. *Oceanography*, 29(3): 136-149. dx.doi.org/10.5670/oceanog.2016.78.

Lane, S.M., C.R. Smith, J. Mitchell, B.C. Balmer, K.P. Barry, T. McDonald, C.S. Mori, P.E. Rosel, T.K. Rowles, T.R. Speakman, F.I. Townsend, M.C. Tumlin, R.S. Wells, E.S. Zolman, and L.H. Schwacke. (2015.) Reproductive outcome and survival of common bottlenose dolphins sampled in Barataria Bay, Louisiana, USA, following the Deepwater Horizon oil spill. *Proceedings of the Royal Society B*, 282: 20151944. doi.org/10.1098/rspb.2015.1944.

Lin, Q., and I.A. Mendelssohn. (2012.) Impacts and recovery of the Deepwater Horizon oil spill on vegetation structure and function of coastal salt marshes in the northern Gulf of Mexico. *Environmental Science and Technology*, 46: 3737-3743. doi.org/10.1021/es203552p.

Lubchenco, J., M.K. McNutt, G. Dreyfus., S.A. Murawski, D.M. Kennedy, P.T. Anastas, S. Chu, and T. Hunter. (2012.) Science in support of the Deepwater Horizon response. *Proceedings of the National Academy of Sciences of the USA*, 109(50): 201212-20221. doi.org/10.1073/pnas.1204729109.

Mager, E.M., A.J. Esbaugh, J.D. Stieglitz, R. Hoenig, C. Bodinier, J.P. Incardona, N.L. Scholz, D.D. Benetti, and M. Grosell. (2014.) Acute embryonic or juvenile exposure to Deepwater Horizon crude oil impairs the swimming performance of mahi–mahi (*Coryphaena hippurus*). *Environmental Science and Technology*, 48(12): 7053-7061. dx.doi.org/10.1021/es501628k.

McCann, M.J., K.W. Able, R.R. Christian, F.J. Fodrie, O.P. Jensen, J.J. Johnson, P.C. Lopez-Duarte, C.W. Martin, J.A. Olin, M.J. Polito, B.J. Roberts, and S.L. Ziegler. (2017.) Key taxa in food web responses to stressors: The Deepwater Horizon oil spill. *Frontiers in Ecology and the Environment*, 15(3): 142-149. doi.org/10.1002/fee.1474.

Michel, J., E.H. Owens, S. Zengel, A. Graham, Z. Nixon, T. Allard, W. Holton, P.D. Reimer, A. Lamarche, M. White, N. Rutherford, C. Childs, G. Mauseth, G. Challenger, and E. Taylor. (2013.) Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. *PLoS ONE*, 8(6): e65087. doi.org/10.1371/journal.pone.0065087.

Murawski, S.A., W.T. Hogarth, G.M. Peebles, and L. Barbeiri. (2014.) Prevalence of external skin lesions and polycyclic aromatic hydrocarbon concentrations in Gulf of Mexico fishes, post-Deepwater Horizon. *Transactions of the American Fisheries Society*, 143(4): 1084-1097. doi.org/10.1080/00028487.2014.911205.

Nixon, Z., S. Zengel, M. Baker, M. Steinhoff, G. Fricano, S. Rouhani, and J. Michel. (2016.) Shoreline oiling from the Deepwater Horizon oil spill. *Marine Pollution Bulletin*, 107(1): 170-178. doi.org/10.1016/j.marpolbul.2016.04.003.

NOAA(a). *What is an Unusual Mortality Event*. Retrieved August 22, 2018 from fisheries.noaa.gov/node/23881.

NOAA(b). (2010-2014.) *Cetacean Unusual Mortality Event in Northern Gulf of Mexico* (Closed). Retrieved August, 22, 2018 from fisheries.noaa.gov/national/marine-life-distress/2010-2014-cetacean-unusual-mortality-event-northern-gulf-mexico.

NOAA(c). *Deepwater Horizon Oil Spill 2010: Sea Turtles, Dolphins and Whales*. Retrieved August 22, 2018 from fisheries.noaa.gov/national/marine-life-distress/deepwater-horizon-oil-spill-2010-sea-turtles-dolphins-and-whales.

NOAA(d). *Impacts of Oil on Marine Mammals and Sea Turtles*. Retrieved August 22, 2018 from bhic.org/media/pdf/OilEffectsOnMammals.pdf.

NRDA (Deepwater Horizon Natural Resource Damage Assessment Trustees). (2016.) *Deepwater Horizon Oil Spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement*. Chapter 4: Injury to Natural Resources. Retrieved August 22, 2018 from gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan.

Pennings, S.C., S. Zengel, J. Oehrig, M. Alber, T.D. Bishop, D.R. Deis, D. Devlin, A.R. Hughes, J.J. Hutchens, Jr., W.M. Kiehn, C.R. McFarlin, C.L. Montague, S. Powers, C. E. Proffitt, N. Rutherford, C.L. Stagg, and K. Walters. (**2016.**) Marine ecoregion and Deepwater Horizon oil spill affect recruitment and population structure of a salt marsh snail. *Ecosphere*, 7(12). doi.org/10.1002/ecs2.1588.

Peterson, C.H., S.D. Rice, J.W. Short, D. Esler, J.L. Bodkin, B.E. Ballachey, and D.B. Irons. (**2003.**) Long-term ecosystem response to the *Exxon Valdez* oil spill. *Science*, 302(5653): 2082-2086. doi.org/10.1126/science.1084282.

Pezeshki, S.R., M.W. Hester, Q. Lin, and J.A. Nyman. (**2000.**) The effects of oil spill and clean-up on dominant U.S. Gulf coast marsh macrophytes: A review. *Environmental Pollution*, 108: 129-139. doi.org/10.1016/S0269-7491(99)00244-4.

Rabalais, N.N., and R.E. Turner. (**2016.**) Effects of the Deepwater Horizon oil spill on coastal marshes and associated organisms. *Oceanography*, 29(3): 150-159. doi.org/10.5670/oceanog.2016.79.

Schwacke, L.H., C.R. Smith, F.I. Townsend, R.S. Wells, L.B. Hart, B.C. Balmer, T.K. Collier, S. De Guise, M.M. Fry, L.J. Guillette,S.V. Lamb, S.M. Lane, W.E. McFee, N.J. Place, M.C. Tumlin, G.M. Ylitalo, E.S. Zolman, and T.K. Rowles. (**2014.**) Health of common bottlenose dolphins (*Tursiops truncatus*) in Barataria Bay, Louisiana, following the Deepwater Horizon oil spill. *Environmental Science and Technology*, 48(1): 93-103. doi.org/10.1021/es403610f.

Silliman, B.R., J. van de Koppel, M.W. McCoy, J. Diller, G.N. Kasozi, K.E., P.N. Adams, and A.R. Zimmerman. (**2012.**) Degradation and resilience in Louisiana salt marshes after the BP-Deepwater Horizon oil spill. *Proceedings of the National Academy of Sciences*, 109(28): 11234-11239. doi.org/10.1073/pnas.1204922109.

Silva, M., P.J. Etnoyer, and I.R. MacDonald. (**2016.**) Coral injuries observed at Mesophotic Reefs after the Deepwater Horizon oil discharge. *Deep Sea Research Part II: Topical Studies in Oceanography*, 129: 96-107. doi.org/10.1016/j.dsr2.2015.05.013.

Stieglitz, J. D., E.M. Mager, R.H. Hoenig, D.D. Benetti, and M. Grosell. (**2016.**) Impacts of Deepwater Horizon crude oil exposure on adult mahi-mahi (*Coryphaena hippurus*) swim performance. *Environmental Toxicology Chemistry*, 35: 2613-2622. doi.org/10.1002/etc.3436.

Turner, R.E., G. McClenachan, and A.W. Tweel. (**2016.**) Islands in the oil: Quantifying salt marsh shoreline erosion after the Deepwater Horizon oiling. *Marine Pollution Bulletin*, 110: 316-323. doi.org/10.1016/j.marpolbul.2016.06.046.

Venn-Watson, S., K.M. Colegrove, J. Litz, M. Kinsel, K. Terio, J. Saliki, S. Fire, R. Carmichael, C. Chevis, W. Hatchett, J. Pitchford, M. Tumlin, C. Field, S. Smith, R. Ewing, D. Fauquier, G. Lovewell, H. Whitehead, D. Rotstein, W. McFee, E. Fougeres, and T. Rowles. (**2015.**) Adrenal gland and lung lesions in Gulf of Mexico common bottlenose dolphins (*Tursiops truncatus*) found dead following the Deepwater Horizon oil spill. *PLoS ONE*, 10(5). doi.org/10.1371/journal.pone.0126538.

White, H.K., P.-Y. Hsing, T.M. Shank, E.E. Cordes, A.M. Quattrini, R.K. Nelson, R. Camilli, A. Demopoulos, C.R. German, J.M. Brooks, H.H. Roberts, W. Shedd, C.M. Reddy, and C.R. Fisher. (**2012.**) Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. *Proceedings of the National Academy of Sciences of the USA*, 109: 20303-20308. doi.org/10.1073/pnas.1118029109.

Zengel, S., C.L. Montague, S.C. Pennings, S.P. Powers, M. Steinhoff, G. Fricano, C. Schlemme, M. Zhang, J. Oehrig, Z. Nixon, S. Rouhani, and J. Michel. (**2016.**) Impacts of the Deepwater Horizon oil spill on salt marsh periwinkles (*Littoraria irrorata*). *Environmental Science and Technology*, 50(2): 643-652. doi.org/10.1021/acs.est.5b04371.

SARA BERESFORD See bio on page 16.

JESSIE KASTLER See bio on page 20.

RACHEL MCDONALD is the Outreach Educator for the Discovery Hall Programs at the Dauphin Island Sea Lab, and the co-Lead for the Alabama Center of Ecological Resilience (ACER) consortium's Education and Outreach, based at the Dauphin Island Sea Lab in Dauphin Island, Alabama.

DAN DINICOLA is a Communications Specialist at the University of Washington's School of Aquatic and Fishery Sciences in Seattle, Washington, and was previously the Outreach Coordinator for the Relationships of Effects of Cardiac Outcomes in Fish for Validation of Ecological Risk (RECOVER) consortium at the University of Miami in Miami, Florida.

KATIE FILLINGHAM See bio on page 20.

Technological Advances in Ocean Sciences Resulting from the Deepwater Horizon Oil Spill

BY LAURA BRACKEN, DAN DINICOLA, JESSIE KASTLER, AND SARA BERESFORD

- In response to the Deepwater Horizon disaster, many innovative researchers adapted instruments not previously used in oil spill research, or invented new instruments that would change the way ocean science is done moving forward.

- From using normal cameras in extraordinary ways to designing new platforms for data collection, scientists collaborated in order to develop new and improved scientific methods to investigate the environmental impacts of the spill on the Gulf's ecosystem.

- The marine science technology developed through the Gulf of Mexico Research Initiative (GoMRI) will be one of the lasting legacies of the program. These tools can be used in other bodies of water, for other spills, to improve the response, and mitigation of future disasters.

- Developing or modifying existing technologies in order to answer specific research questions is common throughout the scientific process. In order to exemplify this process in the classroom, an associated activity will guide students through developing their very own drifters, just like GoMRI scientists did to understand currents in the Gulf of Mexico and where oil will go after an oil spill.

INTRODUCTION

As scientists across the world dove into action following the Deepwater Horizon (DWH) oil spill, many innovative researchers adapted instruments not previously used in oil spill research or invented new instruments that would change the way ocean science is done moving forward. This unprecedented disaster pushed scientists to collaborate and innovate in order to find new and improved scientific methods to investigate the environmental impacts of the spill on the Gulf's ecosystem. Here we highlight a small sample of the many significant contributions made by Gulf of Mexico Research Initiative (GoMRI) researchers.

DRIFTERS

During an oil spill, some of the first questions that arise are "where will the oil go?" and "how fast will it get there?" Answering these questions requires knowledge of the speed, location, and direction of ocean currents. Scientists have used satellite remote sensing (Goldstein et al. 1989) and a series of individual GPS receiver-equipped buoys known as drifters across the globe (Lumpkin and Johnson 2013) to study large currents. But those methods do not provide enough detail about the important small-scale currents needed to understand how oil moves once it reaches the surface.

Consortium for Advanced Research on the Transport of Hydrocarbon in the Environment (CARTHE, http://carthe.org) scientists are studying the small-scale surface currents that drive the initial transport of oil using large-scale experiments in which hundreds of drifters are released into a relatively small area of the Gulf of Mexico (Poje et al. 2014; D'Asaro et al. 2018). The onboard GPS transmits its location every five minutes for about three months, giving the team a detailed track of the drifter's (and therefore the current's) movements.

In order to collect data on the dynamic surface currents in the Gulf, researchers developed a plan to release 1,000 drifters. They spent two years designing and testing a custom-made, GPS-equipped, biodegradable drifter that could be assembled at sea (Novelli et al. 2017). The team began with a wood drifter and quickly realized that the untreated wood would become waterlogged too soon and not float for the two- to three-month timeframe that was needed, so instead they selected polyhydroxyalkanoate (PHA), a compostable bioplastic known to be biodegradable in water.

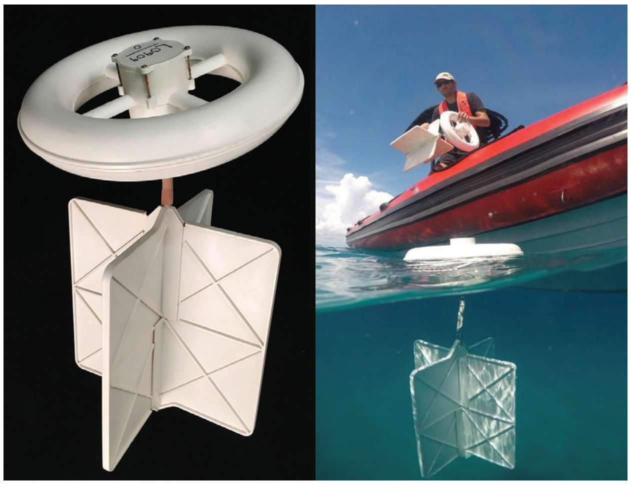


FIGURE 1. (left to right) CARTHE drifter. Courtesy of CARTHE/Cedric Guigand

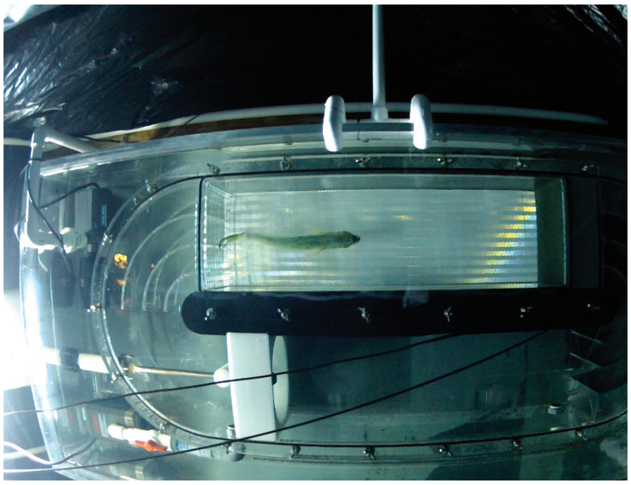


FIGURE 2. Mahi-mahi in a swim chamber; see video https://youtu.be/xz6mwID3aXA. Courtesy of RECOVER

The drifter has a donut-shaped device that floats at the surface and keeps the GPS above the water line (Figure 1). The majority of the drifter stays below the water to avoid being moved by the wind. Two flat, interlocking panels connect quickly to make the "drogue," the underwater sails that catch the water and cause the drifter to move with the current. A flexible neck connects the float and the drogue. The flexible connection was an important addition to later designs because it allowed the float to move with the waves without causing the drifter to "ride the waves."

The finished product is a valuable tool that can be used across the world to study ocean currents and related research questions. These drifters were developed for CARTHE studies in the Gulf, but have also been used in a variety of other bodies of water, including the Arctic Ocean (Mensa et al. 2018) and Biscayne Bay near urban Miami, Florida (Bracken 2016).

The drifter was also used by fellow GoMRI consortium Relationships of Effects of Cardiac Outcomes in Fish for Validation of Ecological Risk (RECOVER, http://recoverconsortium.org/), in work tracking fish movement off the south Florida coast. In 2016, RECOVER scientists released the drifters alongside mahi-mahi fish that had been tagged with pop-up satellite archival tags, which measure temperature, depth, light, and acceleration. Data from the tags revealed where the fish are and how they move in the water, offering insight into spawning and feeding behaviors of mahi that have not been exposed to oil. The drifters documented the extent to which mahi associate with currents.

FISH "TREADMILLS"

Mahi and red drum are also studied in controlled laboratory experiments to give scientists an idea of how oil exposure alters their physiology. RECOVER scientists use specialized swim chamber respirometers that monitor a fish's oxygen consumption and swim performance. Fish swimming in the chamber is similar to humans running on a treadmill (Figure 2).

In the experiments, fish are exposed to oil dissolved in water at concentrations similar to what was observed during the DWH spill (Stieglitz et al. 2016), then placed in the swim chamber where they swim against a controlled, artificial current. During the experiment, a computer monitors how much oxygen is used by each fish swimming at a programmed water velocity. The water velocity is progressively increased until the fish is exhausted and unable to swim at such a speed. The data collected from this type of experiment provide scientists with information that can be used to determine the potential types of impacts oil exposure has on fish.

Scientists are learning that oil-exposed fish cannot swim as long or as fast as their non-exposed counterparts. As a result, fish are less able to avoid predators, feed, spawn, and migrate (Stieglitz et al. 2016).

CAMERAS: In the Lab

RECOVER researchers also use video cameras during lab experiments to document fish behavior. Cameras positioned above the swim chambers allow scientists to monitor the performance of individual fish without impacting the controlled setting. The recorded footage is entered into specialized software that can track specific behavior, such as how often a fish beats its tail. Scientists are using video footage collected with GoPro® cameras to study how oil exposure can impact social interactions as fish compete for limited resources, like shelter. Similarly, GoPros® are used in vision experiments where scientists monitor a fish's ability to track movement in a circular chamber (Figure 3).

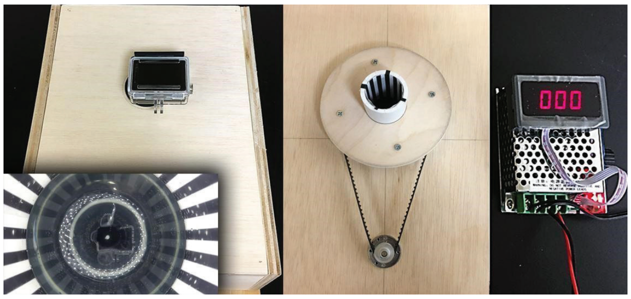


FIGURE 3. GoPro® camera mounted on a fish vision chamber. Inset photo is of downward camera view. Courtesy of RECOVER

CAMERAS: In the Deep Sea

Investigating the impacts of the 2010 oil spill on deep-sea ecosystems has been challenging considering some areas of the Gulf can be as deep as 4,000 meters (m). Remotely operated vehicles (ROVs; operated from the ship to which the vehicle is tethered) and submersibles like the Deep Submergence Vehicle (DSV) *Alvin* (an untethered vehicle operated by a pilot from within) have been critical in studying the impacts on deep-sea ecosystems, such as deep-sea corals.

Over 350 coral colonies have been photographed by Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG, http://ecogig.org) scientists in the years since the spill using high-resolution camera equipment mounted on submersibles. Analysis of these time-series photographs has shed light on the spill's impact on the corals over time (documenting an increase in dead or dying corals and an increase in the number of hydroids on corals) as well as factors influencing their recovery (Fisher et al. 2014a). Cameras have also provided useful information about the movement of the oil and the footprint of the oil spill's impact by showing affected corals much farther than oil was previously believed to have spread (Fisher et al. 2014b). A digital live-feed from the ROV to the research team on the ship gives the scientists virtual "eyes on the bottom" during the dive, enabling them to employ their scientific intuition to make spontaneous decisions about the research (Figure 4).

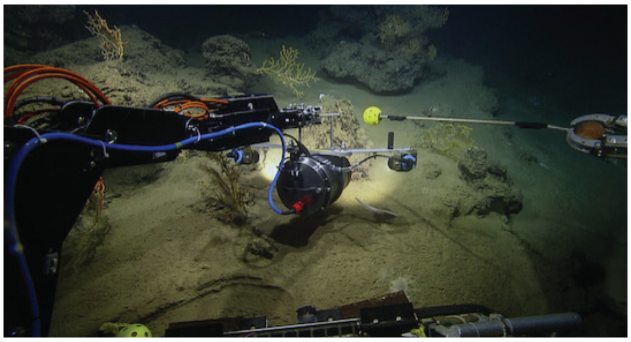


FIGURE 4. Scientists utilized high-definition camera systems mounted on ROVs to photograph deep-sea corals after the oil spill. The whiffle ball is used for scale. Courtesy of ECOGIG and Ocean Exploration Trust

ROVs with high-resolution cameras have also gathered precise measurements of the bubbles and oil droplets rising up out of natural seeps (Figure 5). Using high speed video, scientists from the Gulf of Mexico Integrated Spill Response consortium (GISR, http://research.gulfresearchinitiative.org/research-awards/projects/?pid=137) observed a significant difference in the behavior of the methane bubbles containing oil versus without oil. These data offer insights into how spilled oil rises from a deepwater well and assists with predicting where it might go.

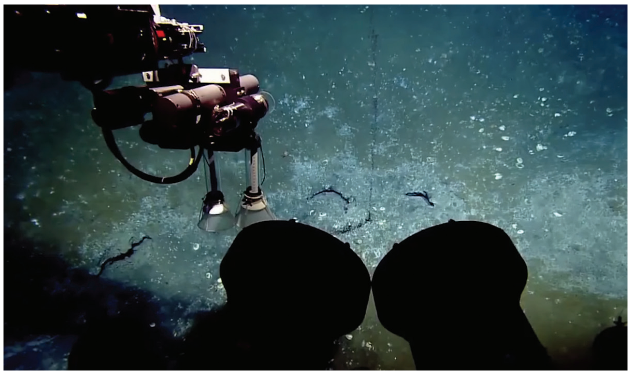


FIGURE 5. Observing bubbles from underwater gas seeps (https://www.youtube.com/watch?v=0sRbaEUKyE4). Video highlighting Gulf of Mexico Integrated Spill Response (GISR) consortium produced by the American Geophysical Union (Wang 2016)

GoMRI scientists have used digital camera systems to document the movement of oil from the surface down as well, clarifying the role of marine oil snow formation (when oil is incorporated into falling debris) in transporting hydrocarbons to the seafloor after the accident. Digital camera systems were utilized to collect vertical profiles of marine snow abundance at multiple locations and depths between the sea surface and seafloor, and were paired with data from sediment traps and particle sinking speed measurements to develop an understanding of how oiled materials are transported from the sea surface to the seafloor.

In addition to using high-resolution cameras in deep-sea vehicles, GoMRI scientists have towed them behind ships, hung them from balloons, and mounted them in marshes. Cameras can document phenomena that cannot be easily seen otherwise and eliminate the risk of damaging the environment being studied.

CAMERAS: On the Sea Surface

Plankton nets towed behind vessels are standard equipment for studying organisms drifting in the ocean that are not big enough to catch on hook and line. However, filtering the water destroys delicate organisms. The Consortium for Oil Spill Exposure Pathways in Coastal River-Dominated Ecosystems (CONCORDE, http://www.con-corde.org) is collecting comprehensive information about plankton populations using cameras instead of nets. The FlowCAM is an onboard instrument that counts and identifies single-celled organisms up to 0.5 millimeters (mm) in length (Figure 6; Sieracki et al. 1998). It collects images and compares them to a database as a water sample flows through, providing quick assessments of populations in the field.

The In-Situ Ichthyoplankton Imaging System (ISIIS) is a camera system that is towed behind a ship (Cowen and Guigand 2008). As the ISIIS moves through the water column, it collects images of everything within a continuously moving box. Scientists can see their study subjects as they appear in the water column and as they compare to other organisms. This device is ideal for viewing mid-sized zooplankton (0.4 mm to 13 centimeters (cm) in length). By observing these particles undisturbed in the water, the ISIIS can show how they are distributed and link them specifically to water quality and flow conditions. This can connect specific types of plankton to conditions like a gradient in salinity, such as that seen where terrestrial freshwater meets ocean saltwater in an estuary. It can also show delicate structures like particles of marine snow, which would be destroyed during collection.

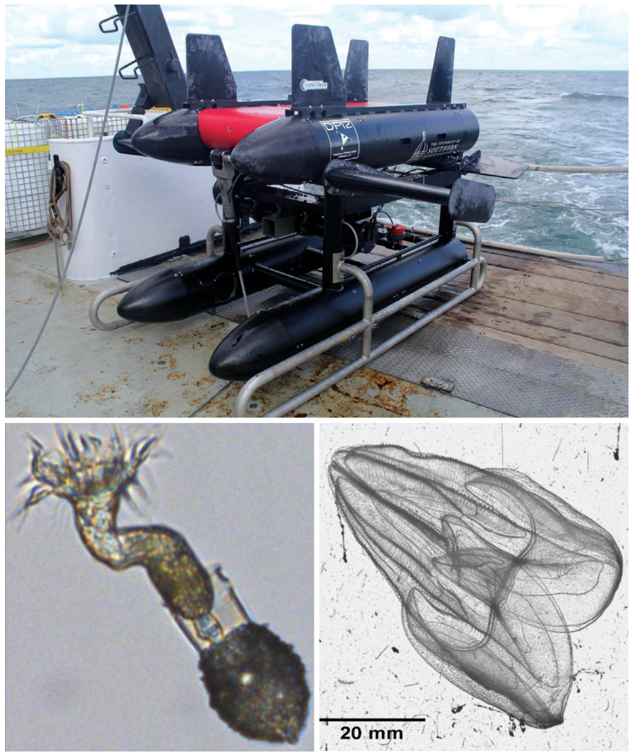


FIGURE 6. (top) ISIIS on ship prepared for deployment; (bottom left) tintinnid, recorded by FlowCAM; (bottom right) ctenophore, recorded by ISIIS. Courtesy of CONCORDE

CAMERAS: In the Air

CARTHE relies on high-resolution cameras mounted to drones (Brouwer et al. 2015; Laxague et al. 2018) and a large balloon called an aerostat (Carlson et al. 2018) to track the initial transport of drift cards (biodegradable bamboo plates) during experiments to measure surface currents (Figure 7). Drones have the advantage of being highly maneuverable; a skilled pilot can easily move one with a patch of drift cards. However, the battery life is still the limiting factor, requiring multiple drones to alternate between flying and charging. The aerostat on the other hand can fly for many hours and is extremely stable, but it is towed behind a ship so maneuvering is more challenging. With either platform, extremely high-resolution cameras are the key to these experiments. The acquired images are used to determine how small-scale mixing driven by waves, winds, and short-lived currents affects how oil spreads and moves over time. While the GPS-equipped drifters discussed earlier measure currents at scales of 200 m to many kilometers (km) over a period of two to four months, the drone and aerostat camera systems allow scientists to see what happens at a scale of 1 to 1200 m while flying over a patch of drift cards for several hours.

Volume 33 • No. 1 • Winter 2019

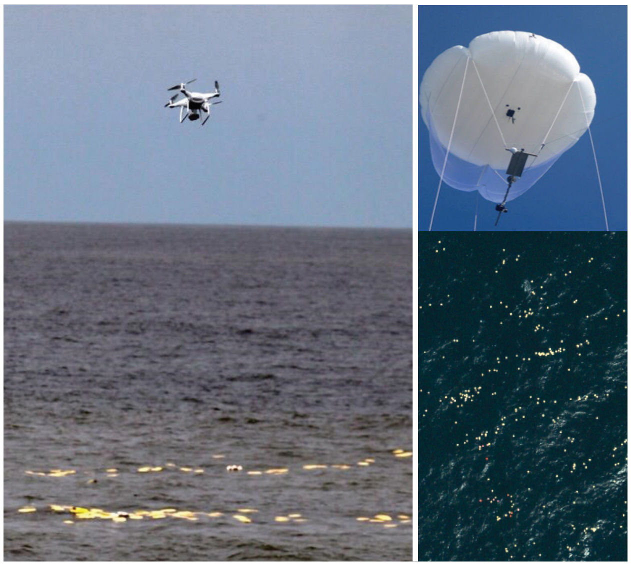


FIGURE 7. (left) Drone monitoring a patch of drift cards during an experiment examining the near-surface layer of the ocean; (right top) high-resolution camera system hanging from the aerostat; (right bottom) image from the aerostat camera of thousands of drift cards gathering into lines during a dispersion experiment. Courtesy of CARTHE

CAMERAS: On Land

Other camera systems are designed to collect data for much longer periods of time. Coastal Waters Consortium (CWC, http://cwc.lumcon.edu/) used time-lapse cameras (GoPros®) to document the daily marsh loss over a year in heavily oiled shorelines in southern Louisiana (Figure 8). Some of these areas were significantly affected by the DWH spill, resulting in loss of root mass (McClenachan et al. 2013). The cameras were placed at two locations on poles facing the marsh edge, initially 1.5 m from marsh vegetation. They were programmed to take photos at two-hour intervals over consecutive four- to six-week periods for more than a year.

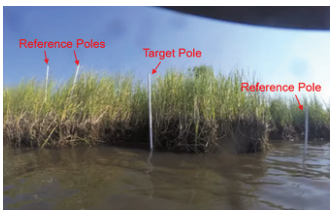


FIGURE 8. Researchers documented daily marsh loss using PVC poles and time lapse photography. Video (https://www.youtube.com/watch?v=bEumDAFWnqw) shows a time lapse of land loss in coastal Louisiana. Courtesy of CWC/Giovanna McClenachan

By photographically documenting significant land loss to erosion in areas with lower root mass, CWC scientists were able to confirm the importance of living roots, which were negatively impacted by the oil, for the maintenance of marsh vegetation and healthy shorelines (McClenachan et al. 2013).

HYDROPHONES

Littoral Acoustic Demonstration Center - Gulf Ecological Monitoring and Modeling (LADC-GEMM, http://www.ladcgemm.org/) scientists are studying marine mammals—specifically whales and dolphins—using techniques inspired by their study subjects. Light doesn't travel far underwater, so marine mammals have evolved to use sound to find food, communicate, and gather information about their environment. Researchers use sound to study the location and movement of marine mammals. Sound is recorded using hydrophones and researchers attach them to (1) ocean gliders: small (~2 m), sleek, buoyancy-driven, deep-diving, autonomous robots; (2) autonomous surface vehicles (ASVs): self-propelled robotic vessels; and (3) moorings placed on the seafloor (Figure 9). These technologies cover varying scales of time and space: ASVs cover distances fairly quickly for days to weeks, while gliders travel more slowly but for many weeks to a few months. Autonomous hydrophones do not move at all, but can remain in place and observe marine mammals for years with routine maintenance. These instruments provide researchers information on the impact of the oil spill on the deep-diving, marine mammal populations in the Gulf.

TECHNOLOGY GUIDES ADAPTIVE SAMPLING

Technology can inform adaptive sampling and allow scientists aboard a ship to process data immediately and change course (figuratively or literally), if needed. Although researchers utilize information from previous studies and their knowledge of a study area to plan a sampling effort prior to going into the field, conditions can change and GoMRI scientists have come up with ways to adapt to the changing conditions that are inevitable during a research cruise or experiment.

One example of adaptive sampling took place during a CONCORDE research cruise. One of the goals of the research was to observe plankton distributions in areas where fresh and salt water mix. Four (7-10 days) research campaigns used massive deployments of instrumentation for comprehensive collections of data. A fleet including two, 35 m research vessels, small boats, an autonomous underwater vehicle (AUV), and drifters were deployed simultaneously.

Volume 33 • No. 1 • Winter 2019

FIGURE 9. (left) Ocean glider. Courtesy of LADC-GEMM. (center) Autonomous surface vehicle. Courtesy of ASV Global. (right) Moored hydrophone (black cylinder) with line of buoys. Courtesy of LADC-GEMM

To ensure the success of the highly choreographed data collection effort, the fleet was supported by the land-based Ocean Weather Laboratory (OWX) that used model interpretations of satellite images to illustrate conditions like phytoplankton pigment (chlorophyll) concentrations and the direction and velocity of water flow.

During this research campaign, OWX detected a sharp transition of chlorophyll concentration from the high values observed in productive waters close to land (red to yellow) to lower concentrations typical of the continental shelf (green to blue). Immediately all of the vessels at sea mobilized, travelling approximately 75 km to sample a filament of shelf water surrounded by highly productive coast water (Figure 10).

A series of ISIIS images were collected in less than two minutes over an approximately 275 m distance and across a gradient from 31 to 35 parts per thousand (ppt) salinity. The images documented increase in the concentration of plankton and the size of marine snow particles (Figure 11). Understanding what happens to plankton and other particles at the boundary between different water masses is important to predicting the movement and impacts of oil in the event of a future spill.

CARTHE uses adaptive sampling to select the location for drifter deployments. With limited resources and the need to collect as much high-quality data as possible in a short time period, CARTHE scientists collect data from satellites, aircraft, and the ship to find fronts, eddies, and other features in the

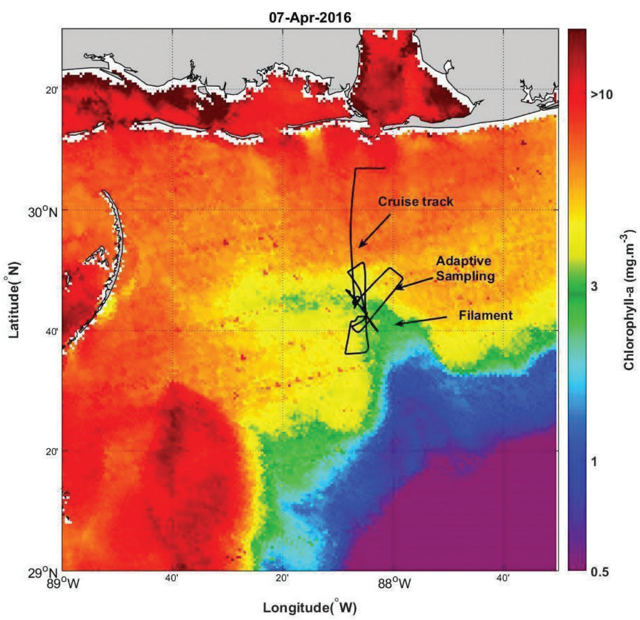


FIGURE 10. Satellite image of enhanced ocean color shows concentrations of the pigment chlorophyll. The black line shows how the cruise track of the R/V *Point Sur* changed to allow researchers to sample the front between the continental shelf filament and surrounding coastal water. Courtesy of CONCORDE/Inia Soto Ramos

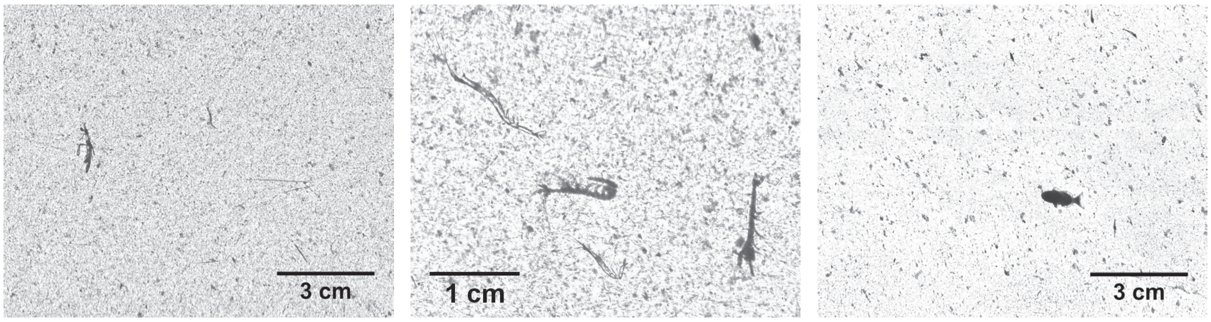


FIGURE 11. ISIIS images collected (from left to right) before reaching the front; within the front showing high concentration of shrimp—note change in scale; and just beyond the front showing increased size of marine snow aggregates. Please note, this sample was collected in 2016, and these are unoiled marine snow particles. Courtesy of CONCORDE/Adam Greer

water. An aerial survey over the northern edge of the Loop Current during a CARTHE experiment spotted an interesting feature (a set of fronts coming from a cyclonic vortex) and alerted the ship team, who dropped 326 drifters in that area (Figure 12). Rather than dispersing, many of these drifters converged into clusters along those fronts (D'Asaro et al. 2018). During an oil spill, the ability to predict such convergence would greatly assist in mitigation efforts.

CONCLUSION

The marine science technology developed through GoMRI since the DWH spill will leave a lasting impact on our understanding of oceanographic, biological, and chemical processes in the ocean. It is also one of the lasting legacies of the program itself. Because of these technological advancements, the scientific community will be better prepared to respond in the event of a future spill.

CLASSROOM ACTIVITY RESOURCES

Design-a-Drifter

Meet Consortium for Advanced Research on the Transport of Hydrocarbon in the Environment (CARTHE) scientists and experience the drifter design process in this fun and informative video: vimeo.com/carthe/drift. Then try your hand at designing and building your own surface drifter. Students are given background information on ocean current research and the guidelines for making drifters, and then invited to brainstorm, plan, build, and test their very own drifters using inexpensive (often free) materials. Drifters can be deployed in a nearby pool, lake, or the ocean to learn about the movement of water in your local area. This challenge blends science, technology, engineering, art, and math (STEAM) and allows students to be creative while working on a very complex physical oceanography research question. Background information and lesson plan can be found at CARTHE.org/drifter_lesson.pdf.

Want More Building Projects?

- LADC-GEMM + SeaGlide model gliders: Your students can build their own fully-functional ocean gliders to learn about buoyancy and engineering at http://www.ladcgemm.org/model-gliders/.
- ACER remotely operated vehicles (ROVs): Do your students want to build ROVs and compete against other budding oceanographers and engineers? Get started at https://www.disl.org/dhp/rov-programs.

ACKNOWLEDGMENTS

In addition to the acknowledgments for the full issue, the authors of this article would like to thank Nancy Rabalais and Dave Mellinger for their contribution to the manuscript; Tamay Özgökmen, Martin Grosell, and Lela Schlenker for review of the article; and Cedric Guigand for his image contributions and review of the article. This article was made possible by funding from GoMRI to CARTHE, CONCORDE, ECOGIG, and RECOVER.

REFERENCES

Bracken, L. (2016.) "Bay Drift Study Hits Biscayne Bay." *CARTHE Blog*. 12 September 2016, carthe.org/blog/bay-drift/.

Brouwer, R.L., M.A. de Schipper, P.F. Rynne, F.J. Graham, A.J.H.M. Reniers, and J.H. MacMahan. (2015.) Surf zone monitoring using rotary wing Unmanned Aerial Vehicles. *Journal of Geophysical Research: Oceans*, 32(4): 855-863. doi.org/10.1175/JTECH-D-14-00122.1.

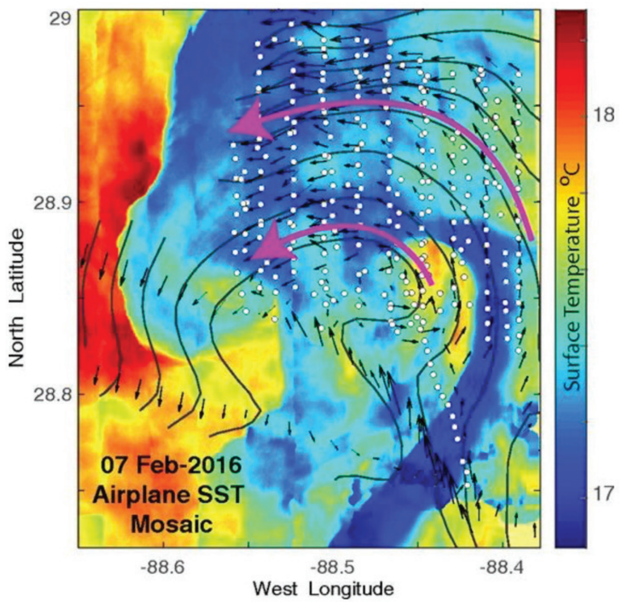


FIGURE 12. (left) Aircraft survey of sea surface temperature; white dots represent initial drifter position. Courtesy of CARTHE/D'Asaro et al. 2018. (top) R/V F.G. *Walton Smith* seen from the plane as it moves toward the drifter release location. Courtesy of CARTHE/Tamay Özgökmen

Carlson, D. F., T. M. Özgökmen, G. Novelli, C. Guigand, H. Chang, B. Fox-Kemper, J. A. Mensa, S. Mehta, E. Fredj, H. Huntley, D. Kirwan, M. Berta, M. Rebozo, M. Curcic, E. Ryan, B. Lund, B. Haus, J. Molemaker, C. Hunt, L. Bracken, and J. Horstmann. (**2018.**) Surface ocean dispersion observations from the ship-tethered aerostat remote sensing system. *Frontiers in Marine Science*, 5:479. doi:10.3389/fmars.2018.00479.

Cowen, R.K., and C.M. Guigand. (**2008.**) In situ Ichthyoplankton Imaging System (ISIIS): system design and preliminary results. *Limnology and Oceanography: Methods*, 6: 126-132. doi.org/10.4319/lom.2008.6.126.

D'Asaro, E.A., A.Y. Shcherbina, J.M. Klymak, J. Molemaker, G. Novelli, C.M. Guigand, A.C. Haza, B.K. Haus, E.H. Ryan, G.A. Jacobs, H.S. Huntley, N.J.M. Laxague, S. Chen, F. Judt, J.C. McWilliams, R. Barkan, A.D. Kirwan Jr., A.C. Poje, and T.M. Özgökmen. (**2018.**) Ocean convergence and the dispersion of flotsam. *Proceedings of the National Academy of Sciences*, 115(6): 1162-1167. doi.org/10.1073/pnas.1718453115.

Fisher, C.R., A.W.J. Demopoulos, E.E. Cordes, I.B. Baums, H.K. White, and J.R. Bourque. (**2014.**) Coral communities as indicators of ecosystem-level impacts of the Deepwater Horizon spill. *BioScience*, 64(9): 796-807. doi.org/10.1093/biosci/biu129.

Fisher, C.R., P. Hsing, C.L. Kaiser, D.R. Yoerger, H.H. Roberts, W.W. Shedd, E.E. Cordes, T.M. Shank, S.P. Berlet, M.G. Saunders, E.A. Larcom, and J.M. Brooks. (**2014.**) Footprint of Deepwater Horizon blowout impact to deep-water coral communities. *Proceedings of the National Academy of Sciences*, 111(32): 11744-11749. doi.org/10.1073/pnas.1403492111.

Goldstein, R.M., T.P. Barnett, and H.A. Zebker. (**1989.**) Remote sensing of ocean currents. *Science*, 246(4935): 12821285. doi.org/10.1126/science.246.4935.1282.

Laxague, N.J.M., T.M. Özgökmen, B.K. Haus, G. Novelli, A. Shcherbina, P. Sutherland, C. Guigand, B. Lund, S. Mehta, M. Alday, and J. Molemaker. (**2018.**) Observations of near-surface current shear help describe oceanic oil and plastic transport. *Geophysical Research Letters*, 4: 245-249. doi.org/10.1002/2017GL075891.

Lumpkin, R., and G.C. Johnson. (**2013.**) Global ocean surface velocities from drifters: Mean, variance, El Nino–Southern Oscillation response, and seasonal cycle. *Journal of Geophysical Research: Oceans*, 118: 2992-3006. doi.org/10.1002/jgrc.20210.

McClenachan, G., R.E. Turner, and A.W. Tweel. (**2013.**) Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion. *Environmental Research Letters*, 8(4): 044030. doi.org/10.1088/1748-9326/8/4/044030.

Mensa, J.A., M.L. Timmermans, I.E. Kozlov, W.J. Williams, and T.M. Özgökmen. (**2018.**) Surface drifter observations from the Arctic Ocean's Beaufort Sea: Evidence for submesoscale dynamics. *Journal of Geophysical Research: Oceans*, 123: 2635-2645. doi.org/10.1002/2017JC013728.

Novelli, G., C.M. Guigand, C. Cousin, E. Ryan, N.J.M. Laxague, H. Dai, B. Haus, and T.M. Özgökmen. (**2017.**) A biodegradable surface drifter for ocean sampling on a massive scale. *Journal of Atmospheric and Oceanic Technology*, 34(11): 2509-2532. doi.org/10.1175/JTECH-D-17-0055.1.

Poje, A.C., T.M. Özgökmen, B.L. Lipphardt, Jr., B.K. Haus, E.H. Ryan, A.C. Haza, G.A. Jacobs, A.J.H.M. Reniers, M.J. Olascoaga, G. Novelli, A. Griffa, F.J. Beron-Vera, S.S. Chen, E. Coelho, P.J. Hogan, A.D. Kirwan, Jr., H.S. Huntley, and A.J. Mariano. (**2014.**) Submesoscale dispersion in the vicinity of the Deepwater Horizon spill. *Proceedings of the National Academy of Sciences*, 111(35): 12693-12698. doi.org/10.1073/pnas.1402452111.

Sieracki, C.K., M.E. Sieracki, and C.S. Yentsch. (**1998.**) An imaging-in-flow system for automated analysis of marine microplankton. *Marine Ecology Progress Series*, 168: 285-296. jstor.org/stable/24828385.

Stieglitz, J.D., E.M. Mager, R.H. Hoenig, D.D. Benetti, and M. Grosell. (**2016.**) Impacts of Deepwater Horizon crude oil exposure on adult mahi-mahi (*Coryphaena hippurus*) swim performance. *Environmental Toxicology and Chemistry*, 35: 2613-2622. doi.org/10.1002/etc.3436.

Wang, B., S.A. Socolofsky, J.A. Breier, and J.S. Seewald. (**2016.**) Observations of bubbles in natural seep flares at MC 118 and GC 600 using in situ quantitative imaging. *Journal of Geophysical Research: Oceans*, 121: 2203-2230. doi.org/10.1002/2015JC011452.

LAURA BRACKEN See bio on page 16.

DAN DINICOLA See bio on page 32.

JESSIE KASTLER See bio on page 20.

SARA BERESFORD See bio on page 16.

Volume 33 • No. 1 • Winter 2019

The Gulf of Mexico Research Initiative Information and Data Cooperative: Data Transparency and Data Sharing + Classroom Activity

BY SANDRA ELLIS AND KATIE FILLINGHAM

- Data are essential to the scientific process; they enable scientists to examine results of their experiments when exploring new hypotheses. Data sharing and data transparency within the scientific community are relatively new practices that have many potential benefits; as the cost of doing science increases, it can promote continued scientific investigations when funding is tight by reducing duplication of effort. However, standards for requiring data sharing and establishing mechanisms to openly access data sets are still in development.

- When the Gulf of Mexico Research Initiative (GoMRI) was established, the Master Research Agreement required that all data collected through GoMRI funding must be made publicly available, and the program does so through the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC). GRIIDC is leading the way as a successful model for promoting data sharing, data compliance, and data standardization.

- A classroom activity provides examples of publications with varying levels of data access and encourages students to discuss the benefits and challenges of data transparency and open access to data.

DATA TRANSPARENCY AND DATA SHARING – BACKGROUND

Publishing scientific results in peer-reviewed journals is considered to be the cornerstone of transparency in science. Ideally, results are published with enough detail to allow reproduction, which in theory allows the scientific community to verify results (McNutt et al. 2016). Scientists may then be evaluated based on the number of papers published, the impact factors of journals that they have published papers in, and the number of citations to their published works (Abbott et al. 2010). Despite the fact that it is the norm for scientists to share their work and results through publications, the effort to make the underlying raw data openly available is an emerging trend.

In 2013, the United States Office of Management and Budget (OMB) issued an executive order mandating an open data policy for federal agencies. To comply with this directive, federal grant funding agencies have established and implemented data management and sharing requirements for grantees. Many scientific journal publishers have adopted requirements towards open data availability (Goldstein et al. 2017). These publishers require that the raw data used to generate the results presented in the peer-reviewed manuscript be openly available so that results can be verified.

Data sharing has many documented advantages, such as increasing recognition for scientists and increasing scientific transparency (McNutt et al. 2016; Piwowar et al. 2007; Belter 2014; Costello 2009). To comply with the requirement to share data, scientists may reference their datasets in the methods, acknowledgments, or references sections of peer-reviewed publications. Certain publishers also permit inclusion of datasets as part of the supplementary information in the journal itself (Lawrence et al. 2011). However, there is no standard method available to authors to reference data that they have collected and shared (Lawrence et al. 2011).

While data sharing has documented advantages and federal grant funding agencies and some publishers have embraced it as a requirement, the scientific community has been reluctant to adapt to this change. Researchers express concerns that they will not receive credit for publicly available datasets or that datasets will be used incorrectly (Costello 2009). They also report insufficient time to publish their research before having to make the data publicly available and a lack of funding required to make data electronically available as two major barriers to data sharing (Tenopir et al. 2011).

To overcome reluctance to share data and promote a culture of data sharing, a number of incentives have been proposed. The main recommendation is to make data a citable research object, similar to papers (Lawrence et al. 2011; Costello

2009). In practice, required data sharing by publishers has been found to be an effective approach to increase the availability of underlying data (Vines et al. 2013).

Sharing data and encouraging scientists to use existing data sets can help continue the development of good science even when science funding is tight and the cost of conducting research is constantly increasing.

IMPLEMENTING THE GOMRI DATA SHARING POLICY

One of the founding principles of the Gulf of Mexico Research Initiative (GoMRI) program, as outlined in the Master Research Agreement (MRA)(http://gulfresearchinitiative.org/about-gomri/master-research-agreement/), is that all data acquired through GoMRI funding must be archived and made publicly available. GoMRI's commitment to data sharing in a timely manner was at the forefront of data sharing requirements when it came into place in 2011 (Gibeaut 2016). GoMRI quickly realized that there were no existing resources to meet the data sharing needs of both GoMRI administration and researchers, and therefore entered into an agreement with the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi to establish the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC, https://data.gulfresearchinitiative.org/).

Advised by the GoMRI Research Board Data Management Subcommittee, GRIIDC is a team of researchers, data specialists, and computer systems developers who are supporting the development of a data management system. The GRIIDC data management system is a part of the GoMRI Legacy (http://gulfresearchinitiative.org/about-gomri/gomri-legacy/) to ensure that all of the information collected by GoMRI scientists will be discoverable and usable by the science community, responders in the event of future oil spills, and the general public long after the program ends in 2020. As of 2018, GRIIDC houses over 2,200 data sets from over 282 research groups and 2,600 scientists and continues to grow every day.

To promote a culture of data sharing within the GoMRI community, a comprehensive approach is used, as outlined in Gibeaut 2016. User-friendly online tools and extensive user training help ease technical barriers that may prevent data from being shared. Disseminating data to national archives, when appropriate, increases research visibility. Publishing digital object identifiers (DOIs) for each dataset provides an internationally recognized tool for citation to further incentivize data submission to GRIIDC. GRIIDC recommends the use of a standard citation, which includes this DOI, if data are used by others in scientific research.

Since there is no standard way within the scientific community to acknowledge, or include an attribution, for data, GoMRI developed a standard attribution statement. In January 2016, GoMRI grantees were asked to use this statement to highlight their publicly available datasets associated with peer-reviewed publications in the acknowledgments section of manuscripts. This standard attribution statement is:

> *Data are publicly available through the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) at https://data.gulfresearchinitiative.org (doi:<doi identifier> [, <doi identifer2>, <doi identifier3>, …].*

The purpose of this standard attribution is to make sure that the author receives credit for data in the GRIIDC system and to confirm that authors are fulfilling the GoMRI requirement to make data openly available at the time of publication. Since January 2016, over 98% of 420 published articles that reported results using data acquired with GoMRI funding have included the standard attribution statement that acknowledges publicly available data.

CLASSROOM ACTIVITY RESOURCE

To help illustrate the benefits of open access to data from science publications and the ease through which this information can be accessed through sites like GRIIDC, please consider the following activity (recommended for grade levels 9-12).

Imagine you are a scientist studying the immediate effects of a recent oil spill and evaluating possible long-term impacts. In particular, you are interested in what may happen to the oil in the deep-sea sediments and/or coastal sediments. During review of the existing literature, you find several articles that are openly available online, which is very helpful, but you determine that you require raw data to assist with your task. You are able to find an article published through GoMRI with links to openly available data sets through GRIIDC. It's a good start!

1. Brooks, G.R., R.A. Larson, P.T. Schwing, I. Romero, C. Moore, G.-J. Reichart et al. (**2015.**) Sedimentation Pulse in the NE Gulf of Mexico following the 2010 DWH Blowout. *PLoS ONE*, 10(7): e01323410. doi.org/10.1371/journal.pone.0132341. data.gulfresearchinitiative.org/data/Y1.x031.000:0001, data.gulfresearchinitiative.org/data/Y1.x031.000:0002, data.gulfresearchinitiative.org/data/Y1.x031.000:0003.

In continuing to collect information for your literature review, you find several other publications that are openly available, but they have many different data availabilities:

2. Tarr, M.A., P. Zito, E.B. Overton, G.M. Olson, P.L. Adhikari, and C.M. Reddy. (**2016.**) Weathering of oil spilled in the marine environment. *Oceanography*, 29(3): 126-135. doi.org/10.5670/oceanog.2016.77.

3. Graham, W.M., R.H Condon, R.H. Carmichael, I. D'Ambra, H.K. Patterson, L.J. Linn, and F.J. Hernandez Jr. (**2010.**) Oil Carbon entered the coastal planktonic food web during the Deepwater Horizon oil spill. *Environmental Research Letters*, 5: 045301. doi.org/10.1088/1748-9326/5/4/045301.

4. North, E.W., E.E. Adams, A.E. Thessen, Z. Schlag, R. He, S.A. Socolofsky, S.M. Masutani, and S.D. Peckham. (**2015.**) The influence of droplet size and biodegradation on the transport of subsurface oil droplets during the Deepwater Horizon spill: A model sensitivity study. *Environmental Research Letters*, 10(2). doi.org/10.1088/1748-9326/10/2/024016.

5. Edwards, B.R, C.M. Reddy, R. Camilli, C.A. Carmichael, K. Longnecker, and B.A.S. Van Mooy. (**2011.**) Rapid microbial respiration of oil from the Deepwater Horizon spill in offshore surface waters of the Gulf of Mexico. *Environmental Research Letters*, 6(3). doi.org/10.1088/1748-9326/6/3/035301.

6. Yin, F., J.S. Hayworth, and T.P. Clement. (**2015.**) A tale of two recent spills - comparison of 2014 Galveston Bay and 2010 Deepwater Horizon oil spill residues. *PloS ONE*, 10(4): e0124645. doi.org/10.1371/journal.pone.0124645.

7. Geng, X., Z. Pan, M.C. Boufadel, T. Ozgokmen, K. Lee, and L. Zhao. (**2016.**) Simulation of oil bioremediation in a tidally influenced beach: Spatiotemporal evolution of nutrient and dissolved oxygen. *Journal of Geophysical Research: Oceans*, 10(4): 2385-2404. doi.org/10.1002/2015JC011221.

ACTIVITY AND QUESTIONS FOR STUDENTS

Students can work independently or in pairs. Ask students to review the above papers to find data attributions or acknowledgments. Data attributions may be in the methods, acknowledgments, or references. For each of the publications identified, what is their data access like? (*See right column for answers.*) Then discuss how easy, or difficult, it might be to obtain data for each publication based on the attribution or lack thereof. How does including an attribution affect the ability to find data? What do students think is the best format for referencing data? If there are no data referenced, how do students think that the data could be obtained?

Have the students find and download the datasets, and recreate some of the plots from the first article (#1) with the published data sets. The Excel spreadsheet "Brooks Larson TC 2015-06-09.xlsx" found in GRIIDC dataset Y1.x031.000:0002 (doi: 10.7266/N70K26H7) has data that is used to generate the "Texture" plots found in Figures 2, 3, and 4 in the associated paper. The figures in the paper present the data based on the depth of the core in centimeters, while the raw data provided uses depth in millimeters. Students will have to convert millimeters to centimeters and remove points to recreate the plots. (Note: the sample IDs in the paper do not directly match the sample IDs in the raw data; for example, P-06 in the paper corresponds to PCB-06 in the data, D-08 corresponds to DSH-08, and D-10 corresponds to DSH-10.) Have the students describe what their plot shows.

Discussion: In what other ways might the data provided be used? Are there other scientists from a different field who might be interested in this data and if so, how could they use it?

Summary: As a class, discuss why data sharing is important, why scientists may be reluctant to share data, and approaches that could encourage data sharing. How can the ability to reuse research results be impacted by data availability?

(Answers: 2. Data in GRIIDC referenced but not with direct link; 3. No data reference; 4. Link to the data, but the link is broken; 5. Some data available through NOAA; 6. States that all relevant data are available in the article; 7. Data available upon request by contacting the author.)

ACKNOWLEDGMENTS

In addition to the acknowledgments for the full issue, the authors of this article thank Gregg Brooks for permission to reference the datasets included as a part of the activity in this article. This article was made possible by funding from GoMRI to the Consortium for Ocean Leadership and GRIIDC. The Brooks et al. 2015 datasets listed in this article are publicly available through GRIIDC at: https://gulfresearchinitiative.org (data.gulfresearchinitiative.org/data/Y1.x031.000:0001, data.gulfresearchinitiative.org/data/Y1.x031.000:0002, data.gulfresearchinitiative.org/data/Y1.x031.000:0003).

REFERENCES

Abbott, A., D. Cyranoski, N. Jones, B. Maher, Q. Schiermeier, and R. Van Noorden. (**2010.**) Do metrics matter? *Nature*, 465: 860-862. doi:10.1038/465860a.

Belter, C.W. (**2014.**) Measuring the value of research data: A citation analysis of oceanographic data sets. *PLoS ONE*, 9(3): e92590. doi:10.1371/journal.pone.0092590.

Costello, M.J. (**2009.**) Motivating online publication of data. *BioScience*, 59(5): 418-427. doi:10.1525/bio.2009.59.5.9.

Gibeaut, J. (**2016.**) Enabling data sharing through the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC). *Oceanography*, 29(3): 33-37. doi:10.5670/oceanog.2016.59.

Goldstein, J.C., M.S. Mayernik, and H.K. Ramapriyan. (**2017.**) Identifiers for earth science data sets: Where we have been and where we need to go. *Data Science Journal*, 16: 23. doi:10.5334/dsj-2017-023.

Lawrence, B., C. Jones, B. Matthews, S. Pepler, and S. Callaghan. (**2011.**) Citation and peer review of data: Moving towards formal data publication. *International Journal of Digital Curation*, 6(2): 4-37. doi:10.2218/ijdc.v6i2.205.

McNutt, M., K. Lehnert, B. Hanson, B.A. Nosek, A.M. Ellison, and J.L. King. (**2016.**) Liberating field science samples and data. *Science*, 351(6277): 1024-1026. doi:10.1126/science.aad7048.

Piwowar, H.A., R.S. Day, and D.B. Fridsma. (**2007.**) Sharing detailed research data is associated with increased citation rate. *PLoS ONE*, 2(3): e308. doi:10.1371/journal.pone.0000308.

Tenopir, C., S. Allard, K. Douglass, A.U. Aydinoglu, L. Wu, E. Read, M. Manoff, and M. Frame. (**2011.**) Data sharing by scientists: Practices and perceptions. *PLoS ONE*, 6(6): e21101. doi:10.1371/journal.pone.0021101.

Vines, T.H., R.L. Andrew, D.G. Bock, M.T. Franklin, K.J. Gilbert, N.C. Kane, J. Moore, B.T. Moyers, S. Renaut, D.J. Rennison, T. Veen, and S. Yeaman. (**2013.**) Mandated data archiving greatly improves access to research data. *The FASEB Journal*, 27(4): 1304-1308. doi:10.1096/fj.12-218164.

SANDRA ELLIS was Program Manager for the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University in Corpus Christi, Texas.

KATIE FILLINGHAM See bio on page 20.

current

THE JOURNAL OF MARINE EDUCATION

NATIONAL MARINE EDUCATORS ASSOCIATION
c/o Jeannette Connors
4321 Hartwick Road, Suite 300
College Park, MD
20740

INSIDE current

Volume 33 No. 1 Winter 2019