THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

VOL.34, NO.1, MARCH 2021

GULF OF MEXICO
RESEARCH INITIATIVE

Ten Years of Oil Spill and Ecosystem Science


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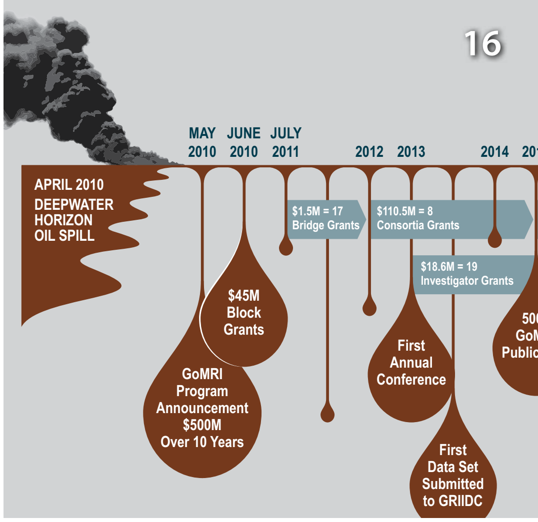
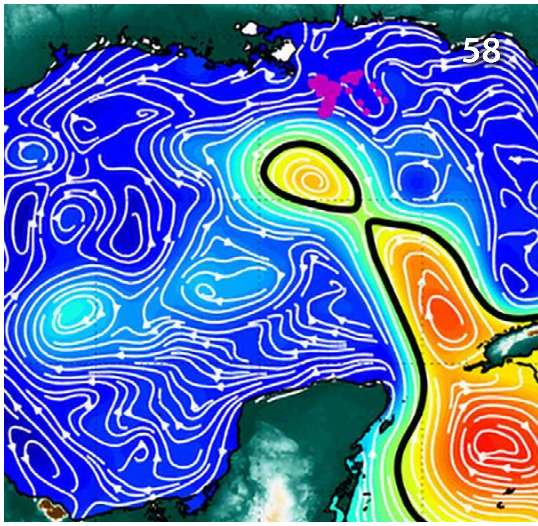
VOL. 34, NO. 1, MARCH 2021

SPECIAL ISSUE ON
THE GULF OF MEXICO RESEARCH INITIATIVE:
TEN YEARS OF OIL SPILL AND ECOSYSTEM SCIENCE





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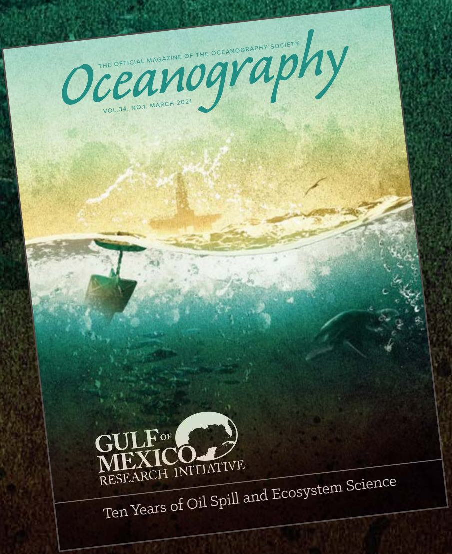
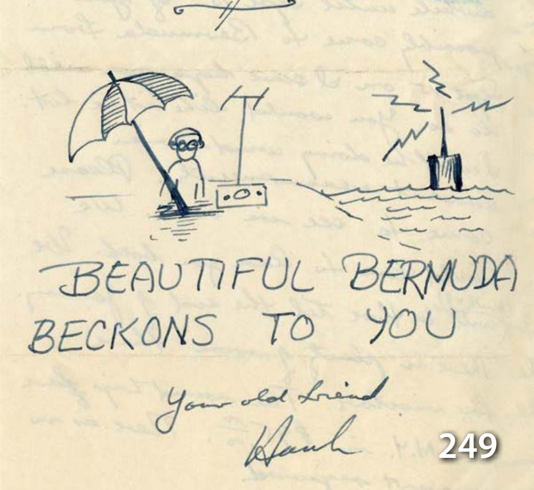


On the Cover. The cover artwork represents the Gulf of Mexico as one of the most prolific and complex bodies of water on the planet. The Gulf is a critical habitat for marine life, while also being one of the most heavily trafficked and utilized bodies of water on the planet. The cover illustrates this delicate balance. *Image created by Jason Mallett, Consortium for Ocean Leadership*



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DEPARTMENTS

CONTACT US
The Oceanography Society
1 Research Court, Suite 450
Rockville, MD 20850 USA
t: (1) 301-251-7708
f: (1) 301-251-7709
magazine@tos.org

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CORRECTIONS
Please send corrections to magazine@tos.org. Corrections will be printed in the next issue of *Oceanography*.

THE OCEANOGRAPHY SOCIETY tos.org

The Oceanography Society was founded in 1988 to advance oceanographic research, technology, and education, and to disseminate knowledge of oceanography and its application through research and education. TOS promotes the broad understanding of oceanography, facilitates consensus building across all the disciplines of the field, and informs the public about ocean research, innovative technology, and educational opportunities throughout the spectrum of oceanographic inquiry.

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Oceanography contains peer-reviewed articles that chronicle all aspects of ocean science and its applications. The journal presents significant research, noteworthy achievements, exciting new technology, and articles that address public policy and education and how they are affected by science and technology. The overall goal of *Oceanography* is cross-disciplinary communication in the ocean sciences.

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Oceanography Happenings

MUCH HAS HAPPENED in our little corner of the world since publication of the December issue of *Oceanography*. Here, I share a few newsworthy items.

1. *Oceanography* News. In an effort to timely share important notices with the ocean science community, we now devote a section of The Oceanography Society home page (https://tos.org/) to *Oceanography* news. A recurring feature in this news section is a listing of early online releases of magazine articles to advertise their availability more prominently. When you next visit the TOS home page, don't forget to scroll down to read the latest *Oceanography* announcements.

2. Translation of hands-on supplement into Japanese. A Japanese language version of the booklet "Teaching Physical Concepts in Oceanography: An Inquiry-Based Approach" by Lee Karp-Boss and colleagues is now available online. Masahiko Fuji of Hokkaido University provided the translation. Published as a supplement to *Oceanography* in 2009, the booklet focuses on educational approaches to engaging students in learning. It offers a collection of hands-on/minds-on activities for teaching physical concepts that are fundamental in oceanography, including density, pressure, buoyancy, heat and temperature, and gravity waves. The Japanese translation is a great addition to the English, Spanish, Catalan, and French versions of this widely used booklet of hands-on activities. You can download all available language versions here: https://tos.org/oceanography/issue/volume-22-issue-03-supplement.

3. Ocean Observing Supplement. We are excited to announce the upcoming December publication of the first annual supplement to *Oceanography* on ocean observing, sponsored by Ocean Networks Canada, the Partnership for Observation of the Global Ocean, the National Oceanic and Atmospheric Administration's Global Ocean Monitoring and Observing Program, and the US Arctic Research Commission. The objective of this supplement is to widely disseminate information about the many ways in which scientists observe the ocean to improve our understanding of planet Earth and support sustainable management of the ocean and its resources. For the inaugural 2021 supplement, we are aligning the content with the priorities of the UN Decade of Ocean Science for Sustainable Development. If you missed the announcement calling for letters of interest by May 20, rest assured you will have a chance to contribute to future ocean observing supplements. More information is available at https://tos.org/pdfs/ocean-observing-supplement.pdf.

4. JEDI column in *Oceanography*. On page 9 in this issue, readers will find the inaugural column contributed by the TOS Justice, Equity, Diversity, and Inclusion (JEDI) committee, which was formed in late 2020. The committee will use the JEDI column as one vehicle to communicate its activities to the ocean sciences community and beyond. Read their first column to learn about the committee's objectives and ways to engage with its members. We would like to see as many TOS members as possible participate in some way with this important JEDI effort.

Happy spring!

Ellen S Kappel

Ellen S. Kappel, Editor

Oceanography

https://tos.org/oceanography

UPCOMING SPECIAL ISSUES

JUNE 2021
Marine Biodiversity Observation Network: An Observing System for Life in the Sea

DECEMBER 2021
Oceans Across the Solar System

DECEMBER 2021 SUPPLEMENT
Ocean Observing

MARCH 2022
The Changing Arctic Ocean

MARCH 2022 SUPPLEMENT
New Frontiers in Ocean Exploration

CALL FOR IDEAS!

Do you have an idea for a special issue of *Oceanography*? Please send your suggestions to Editor Ellen Kappel at ekappel@geo-prose.com.

TOS MAKES PROGRESS ON ITS STRATEGY 2030: LOOKING TO THE FUTURE

IN JANUARY 2021, I took over the position of president of The Oceanography Society (TOS) from Martin Visbeck, who had just finished navigating a remarkably challenging year punctuated by divisive US politics, global unrest, and a devastating pandemic that changed lives everywhere. Science took a back seat, with field seasons canceled, education systems stalled, and many of us struggling to balance our new working arrangements. And yet, under Martin's steady leadership, the Society embraced many positive changes. With a stabilized budget and healthy membership growth, Martin turned his sights to our longer-term strategy—one of his goals for TOS was to articulate a vision for the Society for the coming decade.

After the close of the Ocean Sciences Meeting in San Diego in February 2020, and just weeks before the pandemic shuttered our everyday lives, Martin convened a strategy and visioning workshop for TOS. Drawing energy from the UN Decade of Ocean Science for Sustainable Development, he called the session "Strategy 2030: Looking to the Future" and posed several questions for its participants: "How should TOS adapt to the changes in ocean science? How can TOS provide value for our members? And how can we strengthen the profile and impact of TOS?"

Many exciting ideas were proposed at the first Strategy 2030 workshop, and feeling energized, participants decided that some of these ideas needed to be implemented without delay, before the visioning process was complete. High on the priority list was the notion that we need to both support excellence in core ocean sciences research and exploration and yet firmly encourage a vision that helps ocean science solve some of our planet's most thorny challenges. It appeared that a good starting place for TOS would be to improve our scientific inclusivity, member equity, and diversity. We want broad participation to include members who represent solution-driven science at the intersection of oceanography and socioeconomics, policy, social sciences, big data, and informatics. One way to encourage an inclusive and diverse membership is for the make-up of the TOS Council to reflect the scientific diversity of its members. As a result of this first workshop, we have added an Ocean Data Science Councilor and an Ocean Social Science and Policy Councilor. TOS's commitment to its student and early career members remains strong, and so we have also added an Education Councilor and an Early Career Councilor, and have initiated a Student Committee, chaired by the Council's Student Representative.

An area that has seen explosive growth in engagement and awareness on the national stage, and has some very significant urgency in our own Society, is the issue of justice, equity, diversity, and inclusion (JEDI). The TOS JEDI committee was inaugurated this last year, with the goal of celebrating our differences and creating a culture of belonging. The JEDI committee has been diligently working to firm up our core values and terms of reference, which will soon be shared with the TOS community. As president of TOS, I feel we are in good hands with the wisdom of our JEDI committee.

While the pandemic offered few silver linings, it did turn out to be a time of opportunity for experimenting with member engagement. We have learned that member engagement can be more creative, more personalized, and successful even without the privilege of in-person meetings. Some of the recommendations from the first Strategy 2030 workshop for enhancing member engagement include hosting our annual membership meetings online, a policy we have now adopted and will implement this coming year, and hosting webinars to engage members, which we have also started planning, with a fireside talk webinar focused on "Oceanography and Technology" about to be rolled out.

While some of the actions recommended, and implemented, as a result of the Strategy 2030 workshop are reason to celebrate, my goal as president of TOS is to pick up where Martin left off and complete the TOS Strategy 2030, embracing a use-inspired mission that benefits our global society and the environment. I look forward to the challenges ahead and to working with the TOS Council, and I especially hope I can lean on my predecessors to help find the right path forward.

I am writing to you from the main lab on one of our ocean class research vessels, about to embark on an expedition to explore the intersection of ocean acoustics and shelf break physical oceanography, hopeful that this is the beginning of the end of a painful year in which the pandemic has stifled the advance of observational ocean science. Yet, I am also heavy hearted, knowing that for many international members of our Society, the pandemic is still raging. I look forward to a time when we can all engage equally in this scientific endeavor.

Andone C. Lavery

Andone C. Lavery, TOS President

THE OCEANOGRAPHY SOCIETY'S
HONORS PROGRAM

One of the most meaningful aspects of being a member of The Oceanography Society (TOS) is the opportunity to recognize and celebrate our colleagues' accomplishments. Please take this opportunity to recognize a colleague for their exceptional achievements and contributions to the ocean sciences.

tos.org/honors

DON'T MISS THE
SEPTEMBER 30, 2021
NOMINATION DEADLINE!

TOS FELLOWS PROGRAM

TOS Fellows are individuals who have attained eminence in oceanography through their outstanding contributions to the field of oceanography or its applications during a substantial period of years.

WALTER MUNK MEDAL

The Walter Munk Medal is given biennially to an individual ocean scientist for extraordinary accomplishments and novel insights in the area of physical oceanography, ocean acoustics, or marine geophysics.

WALLACE S. BROECKER MEDAL

The Wallace S. Broecker Medal is given biennially to an individual ocean scientist for extraordinary accomplishments and novel insights in the areas of marine geoscience, chemical oceanography, or paleoceanography.

MARY SEARS MEDAL

The Mary Sears Medal is given biennially to an individual ocean scientist for extraordinary accomplishments and novel insights in the areas of biological oceanography, marine biology, or marine ecology.

NILS GUNNAR JERLOV AWARD

The Nils Gunnar Jerlov Award is given biennially to an individual ocean scientist for having significantly advanced our knowledge of how light interacts with the ocean.

TOS EXPANDS EFFORTS TO PROMOTE JUSTICE, EQUITY, DIVERSITY, AND INCLUSION IN THE OCEAN SCIENCES

By Erin Meyer-Gutbrod, Frank Muller-Karger, and the TOS Justice, Equity, Diversity, and Inclusion Committee

IN LATE 2020, The Oceanography Society (TOS) established a Justice, Equity, Diversity, and Inclusion (JEDI) committee to comprehensively examine the role that TOS can play in promoting JEDI values in the ocean sciences community. The JEDI Committee's charge is to help TOS alleviate barriers to participation and shape a welcoming future for groups that have been historically marginalized in oceanography and related sciences.

An open call for volunteers led to the selection and appointment of 11 committee members (see Box 1). The committee includes international students and early career scientists and professionals. It meets semi-monthly for discussions and agenda setting. During a virtual winter retreat, committee members shared experiences and developed the committee's mission, values, vision, and mandates.

JEDI committee objectives include:

1. Guiding TOS leadership to increase access and participation of historically marginalized groups in TOS events and programming
2. Supporting and amplifying existing efforts to eliminate bias and unfair treatment in oceanography and related fields
3. Creating and sharing tools and resources for dismantling barriers to participation of historically marginalized groups at their places of work or study
4. Hosting an open and welcoming dialogue with the community to accomplish these goals

We invite the TOS membership to contribute thoughts and ideas to this process. To advance justice, equity, diversity, and inclusion in oceanography and related fields, TOS will use its outlets and tools, including TOS meetings, communication channels, and membership networks; *Oceanography* magazine; the biennial Ocean Sciences Meetings; and honors and awards. TOS seeks to engage other professional societies and international organizations as well. A JEDI column will be published quarterly in *Oceanography* to share progress and engage the TOS membership in discussions on these topics. We invite members of the community to continue to publish on this topic and to use the journal *Oceanography* for this purpose.

TOS is committed to supporting a community that encourages the open expression and exchange of ideas, free from all forms of discrimination, harassment, and retaliation. A welcoming, diverse community of individuals will advance oceanography more effectively than a closed community of homogeneous perspectives and backgrounds. These goals require us to dismantle systemic bias and barriers in educational systems, access to resources, hiring, promotion and retention. Additionally, we can learn and benefit from reflecting on how we shape interpersonal relations and conduct business. We envision a community of scholars, scientists, and professionals in which every member contributes actively to dismantling systemic barriers and interpersonal biases, counters aggressions, and contributes to advancing equity and inclusion of diverse people in oceanography and related fields.

Our JEDI work will require consistent and thoughtful actions and continuous evaluation. While we work to establish mechanisms to receive community input and support discussion, you can connect with the JEDI committee or the TOS Council directly. For additional information, please join us on social media or visit our website (see Box 2).

BOX 1. JEDI COMMITTEE MEMBERS

Susanne Craig (co-chair), NASA Goddard Space Flight Center/USRA
Beth Orcutt (co-chair), Bigelow Laboratory for Ocean Sciences
Mona Behl, University of Georgia Sea Grant
EeShan Bhatt, MIT/WHOI Joint Program
Dick Crout, Naval Research Laboratory
Erin Meyer-Gutbrod, University of South Carolina
Frank Muller-Karger, University of South Florida
Tashiana Osborne, Scripps Institution of Oceanography
Charitha Pattiaratchi, The University of Western Australia
James Pierson, University of Maryland Center for Environmental Science
Amber Shearer, Garden School Foundation

BOX 2. STAY IN TOUCH

Twitter: @TOSOceanography
Facebook: @OceanographySociety
Instagram: @tosoceanography
Website: https://tos.org/diversity
Email: JEDIcochairs@tos.org

Larry Philip Atkinson

1941–2020

While it is popular to say that “life is a journey, not a destination”[1] when remembering a colleague, we tend to list the destinations or accomplishments—the greatest hits, if you will—and not the path and history that made them possible. Larry Atkinson began his journey through oceanography in 1941 in Iowa and completed it in December 2020 in Virginia. Along the way, he traveled, lived, and worked all over the world, transforming his own research emphases, helping colleagues, starting research programs, and having a great time wherever he was.

Larry’s outstanding career in oceanography could, without too much exaggeration, be said to have extended from the age of wooden ships to today’s era of satellites, autonomous platforms, and steel research vessels jam-packed with electronic and acoustics gear. As an undergraduate and master’s degree student at the University of Washington in the 1960s, Larry was exposed to an interdisciplinary approach to oceanography, but his early focus was on chemical oceanography under the tutelage of F.A. Richards. Richards’ cadre of student researchers concentrated on suboxic and anoxic conditions found in basins and fjords, and the suboxic waters of the eastern tropical Pacific Ocean. Data from two of British Columbia’s anoxic fjords, Saanich Inlet and Lake Nitinat, were collected from R/V *Hoh*, a surplus army tugboat with a wooden hull. Getting into Lake Nitinat was an adventure because of this fjord’s shallow sill. *Hoh* had to “catch a wave” to reduce the chance of grounding. *Hoh* had a captain/boat operator, but everything else was done by the scientists. Thus, Larry was involved in operating the winches and cooking meals, among other diverse activities. The galley was dual-purpose, serving as the shipboard lab between meals.

During the mid-1960s, the University of Washington was transitioning its ocean-going ship capability from the wooden-hulled *Brown Bear* to the first *Thomas G. Thompson* (since replaced by the present *Thompson*, a much larger and easier-riding ship). Larry participated in *Thompson’s* maiden voyage, a several month adventure that included sampling the anoxic Cariaco Trench and suboxic water in the eastern Pacific Ocean. Larry obtained his MS degree in 1967. His thesis focused on methane and resulted in two peer-reviewed papers.

Subsequently, Larry took a position as a research associate at the Duke University Marine Lab. During this period (1966–1968), he worked closely with Professor Unnsteinn Stefánsson, whom he had first met while Unnsteinn was visiting and working with F.A. Richards at the University of Washington. He also collaborated with several other researchers to produce five peer-reviewed papers focusing on the physical and chemical properties of the waters off the North Carolina coast. Larry decided to pursue a PhD, and 1969 enrolled in the graduate program in oceanography at Canada’s Dalhousie University, where he joined a diverse multinational group of graduate students in Pete Wangersky’s chemical oceanography laboratory. Pete always encouraged independence and creativity, and Larry pursued a combined chemical and physical oceanographic research effort to look at bubbles in the mixed layer and the resulting air-sea gas exchange. Dalhousie’s Department of Oceanography, under Gordon Riley, was a vibrant, exciting place enhanced by graduate students who brought interesting prior experiences. Larry earned his PhD in 1972 and then moved on to other adventures at the Skidaway Institute of Oceanography in Georgia, which was only four years old at the time.

At Skidaway, Larry began to focus on nutrient biogeochemisty in coastal waters, perhaps a reflection of his earlier work at Duke, but his journey in chemical processes started to turn to physical oceanographic aspects. The driver of this change was likely the Department of Energy project on the South Atlantic Bight that Skidaway’s director, Dave Menzel, organized in the late 1970s. Larry’s part of that study focused on nutrient sources, transport, and fate, and the results of his studies provided the framework for our understanding that upwelling along the shelf break dominates the nutrient budget of the shelf. He wanted to understand the timing and mechanisms that controlled this upwelling, and this subject pretty much consumed his research in his later years at Skidaway. It followed that he would develop collaborations with physical oceanographers like Tom Lee (University Miami), Len Pietrafesa (North Carolina State

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[1] Lynn H. Hough, *The Christian Advocate*, 1920

University), and Skidaway's Jack Blanton.

In 1985 it was time for a new journey. Encouraged by former Skidaway faculty William Dunstan and George Oertel, Larry became Professor and Eminent Scholar at Old Dominion University's (ODU's) Department of Oceanography in Norfolk, Virginia. At ODU he continued his studies of coastal physical processes that drive chemical and biological ones, but he also perfected his talent for developing new programs and leading others. Indeed, he coordinated the founding of ODU's Center for Coastal Physical Oceanography in 1991 and was its director until 2003. During the same time, he was the Department of Oceanography's Chair from 1992 to 1997. And, if this wasn't enough, from 1988 to 1992 he was an editor and then the senior editor of the *Journal of Geophysical Research*: *Oceans*, and from 1993 to1997 the editor for The Oceanography Society's *Oceanography* magazine. In addition to his work on *Oceanography,* Larry was a stalwart supporter of The Oceanography Society. He joined as a charter member in 1987, served a term as the Applied Technology Councilor, then as Meetings Chair. He could always be counted on to provide advice and encouragement for TOS initiatives.

For more than 40 years, Larry's research journeys took place aboard research vessels of all types, so he logically served on the University-National Oceanographic Laboratory System (UNOLS) Council from 1989 to 1991, then on the UNOLS Fleet Improvement Committee from 1995 to 1997 and as its chair from 1997 to 2003. While Larry may have started his oceanographic journey on wooden ships, his later years were filled with the newest technology (e.g., high-frequency radar to measure surface currents), and in his usual fashion, he helped everyone make the best use of these new types of data, and he facilitated early career investigators' contributions and participation. In terms of new technology, the Ocean Observatories Initiative (OOI) was spending many millions of dollars to set up these systems, and the National Science Foundation (NSF) asked UNOLS to form a committee to represent the science community. When the Ocean Observatories Science Committee (OOSC) was organized, Larry was called on to be its chair. He served in that position from 2010 until about 2016, overseeing the committee through OOI's installation and commissioning. He worked hard during these years to engage the community and promote OOI. Larry had a particular focus on early career scientists and promoting their use of OOI data. After OOI was fully installed, NSF formed the OOI Facility Board (OOIFB), and Larry was again asked to be the chair. He served in this position from the board's inauguration in 2017 until 2019 (and then transitioned into a past-chair position). Just as with the previous OOSC, Larry focused on inclusion, diversity, and new participants. As a result of his dedication, in May 2020 the OOIFB and NSF honored Larry with the establishment of the Larry P. Atkinson Travel Fellowship for Students and Early Career Scientists.

Larry projected a calm and affable aura, but because he was so well respected, he could make good things happen with a quiet word—likely because there was a lot going on inside his head before he suggested a course of action. When discussing a new idea, how to implement some program, or where to go to dinner or what wine to choose, Larry would lean back, smile slightly or give a small chuckle, and say, "Well, have you considered…" He was a great colleague, a man who always took a no-nonsense approach to finding solutions, a resource for our science, and an advocate for all—particularly early career scientists.

CONTRIBUTED BY

Gregory Cutter, Old Dominion University, and **Louis Codispoti**, University of Maryland (UMCES)

AUTHORS NOTE

When compiling the story of colleague, no one person can accurately tell the tale. The authors thank many for their contributions, particularly Annette De Silva. Jonathan Sharp, and Herb Windom.

DIY OCEANOGRAPHY

In this *Oceanography* section, contributing authors share all of the relevant information on a homemade sensor or instrument so that others can build, or build upon, it. The short articles also showcase how this technology was used successfully in the field.

CALL FOR CONTRIBUTIONS

Oceanography guest editors Melissa Omand and Emmanuel Boss are seeking contributions to DIY Oceanography. Contributions should include a list of the materials and costs, instructions on how to build, and any blueprints and codes (those could be deposited elsewhere). See *Oceanography's* Author Guidelines page for detailed information on submission requirements.

https://tos.org/oceanography/guidelines

SEE THE COLLECTION

Go to the DIY Oceanography web page to view the complete compilation of DIY Oceanography articles.

- The Pressure of In Situ Gases Instrument (PIGI) for Autonomous Shipboard Measurement of Dissolved O_2 and N_2 in Surface Ocean Waters
- Inlinino: A Modular Software Data Logger for Oceanography
- A Simple and Inexpensive Method for Manipulating Dissolved Oxygen in the Lab

https://tos.org/diy-oceanography

Surgical Masks on the Beach

COVID-19 AND MARINE PLASTIC POLLUTION

BY CHERYL LYN DYBAS

COVID-19. The disease has nearly forced the world to a full stop. Cities have emptied, traffic has halted, schools have closed. Beyond causing a serious respiratory illness, the SARS-CoV-2 virus has brought a new, and largely overlooked, threat to human health: more potentially harmful microplastics in the environment, this time from discarded personal protective equipment (PPE).

PPE used to fight COVID-19 becomes plastic waste after its use, adding to the immense worldwide problem of plastic pollution, according to a 2020 World Wide Fund for Nature (WWF) Italy study. That plastic "invades our streets, our sidewalks and our parks," states the report.

Researchers at Italy's Polytechnic of Turin estimated that in Phase 2 of the country's COVID-19 reopening (in which activities are gradually restarted), 1 billion masks and half a billion disposable gloves each month were needed. "These are very high quantities that require those who use them to assume responsibility for their disposal," according to WWF Italy documents. "Each of us must make an effort to ensure that we proceed with the least possible impact on nature."

If even only 1% of the masks were discarded incorrectly, that would result in 10 million masks per month dispersed in various ecosystems. With the weight of each mask about 4 grams, more than 40,000 kilograms of plastic would soon accumulate.

"Just as citizens have acted responsibly in containing the virus by staying at home, now they must prove equally responsible for the management of individual protection devices," says WWF Italy president Donatella Bianchi. "Once these devices become waste, they have a devastating effect on our natural environments."

PPE is just one of the sources of plastic now ubiquitous in the environment around the globe. Eventually, plastic products break down into microplastics; they then contaminate air, water, and soil. Researchers are now intensifying efforts to understand the human health costs of microplastics.

In January 2020, the US National Academies of Science, Engineering, and Medicine in Washington, DC, hosted one of the first workshops on the environmental health effects of microplastics. Since then, the COVID-19 epidemic has made the problem even worse.

MASKS WASHING ASHORE

In the Mediterranean alone, 570,000 tons of plastic end up in the sea every year. It is the equivalent of 33,800 plastic bottles thrown into the water every minute, according to Bianchi. That's pre-COVID-19, however. Now, she says, "we ask that institutions prepare appropriate collectors for masks and gloves and install them near

Scientists at OceansAsia are finding dozens of surgical masks washing up on beaches near Hong Kong. *Photo credit: Gary Stokes*

With millions of people wearing one to two masks each day, the amount of plastic discarded is substantial. *Photo credit: Gary Stokes*

ports and in parks, around villas and at supermarkets. It would be an advantage for the environment—and for our health."

OceansAsia, a marine conservation organization headquartered in Southeast Asia, maintains a remote, boat-access-only test beach on the Soko Islands south of Lantau, Hong Kong. Twice each month, OceansAsia researchers visit the beach to carry out microplastics surveys. "Because the area is so distant, all the plastic there has its origins in the sea," says Teale Phelps Bondaroff, OceansAsia's director of research. "In late February, about six weeks after wearing masks became a widespread practice in Hong Kong, much to our surprise we started noticing a massive influx of surgical masks."

Since then, he says, OceansAsia scientists have continued to find surgical masks "in considerable numbers at beaches around Hong Kong." Gary Stokes, OceansAsia's director of operations, investigated another beach on April 25, 2020—and came across dozens of masks in less than five minutes. Stokes returned to the beach in early June and again found handfuls of masks. "The masks break down into smaller and smaller pieces of microplastic," Phelps Bondaroff says.

Researchers often discover the source of the plastic by identifying certain characteristics, for example, a wrapper from a local restaurant or a pill bottle with the name of the prescribing doctor. "While that's not possible for face masks," says Phelps Bondaroff, "we can look at similar items on the sand, along with the location of the beach and its tidal patterns, to help trace the masks' origins."

The scientists think surgical masks retrieved from Soko Islands beaches likely came from Hong Kong or the nearby Pearl River system. "When you suddenly have a population of 7 million people wearing one to two masks each day, the amount of plastic discarded is going to be substantial," says Stokes.

That is bad news indeed. Researchers recently discovered that microscopic bits of plastic in the ocean are carried aloft in sea spray, where they are ferried far and wide. More than 136,000 tons of microplastics are blowing ashore on the sea breeze every year, scientists at the UK's University of Strathclyde reported in a June 2020 paper in *PLoS ONE*.

"Plastic pollution has entered every ecosystem, with implications for interactions at every level of biological organization," writes Chelsea Rochman of the University of Toronto in the September 2020 issue of *Oceanography*. Rochman gave the 2020 Roger Revelle Commemorative Lecture at the US National Academy of Sciences. "There is no doubt that…plastic debris can have an impact on wildlife, and compelling evidence suggests that macroplastics are already impacting marine populations, species, and ecosystems." Those ecosystems include humans.

In medical masks, it is a case of circular microplastics; to protect human health, we have ultimately endangered human health. Microplastics pose a potential health problem on their own, but treating human diseases is adding to it.

DISCARDED FACE MASKS CLOG THE SEAS

The ocean will be flooded with an estimated 1.56 billion face masks in 2020, according to a report released in December 2020 by OceansAsia. That will result in an additional 4,680 to 6,240 metric tons of marine plastic pollution, states Phelps Bondaroff, lead author of *Masks on the Beach: The Impact of COVID-19 on Marine Plastic Pollution*. The masks will take as long as 450 years to break down, slowly turning into microplastics while impacting marine life and ecosystems.

To arrive at the estimate, the report's authors used a global production number of 52 billion masks in 2020, a conservative loss rate of 3%, and the average weight of 3–4 grams of a single-use polypropylene surgical face mask.

"The 1.56 billion face masks that will likely enter our ocean in 2020 are just the tip of the iceberg," says Bondaroff. "The 4,680 to 6,240 metric tons of face masks are just a small fraction of the estimated 8 to 12 million metric tons of plastic that end up in our ocean each year."

Plastic consumption, which has been steadily rising for years, has increased significantly as a result of the COVID-19 pandemic, he says.

"Hygiene concerns and greater reliance on take-away food had led to increased use of plastics, particularly plastic packaging," adds Stokes. "Meanwhile, measures designed to reduce plastic consumption, like single-use plastic bag bans, have been delayed, paused, or rolled back."

The use of PPE, in particular face masks, has become a common tool for preventing the spread of the virus, with many jurisdictions mandating the wearing of masks in public. The production of PPE has expanded in an attempt to meet skyrocketing demand, and PPE waste has also increased dramatically.

Single-use face masks are made from a variety of meltblown plastics and are difficult to recycle due to composition and the risk of contamination and infection. They enter the ocean when they are littered, when waste management systems are inadequate or non-existent, or when these systems become overwhelmed due to increased volumes of waste.

PLASTIC USE ON THE RISE

Consumer habits have shifted as a result of the COVID-19 pandemic. Virus concerns have led many people to prefer fruit and vegetables individually packaged over unpackaged items.

For example, in Italy, consumer spending on packaged mandarin oranges increased more than 111% in the first week of March 2020 as compared to the previous year. In Lithuania, the use of disposable plastics shot up by 250%–300%, with people throwing away personal protective equipment and discarding reusable bags and containers for fear of the virus. The trend toward disposable plastic items has been seen during previous outbreaks, OceansAsia scientists say.

"Marine plastic pollution in general is devastating our ocean," says Stokes. "Plastic pollution kills an estimated 100,000 marine mammals and turtles, more than a million seabirds, and even greater numbers of fish, invertebrates, and other animals each year. It also affects fisheries and the tourism industry and costs the global economy an estimated $13 billion USD per year."

OceansAsia scientists are asking people to dispose of masks correctly and reduce their overall consumption of single-use plastic. They are also calling on organizations around the world to foster innovation and the development of sustainable alternatives to single-use plastic masks, discourage littering by increasing fines, educate the public about responsible ways to dispose of masks, and repair and improve waste management systems to reduce losses and spillage.

"It is critical that we work to reduce our use of single-use plastics, and we all have a role to play," says Phelps Bondaroff. "There are reusable and sustainable options for almost every single-use plastic item. Please be sure to dispose of all masks responsibly."

ABOUT THE AUTHOR

Cheryl Lyn Dybas (cheryl.lyn.dybas@gmail.com), a Fellow of the International League of Conservation Writers, is a contributing writer for *Oceanography* and a marine ecologist. She also writes about science and the environment for *National Geographic, BioScience, National Wildlife, Natural History, Ocean Geographic, ON Nature,* and many other publications.

The 1.56 billion face masks that likely entered the oceans in 2020 are just the tip of the plastic pollution iceberg. *Photo credit: Colin Sim*

GULF OF MEXICO
RESEARCH INITIATIVE

TEN YEARS OF OIL SPILL AND ECOSYSTEM SCIENCE

ABOUT THE SPECIAL ISSUE

This special issue of Oceanography is the culmination of a decade of research supported by the Gulf of Mexico Research Initiative (GoMRI). The collection of articles describes key advances, surprises, and novel discoveries for the Gulf of Mexico and other regions where GoMRI research was conducted and has application. Also included are lessons learned and outstanding research needs and gaps to inform future activities and efforts. While the issue is not exhaustive, the authors have done their best to represent GoMRI's main scientific accomplishments and provide overviews that facilitate access to the published literature (over 1,500 papers) produced by the program. This body of work has been achieved through wide-ranging interdisciplinary and collaborative research, which has contributed significantly to our knowledge of oil spills and the oceanographic and ecological processes that sustain the Gulf of Mexico ecosystem.

DEDICATION

On behalf of the GoMRI Research Board, we dedicate this issue to the 11 individuals who perished during the Deepwater Horizon disaster and those in the GoMRI community who did not live to see the end of this unprecedented 10-year research program (https://gulfresearchinitiative.org/about-gomri/gomri-legacy/). We thank all of the response workers who helped to minimize the effects of the spill and all the scientists, students and staff who have worked so hard to understand the effect of the spill.

Respectfully,

Rita Colwell, University of Maryland
John Shepherd, University of Southampton
Michael Feldman, Consortium for Ocean Leadership
Chuck Wilson, Gulf of Mexico Research Initiative
Rick Shaw, Louisiana State University
Margaret Leinen, Scripps Institution of Oceanography

Sunset over the Gulf of Mexico from R/V *Weatherbird II*.
Photo credit: C-IMAGE Consotrium, USF

FROM DISASTER TO UNDERSTANDING

FORMATION AND ACCOMPLISHMENTS OF THE GULF OF MEXICO RESEARCH INITIATIVE

By Leigh A. Zimmermann, Michael G. Feldman, Debra S. Benoit, Michael J. Carron, Nilde Maggie Dannreuther, Katie H. Fillingham, James C. Gibeaut, Jennifer L. Petitt, Jarryl B. Ritchie, Rosalie R. Rossi, Stephen H. Sempier, J. Kevin Shaw, Jessie L. Swanseen, Charles A. Wilson, Callan J. Yanoff, and Rita R. Colwell

Partially buried oil at Pensacola Beach, Florida, showing oil deposited in intertidal (partially submerged) and supratidal (exposed) sands. Depending on the location of the oil burial, oil-degrading microbes are exposed to very different environmental settings ranging from permanently submerged to permanently dry. The location of the buried oil also affects the oil's exposure to oxygen, nutrients, and heat and thus impacts the rates of microbial degradation. *Photo by Markus Huettel*

> “We are fighting an omnidirectional, almost indeterminate threat… We are trying to protect the entire Gulf Coast at the same time.”
>
> – Coast Guard Commandant Thad Allen, May 18, 2010, before
> the Senate Committee on Commerce, Science, and Transportation

ABSTRACT. The Gulf of Mexico Research Initiative (GoMRI) was created in 2010 following the catastrophic Deepwater Horizon explosion and oil spill. BP engaged Rita Colwell to form and lead an independent board of experts to oversee an unprecedented program of scientific research on the effects of the spill. As a new and uniquely funded organization, GoMRI quickly developed and implemented a set of management processes, policies, and frameworks while simultaneously building an interconnected research community that eventually grew to nearly 4,500 individuals. The GoMRI Research Board and Management Team successfully produced and operated a system for requests for proposals, grants management, scientific and programmatic data management, and outreach and education, and assembled a scientific synthesis of results to create a lasting legacy 10 years after the disaster. Here, we document the challenges and key decisions underlying the design and operation of GoMRI as a model for independent, industry-funded research. In short, GoMRI represents a unique multi-sector partnership and a community of researchers that will advance science in the Gulf of Mexico and elsewhere for decades to come.

INTRODUCTION

On April 20, 2010, the TransOcean Deepwater Horizon (DWH) drilling rig lost control of a well, resulting in a catastrophic explosion approximately 66 km (41 miles) off the Louisiana coast. The TransOcean drilling rig operated on the BP-owned Macondo lease in the Mississippi Canyon, where the water was ~1,500 m (~5,000 ft) deep. Operations were in progress to temporarily abandon the well, a process involving filling a portion of the well hole with a cement plug. The plug failed, releasing gas and causing a major explosion and fire. Tragically, 11 individuals lost their lives and 17 were injured. Two days later, on April 22, 2010, the rig sank, and oil began to flow from the broken wellhead into the surrounding water (NCBPDHOSOD, 2011).

It was not until 87 days later that the well could be capped. By then, millions of barrels of oil and gas had been released into the Gulf of Mexico. This was when the Gulf of Mexico Research Initiative (GoMRI) story began.

Oil and the Gulf of Mexico Ecosystem

Hydrocarbons have always been a component of the Gulf of Mexico ecosystem, strongly influencing its ecology. Over time, oil deep under the floor of the Gulf worked its way to the sediment surface through fissures and cracks in ancient and subsequently modern sediments. A report of the National Academies of Sciences, Engineering, and Medicine, *Oil in the Sea III* (Transportation Research Board and National Research Council, 2003), estimated that approximately 600 natural seeps in the Gulf of Mexico annually release more than a million barrels (42 million gallons) of oil into Gulf waters. These natural seeps have been sites of scientific investigation for many years, notably because of their unique and diverse ecology, compared to areas without seeps (Weiman et al., 2021, in this issue).

Over the past 200 years, expanding human communities and activities in the Gulf of Mexico region have negatively influenced its rich and productive ecosystem. McKinney et al. (2021, in this issue) describe how the Gulf has become a thoroughfare for commerce and an international center for hydrocarbon mining, storage, and processing, as well as a collection basin for outflows from countries surrounding the Gulf. It has been subjected to many sources of anthropogenic pollution, including hydrocarbons discharged from ships, terrestrial runoff, and oil well failures (McKinney et al., 2021, in this issue; Transportation Research Board and National Research Council, 2003).

Anthropogenic influences on the ecosystem, notably from the exploitation of oil and gas, have on occasion been extreme, with several notable large-scale oil-related releases into the Gulf (Farrington et al., 2021, and Wiesenburg et al., 2021, both in this issue). For example, the 1978 Ixtoc 1 spill that occurred offshore from the Bay of Campeche, Mexico, leaked 3.4 million barrels (142.8 million gallons) of crude oil over a nine-month period, some of which eventually reached the Texas coast. Major storms, such as Hurricane Katrina, have caused damage to oil and gas infrastructure, resulting in episodic release of oil

Approximate Conversions of Crude Oil by Volume

1 barrel = 42 gallons = 0.1364 metric tonnes = 0.159 kiloliters

into vulnerable wetlands, including those along coastal Louisiana and Texas (Pine, 2006). Scientific studies of the nature and impacts of these releases were carried out after each major incident but generally were not extensive until the DWH blowout (McKinney et al., 2021, in this issue). Investigations by the Natural Resource Damage Assessment[1] and associated legal processes concluded BP was responsible for the discharge of 3.19 million barrels (134 million gallons) of oil into the Gulf of Mexico, although the scientific consensus was that the overall input was closer to 5 million barrels (210 million gallons), indicating this to be the most significant accidental oil spill in history (DHNRDAT, 2016).

Formation of the Gulf of Mexico Research Initiative

Immediately following the blowout on April 22, 2010, several federal agencies and the companies involved joined forces to attempt to cap the well under the National Oil and Hazardous Substances Pollution Contingency Plan2 (NCBPDHOSOD, 2011). Within weeks, early discussions were being held regarding establishment of a scientific study of the DWH region; this study would become GoMRI. The framework for a 10-year, $500 million, independent research program to study the impacts and effects of the oil spill was developed voluntarily by BP and initiated with a single phone call from BP Chief Scientist Ellen Williams to Rita Colwell, former director of the US National Science Foundation. A central premise of the program was that neither BP nor the Gulf state governors would influence selection of the research to be funded or the resulting publications. With input from the Gulf of Mexico Alliance (https://gulfofmexicoalliance.org/), Colwell assembled a team of international, US, and Gulf of Mexico-based research scientists and university administrators to direct research associated with the massive spill of oil into the Gulf. GoMRI was formally announced on May 24, 2010, a month after the DWH catastrophe.

Together, the GoMRI Research Board (RB), BP, and the Gulf of Mexico Alliance drafted a Master Research Agreement that provided a formal framework for the program (https://gulfresearchinitiative.org/about-gomri/master-research-agreement/). A management team was established to support RB operations and assist in developing and managing the program. The Master Research Agreement was signed on December 1, 2011, and thereafter provided a blueprint for GoMRI operations, with only small adjustments in subsequent amendments as the program evolved. Tasks undertaken by the GoMRI team included:

- Developing and implementing a request for proposal (RFP) process
- Selecting proposals for funding
- Negotiating and entering into research award agreements, establishing fiscal diligence of expenditure of funds, and managing associated reporting
- Designing and implementing a database to contain the scientific data produced by funded projects, along with programmatic data (funded projects, personnel, and publications)
- Designing and maintaining a website for GoMRI that would be publicly accessible
- Designing and facilitating a program for engagement with key stakeholders via an Outreach and Communications Plan
- Facilitating a scientific synthesis of the research undertaken

GoMRI Research Board and Management Team

Working within the structure created by the Master Research Agreement, the RB established bylaws, a code of conduct, and policies and processes necessary for guiding operations, setting scientific direction, and ensuring program integrity. The RB established a conflict-of-interest policy for all RB members, GoMRI Management Team (GMT) staff, and GoMRI-funded Principal Investigators (PIs) and co-PIs. Colwell chaired the RB, which convened annually as a full board, more frequently as needed. RB members led and served on various committees to provide detailed guidance to the programmatic operations, for example, RFP development, education and communications, data management, and legacy/synthesis.

The RB created a Chief Scientific Officer position to coordinate research activities, liaise with researchers on scientific issues, and facilitate communication across the entire GoMRI program. The Chief Scientific Officer was hired in 2012 and served as a member of the GMT, reporting to the RB Chair and bridging the GoMRI Management Team, the Research Board, the research community, the Gulf of Mexico Alliance, and BP. The Chief Scientific Officer and the Executive Director of the program attended all meetings of the RB ex officio to provide program updates and other information.

The Master Research Agreement assigned leadership, scientific direction, and programmatic oversight to the RB and administrative tasks to the Gulf of Mexico Alliance. The Gulf of Mexico Alliance contracted with the Consortium for Ocean Leadership and the Northern Gulf Institute at Mississippi State University for assistance with project management, RFP development and execution, and outreach

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[1] Natural Resource Damage Assessment (NRDA) is the legal process that federal agencies like NOAA—together with states and Indian tribes—use to evaluate the impacts of oil spills, hazardous waste sites, and ship groundings on public natural resources along the nation's coasts and throughout its interior.

[2] The National Oil and Hazardous Substances Pollution Contingency Plan, more commonly called the National Contingency Plan or NCP, is the federal government's blueprint for responding to both oil spills and hazardous substance releases. The first NCP was developed and published in 1968 in response to a massive oil spill from the oil tanker Torrey Canyon off the coast of England (https://www.epa.gov/emergency-response/national-oil-and-hazardous-substances-pollution-contingency-plan-ncp-overview).

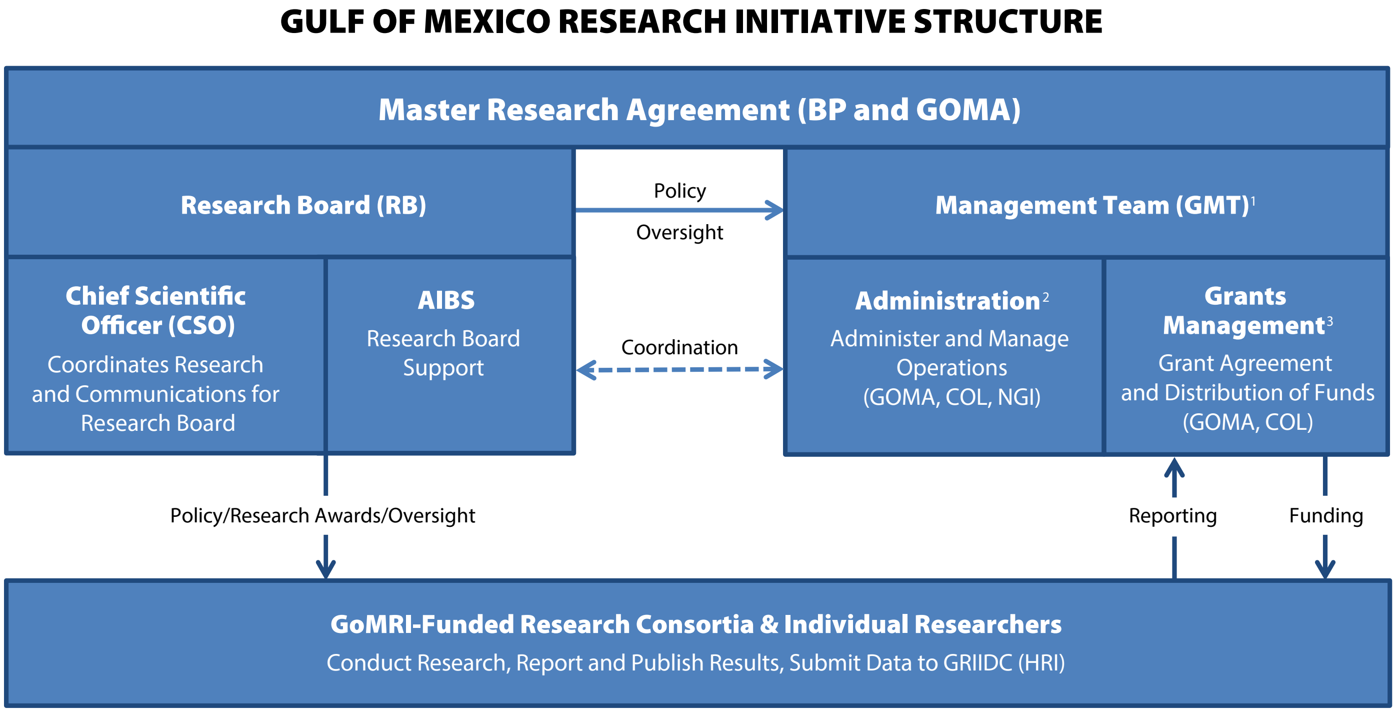
activities. The Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi was selected to serve as data administrator. The American Institute of Biological Sciences was chosen to serve as the RB support entity. Thus, the combination of these groups and responsibilities served as the GMT (**Figure 1**).

Enabling the Best Research

In June 2010, while GoMRI was in its early stage of development, BP distributed $45 million of the designated $500 million for rapid response research and sample collection to academic institutes in Florida, Alabama, Mississippi, and Louisiana, and to the National Institutes of Health. These short-term grants were to enable early sample collection for research on the oil spill until GoMRI was fully organized to begin operations. This distribution was made before the Master Research Agreement was finalized and prior to identification of GoMRI research themes (described below).

Following this initial investment, the RB developed and released the first RFP, or RFP-I, with a goal of building on, and extending, existing scientific research capacity, activity, and collaboration in the Gulf of Mexico region. RFP-I supported teams of scientists, in the form of research consortia, which the RB defined as four or more collaborating institutions led by a single Gulf institution. In addition to research consortia, the RB also chose to support smaller groups of researchers and individual investigators. The RB prepared a second request for proposals (RFP-II) designed to direct funding to individuals and small groups who proposed research that would address the GoMRI research themes (described below) and complement consortia research. Meanwhile, a fast-track, third call for proposals (RFP-III) was implemented to ensure high-priority data collection begun in the previous year would continue during the next field season, namely the summer of 2011. While the larger RFP-I and RFP-II were being prepared for release, RFP-III was the first major RFP funding awarded by the program (**Figure 2**).

During the 10 years the program was in operation, the GoMRI RB released six RFPs, cumulatively awarding more than $410 million for scientific research when combined with the initial investment by BP (**Tables 1 and 2**). Each RFP was unique; RFP-I and RFP-IV funded research consortia, RFP-III funded data collection, RFP-II and RFP-V funded individual investigators and small research teams, and the final call for proposals, RFP-VI, funded both consortia and small investigator teams.



AIBS – American Institute of Biological Sciences
COL – Consortium for Ocean Leadership
GOMA – Gulf of Mexico Alliance
GRIIDC – Gulf of Mexico Research Initiative Information and Data Cooperative
HRI – Harte Research Institute
NGI – Northern Gulf Institute

Notes: COL, NGI, HRI under contract to GOMA
[1] CSO and AIBS member of GMT
[2] Administrative Unit in Master Research Agreement
[3] Grants Unit in Master Research Agreement

FIGURE 1. Structural chart of the Gulf of Mexico Research Initiative (GoMRI) Research Board and Management Team outlining function and lines of communication.

Identification of Research Themes

Concurrent with the establishment of GoMRI, the research community was convened to inform a scientific response to the ongoing spill, and more than 200 scientists assembled on June 3, 2010, at Louisiana State University to discuss the urgent need to respond (Consortium for Ocean Leadership, 2010). Key topics of the meeting covered in breakout sessions included estimating the flow rate of oil at the wellhead, projecting the fate of the oil, and determining potential effects of the oil and dispersants on the environment and human health. Participants identified science challenges associated with the spill: determining its magnitude, tracking the fate and transport of oil, and evaluating ecological and human impacts. The experts also identified several cross-cutting challenges: the need for central coordination in deploying scientific assets, the necessity of avoiding duplication of effort, the importance of central management and standardization of data and metadata formats, and the urgency of launching baseline studies.

Subsequent workshops further refined the list of research and development topics, including dispersant

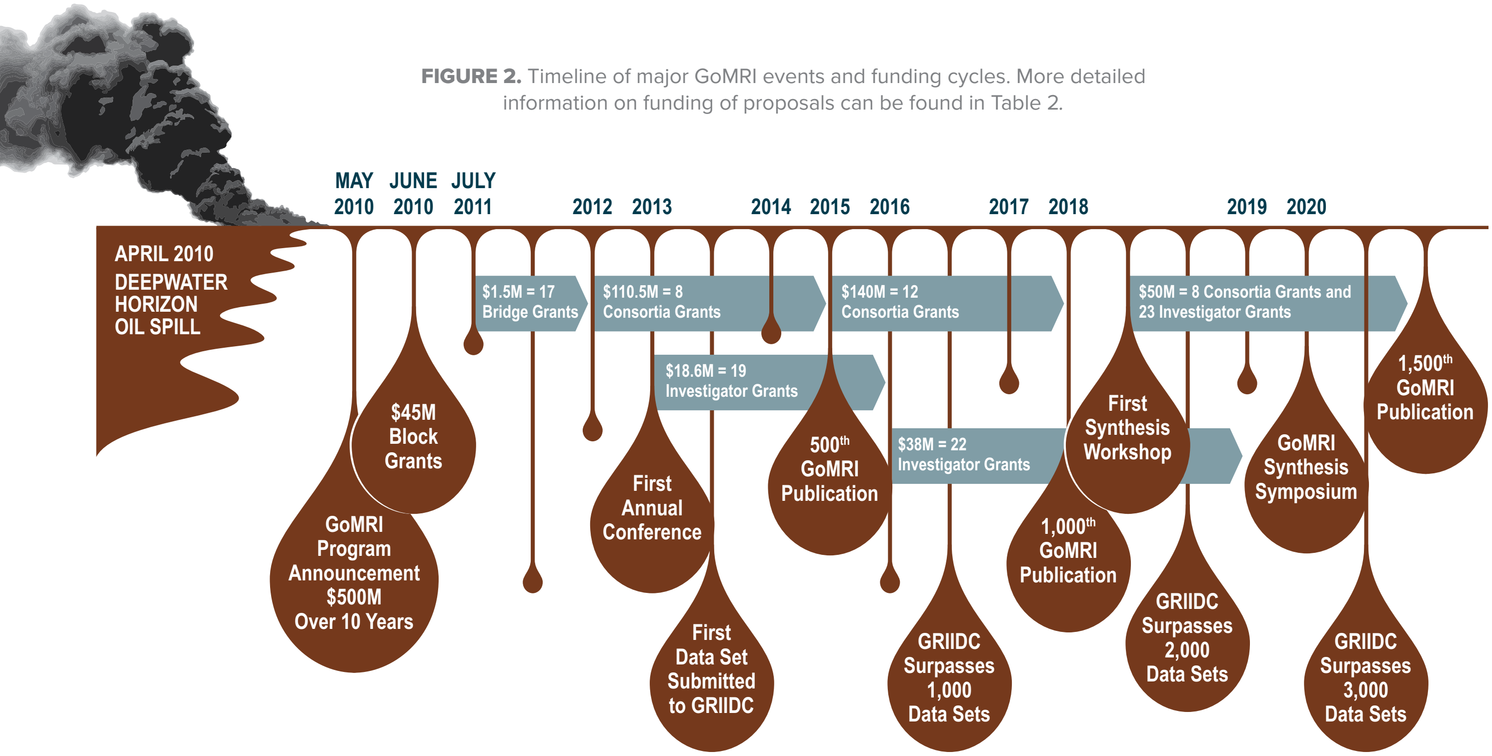


FIGURE 2. Timeline of major GoMRI events and funding cycles. More detailed information on funding of proposals can be found in Table 2.

TABLE 1. Summary of GoMRI funding by investment area. The program was designed to maximize funding awarded to the research community while minimizing administrative and operating costs to approximately 10% of overall funding. Data management, to ensure all data were archived and available for future use, included software development and implementation, storage, and support of GRIIDC through 2030. Outreach and communications included support for external partners but not for activities of the research consortia and their projects, whose costs are captured under research. A multi-year effort to summarize and synthesize research findings is included under research investment.

INVESTMENT AREA	$ MILLION	% OF TOTAL
Research	$413.1	82.6%
Data Archiving	$20.6	4.1%
Outreach & Communication	$15.5	3.1%
Administration & Operations	$50.8	10.2%
TOTAL	**$500.0**	**100.0%**

TABLE 2. Detailed information concerning the six GoMRI RFPs.

RFP	TYPE OF SOLICITATION	PROPOSALS RECEIVED	AWARDS	FUNDING ($ MILLION)
RFP – III	Bridge	111	17	$1.5
RFP – I	Consortia	78	8	$110.5
RFP – II	Investigator	410	19	$18.6
RFP – IV	Consortia	47	12	$148.4
RFP – V	Investigator	288	22	$38.0
RFP – VI	Consortia & Investigator	186	31	$50.0
TOTALS		**1,120**	**109**	**$367.0**

efficacy and effects, spill trajectory modeling, and detection of surface and subsurface oil. The list also included analysis of the human dimension related to spill response, seafood safety, information management, and dialogue among researchers and responders to ensure transfer of research results to effective practices (Institute of Medicine, 2010; Coastal Response Research Center, 2011; Sumaya et al., 2013).

The GoMRI RB incorporated the recommendations from these meetings and the collective expertise of the research scientists to establish five themes to guide GoMRI research:

- PHYSICAL DISTRIBUTION, dispersion, and dilution of petroleum (oil and gas), its constituents, and associated contaminants (e.g., dispersants) under the action of physical oceanographic processes, air-sea interactions, and tropical storms
- CHEMICAL EVOLUTION AND BIOLOGICAL DEGRADATION of the petroleum/dispersant system and subsequent interactions with coastal, open-ocean, and deepwater ecosystems
- ENVIRONMENTAL EFFECTS of the petroleum/dispersant system on the seafloor, water column, coastal waters, beach sediments, wetlands, marshes, and organisms, and the science of ecosystem recovery
- TECHNOLOGY DEVELOPMENTS for improved response, mitigation, detection, characterization, and remediation associated with oil spills and gas releases
- PUBLIC HEALTH IMPACTS of oil spills, including behavioral, socioeconomic, environmental risk assessment, community capacity, and other population health considerations and issues

Request for Proposal Development and Execution

The fundamental goal of the RB was to fund the best science using a solicitation and review process of the highest integrity. An evaluation process was adapted from the US National Science Foundation (NSF) merit review system, including administrative review of each proposal for required elements and compliance. Rigorous peer review was conducted by outside experts who provided recommendations, based on predefined scoring and weighting, to the RFP committee and the RB. The GMT, with instructions from the RB, identified reviewers representing expertise across all five GoMRI research themes. Peer reviewers were required to sign conflict-of-interest and nondisclosure agreements prior to receiving review materials. Final selection of awardees was made by the RB from the most highly ranked proposals.

RFPs were developed by committees of the RB, with logistical support provided by the Chief Scientific Officer and the GMT staff. To be considered, proposals were required to address one or more of the five GoMRI research themes, with emphasis on interdisciplinary science encouraged. The six RFPs varied slightly, based on specific goals and requirements of each RFP. Letters of intent, preliminary proposals, full proposals, or a combination of these elements were used in the RFP selection process. The elements and submission compliance expectations were developed for each RFP solicitation and were clearly defined.

Grants Administration

Because it was a novel and uniquely funded organization, GoMRI, out of necessity, had to develop and implement a set of management processes, policies, and frameworks to ensure each research grant was efficiently and effectively administered and monitored. This process drew on best management practices of established funding organizations, such as NSF, to meet specific goals and objectives of GoMRI. At the end of the 10-year program, the GoMRI grant administration team had successfully executed and managed more than 100 research grants, varying in size from ~$41,000 to ~$21 million, awarded under six RFPs. Primary goals of the grant administration process were to:

- Ensure the GMT and RB monitored progress of every research grant, including spending and impactful changes to the proposed scope of work
- Maintain consistency of management across all awards throughout the lifetime of the GoMRI program
- Minimize management burden on PIs, allowing them to focus their efforts on science
- Enhance the GoMRI mission by encouraging collaboration and communication among research teams and ensuring PIs were kept informed of overall GoMRI activities.

Each grant was managed by an administrator throughout the pre- and post-award processes, in effect managing each award from contract negotiation to closeout. This proved to be an effective strategy that provided each PI a single point of contact for administrative questions and distributed the grant administration workload equitably. It proved especially useful at the height of GoMRI grant activities when RFPs I and II were winding down and RFPs IV, V, and VI were either in full operation or just beginning. GoMRI grant administration practices were essentially stable for the lifetime of the program, with only a few changes needed. Best practices and lessons learned from the GoMRI experience in grant execution and monitoring during the 10 years the program was in operation are highlighted below.

Grant Execution

Upon selection of awards, the GMT engaged each lead institution in negotiations guided by the Master Research Agreement, utilizing a contract framework modeled after that of NSF, a process familiar to management and investigators of all institutions. Contracts were standard for GoMRI research grants and, although negotiation on language was permitted, the overwhelming majority of the contracts were consistent with the GoMRI process. This allowed smooth execution of the contracts, with the process becoming more streamlined with each new RFP, as institutions became increasingly familiar with the GoMRI contract.

An important charge to the grant administration team was compliance monitoring of project expenditures and progress. Whereas NSF tracks semiannual or annual progress, the GoMRI RB opted to require quarterly financial and research progress reports and an annual summary of activities. These reports provided an invaluable source of information, notably for the GMT in anticipating potential problems, keeping the RB informed, identifying website content, and promoting cross-project connections. To minimize the administrative burden for the PIs, standardized templates were created for the reports and were pre-populated with relevant information for each project. Quarterly financial reports allowed comparison of actual expenditures with the approved budget to determine expenditures (i.e., the "burn rate") for each project. Activity reports were submitted in two parts. An activity spreadsheet allowed tracking of publications, presentations, field and outreach activities, and GoMRI participants. These data were incorporated into a Research Information System that we discuss below. In addition, the activity report narrative provided information on plans for the next quarter and an opportunity for the PI to highlight problems and/or obstacles.

While quarterly and annual reports kept the RB and GMT apprised of ongoing activities, GoMRI was designed to be collaborative. Communication across the research community was facilitated by quarterly conference calls that included all PIs, the GMT, and the RB. These calls provided research and administrative updates and encouraged cooperation and sharing of best practices. This proved critical for the RB and GMT in tracking research progress, and, more importantly, in building community and promoting collaboration.

An important monitoring tool implemented by the GMT was the site visit, which included administrative and RB participation. For each award, the grant administrator organized a site visit to review and discuss institution policies for pre- and post-award management. Serious concerns or findings of note proved to be rare, but the site visit was an opportunity for researchers and administrators to forge working relationships and gain context on the science behind each project, enhancing effective and less intrusive grant management. RB site visits were conducted for consortia that received awards under RFP-I and RFP-IV. The purpose of these site visits was to establish direct interaction between researchers and the RB and to provide the RB with detailed updates on research progress and opportunities to discuss findings and new directions with PIs and co-PIs. The site visits also provided context to the RB for requests for significant changes that required RB approval, thus facilitating an efficient and informed approval process.

The final phase of grant monitoring was closeout for each award. Prior to award end date, grantees were provided a checklist (reports, publications, proof of data set(s) submitted to the archives, equipment lists, patents/inventions, final financial statements, certification of costs, and return of unspent funds) required to be completed before the award could be recorded as compliant and officially closed. Mandatory data submittal proved to be a management challenge, particularly for an efficient and timely closeout of an award, but ultimately worth the benefit gained by leaving a working legacy of GoMRI results and findings in the data submissions.

DATA STORAGE AND ACCESSIBILITY

The Master Research Agreement explicitly stated that the program would create and manage a research database to maintain full records of all funded projects, personnel, and publications and ensure resulting scientific data were fully accessible. To meet these two objectives, GoMRI created one system for housing scientific data and a second system for administrative tracking and information collection.

Gulf of Mexico Research Initiative Information and Data Cooperative

The Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) was established at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi to serve as the data repository for all GoMRI research. Although previous oil spills involved significant research, not all data resulting from those events are publicly available (Reichman et al., 2011). Field data collected at a specific time and place are valuable to preserve (McNutt et al., 2016) and extremely useful in providing a baseline, especially for record keeping of research on environmental disasters. There are many benefits in sharing data, because data from previous oil spills can be reanalyzed and verified, preventing duplication of effort and maximizing resources (Tenopir et al., 2011), as well as providing for transparency and reproducibility (Campbell et al., 2018). For these reasons, GoMRI moved to establish GRIIDC as the data repository for the program.

Initially, GRIIDC faced the unique challenge of developing a data management system at the same time researchers were collecting immediate post-spill data. GoMRI researchers were required to submit all data within one year of data collection/generation or at the time of publication, which was not common practice at the time GoMRI was launched. Many researchers had never been required to submit data to a repository and were not aware of best practices for organizing data or collecting the metadata linked to each data set. GRIIDC quickly recognized the need for cooperation by the research community and established an advisory committee to address these challenges. The GRIIDC advisory committee included representatives from the following: each GoMRI research consortium, the GoMRI RB, the National Oceanic and

Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI), the GMT, and GRIIDC. Leadership and guidance provided by the GRIIDC advisory committee proved instrumental in developing best practices.

To encourage data sharing, GRIIDC offered incentives, including citable data packages, digital object identifiers (DOIs), data curation that ensured data were documented, and support in the compliance process. Training and communication provided to the research community were key to successful data submission and implementation of data sharing policies. GRIIDC provided training on data management, submission, and curation, as well as information about the benefits of data sharing. GRIIDC published guidance documents, organized workshops, and held training webinars on best practices for a range of data topics: categorizing, compression, organization, and submission.

Entering properly documented and complete sets of data into the GRIIDC repository was the first step in effective data sharing. GRIIDC employed several strategies to ensure the research database was discoverable, accessible, and useful, not just for scientists but also for the public. GRIIDC joined the Data Observation Network for Earth (DataONE) (https://search.dataone.org/data) as a node and deployed an Environmental Research Division Data Access Program (ERDDAP) server (https://erddap.griidc.org/erddap) to provide user selected subsets of oceanographic data. DOIs assigned to the data sets are accessible through the search application on the GRIIDC website (https://data.gulfresearchinitiative.org/search). GoMRI required all publications to acknowledge GoMRI funding and provide the data set DOI, thus linking GRIIDC data sets to an associated publication.

Innovations and newly developed best practices helped position GoMRI and GRIIDC at the forefront of the data sharing movement (Gibeaut, 2016). Open data, no longer a foreign concept, is now a commonplace activity for researchers, with journals and funding agencies increasingly requiring data to be publicly available. In addition to GoMRI data, GRIIDC houses data generated by the Florida RESTORE Act Centers of Excellence Program; the Mississippi Based Center of Excellence; the Texas OneGulf Center of Excellence; the National Academies of Sciences, Engineering, and Medicine's Gulf Research Program; and the Harte Research Institute for Gulf of Mexico Studies. GRIIDC, with more than 3,000 data sets, 83 terabytes of data, 394 research groups, and 2,850 researchers (as of the date of this publication), ensures a GoMRI data and information legacy as the premier data repository, portal, and resource for the Gulf region.

Research Information System

The Research Information System (RIS) was created and is managed by the Northern Gulf Institute at Mississippi State University as a relational database framework for tracking and collecting information for GoMRI. It was designed to serve as a resource for program management, information dissemination, and administrative oversight. The RIS and associated tools allowed GoMRI to inventory programmatic data from all funded projects carried out by more than 4,500 researchers working at hundreds of institutions in 43 states and 17 countries. RIS allowed GoMRI staff to track metrics of research productivity, including nearly 5,500 conference presentations and more than 1,500 peer-reviewed publications. Additionally, publications were monitored by the RIS, helping to ensure that all GoMRI attribution and data sharing requirements were met.

RIS is publicly accessible on the GoMRI website (https://research.gulfresearchinitiative.org). The site is continuously updated and provides a structured presentation of GoMRI-funded projects. Each project has an information page cataloguing publications, presentations, and personnel. A complete bibliography of GoMRI-funded manuscripts, books, and book chapters is included. Multiple search tools are integrated into the website, providing access to personnel, subject matter, keywords, and thematic search. This site provides program and project background information that integrates the RIS with content throughout the GoMRI main site.

SHARING CRITICAL AND TIMELY INFORMATION

From its initiation, GoMRI, the RB, and BP placed high importance on disseminating research results and discoveries to a wide variety of audiences. The program achieved this objective using a three-pronged approach: outreach activities led by the GoMRI-funded researchers along with outreach professionals; GMT activities at the program level; and partnerships with the Smithsonian Ocean Portal, Screenscope Inc., and four regional Sea Grant programs. GoMRI-funded outreach coordinators and PIs, the GMT, and outreach partners engaged collectively to share successful methods, build capacity, and partner in joint efforts. Outreach activities were designed to achieve both the GoMRI mission and its legacy goals (https://gulfresearchinitiative.org/about-gomri/gomri-legacy/; Benoit et al., 2016).

Investigator-Led Outreach

Consortia were required to plan and budget for outreach and education to complement their research. Individual investigators were not required to implement outreach and education, but were encouraged to do so, and many did. GoMRI did not prescribe outreach programs or activities, allowing each project the flexibility to explore outreach activities suited to their research. Project outreach efforts were extremely effective in promoting GoMRI research results, with individual projects creating programs that directly impacted students, educators, and the public in their local communities.

To maximize the GoMRI investment and ensure GoMRI research and results reached stakeholders, several best practices were developed for outreach programs (Beresford et al., 2018). These programs were successful due to early engagement with outreach professionals initiated during proposal development that resulted in realistic and effective plans, specific budgets, and evaluation metrics. GoMRI outreach professionals established regular communication with research teams in order to understand ongoing research and entrain members of research teams in outreach activities. Each outreach effort capitalized on unique research topics and expertise, infusing new and exciting GoMRI research findings into existing networks and collaborations and broadening impact for relatively low cost (Beresford et al., 2018).

> “The GoMRI model provides important guidance for future efforts seeking to foster interdisciplinary research…to collectively and comprehensively address global threats to ocean ecosystems—certainly an imperative for the immediate future.”

Many of these products are archived on the GoMRI education website (https://education.gulfresearchinitiative.org/), providing a searchable resource for both formal and informal educators. A special issue of *Current: The Journal of Marine Education* (2019), authored by collaborative teams of GoMRI outreach coordinators, illustrates how GoMRI researchers approached the process of science and outreach and how GoMRI research proved useful for exploring the Next Generation Science Standards (https://www.nextgenscience.org/).

Program-Led Outreach

GMT outreach activities were guided by an annual work plan approved by the RB and focused on dissemination of GoMRI research widely; this helped to keep members of the GoMRI community engaged in each other's research. The GoMRI website, https://gulfresearchinitiative.org/, which served as the main point of information dissemination for the program, included funding solicitations and research findings, and was linked to the GRIIDC and RIS websites. In addition to hosting key information, the website includes more than 650 original articles as easy-to-read accounts of ongoing field work and summaries of selected peer-reviewed studies, all created in collaboration with researchers. Social media channels auto populated with content posted on the GoMRI website. Quarterly newsletters were produced from 2013 to 2020 in collaboration with GoMRI researchers, outreach coordinators, program managers, and external outreach partners. These newsletters highlighted members of the GoMRI research community and recent research findings. A biweekly e-newsletter provided aggregations of new web content highlighting the GoMRI community, as well as recent publications, data sets, and program announcements.

Several outreach activities were designed specifically to engage the GoMRI research community. Conference calls with PIs, outreach coordinators, RB members, and GMT staff provided opportunities to share and coordinate outreach. Project PIs and outreach coordinators highlighted activities, shared best practices, and identified partnership opportunities with other GoMRI programs. The RB and GMT shared updates on GMT-led outreach activities, providing a key dissemination channel for these activities to the GoMRI community. A series of webinars, 24 in total, informed the GoMRI research community of ongoing activities. These internal webinars provided a unique forum for sharing research not yet published and provided another opportunity to engage the GoMRI research community.

The first annual meeting of the GoMRI research community was held in 2013, as stipulated by the Master Research Agreement, and, with the dedicated help of many partners, it became the annual Gulf of Mexico Oil Spill & Ecosystem Science (GoMOSES) conference. With an annual attendance of 800 to 1,000 members of the research and resource management community, GoMOSES evolved into a preeminent event for Gulf of Mexico science and oil spill researchers. The venue for the three-to-four-day GoMOSES conference rotated among the Gulf states and featured more than 25 sessions on a variety of topics. Side meetings and informal gatherings at GoMOSES enhanced collaboration and cooperation among the community.

Partner-Led Outreach

The RB was determined that the program reach the broader public audience. To achieve this objective, GoMRI established partnerships with Smithsonian Ocean Portal, Screenscope Inc., and the four Gulf of Mexico Sea Grant Programs. Each of these partnerships served to bring compelling stories of GoMRI research to the public.

Smithsonian Ocean Portal

The Smithsonian Ocean Portal was launched in 2010 as an online complement to the Sant Ocean Hall at the Smithsonian National Museum of Natural History. Shortly after the DWH oil spill, the Ocean Portal began to post stories on a Gulf Oil Spill page. In 2013, GoMRI partnered with Ocean Portal to continue sharing oil spill research and results of the work of GoMRI-funded scientists with the public. The Gulf Oil Spill page (http://ocean.si.edu/gulf-oil-spill) is currently the Ocean Portal's most visited page, with more than 200,000 page views per year.

Ocean Portal writers worked directly with GoMRI researchers to help tell their stories in visually compelling and accessible ways, creating digital communications tools to reach and engage with the public, such as photo slideshows, interactive graphics, and videos. This partnership allowed GoMRI to reach a very large public audience, using unique and high-profile events and an established digital resource with an existing national audience.

Screenscope Inc.

In 2014, as GoMRI expanded and refined its outreach strategies, the RB created a vision for a documentary to explain how research is done and to tell the GoMRI research story. The goal was to enhance public understanding of science, encourage long-term support for protecting resources in the Gulf of Mexico, and promote science literacy. Through a solicitation process, GoMRI partnered with the documentary film production company Screenscope Inc. to produce three films, *Dispatches from the Gulf 1, 2,* and *3.* Screenings of the films took place at film festivals, museums, and universities, and *Dispatches 1* and *2* were broadcast on multiple PBS stations around the United States. Screenscope made these films available to educators free of charge, offering classroom guides and lesson plans. What started as a film project evolved into a multimedia initiative, including short videos and podcasts, to highlight the DWH oil spill research community. The three *Dispatches* films and the suite of complementary materials comprise a major legacy of the GoMRI program (https://dispatchesfromthegulf.com).

Sea Grant

In 2014, GoMRI partnered with Sea Grant programs from Florida, Louisiana, Mississippi-Alabama, and Texas to form the Gulf of Mexico Sea Grant Oil Spill Science Outreach Program. A natural connection existed among the organizations, as Sea Grant programs were already based in communities that GoMRI wanted to reach, and GoMRI research was answering questions Sea Grant was being asked. This program shared oil spill science and findings with those who relied on a healthy Gulf of Mexico and used peer-reviewed research findings to answer community questions. Sea Grant programs rely on building relationships and receiving feedback from audiences they serve (https://seagrant.noaa.gov/). Prior to creating the Sea Grant oil spill outreach team, a social network analysis was conducted to identify individuals who were sharing oil spill science information. Once established, the team met with 530 individuals throughout the region, including those identified as key nodes in the social network analysis, to identify questions and needs. The participants framed 449 oil spill science-related questions, which were prioritized based on frequency of mention. The team used this initial information to develop extension products and services explaining the science surrounding topics of greatest interest. The team presented science firsthand at events and convened science seminars for non-scientific audiences, allowing researchers to explain topics in layman terms. To maintain scientific and social relevance, the team engaged with stakeholders and searched the scientific literature to identify discoveries of interest and kept the RB and the GMT apprised of coastal community concerns.

Based on audience requests, Sea Grant team members expanded their scope of work by creating publications in English, Vietnamese, and Spanish; short videos; and a Science-on-a-Sphere module (https://sos.noaa.gov/What_is_SOS/, in partnership with GRIIDC); and by organizing targeted regional workshops and events that expanded their audience beyond the GOM to the national level. The Sea Grant oil spill team members gave more than 200 presentations and convened 48 seminars featuring GoMRI-affiliated presenters, reaching more than 12,000 individuals. The partnership resulted in more than 60 outreach publications and reports that were disseminated throughout the United State and abroad. All outreach publications, seminar information, additional extension products, and survey results are available on the Gulf of Mexico Sea Grant Oil Spill Science Outreach Programs website (https://gulfseagrant.org/oilspilloutreach).

THE GOMRI SCIENTIFIC LEGACY

Synthesis

In July 2015, five years after the wellhead was capped, GoMRI reached its halfway point. Four RFPs had been funded, and the fifth was undergoing peer review for selection and announcement that year. Nearly 1,000 data sets had been processed and archived by GRIIDC, and over 500 peer-reviewed publications had been published and catalogued in the RIS (**Figure 2**). Planning for the fourth GoMOSES conference was underway, and outreach partnerships were expanding. It was then that the RB focused on development of the sixth and final RFP and on the GoMRI legacy.

The shift in focus to synthesis was reflected in RFP-VI, the final large funding opportunity of the 10-year initiative. Unlike previous calls for proposals, RFP-VI encouraged proposers to emphasize data integration, engage in synthesis between research themes and among consortia, and highlight scientific and technological products of the GoMRI scientific legacy. But these community efforts represented only a part of the synthesis goal.

A group of RB members met in April 2017 to consider gaps in GoMRI synthesis that might not have been addressed by RFP-VI. Before defining the scope of the synthesis, guiding principles were established to ensure the synthesis efforts would be driven by the best available science and that any conclusions reached would be based on peer-reviewed publications. The synthesis team was instructed to take a broader view beyond the Gulf of Mexico and explore the potential for transferability of GoMRI findings to other geographic locations in the United States and around the world. Finally, it was essential to involve the user community, including oil spill responders, nongovernmental organizations, industry, and federal entities, as well as academics, to address effective application of new knowledge gained during GoMRI.

Using the five GoMRI research themes as a framework, the group identified critical gaps, raised key questions, and grouped subject areas into eight core areas (**Box 1**). Leaders from the GoMRI community were identified for each core area, including RB members assigned to serve as motivators and provide guidance.

For seven of the eight core areas, one or more scientific workshops were

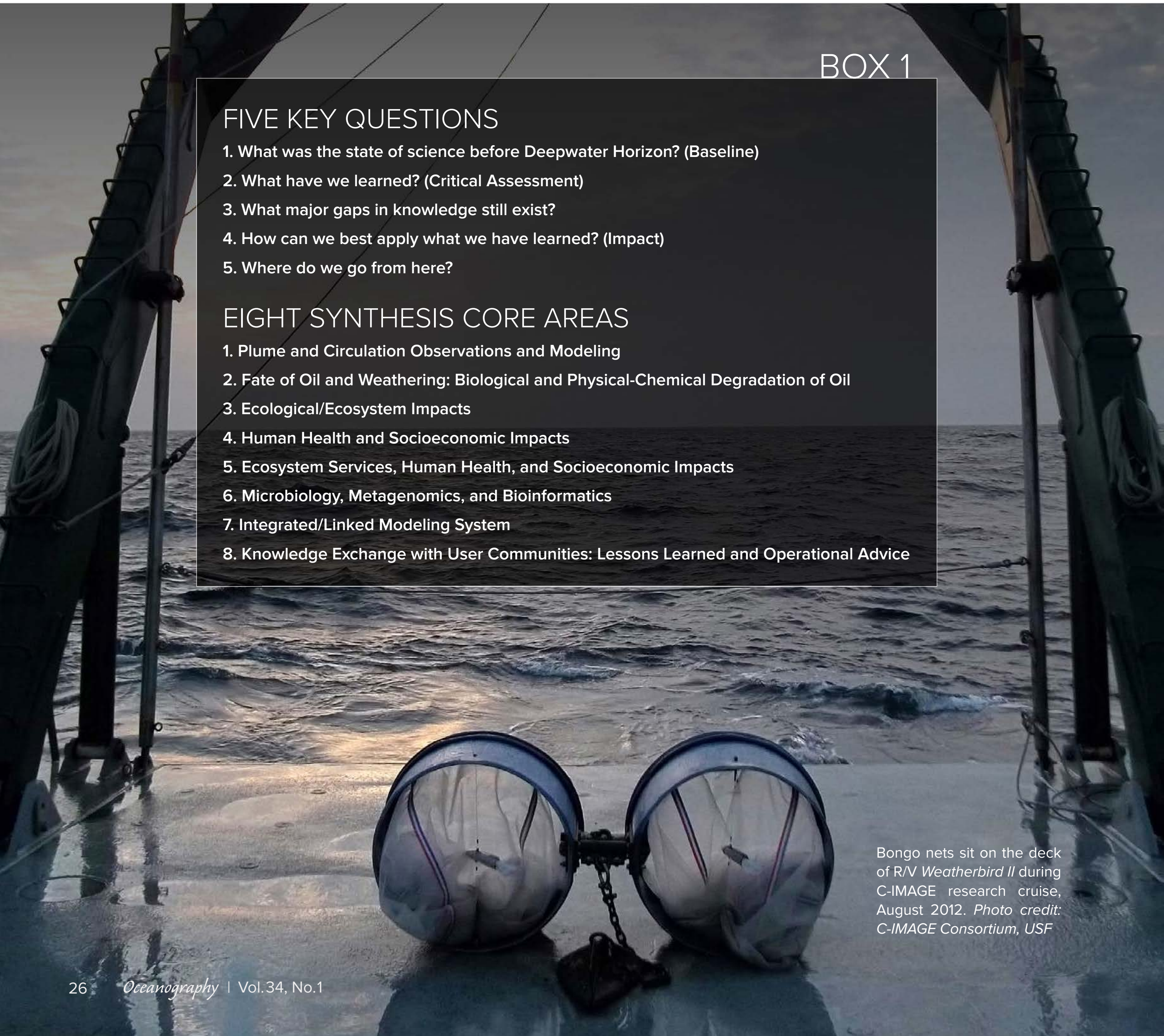
BOX 1

FIVE KEY QUESTIONS

1. What was the state of science before Deepwater Horizon? (Baseline)
2. What have we learned? (Critical Assessment)
3. What major gaps in knowledge still exist?
4. How can we best apply what we have learned? (Impact)
5. Where do we go from here?

EIGHT SYNTHESIS CORE AREAS

1. Plume and Circulation Observations and Modeling
2. Fate of Oil and Weathering: Biological and Physical-Chemical Degradation of Oil
3. Ecological/Ecosystem Impacts
4. Human Health and Socioeconomic Impacts
5. Ecosystem Services, Human Health, and Socioeconomic Impacts
6. Microbiology, Metagenomics, and Bioinformatics
7. Integrated/Linked Modeling System
8. Knowledge Exchange with User Communities: Lessons Learned and Operational Advice



Bongo nets sit on the deck of R/V *Weatherbird II* during C-IMAGE research cruise, August 2012. *Photo credit: C-IMAGE Consortium, USF* convened. They represent a critical aspect of GoMRI synthesis, each designed as working sessions with specific open access outputs. The products have taken the form of journal articles, special journal issues, books, review papers, recorded webinars, conference presentations, workshop reports, and model frameworks (https://gulfresearchinitiative.org/gomri-synthesis/products/). RB motivators facilitated coordination between synthesis efforts to avoid duplication and ensure comprehensive coverage. Initially envisioned as a series of five or six workshops, the synthesis effort evolved into a larger and more ambitious undertaking. In total, synthesis leaders completed 20 workshops over two and a half years, representing the collective efforts of approximately 600 experts. The ensemble of synthesis products from this effort forms a major element of the GoMRI legacy.

The GoMRI Model

Several features of the GoMRI program contributed to the success of this multi-sector partnership. The GoMRI RB played a critical role in ensuring scientific independence of this industry-funded research program. Composition of the board, especially its leadership, was crucial in establishing credibility and building trust within the scientific community. The consistency and collective memory of the RB became an asset as the program progressed. The RB, with the full support of BP, insisted on open data and peer review for both funding solicitations and publications. Notably, the RB had complete discretion in selecting the research to be funded. GoMRI required rigorous project reporting of both financial and research activities quarterly and annually, which allowed real-time tracking of progress. The GoMRI model demonstrates that funding by, and partnership with, industry can support research that is immensely successful, independent, highly reputable, and focused on the best science that addresses a national need.

Because the RB operated independently and determined scientific direction for the program, flexibility proved to be another key strength of this model. It allowed timely shifts and changes in strategy as needed to exploit opportunities and achieve key objectives. An example is the creation of individual investigator projects addressing a singular research theme. While it was initially anticipated by BP that the research would be done by consortia addressing multiple research themes, the RB recognized that additional thematic expertise would be gained through individual investigator awards. The RB was also able to move quickly to create funding to fill gaps, for example, supplementary funds for critical sample collection during the 2011 field season (RFP-III), and to complete sample analysis during the final two years of the program.

GoMRI funding brought together diverse interdisciplinary groups and focused their efforts to a common goal, fostering cross-discipline collaborations that yielded advances and impacts otherwise unattainable. The GoMRI model provides important guidance for future efforts seeking to foster interdisciplinary research by bringing together ocean scientists from physical, chemical, biological, and geological backgrounds and chemists, microbiologists, ecologists, fisheries scientists, engineers, numerical modelers, and other experts to collectively and comprehensively address global threats to ocean ecosystems—certainly an imperative for the immediate future. The GoMRI model also offers a path to more powerful and impactful science by utilizing diverse funding and innovative and transformative strategies to advance basic and applied research to meet common national and international needs.

Building Community

The GoMRI Master Research Agreement was purposely designed to enhance the research capacity of the Gulf of Mexico region. The program drew on an existing network of academic research institutions to create a collaborative community of researchers across all sectors, including government, nongovernmental organizations, and industry. Communication was strengthened among these various groups, illustrated by industry representatives who served in advisory roles to provide guidance on research objectives. Academic researchers participated in government-led oil spill response planning exercises, gaining understanding of the complexities of an operational oil spill response and how to engage in future responses most effectively. Members of critical stakeholder groups from all sectors served as advisors to the synthesis effort, identifying lessons learned, promoting application of research results, and providing operational advice. The enhanced capacity across the Gulf states and expanded collaborations, networking, and integration of the US and global scientific community are GoMRI legacies.

GoMRI research consortia varied in size, number of partnering institutions, and complexity of scope, but all required strategic and adaptive management to coordinate the many components. Rather than having the PI solely responsible, GoMRI encouraged delegation of specific roles, for example, appointment of a program or data manager and an outreach coordinator, and provided funding explicitly for these positions and their tasks. These individuals assisted in coordination and in building a collaborative spirit within consortia. Another important aspect of GoMRI community building was cross-consortia collaboration facilitated by regular internal communication among researchers. The annual GoMOSES conferences built upon those regular interactions and forged long lasting partnerships. Beyond sharing the latest research, the conferences provided opportunities for attendees to interact, resulting in collaborations across sectors, disciplines, research teams, and consortia.

GoMRI had the great benefit of sustained funding for 10 years, and this was particularly empowering. It represented a firm commitment to a network of GoMRI scientists and created a unique mentoring opportunity for a new generation of both oil spill and Gulf of Mexico researchers. Resources were made available to prioritize education and training of approximately 1,200 graduate students, 1,000 undergraduates, and nearly 400 early career professionals. Many of the students were recognized for their excellent contributions through the establishment of a GoMRI Scholars Program. A total of 326 graduate students were recognized as scholars, and these students received their scientific training while conducting GoMRI-funded research. Students and early career researchers, in turn, benefited from the interdisciplinary and collaborative research conducted by the consortia and GoMRI, as an entity. They have progressed into professional careers and represent an important legacy of the program.

> “The GoMRI model also offers a path to more powerful and impactful science by utilizing diverse funding and innovative and transformative strategies to advance basic and applied research to meet common national and international needs.”

Private, sustained funding for basic research, combined with the independence and flexibility of the RB, resulted in major research findings. Many procedures, discoveries, and methods made possible by GoMRI funding have wide applicability, beyond the Gulf of Mexico, to future oil spills, regardless of geography. This type of funding—investment by private industry made credible by the RB—also allowed for GoMRI to prioritize activities frequently overlooked by other funding entities. On the advice of the RB committee focused on ship time, the RB allocated ship-time funding within a project rather than following the NSF model of separate funding for ship time. This allowed PIs greater flexibility and leverage in designing their research expeditions. In 2014, GoMRI initiated the Hydrocarbon Intercalibration Experiment (https://gulfresearchinitiative.org/hydrocarbon-intercalibration-experiment) to advance laboratory quality-assurance/quality-control practices and to create an opportunity for interlaboratory comparison of and calibration for hydrocarbon compounds. Recognizing traditional challenges encountered in funding data repositories, the program provided advanced funding to support GRIIDC’s work through 2030, ensuring a GoMRI data legacy. These are some examples of investments that truly supported the research community, providing tools and support needed to produce first rate, peer-reviewed science.

Next Time, Build it Better

As with any large research effort, there are lessons learned that would benefit the GoMRI program should it be starting today. Integrating research communities that transcend traditional academic departmental structures proved challenging, even with the emphasis that GoMRI had placed on interdisciplinary and collaborative research. For example, GoMRI made a very serious effort to fund research on human health. Engagement of public health experts very early in the development of research themes would have yielded stronger integration of environmental and human health research (Eklund et al., 2019). The decision to fund the best science, regardless of research theme(s), was appropriate, but a funds allocation model, assigning a range of funding to each theme prior to award selection, as was considered in early discussions of the RB, might have resulted in a more equitable distribution among the themes.

At the conclusion of any project, documenting what was learned and communicating that knowledge to interested parties is a significant challenge. For GoMRI, the massive scale of the research program made scientific synthesis at the end of the program an immense task. Synthesis was incorporated into the final research RFP but, given how critical this effort proved to be in providing scientific value for the public, it probably should have been built into RFPs from the start. Opportunities for cross-project collaboration, as specified in RFP-VI, would have been beneficial to the scientific synthesis if launched earlier in the program. Finally, more and earlier interaction and information exchange, especially in synthesis, would have greatly benefited knowledge transfer to ongoing research programs, the operational community, and oil spill responders post GoMRI.

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AUTHORS

Leigh A. Zimmermann (lzimmermann@oceanleadership.org) is Senior Program Manager, and **Michael G. Feldman** (mfeldman@oceanleadership.org) is Program Manager, both at the Gulf of Mexico Research Initiative (GoMRI), Consortium for Ocean Leadership, Washington, DC, USA. **Debra S. Benoit** is Director of Research and Sponsored Programs, Nicholls State University, Thibodaux, LA, USA. **Michael J. Carron** is Program Director, GoMRI, Gulf of Mexico Alliance, Ocean Springs, MS, USA. **Nilde Maggie Dannreuther** is Coordinator, Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS, USA. **Katie H. Fillingham** is Program Specialist, GoMRI, Consortium for Ocean Leadership, Washington, DC, USA. **James C. Gibeaut** is Endowed Chair for Coastal and Marine Geospatial Sciences, Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **Jennifer L. Petitt** is Program Manager, American Institute of Biological Sciences, Herndon, VA, USA. **Jarryl B. Ritchie** is Gulf Coast Liaison, GoMRI, Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS, USA. **Rosalie R. Rossi** is Project Manager, Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **Stephen H. Sempier** is Deputy Director, Mississippi-Alabama Sea Grant Consortium, Ocean Springs, MS, USA. **J. Kevin Shaw** is Program Manager, GoMRI, Gulf of Mexico Alliance, Ocean Springs, MS, USA. **Jessie L. Swanseen**, is Senior Specialist, Project Administration, Consortium for Ocean Leadership, Washington, DC, USA. **Charles A. Wilson** is Chief Scientific Officer, GoMRI, Fairhope, AL, USA. **Callan J. Yanoff** is Program Associate, GoMRI, Consortium for Ocean Leadership, Washington, DC, USA. **Rita R. Colwell** is Distinguished University Professor, University of Maryland, College Park, MD, USA.

AUTHOR CONTRIBUTIONS

Leigh A. Zimmermann and Michael G. Feldman are co-lead authors.

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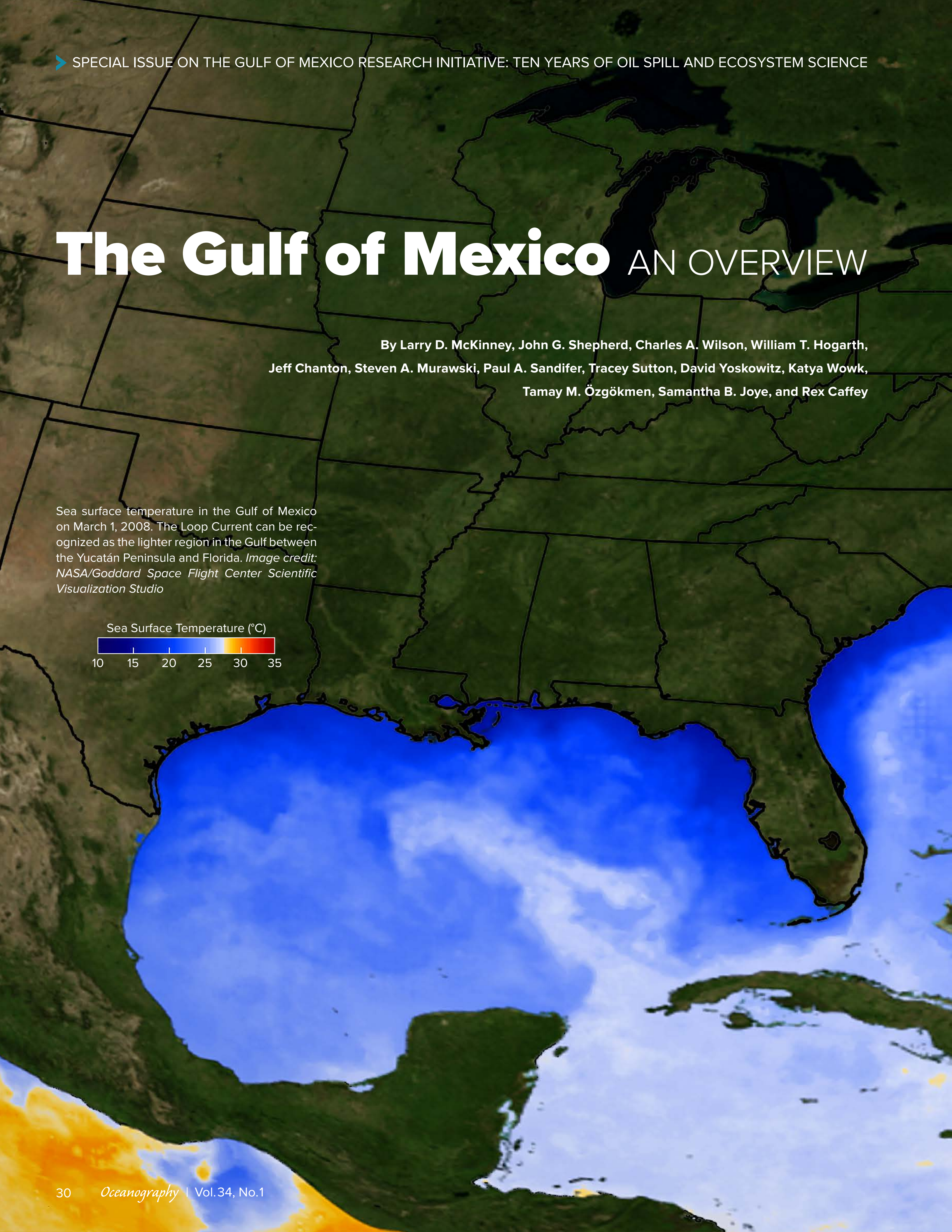
The Gulf of Mexico AN OVERVIEW

By Larry D. McKinney, John G. Shepherd, Charles A. Wilson, William T. Hogarth, Jeff Chanton, Steven A. Murawski, Paul A. Sandifer, Tracey Sutton, David Yoskowitz, Katya Wowk, Tamay M. Özgökmen, Samantha B. Joye, and Rex Caffey



Sea surface temperature in the Gulf of Mexico on March 1, 2008. The Loop Current can be recognized as the lighter region in the Gulf between the Yucatán Peninsula and Florida. *Image credit: NASA/Goddard Space Flight Center Scientific Visualization Studio*

> “While the Deepwater Horizon oil spill was one of the great environmental disasters in US history, the research that it engendered, including that funded by GoMRI, significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work to restore the damage from that oil spill.”

ABSTRACT. The Gulf of Mexico is a place where the environment and the economy both coexist and contend. It is a resilient large marine ecosystem that has changed in response to many drivers and pressures that we are only now beginning to fully understand. Coastlines of the states that border the Gulf comprise about half of the US southern seaboard, and those states are capped by the vast Midwest. The Gulf drains most of North America and is both an economic keystone and an unintended waste receptacle. It is a renowned resource for seafood markets, recreational fishing, and beach destinations and an international maritime highway fueled by vast, but limited, hydrocarbon reserves. Today, more is known about the Gulf than was imagined possible only a few years ago. That gain in knowledge was driven by one of the greatest environmental disasters of this country's history, the Deepwater Horizon oil spill. The multitude of response actions and subsequent funded research significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work needed to restore the damage from that oil spill. Funding for further work should not wait for the next major disaster, which will be too late; progress must be maintained to ensure that the Gulf continues to be resilient.

INTRODUCTION

The environment and the economy of the Gulf of Mexico both coexist and contend with one another. The Gulf hosts a productive and resilient marine ecosystem, ever-changing in response to multiple drivers and pressures. This large system is extremely complex, and certain aspects are only now beginning to be fully appreciated. We must better understand the Gulf ecosystem to ensure its continued resilience as it faces unprecedented natural and human-driven pressures (NASEM, 2018). The articles in this special issue illuminate the complex interactions and processes at work in the Gulf and summarize what we have learned about their effects since the Deepwater Horizon disaster, viewed through the lens of research and outreach activities of the Gulf of Mexico Research Initiative (GoMRI).

The Gulf is neither pristine nor an industrial wasteland. It has, however, been altered by human activities, and it faces many challenges, some common to all oceans and some unique. The Gulf ecosystem is dynamic, and its response to the drivers and pressures that influence its present and future state is complex. It is pressured by temperate influences from the north and tropical influences from the south. With Gulf states boasting about half of the US southern seaboard and capped by the vast Midwest, the Gulf is an ecological and economic keystone for the Americas. It drains much of North America, absorbing both good and bad of what flows down the Mississippi, America's greatest river. Despite these pressures and because of its resilient nature, the Gulf is a renowned for its seafood markets, recreational fishing, and holiday beach destinations. It produces and refines much of the petroleum consumed and exported by the United States. As an international maritime highway, the Gulf provides an essential link for world trade and commerce. As a complex physical system, its influence, via the Gulf Stream, reaches far across the Atlantic Ocean. Growing our knowledge of the interactions that generate and affect these attributes is essential for all who live around the Gulf and depend upon it, if we are to take appropriate and effective actions to assure its future.

Today we know more about the Gulf of Mexico than we might have imagined possible only a few years ago (Figure 1). While the Deepwater Horizon (DWH) oil spill was one of the great environmental disasters in US history, the research that it engendered, including that funded by GoMRI, significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work to restore the damage from that oil spill. Furthering this work should not wait for the next major disaster. That would be too late. We must find the political support and funding to build upon the foundations of the last 10 years and do it now.

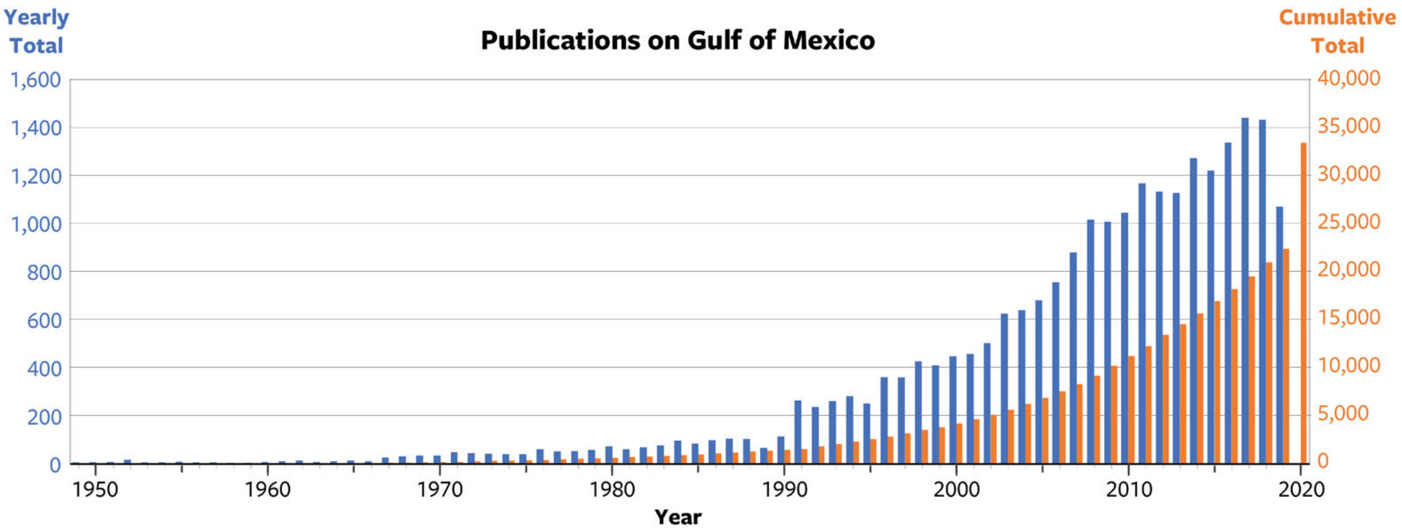


FIGURE 1. The graph shows the results of a web-based search of all documents using the term Gulf of Mexico. It includes articles, proceedings, reviews, meeting abstracts, and book chapters. *Source: Web of Science, https://clarivate.com/webofsciencegroup/solutions/web-of-science/*

What we know today will likely not suffice to support either management efforts or responses to future disasters. Our goal must be to assure the continued resilience of the Gulf of Mexico.

With this article, we provide a brief overview of the Gulf and its complex nature, summarize some of what has been learned since the DWH disaster, and describe how that knowledge has illuminated important aspects of this complex marine ecosystem. Using a conceptual framework to illustrate the linkages between natural and anthropogenic forces that act upon the Gulf and the range of human responses to mitigate or manage the stresses created by those forces, we provide context for how that new knowledge has increased our understanding of system interactions, both natural and human. It will also become evident that much still remains to be learned, and we will provide some fresh ideas about research needs. The future Gulf faces many challenges from climate change and ongoing development pressures. The resilient nature of the Gulf is and will be tested. The more we understand about how the Gulf "works," the more impactful will be our management and restoration efforts in assuring future resilience that is so necessary for its sustained health and productivity.

THE GULF OF MEXICO AS AN INTEGRATED SYSTEM

Using the Gulf of Mexico as a model, Harwell et al. (2019) introduced the EcoHealth Metrics framework as an integrated indicators-and-assessment tool. The framework (Figure 2) can be used to understand the environmental condition of the Gulf in relation to natural and anthropogenic factors (drivers, pressures, stressors, conditions, and responses) as overlaid by management actions, including those focused on restoration. This simple model can be valuable for understanding how chemical, physical, and biological processes affecting the Gulf interact to influence this large marine ecosystem as a whole and how the effects of our actions, both positive and negative, can be discerned through various indicators. Those indicators can then inform both management and research strategies to address problems.

Drivers, among the Figure 2 components, are fundamental natural and anthropogenic forces. The diverse pressures generated by drivers force changes in ecosystems (Oesterwind et al., 2016). In the case of the Gulf of Mexico, drivers push against its resilient nature. *Pressures* are human activities and natural processes arising from drivers that tend to be large scale but spatially and temporally variable. Human activities affecting the Gulf include oil and gas extraction, commercial and recreational fishing, and altered freshwater inflows, among others. Natural processes include hurricanes, nearshore current patterns, and sediment dynamics. Anthropogenically derived pressures can generally be acted upon through various management actions, while natural pressures are beyond management intervention. *Stressors* act upon the ecosystem directly as a result of pressures; physical, chemical, and biological stresses directly cause environmental effects. Physical stressors include changes in salinity and ocean acidification. Chemical stressors include altered nutrient inputs, and oil and chemical spills. Biological stressors include nursery habitat destruction, harmful algal blooms, overfishing, invasive species, and pathogens and disease. Restoration activities are often directed at stressors. Stressors result in a series of impacts on the system and its capacity for resilience in the face of cumulative stressors. *Responses* are human systems reactions to stressors; they include restrictive fishery management, habitat restoration, and limits on the release of toxic chemicals into the environment.

The EcoHealth Metrics framework illustrates how post-DWH knowledge can be used to positively influence the future condition of the Gulf. Our new knowledge has also posed as many questions as it has answered, and this work must continue. The EcoHealth Metrics framework will help prioritize research needs as part of the adaptive management strategies contemplated by Natural Resource Damage Trustees (set up under the Oil Pollution Act of 1990), the RESTORE Gulf Ecosystem Restoration Council, and others who will direct billions of dollars in Gulf restoration and recovery. A better understanding of how these drivers and pressures affect the complex interactions of Gulf physical, chemical, and biological systems helps to refine our responses in maintaining a desirable state or condition of the Gulf that meets societal needs and expectations while assuring its resilient nature.

Management responses may remediate pressures through legislation, regulation, policy, or altered human behavior through education. Restoration may directly address stressors to the same end and contribute to maintaining or restoring a desired "state" or condition that sustains ecosystem services. Our scientific understanding, or lack of it, directly affects our ability to enable effective management responses to maintain that desired state. When adequate, this knowledge can inform adaptive management strategies that will synergistically and iteratively build on lessons learned to enhance their effectiveness. That ability hinges on our understanding of system interactions at the most fundamental level.

The resilience of the Gulf system is determined by the interactions of anthropogenic drivers and pressures with natural processes. People are an integral part of the environment in the Gulf of Mexico, and human interactions are part of the problem as well as (hopefully) its solution. The Gulf can be regarded as a large marine ecosystem, an approach that is widely applied across the world's oceans and coastal regions (Sherman, 2015). However, within the Gulf, there are unique interactions and relationships that define what has come to be called America's Sea (Darnell, 2015). Oil spills in the Gulf can be natural or man-made and constitute a source of organic matter input that may be either productive or toxic. There are interactions between inshore, nearshore, offshore, and deep environments, not all of which are yet well understood. In perhaps few other places are people, environment, and economy so intimately linked, and we are only now learning the cost of ignoring those interrelationships. Effective pursuit of actions that sustain these linkages requires understanding the relationships between drivers, pressures, and stressors, their impacts, and societal responses to them within a framework that helps guide effective action. The framework and adaptive management driven by it will be informed by our scientific understanding of the system interactions that are generated by those forces.

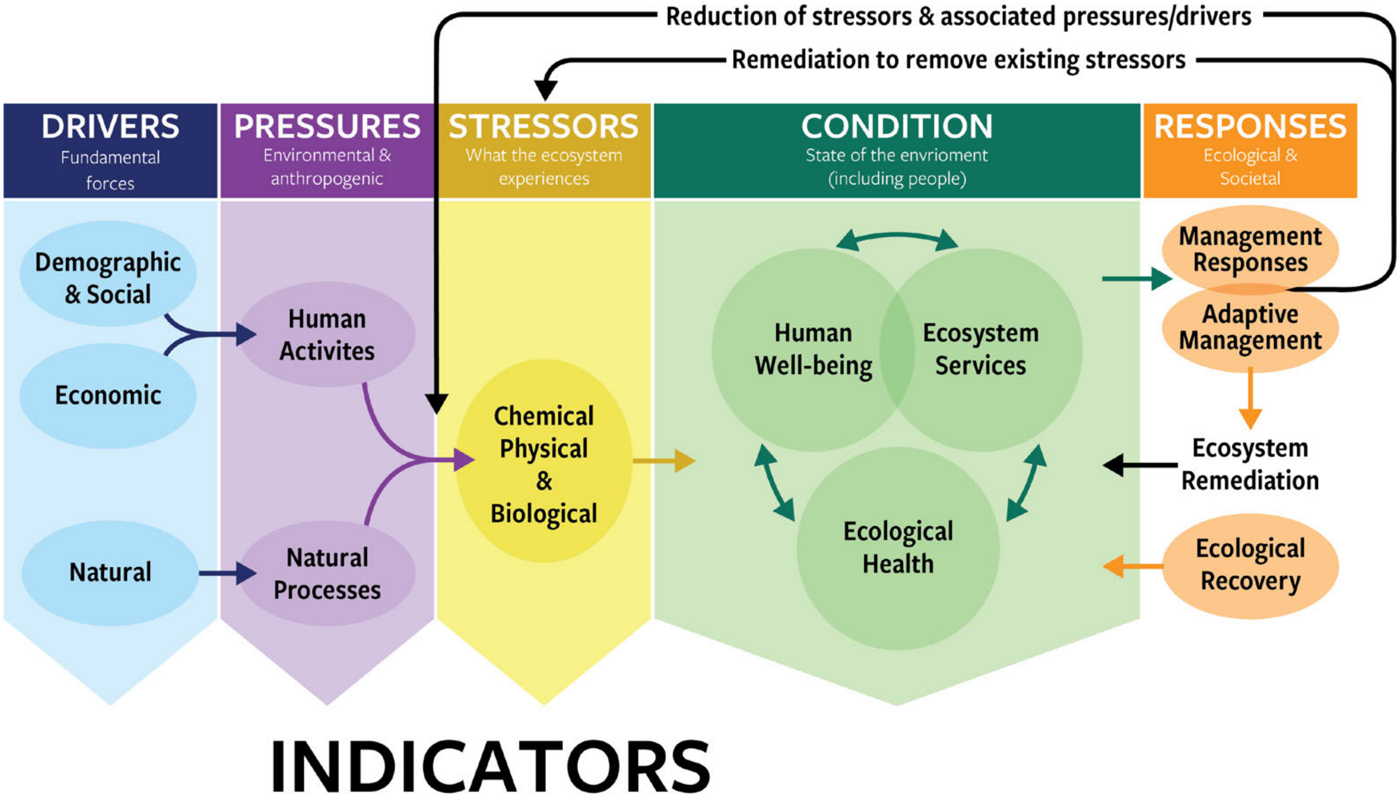


FIGURE 2. EcoHealth Metrics framework. *Modified from Harwell et al. (2019)*

UNDERSTANDING GULF SYSTEMS INTERACTIONS

The Gulf of Mexico is a complex system comprising physical, biogeochemical, ecological, socioeconomic, and human components and processes and their interactions. Figure 3 illustrates this complexity by emphasizing four major subsystems: the ocean environment, the ecosystems that are foundational to that environment, socioeconomic interactions, and human health, all of which affect the environment and are affected by it. This simplified "four-box" view of the Gulf will reappear in elsewhere in this issue in a discussion of attempts to build fully integrated assessment models of the Gulf of Mexico system (Westerholm et al., 2021, in this issue).

Among the four primary domains noted above, there is an overall cyclic progression. The ocean environment is created by the spatial distribution of materials, which is largely determined by physical processes that include the circulation and mixing of water, and modification of those materials (whether living or nonliving) by biogeochemical and microbiological processes. Living resources are supported and influenced by the ocean environment, and they interact with one another to create spatially diverse ecosystems comprising a number of ecotypes that sustain the living resources exploited by humans. Human activities depend upon and modify these natural systems—exploiting them for food, energy, transport, and recreation, among other things. Diverse human communities interact with each other through social and economic processes that ultimately influence their physical and mental health. These in turn determine the nature and extent of their activities, and thus feed back to the state of the systems upon which they depend. The interactions among these subsystems are of primary importance. They need to be understood and modeled as realistically as possible, considering the very long timescale (decades and beyond) for the full effects of human interventions to materialize.

All parts of this system are subject to external driving forces exerted by the natural pressures that establish boundary conditions (climate and seasonal variation), including extreme weather events such as hurricanes and anthropogenic drivers such as the states of global and national economies manifested through pressures such as fishery activities, tourism, and petroleum production. GoMRI has made major contributions to understanding all the components of this system and the interactions between them, and to modeling them (Westerholm et al., 2021, in this issue). Our understanding of the dynamics of human health and well-being (Sandifer et al., 2021, in this issue), however, needs further advances so that a truly holistic approach can become feasible (Helena Solo-Gabriele, University of Miami, *pers. comm.*, 2021).

ADVANCES IN INTEGRATED UNDERSTANDING AND MODELING DURING GOMRI

The GoMRI years saw rapid development of integrated modeling systems that linked together ocean physics, chemistry, biology, and socioeconomic systems.

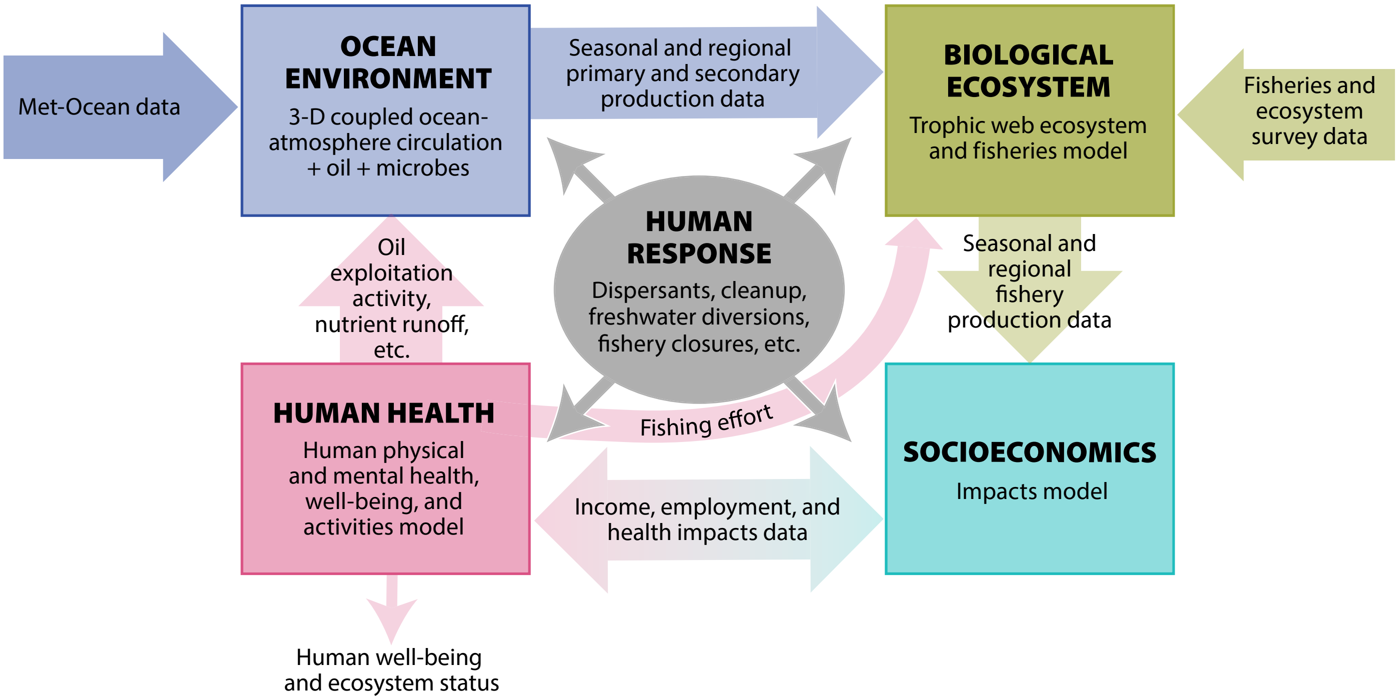


FIGURE 3. Schematic of the four major functional subsystems that interact and ultimately need to be understood and modeled together: the ocean environment (physical, chemical, and biological), the ecosystems that depend upon it, human socioeconomic activities that rely on the ocean ecosystems, and human health and well-being.

Examples include the use of velocity fields from hydrodynamic models coupled to Lagrangian deep-sea oil and gas spill models, the use of oil concentration distributions from these models to drive impacts in ecosystem models, and further chaining of ocean and ecosystem processes to derive inputs for health and socioeconomic models. The collaborative process of integrated modeling requires a broad knowledge base, and it must be amenable to very different model development times and to the timelines of supporting empirical studies. Therefore, a sustained effort is needed, and GoMRI provided a rare consistency and focus across disciplines. An important element is communication, and GoMRI successfully promoted interaction between researchers through events like its annual symposium. Integrated modeling was supported by a robust and responsive program of field and laboratory work. Specific examples include the use of drifters to help validate hydrodynamic models (Beron-Vera and LaCasce, 2016), physiological experiments to determine the rate of clearance of polycyclic aromatic hydrocarbons in fishes (Snyder et al., 2015), high-pressure experiments to determine biodegradation rates (Lindo-Atichati et al., 2016), and oil droplet size distribution experiments conducted under the influence of pressure and gas to support plume modeling (Li et al., 2017; Malone et al., 2018; Pesch et al., 2018).

PHYSICAL, CHEMICAL, AND BIOLOGICAL INTERACTIONS IN THE GULF

The driver-generated pressures that influence the Gulf of Mexico's natural processes and create the physical, chemical, and biological interactions or stressors that constantly test the Gulf's resilience are in some respects unique to the Gulf and in other respects are common across the world ocean (Singleton et al., 2016; Ainsworth et al., 2018; Eklund et al., 2019). The following sections explore some of the interactions most closely associated with the unique character of the Gulf and consider what GoMRI research has revealed regarding those interactions.

Physical and Biochemical Interactions

The Gulf of Mexico is a semi-enclosed sea (Turner and Rabalais, 2019)—a sort of ocean in a bowl—with an area of 1,507,639 km^2, an average depth of 1,615 m, and a volume of 2,434,000 km^3. It is distinctive because it has all the major features of an ocean within the confined space of its semi-enclosed bowl-shaped basin. The Gulf is also distinctive because it is partitioned by numerous rivers, most with watersheds that drain extensive land areas, including about half of the continental United States (Gulf Coast Ecosystem Restoration Taskforce, 2011). The Mississippi River ranks among the world's top 15 rivers in discharge and is responsible for most of the freshwater inflow into the Gulf. Much of what happens to affect water quality in the middle of the United States extends to the water that flows into the Gulf (Robertson, 2010). More toxic waste is released into the Gulf than into any other significant US coastal water body (https://www.epa.gov/trinationalanalysis/watersheds) by almost every measure. In addition to diverse chemical constituents, that inflow brings vast nutrient (Rabalais et al., 1996) and sediment loads (Turner, 2017) from the continental watershed to the Gulf. Unparalleled anywhere in the United States, this outflow enhances both physical and biogeochemical interactions, such as carbon and nutrient cycling from the surface to the deepest Gulf (Fisher et al., 2016). Understanding the Gulf's complex physical and biochemical interactions and their temporal and spatial scales is key to modeling and even managing the health of the Gulf as a large marine ecosystem with more than a local focus.

The Loop Current and the Gulf of Mexico Circulation

The Loop Current dominates the general circulation in the Gulf of Mexico. It is influenced by freshwater inflow from rivers and altered through water density differences and bathymetry. The Loop Current is part of the global ocean circulation, which is a response to temperature and salinity gradients between polar regions and the equator. This global circulation is three dimensional, transporting heat to northern latitudes where colder, denser water sinks near the poles and then upwells to spread above much of the deep ocean at extremely low velocities. It is further modulated by persistent zonal atmospheric winds (which are also driven by the polar-to-equatorial heat difference), as well as by land masses. The circulation is intensified toward the western side of the ocean due to the change in Earth's rotation with latitude. The Loop Current forms near the Yucatán Peninsula, where disorganized flow patterns in the Caribbean Sea are compressed against the continent and merge as they flow into the Gulf of Mexico as a single current.

The Loop Current sheds some of the largest mesoscale eddies in the world ocean and exits the Gulf through the Florida Straits (at which point the western boundary current is called the Florida Current) to become the Gulf Stream. The Gulf Stream flows along the continental slope to Cape Hatteras and then leaves the coastline to flow toward the open ocean, heading across the North Atlantic toward Europe. The extent of the northern intrusion of the Loop Current in the Gulf of Mexico changes greatly on an annual basis, sometimes extending all the way to the northern Gulf and at other times staying close to southern Florida and the northern coast of Cuba. It is modulated by eddy-shedding events, in which Loop Current eddies detach and migrate slowly to the western Gulf, where they slowly dissipate against the continental slope. The meridional position of the Loop Current also affects transport across the Florida continental shelf. It also impacts the strength of hurricanes because it affects the upper ocean heat content, and hence the heat energy driving the hurricanes on their trajectories within the Gulf of Mexico. Finally, there are smaller-scale instabilities along the rim of the Loop Current that interact with freshwater inflow and bathymetry and influence transport near the Louisiana, Mississippi, and Alabama coastlines.

Biogeochemistry of the Waters and Sediments of the Gulf of Mexico

The Gulf of Mexico is a subtropical marginal sea that extends from 21°N to 30°N latitude. Its waters derive primarily from the major inflow through the Straights of Yucatán and a suite of rivers, including the Mississippi-Atchafalaya system, the Usumacinta River that flows into the Bay of Campeche, and the Mobile River along the northern coastline, among many others (Osburn et al., 2019). The Gulf receives drainage from 40% of the continental United States, one-third of Mexico, and parts of Canada, Cuba, and Central America. In addition to river inputs, fluids discharge directly into the Gulf through permeable sediments and sedimentary rock associated with two main types of geologic features. First are the two large karst limestone platforms that define the boundaries of the Gulf. The Florida and the Yucatán platforms deliver significant submarine groundwater to the Gulf via seepage and spring flow (Kohout, 1966; Cable et al., 1996; Burnett et al., 2003). At the base of these platform escarpments, deep seepage brings energy-rich brines to the seafloor, supporting chemosynthetic communities (Chanton et al., 1991; Paull et al., 1991). A second type of permeable seafloor also exists in both the northern and southern Gulf. Salt domes deform the sediments, resulting in faults that serve as conduits for seepage of natural gas, oil, and even asphalt, onto the seafloor (Roberts and Carney, 1997; Sassen et al., 1993; MacDonald et al., 2004).

Rates of ecosystem production are linked to the nutrient content of the specific types of water inputs to the Gulf. The Caribbean waters that enter via the Yucatán Straits are low in the vital nitrogen and phosphorous nutrients that fuel primary production, so the central Gulf is oligotrophic. Riverine and groundwater inputs are more nutrient-rich. The Mississippi-Atchafalaya inputs are particularly enriched, as they drain the heavily fertilized farmlands of the US Midwest. Chlorophyll distributions are surrogates for primary production and can be measured from satellites. Gulf chlorophyll typically shows elevated concentrations in areas associated with surface and groundwater outflow such as the mouths of rivers, particularly the Mississippi, and near the coast of the karst platforms (Bosman et al., 2020). These inputs fuel biological production, resulting in rich fisheries and the deposition of organic matter to the seafloor. Seepages associated with hydrocarbons and brines on the seafloor support chemosynthetic communities (Paull et al., 1984; MacDonald et al., 1990; Fisher et al., 2007), and later the hard grounds that result from this seepage (Roberts and Aharon, 1994) become attachment sites for deepwater corals (Cordes et al., 2008).

In the northern Gulf, the nutrient-laden, low-salinity waters from the Mississippi system flow from the mouth of the river, and a portion of them wrap around the coast to the west. On the continental shelf, they spread out over the saltier and denser seawater. The nutrients in this fresh surface layer drive high primary productivity, and when the phytoplankton die, they sink and deplete the oxygen in the denser, saltier layers of water below. This has resulted in a New Jersey-sized hypoxic zone on the west Louisiana shelf that prohibits macrofauna and fish from fully utilizing the region (Turner and Rabalais, 1991; Rabalais et al., 2002; Bianchi et al., 2010). Sediments transported to the mouth of the Mississippi are rapidly deposited primarily off the shelf edge because of the channelized and levied engineering of the current river flow, thereby starving wetlands of their historic sources of sand, clay, and silt necessary to sustain land mass.

One of the important aspects of sedimentary processes in the Gulf is their role in mitigating the impact of Deepwater Horizon, as shown by a GoMRI-funded project that compared aspects of the Deepwater Horizon spill and the Ixtoc 1 spill that occurred some 31 year earlier, in 1970–1980, in the Bay of Campeche in the southern part of the Gulf. Montagna (2019) noted that the sedimentary environment of the Gulf is highly dynamic, especially within the influence of the Mississippi River outfall in the northern Gulf. Montagna and his team have been studying the impact of Deepwater Horizon on the deep Gulf (Reuscher et al., 2017) and were also able to sample the Ixtoc 1 site to assess how long it would take for normal deposition to cover contaminated sediments to the extent that biological availability was minimized. They found that it would take 100 years to cover the remains of the Ixtoc 1 spill and only 50 years to cover the DWH remains to the extent necessary to isolate contaminated sediments. The driver of this difference is the prodigious sediment output of the Mississippi River, which reaches even into the deepest Gulf. Understanding the biogeochemistry of the water and sediments of the Gulf and its circulation helps explains this phenomenon.

Micro and Macro Biological Interactions

Gulf of Mexico biodiversity is equaled only by its productivity. Its 15,419 species (Felder and Camp, 2009) are a subtropical composite of species whose habitats range from emergent wetlands to coral reefs (Ward and Tunnell, 2017). The fish and macrofauna of the Gulf, especially those commercially sought (Chen, 2017), are much studied. Even some of its special habitats, such as those sustaining chemosynthetic vent communities (Cordes et al., 2007), are well known. We know less about the microbial fauna and the impact on it of DWH, especially in the deep Gulf (Reuscher et al., 2020). The same is true for those macrofauna that have little commercial value but are integral to the Gulf ecosystem from the shoreline to the deep waters.

Gulf Microbial Communities and Their Responses to Deepwater Horizon

We often think of oil spills in the Gulf as being accidental, but according to Kennicutt (2017), in normal times 60% of oil annually discharged into the northern Gulf originates from natural seeps, exceeding 160,000 tonnes released per year. There has been considerable speculation and study as to how naturally generated deep-sea oil seeps may help to "prime" the Gulf to recover from manmade spills. The contributions of these seeps to the support of phytoplankton/bacterial communities are now better understood (D'Souza et al., 2016), as are the roles microbes play in bioremediation (Xu et al., 2018). Many questions still remain regarding the Gulf's natural responses to anthropogenically driven insults in these areas. The microbial community of the Gulf is considered a foundational element, and understanding microbes' roles in assimilating both naturally derived and anthropogenic oil inputs depends upon understanding that broader context, as discussed in Farrington et al. (2021) and Weiman et al. (2021), both in this issue.

Natural seepage of oil and gas supports some of the Gulf's microbial community, enriching its sediments and waters with hydrocarbon-degrading bacteria. These hydrocarbonoclastic microorganisms occupy a "rare biosphere" in the Gulf (Kleindienst et al., 2015). The Deepwater Horizon hydrocarbon infusion initiated a bloom of well-adapted *Gammaproteobacterial* oil and methane degraders throughout the Gulf's waters (Hazen et al., 2010; Crespo-Medina et al., 2014), sediments (Mason et al., 2014; Handley et al., 2017), beach sands (Kostka et al., 2011), and marsh soils (Atlas et al., 2015). Methane oxidation was also stimulated early in the discharge (Crespo-Medina et al., 2014) and may have transmitted organic matter into the food web (Chanton et al., 2012; Wilson et al., 2016; Rogers et al., 2019). Oxidation of oil components occurs through the activities of a series of microbial populations, each preferring a specialized substrate (oil constituent) (Dubinsky et al., 2013). Some oil-degrading bacteria produce natural biosurfactants (Head et al., 2006; Das et al., 2014) to enhance their access to oil and expedite biodegradation. Production of biosurfactants likely stimulated oil biodegradation following DWH, but it also initiated the formation of massive quantities of marine oil snow (MOS), which served to transport oil to the seabed (Suja et al., 2019; Quigg et al., 2021, in this issue). The role of microorganisms in generating MOS and the likelihood that MOS sedimentation short-circuited oil degradation in the water column was unexpected, but in retrospect was also found at the Ixtoc site. Omics-enabled tracking of microbial dynamics in the wake of the Deepwater Horizon (Kostka et al., 2020) also revealed unexpected community dynamics following this massive environmental perturbation. These issues are considered further in Farrington et al. (2021) and Weiman et al. (2021), both in this issue. The application of omics approaches to other environmental disturbances, small and large, will provide an important tool in the future to reveal sentinels of change and indicators of recovery in real time.

Multicellular Biota and Ecosystems

The DWH oil spill occurred in a region of the Gulf inhabited by abundant, diverse, and valuable communities of species that support critical ecosystem services (NRC, 2013). Because of the spill's origination offshore in 1,500 m of water and the prevailing ocean and atmospheric transport processes (currents, surface winds), the spill impacted a surface area of over 147,000 km^2. This area encompassed not only the deep sea, but also the continental slope and shelf as well as coastal habitats of beaches and marshes (Boufadel et al., 2021, in this issue). Given the thousands of species involved, it is efficient to summarize the ecosystem in four broad "ecotypes": (1) deep benthic, (2) open-ocean water column, (3) continental shelf, and (4) coastal/nearshore. These ecotypes are discussed in more detail in Murawski et al. (2021a) and Halanych et al. (2021), both in this issue. Deep-sea benthic habitats consisting of foraminifera (forams), cold-water corals, crustaceans (e.g., crabs, amphipods), bivalves, worms, and bottom-dwelling fishes exhibit a wide range of life-history traits that influence the fates of populations and their recovery potential. Corals are generally very slow growing and long-lived, making impacts on coral communities in the vicinity of the spill severe (Fisher et al., 2016; Schwing et al., 2020). In contrast, many foram species recovered to pre-spill levels within a few years.

The Gulf of Mexico open-ocean community of nekton (pelagic shrimps, squids, fishes, and marine mammals) constitutes one of the most biodiverse mesopelagic (200–1,000 m deep) and bathypelagic (>1,000 m) ocean ecosystems in the world (Sutton et al., 2017, 2020). Typically, many of the constituents of the mesopelagic nekton undergo diel (daily) vertical migrations from very deep waters during the day to surface waters at night, and the reverse, constituting the largest animal migration on Earth (Boswell et al., 2020). Due to the presence of extensive subsurface oil "plumes" and the steady stream of oil rising from the DWH wellhead to the sea surface, the open-ocean nekton communities occurring in those areas were continuously exposed to oil (Romero et al., 2018). These communities, and the open-ocean nekton communities located elsewhere, have been notoriously undersampled. Before the DWH spill, there was no sustained sampling effort to estimate the abundance and biodiversity of these communities. However, beginning in 2010 and through 2018, a number of depth-stratified sampling expeditions were undertaken (Cook et al., 2020; Sutton et al., 2020). Results of these sampling cruises document a precipitous decline in small nekton of the open ocean, on the order of two-thirds to three-quarters for invertebrates and fishes (recent work of author Sutton). As of the 2018 expedition, this community had failed to return to 2010 abundance levels. Offshore populations of marine mammals (whales and delphinids) were also observed swimming in oil-contaminated waters, and some had shifted their distributions to the south and away from the region where DWH oil was apparent (Aichinger-Dias et al., 2017; Frasier et al., 2020). Sea turtle populations were likely affected by oil exposure, as well as oil spill cleanup efforts including skimming and burning activities (Wallace et al., 2017).

The continental shelf regions, where the most lucrative Gulf of Mexico commercial fisheries occur, exhibited a variety of species and community-level changes associated with the spill. Monitoring of natural and artificial reefs saw sharp abundance declines post-DWH in small demersal fish species (e.g., damselfishes) but a concomitant rise in the abundance of invasive lionfishes (Lewis et al., 2020). Coastal and nearshore species and communities exhibited a continuum of effects both from direct oil exposure and due to some of the spill countermeasures deployed (Murawski et al., 2021b). Bottlenose dolphin populations, particularly in Barataria Bay, showed severe health effects and reduced reproductive output, and they continue to exhibit these symptoms (Schwacke et al., 2014, 2017). There were billions of excess mortalities in Eastern oyster populations in Breton Sound and Barataria Bay, presumably associated with persistent low salinity that resulted from opening of river diversions in an attempt to forestall oil entering marshes (Powers et al., 2017a,b,c).

PEOPLE ARE PART OF THE GULF ENVIRONMENT—BOTH PROBLEM AND SOLUTION

Over 15.8 million people, 4.9% of the US population, live along the US Gulf of Mexico coast (Cohen, 2018). It may be the smallest of the US coastal regions, but is has been the fastest growing by far. Between 2000 and 2017, the Gulf added three million people, a growth rate of 26.1%, while the average of all other coastal regions was 15.3%. Jobs, climate, cost of living, and the coastal setting have driven that growth, but there is a price to pay for living on the Gulf coast, because between 2000 and 2017 seven hurricanes caused $456.5 billion dollars in property damage.

More than any other coastal region, Gulf citizens have natural-resource-related occupations, ranging from oil and gas work to fisheries and construction. The connection between Gulf residents and the place they live has broad resonance, and people continue to flock to the region because of that connection. However, the growth and economic development has come at a cost to the Gulf environment. The Gulf's wetlands make up 37% of US coastal wetlands, the most of any region (Dahl, 2011). Wetland loss is also greater in the Gulf than in any other US coastal region (257,150 acres, or 1,040 km^2, between 2004 and 2009), making up 71% of all US losses. Land subsidence due to oil as well as gas removal and water extraction accounted for much of this loss. Other wetland losses were caused by coastal development, saltwater intrusion from storms and freshwater diversions, attenuation of normal sediment deposition from rivers, and climate-forced sea level rise.

As a large resilient marine ecosystem, the Gulf is surprisingly indifferent to many of our most destructive actions. It reacts to resist change, recover from pressures and stressors, or adapt to new conditions. We must either live with the result or take action to return the Gulf to what we consider to be a desirable state. Natural and man-made pressures combine to impinge on Gulf resilience, and the linkage between the Gulf's environment and its people is most evident not only in the socioeconomic condition but also in the health of its citizens.

Gulf Economics and Socioeconomics

The Gulf of Mexico, like other ocean and coastal areas of the world, provides a tremendous amount of traditional and nontraditional goods and services that impact human well-being. In the five US Gulf States, 882,000 people are employed in the ocean economy—living marine resources, marine construction, ship and boat building, marine transportation, offshore mineral extraction, and

> “Some of the impacts of the disaster will be with us for 50 or 60 years, until sediments accumulate to bury the oil and its products in the deepest parts of the Gulf and similarly in salt marshes, where Deepwater Horizon oil is readily identifiable and remains toxic to biota.”

tourism and recreation—and its gross domestic product (GDP) is $117 billion (https://coast.noaa.gov/enowexplorer/). The ocean economy of these five states would, in fact, rank 58th in the world GDP.

The Gulf is therefore a major economic engine for the United States, and two of the biggest natural resources supporting this are fisheries and oil and gas. One-sixth of the commercial fish landings and almost one-third of recreational angling trips come from just the five states, adding $2.3 billion and $9.5 billion, respectively, to the US economy in 2017 (NMFS, 2018, 2020). On a production basis, the Gulf led the lower 48 and was second only to Alaska in commercial landings. Additionally, the aftermath of the DWH oil spill revealed the high value that recreational anglers place on the resource (Alvarez et al., 2014; Court et al., 2017). With respect to the impacts of Deepwater Horizon on fish consumption from the Gulf, the short-term impacts on seafood demand may largely have been attributed to perception rather than reality (Carmichael et al., 2012; Fitzgerald and Gohlke, 2014).

Natural resource use extends to oil production where offshore (federal waters) Gulf of Mexico oil accounts for 15% of US output; when the five Gulf-state waters are included, this figure increases to 59% (EIA, 2020). The spill put a more urgent focus on improving risk management (Reader and O'Connor, 2014; Skogdalen et al., 2011) and response (Leifer et al., 2012; Michaels and Howard, 2012) by bringing new approaches to improve safety, reduce accident probabilities, and hopefully lessen the impacts of future spills through more rapid and effective responses.

The value of our natural environment not captured in typical market transactions can be significant and should be explicitly accounted for in evaluations of oil spills and other disasters in order to make a full assessment of the impacts on human well-being (NRC, 2012, 2013). As part of the process to assess damages of Deepwater Horizon—both biophysical and social—a national valuation survey was conducted and found that there was support to invest at least $17.2 billion to prevent the same type of injuries in the future (Bishop et al., 2017).

Gulf Health and Human Health Are Linked

Disasters occurring in the Gulf impact not only the biota and ecosystems of this large marine ecosystem but also the people that inhabit its shores. This is especially true because the Gulf is situated in a naturally precarious region that is subject to a variety of natural and human-made threats, and the area population exhibits health disparities and suffers continued exposure to environmental contaminants (Lichtveld et al., 2016; Slack et al., 2020). The DWH disaster had extensive adverse physical and mental human health impacts for some responders, cleanup crews, and residents in coastal communities. Two pervasive issues were the lack of baseline health information against which to compare after-spill effects and the overarching role of spill-associated stress on adverse health outcomes (Sandifer et al., 2021, in this issue).

A range of negative health effects were reported for some response workers, including respiratory, heart, skin, gastrointestinal, and other issues, as well as depression and post-traumatic stress disorder (Kwok et al., 2017; Rusiecki et al., 2018). Among residents, mental health impacts from the spill were varied. However, adverse psychological effects were common among those exposed to the spill physically or through associated socioeconomic impacts (e.g., job/income loss; Finucane et al., 2020). Natural resource-dependent communities (e.g., fishers) were particularly vulnerable to mental health effects (Cope et al., 2013; Parks et al., 2020; Slack et al., 2020), as were those who suffered socioeconomic disparities. While children are of special concern for negative health effects from spill exposure and exhibited some impacts (Abramson et al., 2010; Slack et al. 2020), studies of children's seafood consumption (Sathiakumar et al., 2017) and beach play (Ferguson et al., 2020) showed little if any additional health risks associated with potentially contaminated seafood or exposure to contaminated beach sediments (Sandifer et al., 2021, in this issue).

It is also important to consider potential impacts from other types of disasters in the Gulf. In addition to major oil spills like the DWH event, hurricanes and other disasters can adversely impact people's health and well-being, and we know that previous traumatic experiences can exacerbate effects of the next event (Sandifer et al., 2020a,b). Additional research is needed in this area, particularly to document impacts on more vulnerable populations.

SUSTAINABLE SCIENCE FOR A SUSTAINABLE GULF OF MEXICO

As we struggled to respond to the Deepwater Horizon oil disaster, we paid a price for our ignorance about how the Gulf of Mexico works, rooted in the minimal research investments historically made there. Our lack of knowledge about linkages between the deep Gulf, the open ocean, and the coastal margins hindered response and early mitigation planning. The fate of oil spilled in the deep ocean and its interactions with novel use of chemical dispersants in the deep sea were not at all well understood. Some of the impacts of the disaster will be with us for 50 or 60 years, until sediments accumulate to bury the oil and its products in the deepest parts of the Gulf and similarly in salt marshes, where Deepwater Horizon oil is readily identifiable and remains toxic to biota. Long-lived animals such as sperm whales, porpoise, and turtles may not fully recover for a very long time. Beaches and wetlands still occasionally release traces of oil when disturbed by storms. Some fish, especially deep dwellers, continue to carry the effects of the spill in their tissues. As a result of research carried out since the spill—funded by penalty fines, the eventual settlement, and most especially GoMRI—we know so much more now than we did then. This research has vastly increased our knowledge of the Gulf but also raised many questions. As restoration actions go forward, even more questions regarding the sustainability of Gulf resources in the face of multiple simultaneous threats will emerge. But we must also be cognizant of and prepared for the *next* large spill in the Gulf of Mexico. The year 2019 (before the pandemic) saw record oil production from the US Gulf of nearly 700 million barrels, the majority of which was extracted from depths >1,500 m. As the industry changes and adapts to the frontiers of oil exploration and production, so too must our research vision focus on the Gulf as it will be and not as it was.

To answer these questions, we shall need to both understand and ultimately be able to model the interactions that we have described above. The GoMRI years brought rapid development of integrated modeling systems that link ocean physics, chemistry, biology, and socioeconomic systems of the Gulf. Examples include the coupling of velocity fields from hydrodynamic models with Lagrangian deep-sea oil and gas spill models, the use of oil concentration distributions from these models to drive impacts in ecosystem models, and further chaining of ocean and ecosystem processes to derive inputs for socioeconomic and human health models. A paper being prepared by Helena Solo-Gabriele, University of Miami, and colleagues will provide an up-to-date review of such integrated modeling in GoMRI. The collaborative process of integrated modeling requires a broad knowledge base that must be amenable to very different model structures and development times, and to the timelines of supporting empirical studies. Therefore, a sustained research effort is needed, and GoMRI has provided a rare opportunity to apply consistency and focus across all the disciplines involved. An essential prerequisite is communication, exemplified by GoMRI's successful promotion of interaction between researchers in diverse disciplines through events like the Gulf of Mexico Oil and Ecosystem Science Conferences. Such efforts need to be maintained and enhanced in the future, most notably for better understanding of the interactions between socio-economic conditions and human health and well-being, where our knowledge remains relatively rudimentary. These are major challenges for the years to come.

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AUTHORS

Larry D. McKinney (larry.mckinney@tamucc.edu) is Chair for Gulf Strategies, Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **John G. Shepherd** is GoMRI Research Board member and Professorial Research Fellow, School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton, UK. **Charles A. Wilson** is Chief Scientific Officer, Gulf of Mexico Research Initiative, Fairhope, AL, USA. **William T. Hogarth** is Dean Emeritus, College of Marine Science, Florida Institute of Oceanography, St. Petersburg, FL, USA. **Jeff Chanton** is Professor, Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, USA. **Steven A. Murawski** is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Paul A. Sandifer** is Director, Center for Coastal Environmental and Human Health, College of Charleston, Charleston, SC, USA. **Tracey Sutton** is Associate Professor, Oceanic Ecology Laboratory, Halmos College of Arts & Sciences, Nova Southeastern University, Fort Lauderdale, FL, USA. **David Yoskowitz** is Senior Executive Director, and **Katya Wowk** is Senior Associate for Strategic Planning & Policy, both at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **Tamay M. Özgökmen** is Professor, Department of Ocean Sciences, University of Miami, Coral Gables, FL, USA. **Samantha B. Joye** is Professor, Department of Marine Sciences, University of Georgia, Athens, GA, USA. **Rex Caffey** is Professor, College of Agriculture, Louisiana State University, Baton Rouge, LA, USA.

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A localized 2010 in situ burning operation in the Gulf of Mexico created a large smoke plume. *Reprinted from Gullett et al. (2016), Graphical Abstract, with permission from Elsevier.*

WHAT WAS RELEASED?

Assessing the Physical Properties and Chemical Composition of Petroleum and Products of Burned Oil

By Jürgen Rullkötter and John W. Farrington

ABSTRACT. The severity of oil spills depends on the quantity of material released and its physical and chemical properties. The total amount of petroleum spilled during the Deepwater Horizon incident and the relative fractions of the chemical compound classes of the Macondo oil were obtained by measurements, observations, and model calculations, with a significant amount of uncertainty. Because petroleum is an extremely complex mixture of many thousands or more of gaseous, liquid, and solid constituents, full elucidation of their compositions at the molecular level is impossible with presently available analytical techniques. This paper reviews published work on widely used analytical techniques and points out that scientists' varying approaches to research questions and preferences for methods of analysis constitute a source of uncertainty. In addition, the focus is on two technical advancements developed over the last two decades, namely two-dimensional gas chromatography and Fourier transform ion cyclotron resonance mass spectrometry. Both were particularly valuable in the analysis of the spilled Macondo oil and its weathering products. Among the different processes of alteration of the original oil, only in situ oil burning is dealt with in this paper. This review reveals the paucity of data on this mitigation process and shows the need for more systematic coordination of methods in burned oil research studies.

INTRODUCTION

The significance of the Deepwater Horizon (DWH) oil spill arises from the sheer quantity of petroleum released, uncontrolled, from the Macondo petroleum reservoir—it is the largest incident of this kind in history. Addressing the full impact of the released petroleum on Gulf of Mexico flora and fauna, coastal areas, and human health requires consideration of both the quantity and the chemical composition of discharged materials.

This paper addresses estimated quantities of original petroleum discharged from the damaged DWH wellhead at the bottom of the Gulf of Mexico as well as the physical properties and chemical composition of the petroleum released into the environment. The complexity of petroleum, in itself, poses a barrier to conducting an analysis that everyone can agree upon. Investigators use their varying preferred methods, with attendant additional problems and uncertainties.

The products that result from the burning of oil as a specific measure in oil spill response are a second aspect of this review; other papers in this special issue examine the use of dispersants (Quigg et al., 2021) and alteration of the original petroleum by physical (e.g., evaporation, dissolution), chemical (e.g., photo-oxidation by sunlight at the water surface), and biological processes (microbial transformation and degradation), collectively called weathering (Farrington et al., 2021).

PETROLEUM

Petroleum is generated from the remnants of (mainly) plant biomass in fine-grained sediments deposited long ago in aquatic environments under low oxygen conditions. Upon progressive burial, the sediments are compacted into petroleum source rocks, typically at depths of several thousand meters. Over millions of years, the organic material in these rocks is transformed into gas and oil under the influence of geothermal heat flow. Increase in pressure due to the conversion of solid material into gases and liquids forces these products out of the source rocks into more porous carrier rocks. The petroleum then migrates upward because its density is lower than that of pore waters. When it reaches a rock formation that is isolated at the top by an impermeable cap rock (like claystone or salt), it accumulates in a deep reservoir rock (e.g., Tissot and Welte, 1984; Hunt, 1996; Welte et al., 1997; Overton et al., 2016).

Petroleum is an extremely complex mixture of many thousands, if not millions, of individual constituents at the molecular level. As used by the oil industry, petroleum is a collective term comprising gaseous (natural gas), liquid (crude oil), and solid (asphalt) components. Due to co-dissolution effects and elevated temperatures, petroleum commonly exists as a single phase or in two phases (gas and liquid) in reservoirs.

Physical Properties

The most common physical properties used to describe petroleum are density, viscosity, and boiling point ranges. The density of crude oils is usually expressed as API (American Petroleum Institute) gravity, which is inversely related to specific density. Viscosity, a measure of a fluid's internal resistance to flow at a given temperature and pressure, depends on the chemical composition of the petroleum, including the amount of dissolved gas it contains. The upstream oil industry (i.e., refineries) uses the boiling point properties of crude oils to produce distillation fractions (cuts) of defined boiling ranges, each with a mixture of different chemical compound types. These cuts, after further refinement, are the oil fractions known as gasoline, kerosenes (jet fuels), fuel oils, and others.

A broad classification of petroleum is that of light or heavy oil, based upon viscosity or API gravity (Table 1). According to this scheme, the Macondo oil of 40° API gravity spilled in the Gulf of Mexico in 2010 is a light oil lean in sulfur content (<0.5% wt.; "sweet"; Reddy et al., 2012).

Chemical Composition – General Aspects

Analysis of spilled oil in terms of its origin and transformation by physical (evaporation, dissolution) or (bio)chemical (photo-oxidation, microbial oxidation, selected incorporation into biomass or other forms of metabolism) processes is in most cases targeted toward its chemical composition rather than its physical properties. The common strategy applied as a first step, after evaporation of the most volatile components (topping), is to separate the complex mixture of oil components into compound classes by polarity using liquid chromatography with various adsorbents on thin-layer plates, in gravity columns, or by medium-pressure or high-performance liquid chromatography. The compound classes usually obtained are <u>s</u>aturated hydrocarbons (alkanes), <u>a</u>romatic hydrocarbons (including some heteroaromatic species), <u>r</u>esins, and <u>a</u>sphaltenes (SARA). Saturates, aromatics, and resins com-

TABLE 1. Oil classification by API gravity ranges with a few examples from different sources. For comparison, water has an API gravity of 10°.

OIL TYPE	API GRAVITY*	EXAMPLES (API)	REFERENCES
Condensate	>45°	Agbami, Nigeria (48°)	Speight (2015)
Light oil	35°–45°	West Texas Intermediate (40°), Macondo (40°)	Speight (2015) Reddy et al. (2012)
Medium oil	25°–35°	Alaska North Slope (32°)	Speight (2015)
Heavy oil	15°–25°	Venezuela Heavy (17°)	Speight (2015)
Extra heavy oil	<15°	Tar sands: Orinoco, Venezuela (8°–12°), Athabasca, Canada (6°–10°)	Tissot and Welte (1984)

* API gravity = (141.5/specific gravity at 15.6°C) – 131.5

prise a single solubility fraction, collectively called "maltenes." They are soluble in alkane solvents (most commonly *n*-pentane or *n*-heptane), while the asphaltenes are isolated by alkane solvent precipitation (insolubility). Further subfractions can be obtained by employing a number of more sophisticated techniques (e.g., Peters et al., 2005a).

Alkane (Figure 1) is a synonym for a saturated hydrocarbon (i.e., a chemical compound that contains only carbon and hydrogen and has no double bonds or aromatic units). Alkanes can be straight chains of CH_2 groups with methyl (CH_3) groups at the end (*n*-alkanes). They can have one or more alkyl side chains (branched and isoprenoid alkanes), or they can contain one ring or several rings (cyclic and polycyclic alkanes). Several of the polycyclic saturated alkanes like (tetracyclic) steranes and pentacyclic triterpanes are classified as biomarkers. Their presence and relative abundance as well as their remarkable stability under weathering allow their use as fingerprints to gain information on the origin of crude oils and to distinguish crude oils from different sources (for fundamental background and overviews see, e.g., Mackenzie, 1984; Brocks and Pearson, 2005; Peters et al., 2005b; Gaines et al., 2009; Brocks and Summons, 2014; Stout and Wang, 2018). Biomarkers (also termed biological markers, molecular fossils, fossil molecules, or geochemical fossils) are organic compounds in natural waters, sediments, soils, fossils, crude oils, or coal that can be unambiguously linked to specific precursor molecules biosynthesized by living organisms. The main reason for this specificity is that the bonds to the four neighboring atoms (carbon or hydrogen) are sterically oriented (tetrahedral). Thus, the rings are not planar as in aromatic hydrocarbons, but rather have a (sometimes slightly skewed) three-dimensional chair or boat configuration. Biosynthesis leads to specific steric orientation of several bonds in the biomarkers (chiral centers, optical activity). The orientation of some of these chiral centers is altered during the geothermal transformation of organic matter in petroleum source rocks (stereoisomerization) into thermodynamically more stable species, providing clues to the geothermal history (maturation) of the organic matter.

Aromatic hydrocarbons (Figures 2 and 3) contain one or more hexagonal, six-carbon ring structures with the equivalent of three conjugated double bonds; in reality, the electrons are not localized in three separate bonds but are shared among the six carbon atoms. As a consequence of the specific bond type, aromatic hydrocarbons are planar. In heteroaromatic compounds, a carbon atom in the six-membered ring is replaced by a nitrogen atom (e.g., pyridinic species). Other heteroatom-containing compounds in petroleum have a sulfur, a nitrogen, or, less commonly, an oxygen atom in a conjugated five-membered ring, either alone or adjacent to one or more aromatic ring(s). These classes of compounds are known as thiophenic (sulfur), pyrrolic (nitrogen), or furanic (oxygen). The term "aromatic" stems from the fact that many naturally occurring compounds that contain aromatic rings have distinctive scents. Polycyclic aromatic hydrocarbons (PAHs) have two or more fused aromatic rings and can be quite large. PAHs occur in petroleum and form by incomplete combustion of organic matter. They are common air and water pollutants. They can be toxic, carcinogenic, or mutagenic, and are relatively persistent in the environment. While most aromatic hydrocarbons in petroleum carry one or more alkyl substituents (methyl groups or longer alkyl chains such as those in the alkylated homologues of naphthalene, phenanthrene, dibenzothiophene, fluorene, and chrysene; Figure 2), products of incomplete combustion are predominantly unsubstituted (parent) PAHs (Figure 3; see Yang et al., 2014, for a recent overview). In this respect, the aromatic hydrocarbon composition of petroleum differs from that in products of incomplete combustion like those from oil that is burned during spill mitigation.

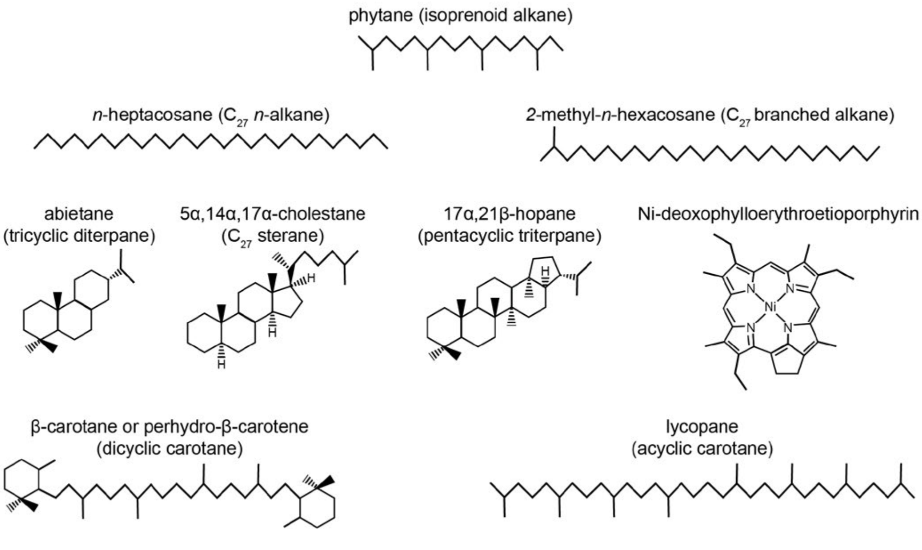

FIGURE 1. Examples of common saturated hydrocarbon biomarkers and a nickel porphyrin in crude oils.

Resins (also called heterocompounds or N,S,O-compounds) are the most polar maltene fractions obtained by liquid chromatographic separation of crude oils. The precise chemical structures of most of the individual components are ill-defined, but the elevated polarity of the resin fraction is due to the presence of heteroatoms like nitrogen, sulfur, oxygen, and metals (as in the petroporphyrins; Figure 1), as well as the larger molecular size of many of the compounds. Resin fractions are not commonly analyzed in detail, but their relative proportions are determined gravimetrically.

Asphaltenes, the most polar fraction of crude oils, can be extracted from sedimentary rocks rich in organic matter by polar solvents as part of the total extract (bitumen). They are defined by their insolubility in alkane solvents (i.e., *n*-pentane or *n*-heptane) but solubility in aromatic solvents (i.e., benzene or toluene). In chemical composition (in particular, molecular size and polarity), asphaltenes are intermediate between resins and kerogen, the insoluble high-molecular-weight organic matter in petroleum source rocks. Representations of possible asphaltene molecular structures are found in the literature, but are highly speculative (e.g., Rullkötter and Michaelis, 1990; Snowdon et al., 2016). Asphaltenes are obtained by precipitation of a solution of crude oil in a small amount of a polar solvent following the addition of excess nonpolar solvent (*n*-pentane or *n*-heptane) before liquid chromatographic separation. The yields are solvent dependent (i.e., the less polar solvent *n*-pentane yields higher amounts of asphaltenes than the slightly more polar *n*-heptane). Thus, all these subfractions of crude oil are defined by the procedures used to separate them as well as by their chemical natures.

Quantities Released During the Deepwater Horizon Oil Spill

Quantification of oil and gas released over an 87-day period after the DHW accident from the Mississippi Canyon Block 252 (MC252) reservoir of mid-Miocene turbiditic sand was not straightforward. It required a combination of measurements, calculations, and mathematical modeling. According to the information provided in the review by Kujawinski et al. (2020), the broken well released 530,000 tonnes of oil (defined as hydrocarbons with six or more carbon atoms that are liquid at ambient pressure). In addition, 170,000 tonnes of natural gas (hydrocarbons with five or less carbon atoms that are gases at ambient pressure) escaped near the seafloor, in 1,500 m water depth at high pressure and with a temperature of about 100°C, into the overlying cold water column (Reddy et al., 2012; note that these amounts are approximate, and slightly different numbers can be found elsewhere in the literature; according to Lee et al., 2018, a federal court ruled in January 2015 that "BP was liable for 3.19 M barrels of crude oil that leaked into the Gulf" of Mexico).

The "live oil," a technical term used by the petroleum industry for the reservoir-derived mixture of gaseous and liquid petroleum components, was affected right after its release due to the change in pressure and temperature. Extensive dissolution of particularly the gaseous hydrocarbons in the deep sea (Kessler et al., 2011; Valentine et al., 2010) occurred in the subsurface plume at around 1,100 m water depth. Thus, according to Reddy et al. (2012), differences in calculated total amounts of petroleum released by various investigators are most likely due to different assumed gas-to-oil ratios (GOR). These different assumptions in turn relate back to variations in the composition of samples affected to different extents by dissolution processes (e.g., see differences in GOR in the two samples in Table 2).

The remainder of the petroleum reached the sea surface, where 140,000–200,000 tonnes of the volatile compounds (about up to the volatility of *n*-hexadecane) evaporated into the atmosphere within 3–10 h of surfacing (Gros et al., 2017; Ryerson et al., 2012; Drozd

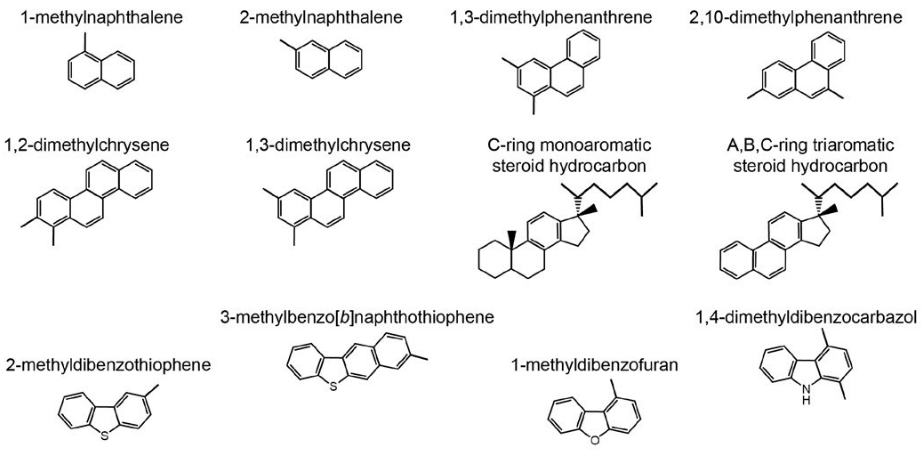

FIGURE 2. Examples of structures of alkylated aromatic hydrocarbons, aromatic hydrocarbon biomarkers, and alkylated heterocyclic aromatic hydrocarbons in crude oils.

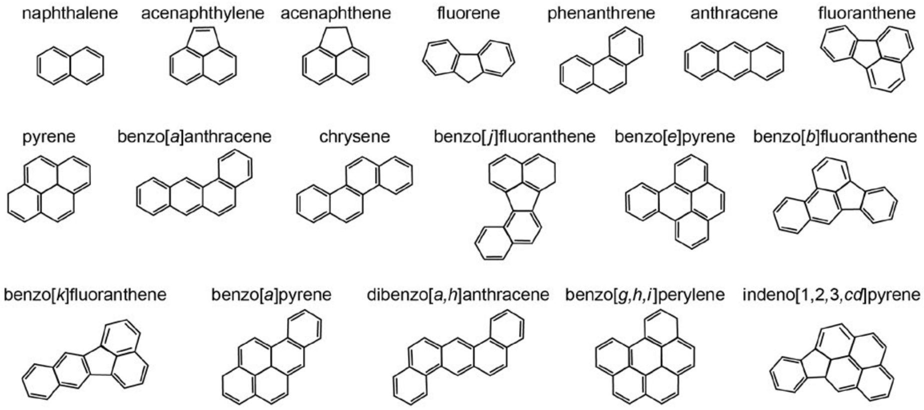

FIGURE 3. Sixteen US Environmental Protection Agency parent polycyclic aromatic hydrocarbons (PAHs) plus benzo[*j*]fluoranthene and benzo[e]pyrene.

et al., 2015) and 330,000–360,000 tonnes of the less volatile compounds spread over 11,000 ± 5,000 km^2 (Ryerson et al., 2012; Drozd et al., 2015; McDonald et al., 2015; Gros et al., 2017), reaching a total of 2,000 km of coastline along five Gulf of Mexico states (Nixon et al., 2016). Approximately 2%–20% of the total released hydrocarbons were deposited on the seafloor (Passow and Stout, 2020), primarily as oil residue. In response to the disaster, 2.9 million and 4.1 million liters of chemical dispersants were applied at the wellhead near the seafloor and at the sea surface, respectively (Lehr et al., 2010). These efforts to sequester oil in the deep sea and reduce surface oil slicks used quantities of dispersants higher than during any other known application in history (for more information on dispersants, see Quigg et al., 2021, in this issue). In total, the unintentional DWH oil release and its mitigation were unprecedented by almost any metric of marine oil discharge disasters, including in terms of volume and scale of hydrocarbon release, depth of the discharge, and application of surface and subsurface dispersants. Only the war-related intentional destruction of oil installations during the Iraqi invasion into Kuwait near the Arabian-Persian Gulf in 1990 released more petroleum into the ocean (Tawfiq and Olsen, 1993).

TABLE 2. Composition of hydrocarbon gases (C_1 to C_5) and oil sample MW-1 collected from the Macondo well on June 21, 2010 (Reddy et al., 2012), and a comparison of gas end members estimated from field data collected by Valentine et al. (2010).

ANALYTE	MW-1 CONTENT	VALENTINE ET AL. (2010)[a]
GAS[b]		
Methane	82.5% ($\delta^{13}C$ = −57.5‰; δD = −187‰)	87.5% ($\delta^{13}C$ = −61.3‰)
Ethane	8.3% ($\delta^{13}C$ = −31.5‰; δD = −147‰)	8.1%($\delta^{13}C$ = −30.5‰)
Propane	5.3% ($\delta^{13}C$ = −29.2‰; δD = −123‰)	4.4% ($\delta^{13}C$ = −29.0‰)
Isobutane	0.97% ($\delta^{13}C$ = −29.9‰)	NA
n-Butane	1.9% ($\delta^{13}C$ = −27.9‰; δD = −119‰)	NA
Isopentane	0.52%	NA
n-Pentane	0.52%	NA
Methane/ethane	9.9	10.85
Methane/propane	15.5	19.8
GOR (measured)	1,600 standard cubic feet per barrel	NA
GOR (estimated)	1,730 standard cubic feet per barrel[c]	NA
GOR		3,000 standard cubic feet per barrel[d]
OIL (SELECT PROPERTIES)[e]		
Density	820 g L^{-1}	NA
Gravity	40° API	NA
Carbon	86.6%	NA
Hydrogen	12.6%	NA
Nitrogen	0.38%	NA
Sulfur	0.39%	NA
Saturated hydrocarbons	74% ($\delta^{13}C$ = −27.9‰)	NA
Aromatic hydrocarbons	16% ($\delta^{13}C$ = −26.5‰)	NA
Polar hydrocarbons	10%	NA

GOR = Gas-to-oil ratio; NA = not applicable

[a] Valentine et al. (2010) defined only the relative abundances for the endmembers methane, ethane, and propane from field samples. The relative percentages of hydrocarbon gases measured in MW-1 were calculated using methane through pentanes.

[b] Reddy et al. (2012) measured butanes and pentanes in both the gas and oil in MW-1. Here, only the butanes and pentanes isolated in the gas fraction are shown. For a complete accounting of all compounds collected, see supplementary material in Reddy et al. (2012).

[c] Estimated from Mango ratios (Jarvie et al., 2015) using the composition of 2- and 3-methyl pentanes and 2- and 3-methyl hexanes in MW-1 oil (Table S2 in Reddy et al., 2012)

[d] Valentine et al. (2010) chose this value based on “information released by BP.”

[e] See SI text in Reddy et al. (2012) for discussion of properties listed in this section of the table.

Physical Properties and Chemical Composition of Macondo Oil

Oil droplets released during the Macondo oil spill occurred in three size categories, each with different buoyancies but with overlapping chemical compositions (Ryerson et al., 2012). Oil droplets greater than 0.3 mm diameter exhibited sufficient buoyancy to rise to the ocean surface in less than four hours (Ryerson et al., 2012), transporting a mixture of soluble and insoluble compounds, some of which volatilized into the atmosphere (Ryerson et al., 2011; de Gouw et al., 2011). The medium-sized droplets (0.1–0.3 mm) ascended more slowly (rise times below 10 h), and their behavior was very sensitive to initial oil composition and release dynamics. For example, moderately soluble hydrocarbons such as toluene, xylene, naphthalene, cyclopentane, and methylcyclopentane partitioned to the aqueous phase from all droplet sizes as a function of the droplets' exposure time and surface area-to-volume ratio, as well as their relative concentrations in the oil (Ryerson et al., 2012). In contrast, droplets smaller than 0.1 mm and soluble gases (methane, ethane, propane) lacked the buoyancy to rise after being emplaced in deep-sea intrusions, although the degree of hydrocarbon dissolution could not be measured due to challenges in separating oil droplets from the surrounding water (Ryerson et al., 2012). A substantial fraction of the released oil and gas (by mass) was retained in the deep-sea intrusions because of the relatively high proportion of gases in the DWH blowout. However, reducing the sea surface concentrations of released hydrocarbons was a high priority during DWH spill mitigation. Thus, responders decided to convert the larger, faster-rising oil droplets into small droplets that would remain in the deep sea applied chemical dispersants directly at the outflow near the seafloor.

Overton et al. (2016), Kujawinski et al. (2020), and Oldenburg et al. (2020) included bulk and molecular information on the Macondo oil in their reviews of the chemical analysis of original and transformed petroleum spilled during the DWH incident at mid-term and toward the end of the Gulf of Mexico Research Initiative (GoMRI), respectively. Petroleum sampled directly above the Macondo well during the blowout ("live oil"; Table 2) was determined to have a GOR of 1,600 standard cubic feet per barrel petroleum (Reddy et al., 2012). Valentine et al. (2010) and Reddy et al. (2012) both reported the gas being composed of mainly methane (87.5% and 82.5%, respectively) and smaller amounts of ethane (abundance just above 8%) and propane (around 5%). The ^{13}C and ^{2}H stable isotope contents increased with increasing carbon number of the gases (Table 2), indicating generation of the hydrocarbons from mature organic matter in the petroleum source rock (cf. Sherwood Lollar et al., 2002). Reddy et al. (2012) assessed the Macondo oil as a light oil (API gravity 40° with a density of 820 g L^{-1}), whereas Daling et al. (2014) reported that the oil collected through the riser insertion tube tool (RITT) on the drillship *Discoverer Enterprise* on May 22, 2010, had a density of 833 g L^{-1}, a pour point of –27°C, and an interfacial tension of 20 mN m^{-1} (millinewtons per meter). The initial viscosity of the Macondo oil was evaluated to be 3.9 cP at 32°C (Daling et al., 2014). The relative distribution of compound groups of the pyrrolic N1 heteroatom class, namely, double bond equivalent (DBE) 9 (alkylated carbazoles), DBE 12, and DBE 15 (alkylated benzo- and dibenzocarbazoles, respectively) as established by Oldenburg et al. (2014) indicated a maturity level of 0.9% vitrinite reflectance equivalent (%R_e) for the Macondo oil. This is consistent with %R_c of 0.94 calculated from the Methyphenanthrene Index 1 (MPI-1; Radke and Welte, 1983) based on the relative PAH concentrations displayed in Figures 2 and 3 of Overton et al. (2016). Both values render the Macondo oil moderately mature near the peak of oil generation, consistent with the stable isotope composition of the gases (Table 2).

Reddy et al. (2012) found the nonbiodegraded Macondo oil to be dominated by saturated hydrocarbons (74%), followed by aromatic hydrocarbons (16%) with the non-hydrocarbon (polar) fraction comprising 10%. The authors reported that the GC-MS amenable Macondo oil composition (C_5 to C_{38} saturated and aromatic hydrocarbons) was dominated by branched alkanes (26%), followed by cycloalkanes (16%) and *n*-alkanes (15%), and that aromatic species such as alkylbenzenes and indenes (9%) and polycyclic aromatic hydrocarbons (4%) were less abundant. The GC-MS amenable content of polar oil constituents was 10% (e.g., dibenzothiophenes), with sulfur and nitrogen elemental abundances of the Macondo oil assessed as 0.4% each.

Mass chromatograms of saturated hydrocarbon biomarkers in the Macondo oil (Overton et al., 2016) show the typical distribution pattern of thermally stable 17α-hopanes (*m/z* 191, displayed in the C_{27} to C_{33} range of pseudohomologues) and steranes (*m/z* 217), indicating generation from a source with a clastic rock matrix (due to significant amounts of diasteranes, or rearranged steranes; e.g., Mello et al., 1988) and moderate maturity of the oil (based on the amount of 5α,14β,17β- relative to 5α,14α,17α-steranes; Mackenzie, 1984; Seifert and Moldowan, 1986). The PAH distribution patterns, besides moderate amounts of the respective parent hydrocarbons, exhibit a prominent series of alkylnapthalenes followed in abundance by alkylphenanthrenes, alkyldibenzothiophenes, alkylpyrenes and alkylchrysenes (Overton et al., 2016).

As only a very small percentage of the non-hydrocarbon (polar) fraction is GC-amenable due to high boiling points, Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR MS) was the analytical method of choice to study this oil fraction. McKenna et al. (2013) characterized more than 30,000 acidic, basic, and nonpolar unique neutral elemental compositions for the Macondo crude oil constituents (see below). However, while certain chemical characteristics of these compounds are known, the exact chemical structures are not yet elucidated. That is a challenge going forward.

Analytical Techniques for Oil Spill Sample Analysis

The challenge of analyzing crude oil of any origin, native or altered, arises from the complexity of this substrate on the molecular level. Attempts made many decades ago to achieve a complete inventory of all constituents of petroleum (Rossini and Mair, 1959; Smith, 1968) turned out to be illusory. The task is to simplify the mixture by fractionation and then search these fractions for characteristic components of high significance, such as biological markers as indicators of origin or selected PAHs as indicators of source and/or toxicity. White et al. (2016a) provided a helpful review of the analytical chemistry used to study the Macondo oil and samples taken to study the fates and effects processes. We present a brief synopsis and an update of what has been learned since that review.

Fractionation uses "dead oil" (i.e., the most volatile components have been evaporated so that they do not interfere with gravimetric determination of the proportions of the separated fractions). The process starts with removal of asphaltenes (as described earlier), which may otherwise precipitate during chromatography and cause bad separation performance.

Column chromatography, a technique for separating mixtures of organic compounds, involves dissolving the mixtures in a mobile phase and passing them through a column filled with a stationary phase. Compounds in the mixture have different affinities for the mobile and stationary phases. They are adsorbed onto the stationary phase and then, as the mobile phase flows through the column, separated and sequentially released and collected. A compound's residence time in the column depends on the stationary and mobile phases, and its boiling point, molecular size, molecular shape, and polarity. Column chromatography refers to the use of a vertical glass column filled with silica gel or aluminum oxide, as stationary phase; an organic solvent dripped into the top of the column, as mobile phase; slow percolation through the column under the force of gravity; and separated groups of compounds collected as they drip out the bottom. In a more general sense, thin-layer chromatography (TLC), medium-pressure liquid chromatography (MPLC), high-performance liquid chromatography (HPLC), and preparative gas chromatography (prep GC) are forms of chromatographic separation with different stationary and mobile phases (e.g., Vitha, 2016). This initial step is occasionally followed by further fractionation including separation of straight-chain, branched, and cyclic saturated hydrocarbons by (thio)urea adduction or application of zeolites with different pore sizes (e.g., Peters et al., 2005a), or by separation of aromatic hydrocarbons into classes of different ring numbers (e.g., Radke et al., 1984).

Even after fractionation, the identification of individual constituents of crude oils and related substances is not straightforward. A breakthrough in the 1970s was the development of capillary columns a few tens of meters in length and internally coated with different types of silicone oil as stationary phases. Shortly after, this was followed by the construction of devices for coupling such columns to fast-scanning mass spectrometers with connected computers for data processing. Continuous development of the gas chromatography-mass spectrometry (GC-MS) technique over about two decades was the basis for a rapid increase in understanding of the molecular composition of organic matter in sedimentary rocks and petroleum, and of changes in its composition as a function of geological and environmental conditions.

The straight-chain alkanes (*n*-alkanes) and isoprenoid alkanes pristane and phytane that are abundant in most unaltered crude oils can be identified and quantified by gas chromatography with flame ionization detection (GC-FID; e.g., Peters et al., 2005a). (This rarely applies to other compounds, which may not have the regular retention time pattern on a GC column or are abundant enough for easy detection.) They require the power of mass-specific detection and benefit from the fact that entire groups of saturated hydrocarbon biomarkers have a common mass spectrometric key fragment. Thus, mass chromatograms, which by a factor of about 30 are more sensitive than entire mass spectra, reveal the presence of the full range of these compounds (e.g., Peters et al., 2005b; Overton et al., 2016). An even further advanced mass spectrometric detection technique, mass fragmentography (GC-MS-MS), further increases the sensitivity by another factor of up to five and is also more compound-specific than mass chromatography (e.g., Summons et al., 1999; He et al., 2018).

Similarly, comprehensive two-dimensional gas chromatography (GC×GC) increases the resolution of complex mixtures. Gaines et al. (1999) published an early application of this technique to a marine oil spill. Using two sequentially coupled gas chromatographic columns with different separation efficiencies related to molecular properties (e.g., volatility and polarity), GC×GC produces a two-dimensional retention surface, which significantly improves compound identification compared to the one-dimensional retention data of a normal GC column. Compounds with similar chemical structures are grouped together in the chromatogram, allowing rapid preliminary identification with even minor components being separated and detectable. The GC×GC technique considerably matured scientifically in the course of the GoMRI research. It was intensely used to examine changes in the abundance of Macondo oil constituents, and the products were ascribed to various categories of physical and chemical weathering (e.g., Hall et al., 2013; Aeppli et al., 2014, 2018; Gros et al., 2014, 2016).

The two-dimensional retention surfaces from GC×GC analysis of crude oils and their transformation products after an oil spill, despite the additional dimension of separation, are still very complex. Figure 4 illustrates the principles of this technique for a simple case study. Aeppli et al. (2013) analyzed oil sheens that were first observed in September 2012 close to the DWH disaster site more than two years after the Macondo well had been sealed. Linear unsaturated alkenes common in synthetic drilling fluids led them to identify an 80-ton cofferdam, abandoned during the operation to control the Macondo well in May 2010, as the source of the sheens. Figure 4a–d compares the GC×GC data for the cofferdam oil, an oil sheen sample, the hydrogenation product of the oil sheen sample, and drilling mud from the multi-purpose supply vessel *HOS Centerline*, which supplied drilling mud during the Top Kill and Static Kill operations at the DWH site. The more polar alkenes occur slightly higher on the second dimension separation (y-axis) than the *n*-alkanes. The white dashed lines in the four diagrams denote the surface where drilling-mud olefins elute. The compounds have disappeared in the oil sheen hydrogenation product because the alkenes were transformed into *n*-alkanes (see Figure 4 caption).

Even with the expanded compositional information from GC×GC (Hall et al., 2013), GC-based techniques are unable to detect many oxidation products, notably those that are highly oxidized with boiling points or thermal stabilities outside of the GC range (Aeppli et al., 2018). As determined through ultrahigh resolution mass spectrometry (FT-ICR MS), elemental assignments for tens of thousands of molecules in the native (unaltered) and weathered Macondo oil revealed the chemical changes induced by weathering (Figure 5d; Ruddy et al., 2014). Subsequent analysis of different crude oil fractions (oil-soluble non-interfacially active, oil-soluble interfacially active, and water soluble) indicated that decreasing carbon and increasing oxygen numbers determined the progression of molecules from oil-soluble to water-soluble (Zito et al., 2020). Thus, weathering-induced chemical changes (see arrows in Figure 5) were linked to changes in oil solubility. Both the oil- and water-soluble photo-transformed species span aliphatic to highly aromatic structures (Ruddy et al., 2014; Niles et al., 2019), indicating that these products originate from both aliphatic and aromatic hydrocarbon precursors (Hall et al., 2013). These results suggest that both direct and indirect photo-oxidation contributed to the generation of most of the transformation products identified in field samples. Thus, FT-ICR MS developed into an extremely powerful technique for analyzing high-molecular-weight and polar constituents of crude oil and its transformation products within GoMRI research and for an understanding of the fate of petroleum during weathering.

FT-ICR MS was responsible for only part of the progress made in molecular insight into oil spill processes. The complexity of oil required a suite of analytical tools to comprehensively explore weathering mechanisms and products (Figure 5a–d). In addition to the GC-based and FT-ICR MS tools described above, thin-layer chromatography-flame-ionization detection (TLC-FID; Aeppli et al., 2012) and Fourier-transform infrared spectroscopy (FT-IR; White et al., 2016b) provided quantitative and informative estimates of functional group changes from weathering processes.

Evans Seeley et al. (2018) followed a different route to unravel the complexity of weathered petroleum from the DWH oil spill. They explored the analytical capabilities of ramped pyrolysis-gas chromatography–mass spectrometry (py-GC–MS) and showed that bulk-flow py-GC–MS can quantify the overall degree of petroleum hydrocarbon weathering. Furthermore, thermal slicing py-GC–MS can quantify specific compounds in the "thermal desorption zone" (50°–370°C), as well as characterize pyrolyzed fragments from non-GC-amenable petroleum constituents (including oxidation products) in the "cracking zone" (370°–650°C). Their data suggest an increase in thermodynamic stability, concentration of oxygenated products, and complexity of high-molecular-weight and/or polar components with advanced weathering. Wang et al. (2020) further applied this approach to gain insight into formation mechanisms and structures of some of the asphaltenes generated by photo-oxidation.

Stable carbon and hydrogen isotopes are widely used to characterize crude oils and their constituents (cf. Table 2). For tracing the fate of the Macondo oil spilled during the DWH disaster (i.e., mixing with organic matter of recent origin on the seafloor or the incorporation of carbon from the microbial transformation of Macondo oil components into biomass and food webs), measurement of the radioactive carbon (^{14}C) contents of sedimentary and biological substrates was the method of choice. Because it has been so long since the petroleum source organic matter was buried and transformed from plant biomass into petroleum, the ^{14}C isotopic content of petroleum is zero when compared to recently produced plant biomass (Chanton et al., 2015). Thus, radiocarbon contents lower than those of fresh biomass indicate mixing with petroleum-derived carbon.

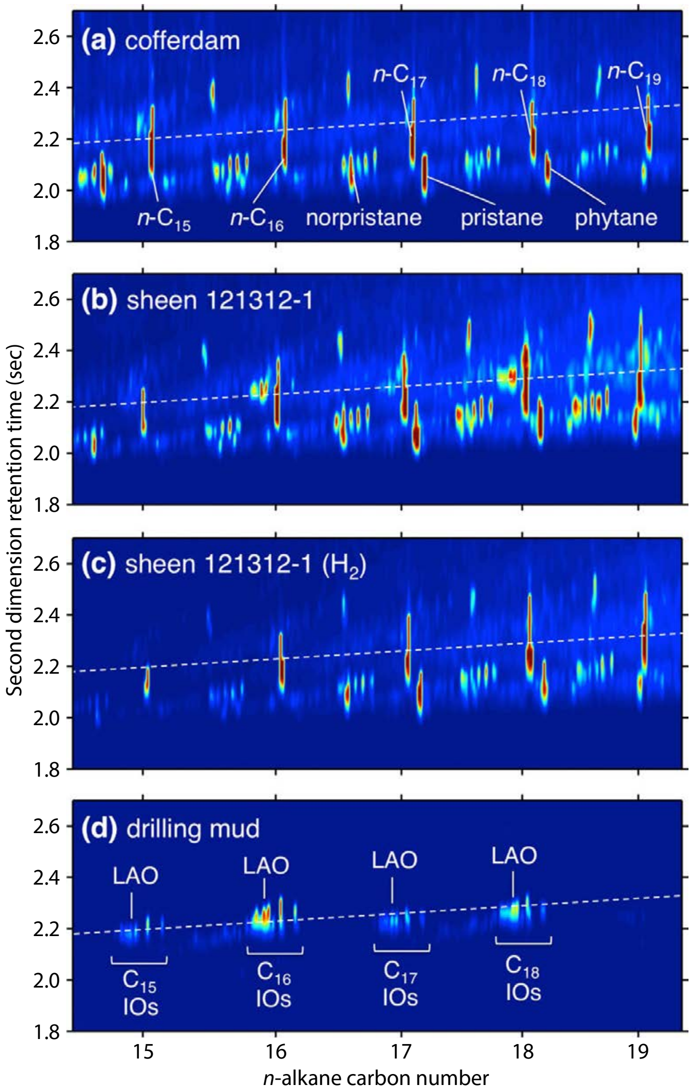

FIGURE 4. Partial two-dimensional gas chromatography flame-ionization detection (GC×GC-FID) chromatograms of (a) cofferdam oil, (b) oil sheen 121312-1, (c) hydrogenated oil sheen 121312-1, and (d) drilling mud from the multi-purpose supply vessel *HOS Centerline*. White dashed lines denote the surface locations where drilling-mud olefins elute. The sum of the C_{16}-, C_{17}-, and C_{18}-olefins relative to the whole FID signal was 1.2% in the sheen sample (b) and not detectable in the cofferdam oil (a). The olefins in the sheen sample disappeared upon hydrogenation and exhibited a pattern like that of pure drilling mud, which represents an isomer mixture of C_{15} to C_{18} internal olefins that includes one linear α-olefin per carbon number. The data are displayed as color contour plots, with blue representing low signal, yellow representing medium signal, and red representing high signal. In order to visualize minor peaks, the plotted dynamic range is less than the total dynamic range of the sample, with the intensity saturated near the point of maximum elution. *Reprinted with permission from Aeppli et al. (2013). Copyright 2013 American Chemical Society*

As summarized by Kujawinski et al. (2020), dioctyl sodium sulfosuccinate (DOSS) was used to track the fate of the deep-sea dispersants applied for spill mitigation during the DWH disaster; this compound was selected because it comprises a large and relatively constant fraction of Corexit and other dispersant formulations, and it was amenable to existing analytical protocols. Samples taken during and a few months after the disaster indicated that DOSS persisted in the subsurface intrusion and was not degraded (Kujawinski et al., 2011), contrary to expectations based on laboratory experiments performed under surface conditions (Baelum et al., 2012). These data suggest that some of the chemical dispersant components were not degraded appreciably in the deep sea in the aftermath of the DWH disaster. Subsequent laboratory work showed that DOSS was less labile than the solvent carriers in the dispersants under deep-sea conditions (Baelum et al., 2012), and others found minimal degradation of DOSS at low temperatures (Campo et al., 2013), further supporting this conclusion.

IN SITU BURNING OF OIL AT THE SEA SURFACE

In situ burning (ISB) of spilled oil on the surface of the water (see photo on first page of this article) is controversial because of concerns about chemicals produced and/or released to the atmosphere during the burn process and concerns about the chemicals left in the unburned residues at the water-atmosphere interface or in the unburned slick (Stout and Payne, 2016). During the DHW spill response, an estimated 220,000–313,000 barrels of oil at the ocean's surface were removed during 411 carefully conducted ISB operations. This estimated 5% of the spilled oil (Schaum et al., 2010) is considered to have "played a significant role in reducing the amount of oil on the water's surface" (NOAA Office of Response and Restoration, 2020). For comparison, the 5% Macondo oil removed by ISB is roughly equal to the estimated total oil released during the 1989 *Exxon Valdez* tanker accident (Stout and Payne, 2016).

The ISB operations were informed by experience gained between the 1970s and 2010 from laboratory tests, controlled field experiments, and a few oil spill responses (e.g., Fritt-Rasmussen and Wegeberg, 2015; Gullet et al., 2017; Bullock et al., 2019, and references therein). The different mixes of gas and oil and their variable compositions, and environmental conditions such as temperature and wind, can influence the efficiency of ISB and the composition of products formed. Burning of oil yields mainly carbon dioxide and water. According to a liter-

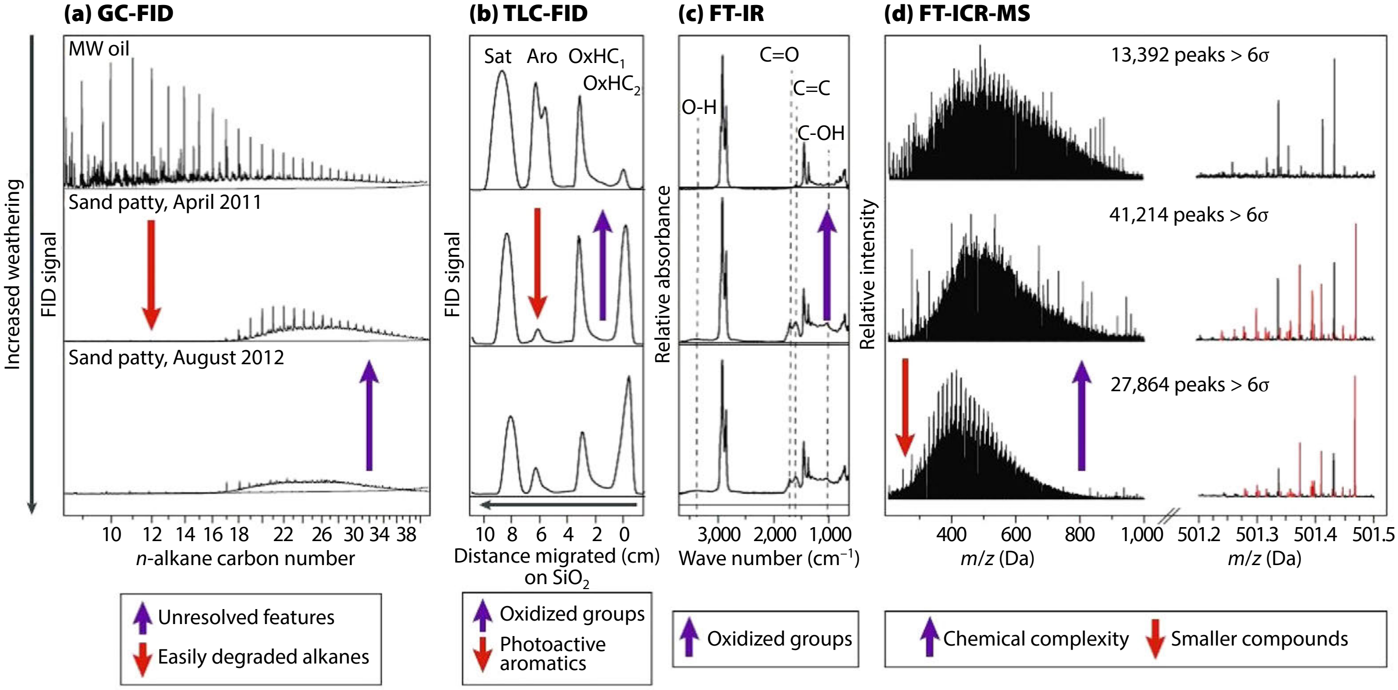

FIGURE 5. Analysis of Deepwater Horizon oil and field sample chemical compositions. Four different techniques capture the collective effects of abiotic and biotic weathering on oil (initial oil spectra along top row), which are manifested in changes of: (a) gas chromatography flame-ionization detection (GC-FID) chromatograms, (b) thin-layer chromatography flame ionization detection (TLC-FID) chromatograms, (c) Fourier transform-infrared (FT-IR) absorbance, and (d) broadband Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) spectra. Field samples include sand-oil patties collected from Gulf of Mexico beaches. Overall, weathering led to degradation of saturated and aromatic compounds leaving recalcitrant compounds in the unresolved complex mixtures, an increase in oxidized hydrocarbon (OxHC) fractions relative to saturated and aromatic hydrocarbon compounds, and increases in hydroxyl and carbonyl functional groups. The negative ion mode ESI FT-ICR MS revealed a complexity increase in the number of peaks (from *m/z* 200–1,000), and the appearance of oxygenated species (red peaks) in a mass-scale expanded 400 mDa segment at 501 Da. Similar molecular information is available for all other nominal masses in the mass spectrum. *Reprinted from Kujawinski et al. (2020) with permission from Springer Nature; panels a–c were adapted from Aeppli et al. (2012) with permission from the American Chemical Society*

ature compilation of different oil burning experiments using various substrates (Booher and Janke, 1997, mostly based on the work of D.D. Evans, National Institute of Standards and Technology, in the early 1990s), products of burning oil, excluding water, are about 92% carbon dioxide, 3.2% carbon monoxide, 4.6% smoke (soot/black carbon), 0.03% PAHs, and 0.27% volatile organic chemicals (VOCs). Of the VOCs, about 0.14% are C_2-C_6 hydrocarbons and 0.12% are C_1-C_{16} aldehydes/ketones (organic compounds escaping complete combustion), 0.9% SO_x and 0.0004% NO_x (Figure 6a).

Gullett et al. (2017) performed laboratory-scale experiments by burning representative crude oil in two outdoor pans with areas of 0.47 m^2 and 0.93 m^2. The pans were filled with seawater and a Strategic Petroleum Reserve Bayou Choctaw Sweet crude oil reported to have chemical composition and physical characteristics similar to that of the Macondo oil. They measured 82% carbon dioxide, 2.5% carbon monoxide, 7.0% total particulate matter, 0.34% volatile organics, and 0.10% PAHs in the resulting smoke (Figure 6b), but because 7.6% of products were not accounted for among the components listed, the differences from the Booher and Janke (1997) compilation are not substantial.

US NOAA aircraft-based measurements during active surface burning of Macondo oil slicks led to estimates of 4% of the burned material or an estimated 1.35 ± 0.72 thousand tonnes released as black carbon into the atmospheric plume (Perring et al., 2011). Those authors reported the black carbon particles had little non-refractory material and were typical of black carbon from fairly efficient fossil fuel burning.

The combustion products of main concern were residues of black carbon and other components of soot. Most attention focused on PAHs formed during combustion and associated with the soot and black carbon. Combustion-derived PAHs have an overlapping chemical composition with PAHs native to crude oils. Numerous studies have shown that PAHs from combustion sources contain more of the parent, non-alkylated PAHs compared to crude oils and fuel oils, with the predominance of the parent, non-alkylated PAHs increasing with higher temperatures of combustion (e.g., Lima et al., 2005). The composition of the PAHs associated with the soot and black carbon were assessed by several studies that measured mainly a number of parent PAHs in the molecular range of naphthalene through benzo[*ghi*]perylene (e.g., Gullett et al., 2016, 2017). Insights into the general mechanisms of rapid molecular clustering that could lead from combustion-formed PAHs to black-carbon soot in general are provided by Johansson et al. (2018).

There is a paucity of published data for the chemical composition of ISB residues (i.e., the tarry, flakey-like material found floating at the surface near or in oil slicks subjected to ISB). This is understandable. Air sampling and the smoke plume have taken priority in the past because of human health concerns (see Sandifer et al., 2021, in this issue, regarding factors that are considered in response options). Thus, it is fortunate that Stout and Payne (2016) collected two not-yet-cooled floating ISB residues immediately after ISB events. They also collected three ISB residues from the seafloor between 1,400 m and 1,440 m depth using coring and slurp gun samplers mounted on a remotely operated vehicle. All samples analyzed by gas chromatography and gas chromatograph-mass spectrometry showed some percent enrichment of pyrogenic PAHs mixed with unburned, relatively fresh Macondo oil when compared to samples of DWH oil slicks not subjected to extensive weathering. One ISB residue from the seafloor appeared to contain some admixed diesel fuel-like lower-molecular-weight hydrocarbons. The other two samples were similar in hydrocarbon composition to the ISB residues collected at the sea surface.

Stout and Payne (2016) estimated that most or all ISB residues eventually sank to the seafloor. ISB residues and their associated PAHs added to the uptake of toxic

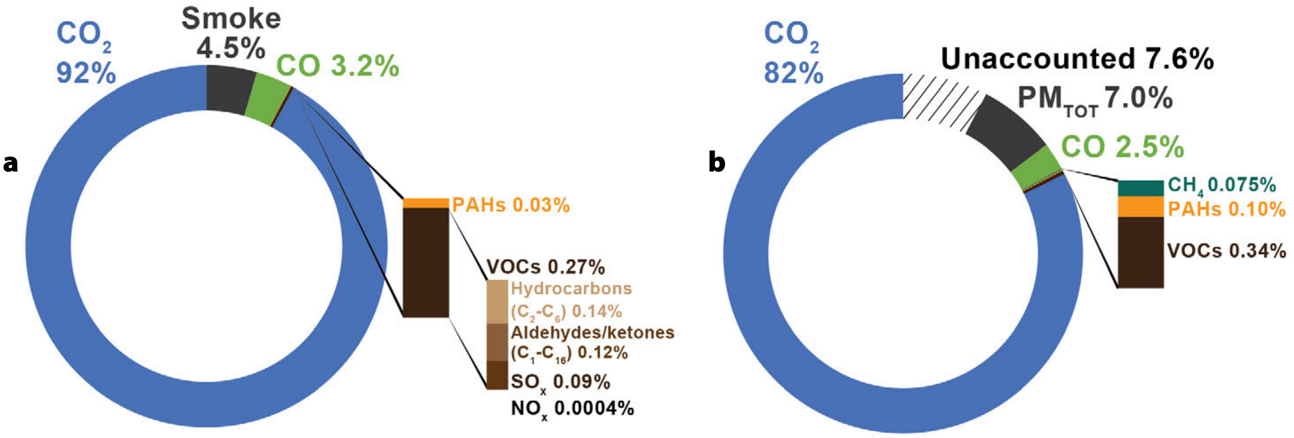

FIGURE 6. Fate of combusted oil into products (excluding water), by weight. (a) Percentages adapted from a literature compilation of Booher and Janke (1997). (b) Percentages of combustion products from experimental burning of a Strategic Petroleum Reserve Bayou Choctaw Sweet crude oil with reported chemical composition and physical characteristics similar to that of the Macondo oil (after Gullet et al., 2017). The amount of unaccounted material affects the relative proportions of the identified products. VOCs = Volatile organic compounds. PM_{TOT} = Total particulate matter.

materials and their potential adverse effects on benthic organisms (Murawski et al., 2021, in this issue). The composition of the PAHs in the floating ISB residues indicated definite loss of PAHs of lower molecular weight (e.g., naphthalene and alkylated naphthalenes), slightly less loss of phenanthrene and alkylated phenanthrenes, and less or no loss of the higher-molecular-weight PAHs relative to 17α-hopane used as a relatively stable internal hydrocarbon standard (see earlier discussion, although 17-α-hopane during ISB may not be as stable as during geothermal transformation or weathering). The sunken ISB residues contained some increase in relative concentrations of a few higher-molecular-weight PAHs indicative of contributions of combustion product PAHs to a petroleum or oil-type PAH mixture (Stout and Payne, 2016).

A US EPA 4.0 m diameter, helium-filled aerostat-lofted instrumentation package sampled plumes of 27 surface fires of various sizes using quartz filters and also polyurethane foam (PUF/XAD2/PUF) sorbent (Aurell and Gullett, 2010; Gullett et al., 2016). The samples were analyzed for polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). This assessment was undertaken because incomplete combustion of organic matter in the presence of chloride can form small amounts of PCDDs and PCDFs, and seawater admixed with the surface oil is potentially an abundant source of chloride. Aurell and Gullett (2010) reported that the analysis of a single composite sample resulted in an emission factor of 1.7 ng toxic equivalency (TEQ) of polychlorinated aromatics per kg of oil burned.

One unintended sampling occurred during the campaign described above when it was recognized that sail fabric of the aerostat collected fine particles that could be sampled, extracted, and analyzed for various chemicals such as PAHs (Gullett et al., 2016). The focus was the long-standing EPA Priority Pollutant PAHs (initially defined for water samples; see **Figure 3**) that are also common in combustion products. However, a few other PAHs were detected such as alkylated naphthalenes, methylfluorene, and methylpyrene, and their presence indicates that the sample may contain some lower-temperature combustion products.

Schaum et al. (2010) screened the low-level risks that could be attributed to "dioxin" emissions from burning of Macondo oil at the sea surface. The components of both the PCDD and PCDF groups are of serious concern for human health (e.g., Van den Berg et al., 2006). The screening level assessment by Schaum et al. (2010) indicated that human cancer risks from PCDDs/PCDFs formed during the ISB did not exceed 1×10^{-6}. They noted that US EPA "typically considers the risk range of 10^{-6} to 10^{-4} to be a range where consideration is given to additional actions." Schaum et al. (2010) found sparse sampling and analysis information on the generation of PCDDs and PCDFs prior to these studies of the Macondo oil ISB. These pioneering studies were limited in scope. However, they indicate that more studies of a similar nature under varying conditions for ISB of different types of oils are needed due to the human health risks associated with the PCDD/PCDF chemicals.

An intriguing laboratory-scale experiment of ISB of a slick on water surface was conducted by Jaggi et al. (2019) and assessed using FT-ICR MS, as described earlier. They reported that both unburned oil slicks and ISB result in the release of organic compounds to the water beneath a slick. An important finding was that ISB strongly increases the concentrations of oil-related chemicals entering the water phase as a result of production of oxidized organic compounds that are soluble in water. Jaggi et al. (2019) reported that this mixture was different in composition from the organic compounds entering the water from unburned oil in that the mixture from ISB contained significantly more condensed aromatic chemicals with varying amounts of the elements nitrogen, oxygen, and sulfur. This is an important finding that merits follow-up research in the laboratory and in the field. Jaggi et al. (2019) note: "The effect of these highly unsaturated and oxygenated organic species on oil spill fate and their ecosystem impact is currently unknown."

CHALLENGES

Analytical Chemistry Methods and Applications

The complexity of oil, including the Macondo oil, represents a challenge even with present advances in analytical chemistry. During research to elucidate the fates and effects of the DWH spilled oil (Farrington et al., 2021; Halanych et al., 2021; and Murawski et al., 2021, all in this issue), inconsistencies were noted in the various analytical methods used or in which chemicals were measured. For example, investigators might measure different sets of specific PAHs, thus complicating comparison of total PAHs from different parts of the Gulf of Mexico. The same applies to ascribing a particular type and intensity of effect to the presence of individual chemical components or types of components in the Macondo oil or weathered, transformed, and/or biodegraded oil. This is the result, in part, of researchers asking different research questions or using their preferred methods, and that poses additional problems and uncertainties. Thus, while some researchers utilized GC×GC-MS, others employed single column fused-silica capillary GC with FID or GC-MS detection.

The US National Institute of Standards and Technology (NIST) prepared a Standard Reference Material for a reasonable number of Macondo oil hydrocarbons to assist with quality control and quality assurance of analyses (NIST, 2020). Pairs of this sample and a sample of the Macondo oil that had been field-weathered (Candidate SRM 2777) were distributed to laboratories involved in GoMRI research plus several others. The report of the results of this GoMRI quality control/quality assurance laboratory intercomparison is available as a NIST report (Murray et al., 2016). It provides a basis for assessing potential uncertainties when comparing analyses from the laboratories involved. These uncertainties are similar to those that became evident from an interlaboratory comparison published nearly two decades ago at the end of the Cooperative Monterey Organic Geochemistry Study based on rock samples from Naples Beach and Lions Head sections of the Monterey Formation and related Monterey crude oils (Isaacs, 2001). An informative and thorough discussion of the use of intralaboratory and interlaboratory quality assurance/quality control for the laboratories involved in the US NOAA DWH Natural Resource Damage Assessment analyses for petroleum compounds is available in Litman et al. (2018).

Only a few GoMRI researchers had access to or employed FT-ICR MS analyses. This most likely was due to the expense of the instrument and fewer people having familiarity with the method at the time. There are relatively few advanced high magnetic FT-ICR MS instrument facilities in the world. Fortunately, GoMRI research did involve the National High Magnetic Field Laboratory at Florida State University (https://nationalmaglab.org/user-facilities/icr). The researchers at this laboratory collaborated with several other GoMRI researchers to provide new insights into the composition of the asphaltenes and other high-molecular-weight chemicals native to the Macondo oil and also to provide key insights into photochemical reaction pathways and products of these reactions as noted in references cited previously. Despite these important insights, the exact molecular structures of these chemicals remain to be elucidated. Thus, the detailed pathways of, for example, some of the photo-oxidation reactions and their products remain a challenge.

Agencies responsible for oil spill response and assessment of the fates and effects of spills are challenged with planning for appropriate incorporation of these advanced analytical methods into their response and assessment activities.

CONCLUSIONS

Assessment of the full impact of the petroleum released during the Deepwater Horizon oil spill on Gulf of Mexico flora and fauna, and on human health in the region, requires determination of the quantities of materials that entered the environment, including the amounts of dispersants used during spill mitigation. In addition, chemical analysis of the composition of the released materials and their relative proportions are of similarly high importance.

Chemical analyses of the released petroleum and the products of physical, chemical, and biological alteration were performed using a wide range of techniques that were developed in analytical chemistry, petroleum organic geochemistry, and environmental chemistry over several decades since the 1970s. In addition, more advanced techniques like the sequential combination of two gas chromatographic columns with different separation efficiencies (GC×GC) and ultrahigh-resolution mass spectrometry (FT-ICR MS) were the methods of choice for shedding light on the complex mixtures of high-molecular-weight and very polar petroleum constituents, particularly those newly formed during photo-oxidation of liquid oil. Photo-oxidation is a very important, but hitherto underestimated, weathering process. Together, this suite of analytical methods provided not only an inventory of the most important constituents of the released petroleum but also a greater understanding of the reaction mechanisms of weathering processes such as photo-oxidation and the identity of its transformation products, as well as their impacts on physical properties, bioavailability, and toxicity of the discharged oil. Expanded understanding, combined with application of complementary analytical techniques, will inform real-time responses in future oil spills.

Finally, important insights have been gained in the past 10 years about the chemical composition of products of in situ burning of oil at the water surface. However, field assessment and laboratory data are limited, and these exciting new insights need further research to provide much needed information on in situ burning.

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AUTHORS

Jürgen Rullkötter (juergen.rullkoetter@uni-oldenburg.de) is Professor (retired), Institute of Chemistry and Biology of the Marine Environment, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany. **John W. Farrington** is Dean Emeritus, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.

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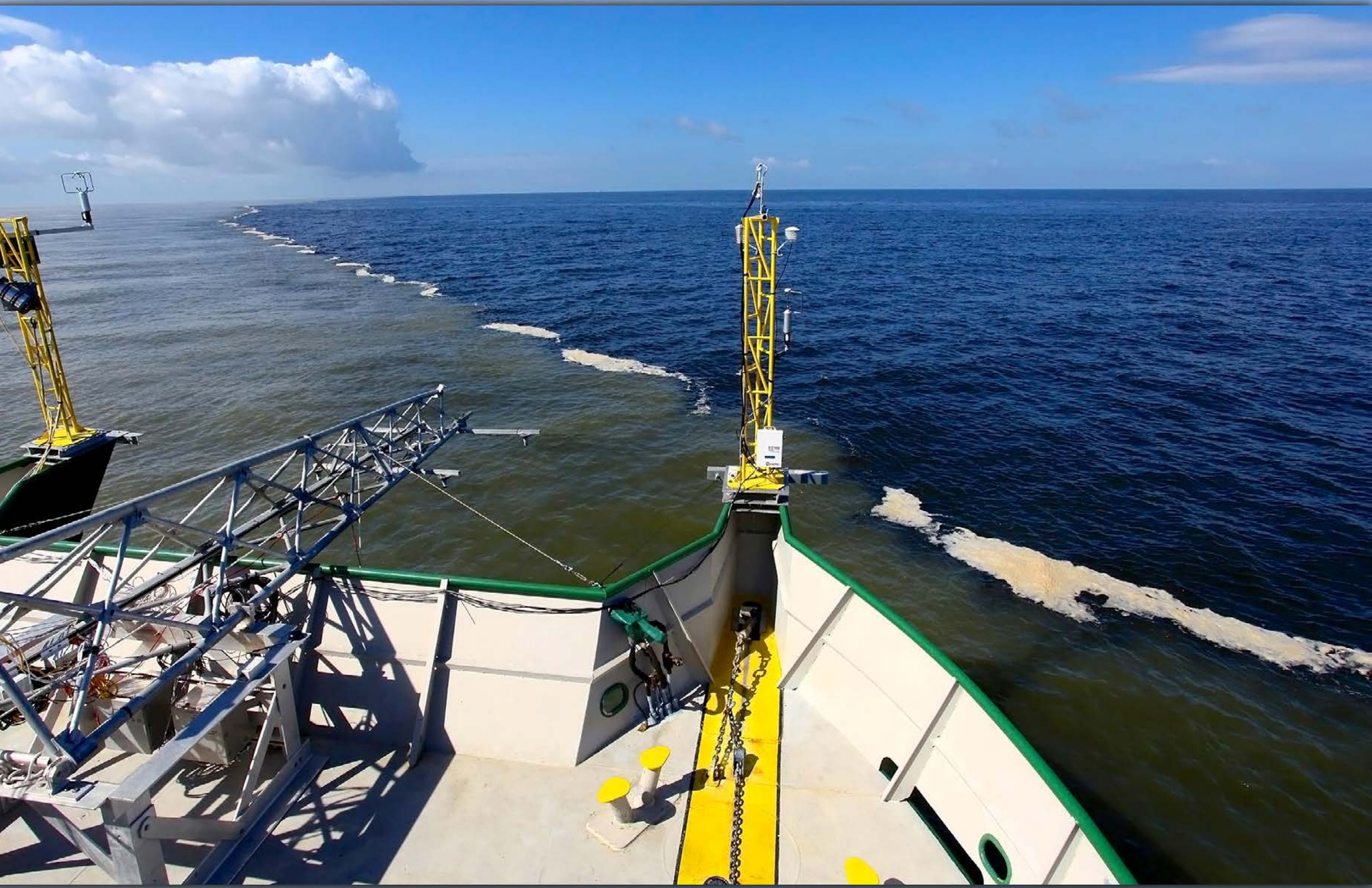
Physical Transport Processes that Affect the Distribution of Oil in the Gulf of Mexico

OBSERVATIONS AND MODELING

By Michel Boufadel, Annalisa Bracco, Eric P. Chassignet, Shuyi S. Chen, Eric D'Asaro, William K. Dewar, Oscar Garcia-Pineda, Dubravko Justić, Joseph Katz, Vassiliki H. Kourafalou, Ian R. MacDonald, Tamay M. Özgökmen, Claire B. Paris-Limouzy, Scott S. Socolofsky, David Halpern, and John G. Shepherd



View from R/V *Walton Smith* where Gulf of Mexico and Mississippi River waters meet. *Photo credit: Tamay Özgökmen*

ABSTRACT. Physical transport processes such as the circulation and mixing of waters largely determine the spatial distribution of materials in the ocean. They also establish the physical environment within which biogeochemical and other processes transform materials, including naturally occurring nutrients and human-made contaminants that may sustain or harm the region's living resources. Thus, understanding and modeling the transport and distribution of materials provides a crucial substrate for determining the effects of biological, geological, and chemical processes. The wide range of scales in which these physical processes operate includes *microscale* droplets and bubbles; *small-scale* turbulence in buoyant plumes and the near-surface "mixed" layer; *submesoscale* fronts, convergent and divergent flows, and small eddies; larger *mesoscale* quasi-geostrophic eddies; and the overall *large-scale* circulation of the Gulf of Mexico and its interaction with the Atlantic Ocean and the Caribbean Sea; along with air-sea interaction on longer timescales. The circulation and mixing processes that operate near the Gulf of Mexico coasts, where most human activities occur, are strongly affected by wind- and river-induced currents and are further modified by the area's complex topography. Gulf of Mexico physical processes are also characterized by strong linkages between coastal/shelf and deeper offshore waters that determine connectivity to the basin's interior. This physical connectivity influences the transport of materials among different coastal areas within the Gulf of Mexico and can extend to adjacent basins. Major advances enabled by the Gulf of Mexico Research Initiative in the observation, understanding, and modeling of all of these aspects of the Gulf's physical environment are summarized in this article, and key priorities for future work are also identified.

THE VIEW FROM ABOVE: OBSERVATIONS OF SURFACE OIL

Important advances have been made in ocean observing through both in situ and remote-sensing technologies that include drifters, satellite and aircraft sensors, and high-frequency ocean radar (HFR) systems, tools that are especially useful for determining transport at and immediately below the ocean surface (Morey et al., 2018; Rodríguez et al., 2018). Data collected using these methods show that the velocities measured right at the ocean surface, as opposed to many centimeters or meters below it, are much greater than previously thought, and these differences need to be accurately represented in models (Le Hénaff et al., 2012; Wenegrat et al., 2014). From April 22 to August 2, 2010, every available satellite was tasked with observing the northeastern Gulf of Mexico at every possible opportunity. Their collective mission was to detect floating oil that reached the ocean surface from wreckage of the Deepwater Horizon (DWH) rig and the blowout of the exploration well in the Macondo MC252 lease block. The effort yielded an unprecedented data set comprising over 200 optical and 600 synthetic aperture radar (SAR) scenes that imaged portions of a surface oil layer (slick) that covered an average of 11,200 km^2 (sd 5,028) for 87 days. The slick's "footprint" changed on an hourly basis as the oil drifted with wind and currents, sank and resurfaced, landed on the Gulf coast, and ultimately dissipated.

This summary focuses on results from analysis of 166 of these high-resolution SAR images of small-scale sea surface elevation and roughness conducted under the auspices the NOAA National Resource Damage Assessment (NRDA) program, with additional support from the Gulf of Mexico Research Initiative (GoMRI) ECO-system impacts of fluid and Gas Inputs from the Geosphere (ECOGIG) I and II consortia (MacDonald et al., 2015). Satellite SAR images detect floating oil layers because oil suppresses small capillary and gravity waves, thus creating a smooth surface that deflects radar energy more effectively than does surface water that is free of oil. These oil layers are imaged as dark patches that contrast with the unoiled sea (Garcia-Pineda et al., 2013b). The contrast is most visible when wind speeds are moderate, in the range of 2–10 m s^{-1} (Daneshgar Asl et al., 2017). Unlike optical sensors, satellites with SAR detectors function irrespective of cloud cover or time of day (Leifer et al., 2012). The SAR scenes used in the study originated from Radarsat-1, Radarsat-2, TerraSAR-X, CosmoSKY-MED 1-2-3-4, ENVISAT, ALOS-1, and ERS-2. The resolution of this large SAR data set ranged from 10 m to 25 m per pixel over 25 km to 450 km swaths. The Gulf of Mexico region where oil was detected in each SAR scene was gridded at a 5 km scale so that results could be summarized across large ocean areas in a time lapse throughout the duration of the spill (Holmes et al., 2017).

The NRDA team developed two innovative approaches to further analyze the data. While each scene generally covered hundreds of square kilometers, the total extent of the floating oil was often much greater in area; thus, each image captured only samples of the larger phenomenon. To obtain an interpolated and gridded time series showing the areal extent of the entire oil slick at 12 h intervals, MacDonald et al. (2015) authors Solow and Beet developed a statistical method in which the oiled areas detected in each SAR scene were treated as unbiased samples of the total oil layer. Images of floating oil slicks were highly patchy and heterogeneous in apparent thickness. To estimate the volumes of oil represented by different portions of the oil layer, Garcia-Pineda et al., 2013a,b) developed image-processing methods that analyzed the signal strength of SAR pixels to distinguish between "thin" or "thick" layers (nominally 1 μm and 72 μm, respectively).

Results could be interpreted in relation to environmental factors (e.g., wind speed), the rate of discharge from the well, and in the context of response operations such as surface oil burning and application of dispersant by aerial and submarine methods. Figure 1 shows the average extent of surface oil in units of m^3 km^{-2}. An animation of the 12 h estimates, augmented with data wind speed can be viewed at https://www.youtube.com/watch?v=v1kkniG7atA&t=4s, and origi-

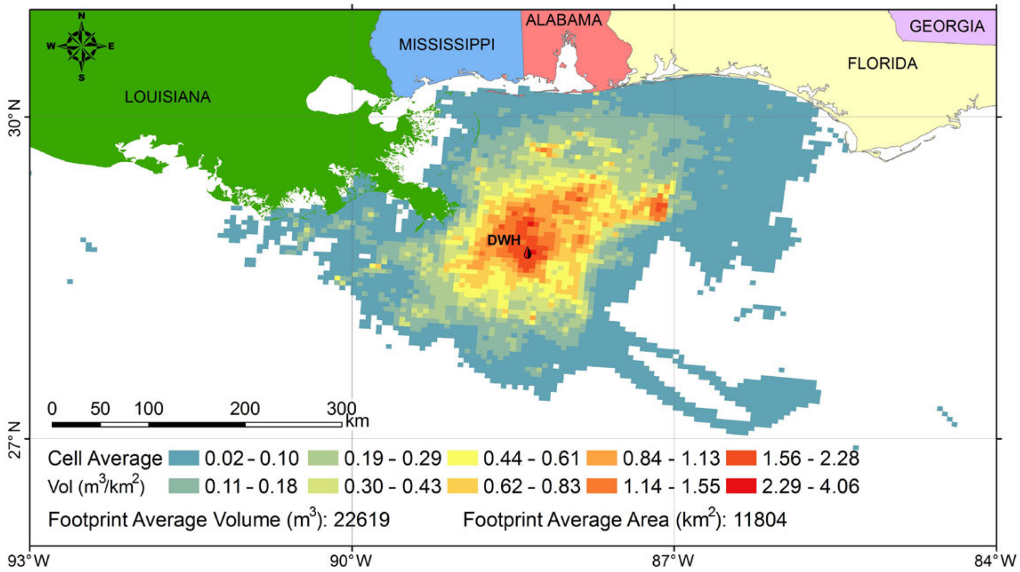


FIGURE 1. Distribution and average volume of surface oil (m^3 km^{-2}) from the Deepwater Horizon (DWH) discharge, gridded at 5 × 5 km scale across a cumulative footprint of 149,000 km^2, from April 24, 2010, to August 3, 2010. *From Figure 3 in MacDonald et al. (2015)*

nal data can be retrieved from the GRIIDC database (MacDonald, 2019).

The unprecedented remote-sensing data set has been used not only to better understand the extent and impact of the DWH spill but also to develop better methods and technologies for detecting oil spills. For example, during the spill in 2010, it could take several days to provide spill responders with a processed satellite image; this process has now been narrowed to a matter of minutes. In parallel, methods for extracting more detailed characterizations of the floating layers of oil from SAR satellite images (emulsification, thicknesses, and/or discerning false positives) have also been substantially improved.

The findings from this study have been used in a number of subsequent investigations, including how floating oil impacts benthic deposition by marine snow (Daly et al., 2016); the responses of the microbial community to the spill (Joye et al., 2016b); the spill's impacts on seabirds (R.M. Huang et al., 2017), fishes (Price and Mager, 2020), and cephalopods (Romero et al., 2020); and the extent of fishery closures (Berenshtein et al., 2020). One novel result concerned the possible impact of dispersant applications. There were two roughly equivalent periods of the oil spill during which winds were low and oil slicks could spread with reduced mixing from wave action: peaks in the total area and the volume of the floating oil layer were observed on May 23 and June 18, 2010. Between these peaks, the total volume of floating oil decreased by 21%, while the ocean area over which the floating oil spread increased by 49% (Figure 2). On approximately June 3, responders began application of up to 50,000 L d^{-1} of Corexit dispersant directly into the discharging oil plume at depth (Lehr et al., 2010). Thus, the satellite data suggest that the submarine dispersant application may have achieved a reduction in the total volume of surface oil, but with the side effect of increasing the area over which the residual volume was dispersed. In addition, after June 1–3, the damaged end of the riser of the well was cut off, and a new cap/collection system was installed that siphoned off ~15,000 barrels per day, or 20%–25% of the oil released (Griffiths, 2012), also contributing to the measured decrease in floating oil. It is hoped that this experiment in satellite remote sensing of an oil spill will not be repeated, but the data obtained were and will remain an important resource for understanding the dynamics of floating oil in the marine environment.

MICROSCALE PHYSICAL (AND BIOPHYSICAL) PROCESSES

GoMRI research included a series of studies focused on measuring and modeling the very small-scale physical and chemical processes that affect the interactions of oil with the marine environment. These investigations include: (a) physical breakup of oil slicks by waves and the associated effects of dispersants; (b) measuring and modeling the breakup and droplet generation in submerged oil jets and plumes; (c) applications of Large Eddy Simulations (LES) to simulate coherent oil plumes in the marine environment; (d) characterization of interfacial phenomena involving oil, dispersants, and bacteria, and mass transport at oil-water interfaces; and (e) phenomena involving the aerosolization of oil. All of these aspects are discussed below.

Breakup of Oil Slicks

Wave tank measurements (C. Li et al., 2017; Afshar-Mohajer et al., 2018) provide a comprehensive database on the spatial and temporal size distribution of subsurface droplets as a function of wave energy, dispersant concentration, oil viscosity, depth, and time after wave breaking. The measured time evolution of turbulence in the tank has been used for correlating the evolution of droplet size distribution to their subsurface transport. As expected, for fresh crude oil without dispersant, after wave breaking, the measured rate of droplet disappearance from the water column increases with buoyancy and with droplet size. This can be predicted based on a solution to an

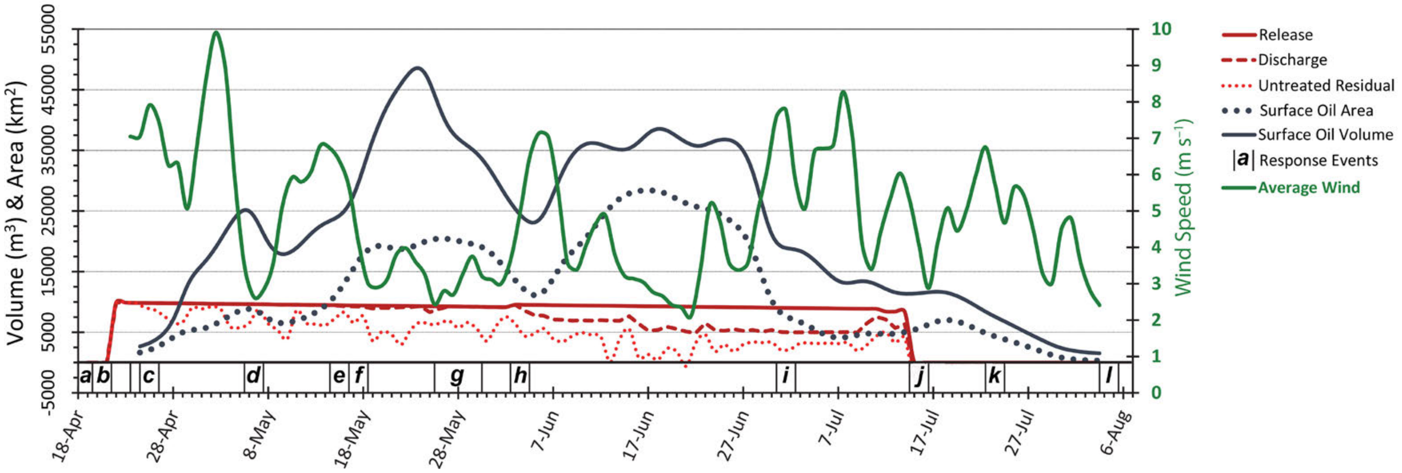


FIGURE 2. Time series of DWH discharge during 2010, plotted with surface oil and average wind speeds. Release magnitudes show best daily estimates of oil escaping from the damaged well. Discharge subtracts the oil recovered from the gross release, while treatment further subtracts that burned and dispersed by aerial and subsea applications of Corexit at maximum efficacy. Response events that potentially affected the spread of surface oil are: (a) Macondo well blowout occurs, (b) DWH drillship sinks and release begins, (c) aerial dispersant application begins, (d) containment dome attempt fails and burning of surface oil begins, (e) subsea dispersant campaign begins (May 5), (f) flaring of recovered oil begins, (g) top-kill attempt made, (h) riser is cut from blowout preventer and direct oil collection subsea and injection of subsea dispersant begins, (i) Hurricane Alex makes landfall, (j) capping stack closure stops release, (k) Tropical Storm Bonnie makes landfall, and (l) well is killed by static backfill. *From Figure 7 in MacDonald et al. (2015)*

unsteady advection–diffusion (turbulent) equation, and the characteristic droplet sizes are consistent with models involving turbulent Weber numbers.[1] The results have subsequently been used for validating predictions of wave breaking and for modeling oil transport after spills, and also to support parallel numerical simulations and characterization of chaotic phenomena in wave breaking (Wei et al., 2018). Application of dispersant (Corexit 9500) causes major changes in droplet size distributions, reducing the concentration of millimeter-size droplets and increasing the concentrations of microdroplets. For a dispersant-to-oil ratio (DOR) of 1:25 in particular, the micron-scale droplets are generated by an interfacial phenomenon called tip streaming (Gopalan and Katz, 2010). This phenomenon involves generation of long oil strings that extend from separation points on the surface of the droplet. The Weber-number-based predictions of droplet sizes do not account for these interfacial phenomena, and hence they overpredict droplet sizes. A computational study aimed at elucidating the causes for tip streaming (Tseng and Prosperetti, 2015) shows that it is generated by an instability that occurs near special points on the interface. Wherever the flow at the interface is locally convergent, any small perturbation on the interface tends to grow because of the combination of compression and viscous shear stress. The effect of surface tension opposes this growth, but its influence is inhibited in the presence of surfactants, especially because the convergent flow also accumulates the surfactants in its vicinity.

Droplets in Oil Jets and Plumes

Considerable effort has been made to measure and model droplet size distributions in jets and plumes. Relying on classical turbulent models, Johansen et al. (2013) introduced a semi-empirical Weber-number-based model for the size of oil droplets in jets that has been subsequently updated using experimental data (Brandvik et al., 2013, 2014; Johansen et al., 2013, 2015). They also characterized depth effects (Brandvik et al., 2019), and introduced new methods for classifying oil droplets, particles, and bubbles based on their quasi-silhouette images (Davies et al., 2017). Corrections for large jets, which account for the maximum possible droplet size, are discussed by Z. Li et al. (2017a,b). These models also account for the effect of dispersant through reduction of the interfacial tension, but not for the interfacial processes, such as tip streaming, which is believed to be responsible for generating micron-size droplets Murphy et al., 2016; Zhao et al., 2017). Another approach, the VDROPJ model (Zhao et al., 2014a) uses the droplet population dynamical model VDROP (Zhao et al., 2014b) and applies it to control volumes in the near fields of the jet/plume, thus allowing for changes in jet hydrodynamics to impact the size distribution. VDROP allows for breakup and coalescence of droplets, accounts for resistance to breakup by interfacial tension and viscosity, and includes modules that simulate tip streaming. While the microdroplets account for only a small percentage of the total oil volume, they are more likely to be entrained into the intrusion layers (D. Wang and Adams, 2016; Gros et al., 2017), whereas larger droplets (e.g., >500 µm) tend to rise directly to the surface (Zhao et al., 2015).

Murphy et al. (2016) describe droplet sizes and spatial distributions and the flow mechanisms affecting them in the near field of oil jets in realistic cross-flow conditions. They show that the bottom

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[1] The Weber number describes the magnitude of the hydrodynamic forces that tend to disrupt droplets, relative to the surface tension that tends to stabilize them.

part of the oil plume near field is dominated by entrainment of droplets into the counter-rotating horizontal vortex pair set up by the cross flow, while the upper part is determined by the buoyant rise of relatively large droplets. Because the plume structure is strongly influenced by the droplets' size distributions, subsequent studies have focused on the breakup of vertical oil jets into droplets. Observations involving refractive index matched jets (Xue and Katz, 2019) show that most of the oil droplets are actually compound droplets; they contain smaller water droplets, which sometimes contain even smaller oil droplets. The fraction of compound droplets increases with droplet size, exceeding 80% for 2 mm droplets. These compound droplets are generated when early phase shear layers roll up into vortices and entrain water filaments into the oil.

Computational Modeling of Plume Behavior

Studies of plume dispersion are challenging because of the multiscale flow physics involved, ranging from individual oil droplets to an entire plume and to mesoscale eddies in the upper ocean boundary layer. Applications of LES[2] methods to characterize such flows require parameterization of the subgrid-scale processes that are not resolved, including oil droplet and gas bubble formation, coalescence and breakup, gas dissolution, biodegradation, and hydrate formation. Several LES-based studies of oil and gas plumes have investigated the effect of droplet-scale physics on the plume-scale dispersion phenomena (Yang et al., 2016; B. Chen et al., 2016b, 2018). Among the many findings, they show that: (1) the significant reduction of oil droplet size caused by dispersant also enhances the vertical mixing of the oil in the ocean mixed layer, resulting in an Ekman-spiral-induced shift of the mean plume transport direction; (2) application of a recent droplet population balance model (Aiyer et al., 2019) in an LES framework (Chamecki et al., 2019) to simulate the effect of turbulence on oil droplet breakup reproduces the measured droplet size distributions (Murphy et al., 2016); (3) LES of subsurface plumes shows that gas dissolution from bubbles causes a considerable reduction in plume buoyancy and impacts the peeling/intrusion processes. A related theoretical study investigated the dissolution of multi-component oil drops in water, where the surface concentration of solutes depends on the drop composition and varies as the drop dissolves due to the different solubilities of individual components (Chu and Prosperetti, 2016). The analysis involves a first-principles demonstration of the necessary modeling strategy based on the fundamental law of equality of each component's chemical potentials in the drop and in the external solvent.

Interactions Between Microbes, Particles, and Oil Droplets

A series of experimental studies have focused on micrometer-scale interactions between microbes, particles, and oil droplets (Sheng et al., 2006; Molaei and Sheng, 2014; Jalali et al., 2018; White et al., 2019a). The degradation of 5–100 µm droplets through dissolution and biodegradation by bacterial isolates and natural microbial consortia, with and without dispersant, was measured using microfluidic flows over a surface textured with microdroplets (Jalali et al., 2018). For 100–1,000 µm droplets, the experiments were performed in a unique ecology-on-a-chip microcosm platform that allows examination of bacterial behavior and microbial community responses around a rising micro-oil droplet, along with measurements of associated flows and rheological mechanisms (White et al. 2019a,b). These studies demonstrate the formation of polymeric microbial aggregates as well as extra-cellular polymeric substance (EPS) streamers around rising oil droplets, both of which affect the droplets' hydrodynamic impacts—even a few isolated streamers can increase the drag on a drop by 80%. Another study of bacterial interactions with alkane-aqueous interfaces (Vaccari et al., 2017) shows that these interactions depend strongly on the particular strain of bacteria. The bacteria can either continue to swim adjacent to the interface or become attached to it. If they become attached, they may form a thin solid elastic film (Vaccari et al., 2015). Some, but not all, of the observations suggest that the ability to form such elastic films relies on the ability of the bacteria to metabolize the oil phase (Niepa et al., 2017). Bacteria near interfaces display a range of behaviors that includes Brownian motion, swimming in circular trajectories, and directed swimming (Deng et al., 2020). These motions can also enhance the dispersion and transport of micron-scale droplets (Vaccari et al., 2018).

Aerosolization of Oil

Surface oil slicks can be aerosolized either by splashing during wave breaking or by bursting of entrained bubbles as they rise back to the surface. While the size distributions of marine aerosols have received considerable attention (Veron, 2015), very limited information exists about the process of aerosolization of oil slicks. However, a series of experiments investigated the effect of dispersants on the aerosolization of oil slicks by breaking waves (Afshar-Mohajer et al., 2018), and subsequently, the effect of bubble bursting at an oil-water interface (Sampath et al., 2019; Afshar-Mohajer et al., 2020).

In these wave tank experiments (Afshar-Mohajer et al., 2018), the aerosol size distributions were measured in sizes ranging from 10 nm to 20 µm using a scanning mobility particle sizer (SMPS) for the 10–400 nm size range and an aerodynamic particle sizer (APS) for

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[2] Large Eddy Simulation (LES) methods deliberately filter out very small-scale motions, which are the most computationally expensive to resolve, producing results that are smoothed somewhat in both space and time but that preserve the larger scale features.

the 0.5–20 μm range. Digital holography (Katz and Sheng, 2010; C. Li et al., 2017) has also been used in parallel for detecting airborne droplets larger than 4 μm, showing good agreement with the APS data. The total particle-bound polycyclic aromatic hydrocarbons (pPAH) and the total volatile organic compounds (TVOCs) were measured concurrently. Data have been obtained for plunging breaking waves entraining slicks of crude oil (MC252 surrogate), crude oil-dispersant mixtures, and dispersant only. The results show that slicks of crude oil do not alter the concentration of nanodroplets. In contrast, the concentrations of nanoparticles originating from oil-dispersant mixture and dispersant alone are one to two orders of magnitude higher than those from crude oil alone across the entire nano-scale range, reaching 100 times for 20 nm particles. Conversely, adding dispersant has little effect on the concentration of micro-aerosols. The average concentrations of pPAH remain similar in range (150–270 ng m^{-3}). However, the VOC concentrations for crude oil-dispersant mixtures are two to three times lower than those of crude oil, in agreement with prior studies (Gros et al., 2017). An analysis of the health risk associated with the measured VOC and airborne particles is discussed in Afshar-Mohajer et al. (2019). Their results show that on the one hand, the lower VOC reduces the health risk. On the other hand, inhalation of the nanoparticles increases the total mass of deposited particles in the upper respiratory tract and tracheobronchial regions of the lungs, although the measured quantities were still well below the health risk threshold. However, the concentration of total suspended particles (micro plus nano scale) close to the source only just exceeds the hazard threshold level by 1.1 times for crude oil without dispersant, but by 6.8 times for crude oil premixed with dispersant.

In an attempt to identify and characterize the mechanisms affecting the generation of nanodroplets, subsequent studies focused on generation of airborne droplets by bursting of rising gas bubbles at the liquid-air interface (Sampath et al., 2019). Bubbles with different size ranges were injected into a seawater column covered by slicks of crude oil, pure dispersant, and a DOR 1:25 dispersant-oil mixture; the sensors mentioned above were used to measure nano- and micro-aerosol size distributions in both clean and ambient air environments. An order of magnitude increase in nanoparticle concentration was observed during bursting of bubbles larger than about 0.5 mm in slicks containing dispersant at a DOR of 1:25 of oil, and for a 50 μm layer of pure dispersant, compared to smaller bubbles and tests not involving dispersant. These observations suggest that of the two mechanisms causing generation of airborne droplets during bubble bursting, namely jet droplets and film droplets (Veron, 2015), the nano-aerosols originated from breakup of the thin water film above the bubbles. In the micron range, all the bubble plumes generate micron-sized aerosols, but trends vary with bubble size and slick thickness, and the presence of dispersant does not cause an increase in the concentration of micro-aerosols compared to that for dispersant-free conditions. Based on their characteristic sizes, the micro-aerosols originated from jet droplets. In general, for the same surface contaminant, the microdroplet concentration *decreases* when the oil slick is thicker. A reduction of two orders of magnitude in the microdroplet concentration when medium and small bubbles burst in a thick (500 μm) surface slick of crude oil is particularly striking.

Another study involving slicks of crude oil and oil-dispersant mixtures at DORs of 1:25 and 1:100 focused on the chemical composition of airborne PM2.5 particles (Afshar-Mohajer et al., 2020). These measurements included chemical analysis by gas chromatography and mass spectrometry, as well as use of a cascade impactor for size-fractioning of the particles. Results show that the total PM2.5 concentration released from the DOR 1:25 slick is about nine times higher and the oil content in them is about 2.4 times higher than those for pure crude oil. For particles smaller than 220 nm, the crude oil concentrations for DOR 1:25 and 1:100 are about six and three times higher, respectively, than those for pure crude oil.

Several other studies involving aerosolized oil should also be mentioned. First, the generation of airborne droplets when raindrops impact oil slicks is discussed in Murphy et al. (2015). They show that the presence of oil slicks and dispersant alter the splashing and aerosol generation processes, and that the number of microdroplets increases both with oil layer thickness and with addition of dispersants. Second, M. Li et al. (2019) apply a wave-effect-resolving LES to simulate the transport of oil droplet aerosols by wind over surface waves in the marine atmospheric boundary layer. They show that wind considerably enhances oil droplet suspension and both vertical and lateral spreading, and that the spatial distribution of aerosols exhibits significant streamwise variations. Finally, Almeda et al. (2018) show that oil spills and dispersants can increase harmful algal blooms (HABs) and their associated toxins in the upper water column. Hence, in addition to risks associated with aerosolization of oil, changes to the resulting airborne toxins should also be considered if and when HABs are present.

NEAR-FIELD PROCESSES: PLUME FORMATION AND DYNAMICS

Above the primary bubble and droplet breakup zone, a buoyant plume of gas, oil, and entrained water forms and rises through the density-stratified ocean water column (Socolofsky et al., 2016; Boufadel et al., 2020). Depending on the water depth and stratification, the plume may pass through a level of neutral buoyancy, be arrested in its vertical ascent, and form a lateral intrusion layer (Socolofsky et al. 2011). During the Deepwater Horizon incident, this lateral intrusion was the basis of the subsea plume of oil and dissolved hydrocarbons at about 1,000 m water depth that extended for many kilometers (Gros et al., 2017; Hazen et al., 2010; see section on The Deep Plume and Intrusion Layer). Above the intrusion layer, gas bubbles and oil droplets may continue to rise at individual terminal rise velocities and advect downstream with the local currents (Gros et al., 2017; Dissanayake et al., 2018). Eventually, oil and gas either fully dissolve, impact the seafloor of the continental slope, or reach the ocean surface (Lindo-Atichati et al., 2014). Surfacing volatile compounds evaporate into the atmosphere (DeGouw et al., 2011; Le Hénaff et al., 2012; Gros et al., 2017), whereas residual oil creates surface slicks and interacts with surface mixing processes (see section on Small-Scale Near-Surface Circulation Processes).

The near-field dynamics encompass a lateral region of up to a few kilometers' distance from the release, within which the vertical plume and potential intrusion layer formation are contained, and larger gas bubbles and oil droplets rise to the sea surface. Outside the near-field region, spatial and temporal variability of ocean currents becomes important (as discussed in sections below on Coastal to Offshore Linkage, Circulation, and Transport and The Deep Plume and Intrusion Layer).

Two main classes of models have been applied to the evolution of the near-field oil and gas plume (Socolofsky et al., 2016; Boufadel et al., 2020). Computational fluid dynamics (CFD) models based on the LES approach were developed to simulate the complex, unsteady interaction of the oil and gas with the surrounding seawater explicitly and in detail. These models treat the oil droplets and gas bubbles in two main ways. Oil droplets and gas bubbles may be treated as a continuous distribution, allowing for larger-scale simulations (Yang et al., 2016; Fabregat et al. 2016a,b). Alternatively, individual bubbles or droplets can be tracked, allowing finer details to be revealed, but at limited scale (Fraga et al., 2016). CFD models also show the important influence of Earth's rotation on near-field plume dynamics that affect both entrainment rates and detrainment levels.

Integral plume models, which model plume dynamics as an entity, use a cross-sectionally averaged velocity profile and solve for the variation of the flow rate, trajectory, plume width, and other plume parameters through a set of conservation equations (Johansen, 2003; Zheng et al., 2003; Dissanayake et al., 2018). These models are much less computationally expensive; hence, they lend themselves to rapid, full-scale modeling, so that predictions can be available in a matter of hours for making rapid forecasts (Barker et al., 2020). These models were extended recently to handle arbitrary bubble and droplet size distributions and to track the real-fluid equations of state and the dissolution of individual components of the oil and gas mixtures (Gros et al., 2016, 2017, 2018; Dissanayake et al., 2018). One example is the Texas A&M Oilspill Calculator (TAMOC), an open-source model available from Github (Dissanayake et al., 2018). Because these models are designed to handle the real-world scale of a blowout, Lagrangian[3] particle-tracking models for the far field (from a few to many kilometers away) were coupled offline to such integral models to simulate the Deepwater Horizon spill (North et al., 2011, 2015; Paris et al., 2012; Lindo-Atichati et al., 2016; French-McCay et al., 2018; Perlin et al., 2020), as well as dynamically coupled to one another (Vaz et al., 2019). These models can track both the liquid oil droplets and the passive tracers associated with dissolved hydrocarbon in both the near-field plume and the subsea lateral intrusion (Bracco et al., 2020).

Several laboratory, tank, and field experiments have been conducted in the last 10 years and used to test and validate both CFD and integral-type models of the near field. These studies include turbulence in bubble plumes (Lai and Socolofsky 2019; B. Wang et al., 2019), the dynamics of buoyant oil jets with and without dispersant injection (Murphy et al. 2016), and field experiments to track the evolution of gas bubbles associated with natural seeps (B. Wang et al., 2016, 2020).

The most important processes occurring in the near-field plume (see, e.g., Gros et al., 2016, 2017; Dissanayake et al., 2018) include (1) partitioning of the released fluids into separate gas and liquid petroleum phases, each containing a complex mixture of the released hydrocarbons; (2) primary breakup of the gas and liquid into bubbles and droplets; (3) dissolution of many lighter compounds from the gas- and liquid-phase particles; (4) the dynamical interaction of the buoyant plume with surrounding waters; (5) rapid vertical transport of the coherent plume into the intrusion layer (if present) or to the surface (in the case of shallower releases); (6) formation of intrusions that contain most of the dissolved hydrocarbons from the plume and some of the smaller oil droplets; and finally, (7) release of remaining gas bubbles and oil droplets from the intrusion layer. Near-field models aim to accurately predict phase separation, dissolution, and intrusion formation at scales up to a few kilometers (see also the section on The Deep Plume and Intrusion Layer). Intermediate and mesoscale (from a few up to a few hundred kilometers) and far-field (larger-scale) models need to be coupled within a region following intrusion formation. Because a large volume of hydrocarbons may enter such intrusions, far-field models need to track them, along with the droplets and the dissolved oil within and around them (e.g., Vaz et al., 2019). With respect to issues requiring further research, many questions remain about oil droplet size distribution (Failletaz et al., 2021), as discussed above in the section on Microscale Physical (and Biophysical) Processes. Improvements in the time-varying estimation of initial droplet size distribution as live oil rises from the buoyant plume

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[3] In a Lagrangian approach, observations and estimates are made at points that travel along with the flow.

into the far-field water column will likely result in the next breakthrough. These estimates should be based on our understanding of multiphase and pressure-drop processes on the gas portion of the gas-saturated droplets (Griffiths, 2012; Socolosky et al., 2016; Vaz et al., 2020; Malone et al., 2020; Faillettaz et al., 2021), their evolution through partitioning and degassing during oil ascent in the water column (Gros et al., 2016; Jaggi et al., 2017, 2020; Pesch et al., 2018) and biodegradation (Joye et al., 2016b), and on the acquired knowledge of the effect of subsea dispersant injection (Paris et al., 2012, 2018; French-McCay et al., 2019).

SMALL-SCALE, NEAR-SURFACE CIRCULATION PROCESSES

Predicting the distribution of oil, buoyant plastics, flotsam, and marine organisms near the ocean surface remains a fundamental problem of practical importance. Work on this topic during GoMRI is summarized here, with an emphasis on the accumulation of floating material into highly concentrated streaks on horizontal scales from a few meters to tens of kilometers. A more detailed review of this topic is available in D'Asaro et al. (2020).

Prior to the GoMRI period, two new paradigms for surface distributions had emerged: one for the larger scales, emphasizing the importance of submesoscale (hundreds of meters to tens of kilometers) frontal dynamics, and the other for the smaller scales, emphasizing the importance of wind-surface-wave-driven Langmuir turbulence,[4] with a broad transition between the two occurring near 100 m. The small-scale motions are non-geostrophic, they are fully three-dimensional (especially at the smallest scales), and they involve substantial vertical motions that are largely confined to the near-surface mixed layer. Such motions cause both convergence and divergence of water at the surface, leading to the concentration (and sometimes subduction) of any floating materials. Pollutants, including oil, together with nutrients, *Sargassum* algae, larvae, and low-salinity waters of river origin therefore tend to accumulate along submesoscale fronts that are characterized by strong lateral convergence (Huntley et al., 2015; Choi et al., 2017). Such fronts may be river-induced and thus represent a conduit that links the coastal to the open ocean, and they are key to both alongshore and cross-shore transport (Androulidakis et al., 2018) and to connectivity among coastal areas distant from one another. The importance of submesoscale motion in winter was accentuated away from the Mississippi River outflow, with perhaps the primary unanticipated result near the outflow being the remarkable and controlling influence of the associated freshwater anomalies and their expression at the submesoscale, quite likely independent of season, though dependent on river outflow rate.

In the open ocean, the Loop Current and its detached eddies (with diameters of 100–200 km) and submesoscale circulations all interact and contribute to the spreading of the riverine discharge offshore. In the northern Gulf of Mexico, submesoscale circulations are prevalent at the ocean surface not only in winter, as found in other basins, but also in summer, due to the amplification of the frontogenetic tendency associated with the abundant low-salinity water discharged by the Mississippi River system (Luo et al., 2016; Barkan et al., 2017).

Rapid progress in studying these processes has resulted from the combination of high-resolution numerical modeling tools, mostly developed before GoMRI, and new observational techniques developed during GoMRI (Mensa et al., 2018). Massive deployments of inexpensive and biodegradable satellite-tracked surface drifters combined with aerial tracking of oil surrogates (drift cards) enabled simultaneous observations of surface ocean velocities and dispersion over scales of 10 m to tens of kilometers. Surface current maps produced by ship-mounted radar and aerial optical remote sensing systems, combined with traditional oceanographic tools, enabled a set of coordinated measurement programs that supported and expanded these new paradigms (Özgökmen et al., 2018; see also sections below on Offshore Circulation and Transport and Coastal to Offshore Linkage, Circulation, and Transport).

Submesoscale fronts caused floating material to both accumulate at fronts and disperse as they evolved, leading to higher localized concentrations in some places, but nevertheless increased overall larger-scale dispersion (D'Asaro et al., 2018). Analyses of both model results and observational data confirmed the distinct submesoscale dynamics of this process and the complexity and variability of the resulting surface concentration fields. Existing analytical and modeling tools could be developed into predictive models for submesoscale processes on a statistical basis, but prediction of individual submesoscale features will likely always remain limited by the data that can be obtained and the transient nature of the processes involved. Away from fronts, measured rates of accumulation of material in and beneath surface windrows was found to be consistent with Langmuir turbulence, but highly dependent on the rise rate of the material and thus, for oil, on the droplet size (Chen et al., 2016b). Models of this process were developed and tested and could be further developed into predictive tools (Sullivan and McWilliams, 2018). Both the submesoscale and Langmuir processes are sensitive to coupling with wind and surface waves as well as air-sea interaction processes, further complicating forecasting of the submesoscale distributions of floating materials. In addition, competition between Langmuir turbulence and submesoscale dynamics has been found

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[4] Langmuir turbulence is the near-surface three-dimensional turbulent motion associated with Langmuir circulation cells. They are long, shallow overturning cells that form when surface currents interact with wind-driven waves.

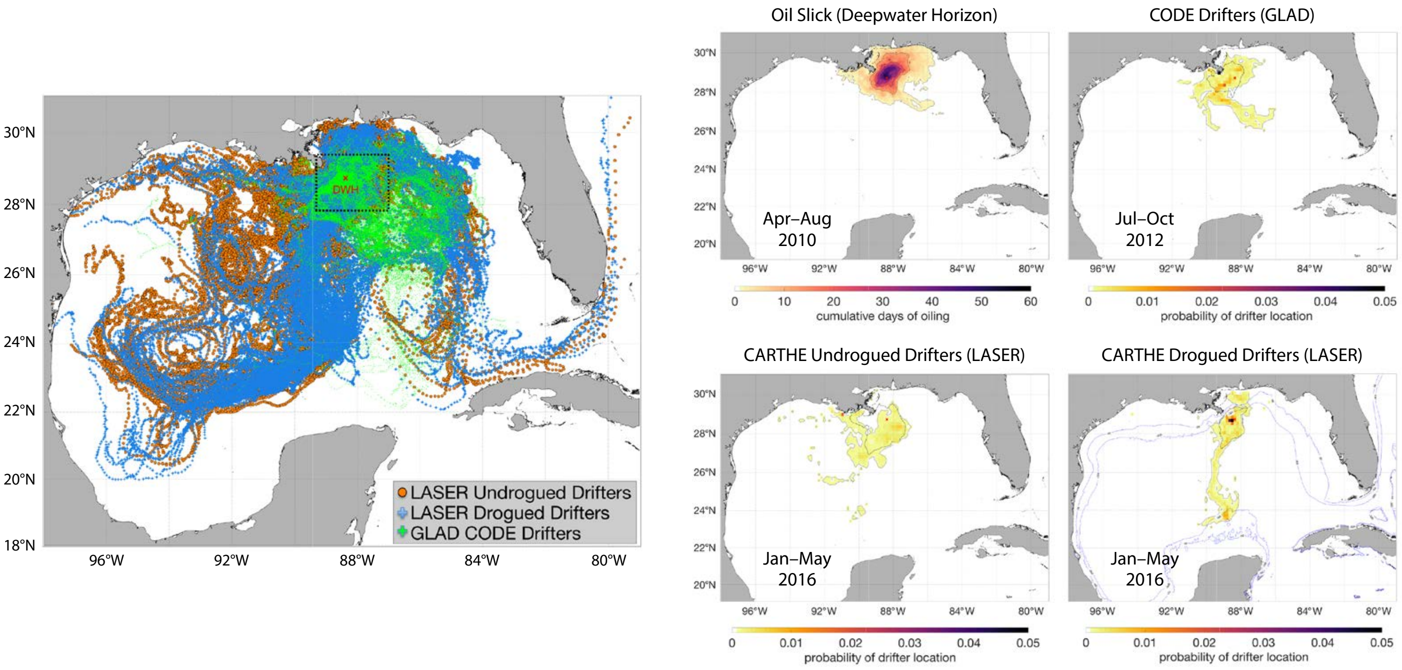

FIGURE 3. (left panel) Cumulative spatial span of all Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) drifters deployed in the northern Gulf of Mexico. (right panels) Oil coverage from the DWH event compared to drifter density from the Grand LAgrangian Deployment (GLAD) and LAgrangian Submesoscale ExpeRiment (LASER), with drogued and undrogued drifters shown separately. *From Novelli et al. (2020)*

to be quite important, if somewhat intermittent in space and time. Finally, and importantly, boundary layer turbulence due to an external source, such as wind or convection, can couple to the submesoscale dynamics via a turbulent thermal wind effect[5] on the cross-front balance between the pressure gradient and the Coriolis force. Here, both the turbulent intensities and the submesoscale frontogenesis can be affected. The interactions discussed here provide important directions for future research.

OFFSHORE CIRCULATION AND TRANSPORT

When hydrocarbons from a deep oil spill reach the surface, they are strongly influenced by air-sea forcing, including surface dispersion by ocean currents, mixed layer dynamics, wind, and waves, all of which vary greatly over time and with weather conditions (Judt et al., 2016). The impacts of processes operating over a very wide range of spatial and temporal scales must therefore be taken into account when responding to an oil spill. Advection of the oil by large-scale flows (tens to hundreds of kilometers, for example, the Loop Current and associated eddies) provides a first-order description of the oil's trajectory, but small-scale (100 m to 10 km) processes critically impact transport and mixing in the upper ocean. In particular, Stokes drift[6] from surface waves and Ekman transport from wind stress combine to form the near-surface currents that advect the oil. The depth of such currents is controlled by boundary layer turbulence, including Langmuir circulations, that are driven by air-sea fluxes and surface waves. These processes create complex distributions of material and produce very different patterns of the oil spread than would be obtained considering only the larger-scale flows.

During GoMRI, the Gulf of Mexico's near-surface circulation was investigated by deploying thousands of biodegradable Lagrangian drifters, notably in the Grand LAgrangian Deployment (GLAD) and the LAgrangian Submesoscale ExpeRiment (LASER) (Novelli et al., 2017) of the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE). Lagrangian deployments are naturally suited for studies of the tracer transport problem because they do not suffer from the sampling and averaging errors of fixed and ship-based measurements, and they continue to sample the velocity field long after the cruise period ends, even under adverse conditions. Cumulative trajectories from CARTHE's sampling of the Gulf of Mexico are shown in Figure 3. After being released near the DWH site, drifters dispersed across almost the entire basin (with the exception of continental shelves) in three to six months. A comparison with the oil concentration from the DWH event shows that the GLAD (summer) and undrogued LASER (winter) drifters have a very similar spatial distribution to that of oil from the DWH spill, while

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[5] When a balanced front is disturbed by turbulent mixing, a secondary circulation with flow in the cross-front and vertical directions develops. The horizontal convergence associated with the secondary circulation intensifies development of the front (see, e.g., Crowe and Taylor, 2018)

[6] Stokes drift is the systematic net motion of material particles in a surface wave field caused by the difference between the Lagrangian and Eulerian average velocities, effectively the difference in particle velocities between the top and the bottom of their approximately circular trajectories.

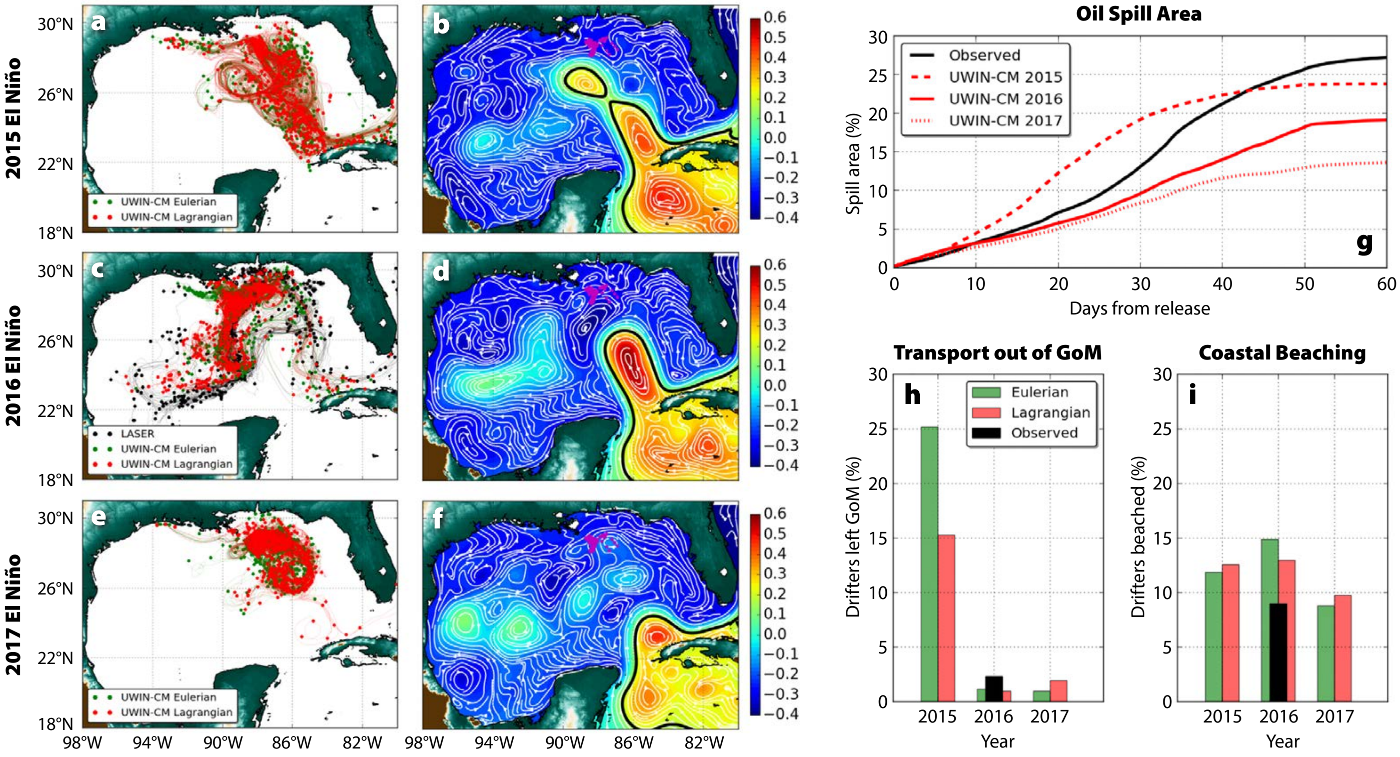

FIGURE 4. (LEFT PANELS) Unified Wave Interface-Coupled Model (UWIN-CM) simulations of Gulf of Mexico (GoM) circulation. Panels (a), (c), and (e) show simulated Eulerian (green) and Lagrangian trajectories (red), and panels (b), (d), and (f) illustrate average sea surface height (SSH, in colors) and surface circulation (streamlines, in white) between January 21 and March 29 in 2015, 2016, and 2017. Panel (c) also shows observed LASER trajectories (black). Initial drifter locations are indicated with magenta dots near the DWH site. The Loop Current is shown by the 17 cm SSH contour (thick black line). (RIGHT PANELS) Simulated and observed characters of the oil spill: (g) evolution of oil spill area, (h) transport out of the Gulf, and (i) coastal beaching for 2015–2017 (data supplied by author Chen).

drogued drifters from LASER tend to follow a mesoscale filament southward all the way to the Mexican shelf break (Haza et al., 2018, 2019). This led to the conclusion that upper-ocean vertical shear and seasonality play important roles in transport patterns. It is important to keep in mind that, over the long term (weeks, months), drifters differ from oil in many ways, in that they do not evaporate or undergo other complex transformations.

Coupled atmosphere-wave-ocean models can be used in conjunction with the drifter measurements. Figure 4 displays model-simulated drifter transport pathways for the winters of 2015, 2016, and 2017 from the Unified Wave Interface-Coupled Model (UWIN-CM; Chen et al., 2013; Chen and Curcic, 2016) with both atmospheric and oceanic components fully coupled to the surface wave model. Thus, it allows for an accurate exploration of wind-wave-current coupling and the influence of Stokes drift on surface material transport. The transport patterns are modulated to a large degree by the structure of the Loop Current, whose northern intrusion varied greatly during 2015–2017. These three years correspond to the 2015–2016 El Niño and the subsequent weak La Niña in 2017. The area of the spill and the transport of simulated drifters out of the Gulf through the Florida Straits both depend on the structure of the Loop Current, while coastal beaching remains more or less the same across these three years and must therefore depend on smaller-scale features of the circulation. The UWIN-CM simulations and the LASER drifter data for 2016 show reasonable agreement. Wind-induced surface waves enlarge the area of spilled oil in general (denoted as Lagrangian vs. Eulerian in Figure 4h,i), which can affect how oil and drifters interact with the Loop Current. The simulated Lagrangian drifters spread faster over a larger area than the simulated Eulerian drifters, which remain more concentrated near the Loop Current and may be transported out of the Gulf. Overall, Figure 4 provides a rather striking picture of multiscale air-sea interaction, especially the interannual variability of surface transport patterns in the entire Gulf of Mexico.

Near-field, short-term dispersion is, however, more important than long-term transport for guiding a spill response effort. To this end, local and real-time assimilation of data to initialize and constrain the models, using adequate data sources and good assimilation schemes, is critical for a good forecast. For example, the upper left panel of Figure 5 shows Lagrangian coherent structures (LCSs)[7] computed from the Navy Coastal Ocean

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[7] Lagrangian coherent structures are systematic patterns of circulation within a turbulent flow field that lead to the formation of coherent patterns in the distribution of tracer materials (e.g., blobs and streaks).

Model (NCOM) during the GLAD expedition. There is a significant mismatch with a concurrent chlorophyll image collected by the Moderate Resolution Imaging Spectroradiometer (MODIS). In fact, Jacobs et al. (2014) found that LCSs computed from satellite-altimeter-derived geostrophic velocity directly, without assimilating into NCOM, initially were in better agreement with this chlorophyll image. This implied the need for modification of procedures followed during data assimilation into NCOM when there was a scarcity of altimeter tracks over the Gulf of Mexico. After the procedures were modified, much better agreement was attained (lower left panel of Figure 5). Assimilation of data from the large numbers of drifters further improved model performance. By developing appropriate Lagrangian data assimilation algorithms, Carrier et al. (2014) and Muscarella et al. (2015) found that the assimilation of even a small number of (GLAD) drifter trajectories improved NCOM realism (right panels of Figure 5). In particular, for oil spills, drifters can be deployed repeatedly right on top of the spill to track it during nighttime and bad weather, as opposed to hoping that satellite tracks will coincide with the spill's location. However, because results at scales that are not constrained by data become chaotic and do not have useful forecasting value, high-resolution modeling requires high-resolution data. By themselves, however, high-resolution models may still provide insight into the potential ensemble of possible flow characteristics, and on the importance of the various physical processes at play.

It should be noted that not all of the oil from the Deepwater Horizon blowout reached the surface. A substantial percentage of the oil was entrained into deep plumes and biodegraded therein. The behavior of such plumes is not easily predictable, because of lack of knowledge of the deep circulation and how it is modified by diapycnal mixing. This issue is discussed in detail in section below on The Deep Plume and Intrusion Layer.

COASTAL TO OFFSHORE LINKAGE, CIRCULATION, AND TRANSPORT

Under the auspices of GoMRI, much has been learned about transport processes in the Gulf of Mexico along the very important land-ocean continuum, from the coast, estuaries, wetlands and shelves to the deep ocean interior. An in-depth synthesis of this research will be available in a forthcoming paper by author Justić and colleagues. Advances have been particularly outstanding with respect to the tools and methodologies available for collecting, analyzing, and synthesizing data and for simulating coastal to offshore linkages and transport. Taken together, these improvements enable better short- and long-term forecasting capabilities as well as better-informed decisions for coastal resource and ecosystem management. Below, we summarize major progress in a geographical progression, moving from the land-ocean boundary to the open ocean.

Observations, laboratory experiments, and data analyses have all contributed to a better understanding of estuarine and coastal hydrodynamics and associated transport of freshwater, sediments, nutrients, and pollutants (Zheng and Weisberg, 2010; Beland et al., 2017; Valentine and Mariotti, 2019). The unstructured grid models that are now available are better equipped to simulate the complex coastal geometries of marshes, wetlands, and estuaries, and their multiscale time variabilities (Justić and Wang, 2014; White et al., 2019c). There are also improvements in model-

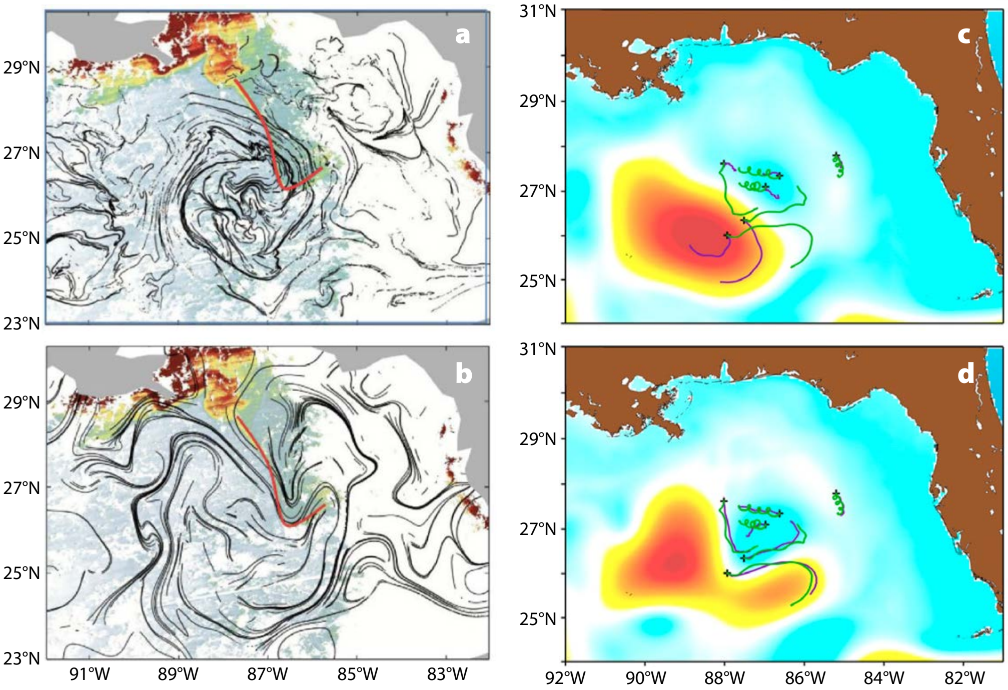

FIGURE 5. Improvement of model predictions using data assimilation. (left panels) Navy Coastal Ocean Model (NCOM) simulation of particle tracks with superimposed sea color images, both without (a) and with (b) assimilation of altimeter data. Note the improved alignment of the flow field with the long filamentary "intrusion." *From Jacobs et al. (2014)* (right panels) Further improvement of NCOM simulations, both without (c) and with (d) assimilation of GLAD drifter data. Note the improved alignment of fronts with drifter tracks. *From Muscarella et al. (2015)*

ing of river-estuarine coupling, and there is widespread assimilation of operational meteorological or reanalysis products. For example, we have come to realize that river diversions influence estuary dynamics within 20–25 km from the diversion, but they may not significantly impact the transport of oil slicks further offshore (H. Huang et al., 2011). However, large-scale sediment diversions have the potential to influence estuarine flushing further than 60 km from the diversion sites, albeit with significant ecological trade-offs associated with estuarine freshening (Cui, 2018). The emerging consensus on the use of river diversions in the case of DWH is that they were ineffective in achieving their primary objective to push the oil away from coastal wetlands and rather resulted in unanticipated deleterious ecological impacts (Westerholm et al., 2021, in this issue). This was due to the complex interaction of Mississippi River plume waters with the oil that was moving onshore (Kourafalou and Androulidakis, 2013), interaction that was dependent on the offshore currents over the shelf (dominated by wind and river discharge variability) and on the open sea (dominated by the Loop Current and associated eddies).

In the past 10 years, we have come to appreciate the importance of both horizontal and vertical resolution in coastal and regional models. High vertical resolution is required to achieve good representation of the Ekman layers at the ocean surface and near the seafloor (within which currents are diminished and rotated by the joint effects of viscous drag and the Coriolis force; Weisberg et al., 2014) and to properly capture diapycnal[8] mixing in both coastal areas and in the open ocean (Bracco et al., 2018). Furthermore, at the land-ocean interface, especially in the presence of barrier islands and beaches, representation of flooding and drying is important and should be directly included in the vertical coordinate system (Zheng and Weisberg, 2012; Weisberg et al., 2014). High-resolution coastal and regional models should pay close attention to the representation of inlets and islands (Androulidakis et al., 2019, 2020) and the effects of wind-wave-current coupling on transport due to Stokes drift (Curcic et al., 2016), whose influence varies depending on water depth. Stokes drift did indeed contribute to the deposition of oil on beaches following the DWH spill (Le Hénaff et al., 2012).

Finally, major refinements of transport modeling tools have improved our ability to predict ecosystem connectivity (the interrelationships within and between species in different places) and oil transport. On the ecosystem side, we have made much progress in understanding and predicting movement of adult and juvenile fish, coral larvae, and other taxa (Cardona et al., 2016; Ainsworth et al., 2018; Martin et al., 2020; Paris et al., 2020) and in estimating connectivity among coastal habitats, shelves, and estuarine wetlands of the Gulf of Mexico. Regarding the transport of oil, the initial surface trajectory models used as part of the rapid response to the DWH spill have been augmented by simulations that include oil droplet size variations and subsea chemical dispersant applications, using both Eulerian[9] and Lagrangian approaches. Through modeling and observational efforts, we have better quantified the important role that Stokes drift played in modifying the dispersion of the oil toward both the coastline and open waters. We have also realized that river diversions have limited effectiveness in keeping the oil away from the estuaries (H. Huang et al., 2011), that the Mississippi River plume exerts buoyancy-driven effects on the oil that may vary significantly in space (Dagestad et al., 2018; Hole et al., 2019), and that there is an elevated risk of remobilization of oil stored in shallow sediments during energetic storms (Zengel et al., 2015).

Challenges remain in both the observational and the modeling realms. They pertain to the high computational costs associated with current algorithms for simulating wetlands, estuaries, river-estuary coupling, and shelf exchanges at the high spatial resolution needed. The mechanisms controlling wave-current interactions in river deltas and the relative importance of atmospheric fluxes, riverine fluxes, and ocean circulations also remain uncertain, especially in rough weather conditions. When investigating transport across and along coastal areas, better coordination of observational and modeling efforts should be strongly encouraged; the uncertainties in atmospheric forcing and boundary conditions (wind stress and heat flux) should be quantified and, if possible, reduced; and simulations of circulations around barrier islands and beaches should have longer time horizons. A multiscale approach, using multiple models at different scales simultaneously through nesting techniques, is recommended. Such an approach should be augmented by an in-depth exploration of mesoscale-submesoscale linkages and by an investigation of model dependency on vertical discretization. Riverine forcing should be better monitored and accurately modeled not only to improve forecasting and response planning in the event of another spill but also to better monitor and manage the Gulf marine ecosystem. In this regard, more observations are needed to constrain how species behavior contributes to coastal-open ocean ecological linkages. Finally, further model intercomparison studies using different hydrodynamic and oil (particle-tracking) models should be prioritized in order to improve model formulations for oil-tracking purposes.

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[8] Mixing in the deep ocean occurs predominantly along isopycnals (the approximately horizontal surfaces of constant density). A much smaller but nevertheless extremely important amount of mixing occurs across or between density surfaces, known as diapycnal mixing.

[9] In an Eulerian approach, observations and estimates are made at fixed points in space, whereas in a Lagrangian approach they are made at points that travel along with the flow.

In summary, much progress in understanding transport processes has been achieved in the past 10 years. To sustain such growth and amplify its benefits, we recommend the development of a suite of appropriately scaled ocean circulation and wave models that are capable of strategically zooming into the key components of the land-ocean continuum, and that are supported by observing arrays designed to target process understanding, data assimilation, and model validation.

THE DEEP PLUME AND INTRUSION LAYER

As mentioned in the section on Offshore Circulation and Transport, not all the oil from the DWH blowout reached the surface. A significant proportion (up to 50%) was entrained into deep subsurface plumes or intrusion layers that traveled laterally at approximately 1,200 m depth along the continental slope and was biodegraded therein. The largest and best sampled of these was discovered through in situ measurements in August 2010 (Camilli et al., 2010; Diercks et al., 2010; Kessler et al., 2011). Since its discovery, the scientific community has made significant progress in understanding and modeling the transport, evolution, and fate of the hydrocarbons trapped in the plume (Gros et al. 2017; also reviewed in Bracco et al., 2020). However, a major challenge for data assimilative ocean models that seek to predict the circulation of the Gulf of Mexico below 1,000 m depth remains due to the absence of any continuous monitoring systems that extend below the ocean's surface (Cardona and Bracco, 2016).

The deep tracer release experiment by the GoMRI-funded Gulf of Mexico Integrated Spill Response (GISR) Consortium was designed to address the limited knowledge of key physical variables below the mixed layer by providing an estimate of interior diapycnal mixing. In August 2012, Ledwell and collaborators from the GISR Consortium injected a streak of trifluoromethyl sulfur pentafluoride (CF3SF5) at about 1,100 m depth near the DWH site to quantify its dispersion (Ledwell et al., 2016). The tracer was sampled one week, four months, and finally one year after its release. A turbulent diapycnal eddy diffusivity greater than 4×10^{-4} m^2 s^{-1} was estimated for the boundary region (close to the seafloor of the continental slope), which is very high relative to typical values for the deep ocean interior ($<10^{-5}$ m^2 s^{-1}), but lower values were found for the interior of the plume. The main conclusion from this exercise was that diapycnal mixing at mid-depth in the northern Gulf of Mexico is much greater near the continental slope than in the interior and that homogenization of a tracer released near the continental slope proceeds much faster than in the open ocean (Polzin et al., 2014). These effects are not yet included in operational models.

Bracco et al. (2016) examined the generation mechanisms and mixing implications of mesoscale and submesoscale circulations near the ocean floor. They showed that the diapycnal mixing coefficient increased near to the continental slope compared to the interior, as observed in the tracer data, and also to the west of the Mississippi Fan, where submesoscale processes were more abundant compared to De Soto Canyon. Later, the contribution of horizontal and vertical model resolutions to the representation of diapycnal diffusivities and the advection of a passive tracer was further explored (Bracco et al., 2018, 2019). Results suggested that a deep spill that occurred to the west of the Mississippi Fan would impact the continental slope far more extensively than did the DWH spill by mixing the hydrocarbons more rapidly and distributing them over a larger area in a few months (Rogener et al., 2018).

In terms of hydrocarbon modeling, major improvements made include better estimations of the initial droplet size (Bandara and Yapa, 2011; Paris et al., 2012; Johansen et al., 2013; Zhao et al., 2014a,b, 2016; Aman et al., 2015; C. Li et al., 2017; Malone et al., 2018; Pesch et al., 2020a) and more accurate representations of plume dynamics (Paris et al., 2012; Lindo-Atichati et al., 2016) and of the pressure-dependent process of internal degassing in two-phase droplets (Pesch et al., 2018, 2020b). Focusing here on the representation of the lateral plume evolution in the far field, state-of-the-art models simulate the advection of individual droplets by the velocity field generated in hydrodynamic models (North et al. 2011, 2015; Paris et al., 2013; Perlin et al., 2020) and the dissolution and biodegradation of gas and oil droplets as functions of the local environmental and biogeochemical conditions (Chen et al., 2016a; Joye et al., 2016a,b). It is now also possible to realistically simulate droplet aggregation with both organic and inorganic matter and the subsequent settlement of the heavier aggregates on the seafloor (Khelifa et al., 2008; Zhao et al., 2016; Daly et al., 2016, 2020; Dissanayake et al., 2018; Vaz et al., 2020), and also to allow for the effect of subsea dispersant injection (Paris et al., 2012, 2018; French-McCay et al., 2019).

With respect to issues requiring further research, many questions remain concerning the spatial and temporal evolution of flows in midwater and in the bottom boundary layer, and specifically how processes at scales of centimeters to hundreds of meters translate into large-scale transport impacts (Bracco et al., 2020). Improved theoretical understanding of ocean near-bottom dynamics is needed and could be achieved with a few years of targeted monitoring using acoustic Doppler current profilers (ADCPs) to quantify velocities and their variability, while the current generation of high-resolution, regional models could identify locations to prioritize for the observational efforts. Because detection and modeling of subsurface oil is difficult, advances will also emerge from the use of ensemble probabilistic modeling (Perlin et al., 2020) for guiding underwater remotely operated vehicles. Finally, intercomparison of modeling strategies (e.g., Socolofsky et al., 2015) should be prioritized to improve the predictions of deep plumes and the response trade-offs for any future deep-sea spills (Murawski et al., 2019).

CONCLUSIONS AND KEY FINDINGS

While the physical processes described above constitute dominant influences on the spatial distribution of materials including oil, a major discovery has also been the importance of the marine oil snow sedimentation and flocculent accumulation (MOSSFA) process, as described by Farrington et al. (2021) and Quigg et al. (2021), both in this issue. Here, physical, chemical, and biological processes interact to produce negatively buoyant particles that sink to the seafloor, countering the general tendency of oil to rise toward the surface. Further notable conclusions are:

- Major advances in understanding of pressure-induced processes on gas-saturated oil and refinements of transport modeling tools have improved our ability to predict both ecosystem connectivity and oil transport.
- CFD models have shown the importance of Earth's rotation in near-field plume dynamics that affect both entrainment rates and detrainment levels.
- Recent model improvements include high-resolution regional coupled atmosphere-wave-ocean modeling, river-estuarine coupling, ability to resolve surface and bottom Ekman layers, consideration of Stokes drift, and the widespread adoption of operational meteorological or reanalysis products.
- There is an emerging consensus that the use of river diversions in the case of DWH was ineffective in achieving its primary objective to push the oil away from coastal wetlands and, rather, that it resulted in unanticipated deleterious ecological impacts.
- River-induced fronts play important roles in alongshore and cross-shore transport, acting both as barriers to material transport and as convergence zones that guide transport along frontal lines.
- Advection of pollutants along pathways that link coastal areas and the open ocean is influenced by both mesoscale and submesoscale circulation features.
- Better understanding of the effects of multiscale atmosphere-wave-ocean coupling on ocean transport, on hourly to interannual timescales, can help improve prediction not only in the Gulf of Mexico but also elsewhere.

Under the auspices of GoMRI, important advances were thus made with respect to the tools and methodologies for collecting, analyzing, and synthesizing data and for simulating coastal to offshore and deep-sea linkages and transport. To sustain such progress, and amplify its benefits, we recommend developing and maintaining a regional forecasting system in order to be better prepared for any future oil spill events. It should be based on a suite of appropriately scaled ocean circulation, atmospheric, and wave models capable of strategically zooming in on the key components of the land-ocean continuum and should be supported by well-designed observing arrays that target process understanding as well as data assimilation and model validation.

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AUTHORS

Michel Boufadel is Professor, Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, USA. **Annalisa Bracco** is Professor, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA. **Eric P. Chassignet** is Director, Center for Ocean-Atmospheric Prediction Studies, and Professor, Department of Earth, Ocean, and Atmospheric Sciences, Florida State University, Tallahassee, FL, USA. **Shuyi S. Chen** is Professor, Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA. **Eric D'Asaro** is Senior Principal Oceanographer, Applied Physics Laboratory, University of Washington, Seattle, WA, USA. **William K. Dewar** is Professor, Department of Earth, Ocean, and Atmospheric Sciences, Florida State University, Tallahassee, FL, USA. **Oscar Garcia-Pineda** is Director, Water Mapping LLC, Gulf Breeze, FL, USA. **Dubravko Justić** is Professor, Department of Oceanography and Coastal Sciences, College of the Coast & Environment, Louisiana State University, Baton Rouge, LA, USA. **Joseph Katz** is Professor, Center for Environmental and Applied Fluid Mechanics, Johns Hopkins University, Baltimore, MD, USA. **Vassiliki H. Kourafalou** is Research Professor, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. **Ian R. MacDonald** is Professor, Department of Earth, Ocean, and Atmospheric Sciences, Florida State University, Tallahassee, FL, USA. **Tamay M. Özgökmen** is Professor and **Claire B. Paris-Limouzy** is Professor, both in the Department of Ocean Sciences, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. **Scott S. Socolofsky** is Professor, Zachry Department of Civil & Environmental Engineering, Texas A&M University, College Station, TX, USA. **David Halpern** is GoMRI Research Board member and Affiliate Researcher, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA. **John G. Shepherd** (jgs@noc.soton.ac.uk) is GoMRI Research Board member and Professorial Research Fellow, School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton, UK.

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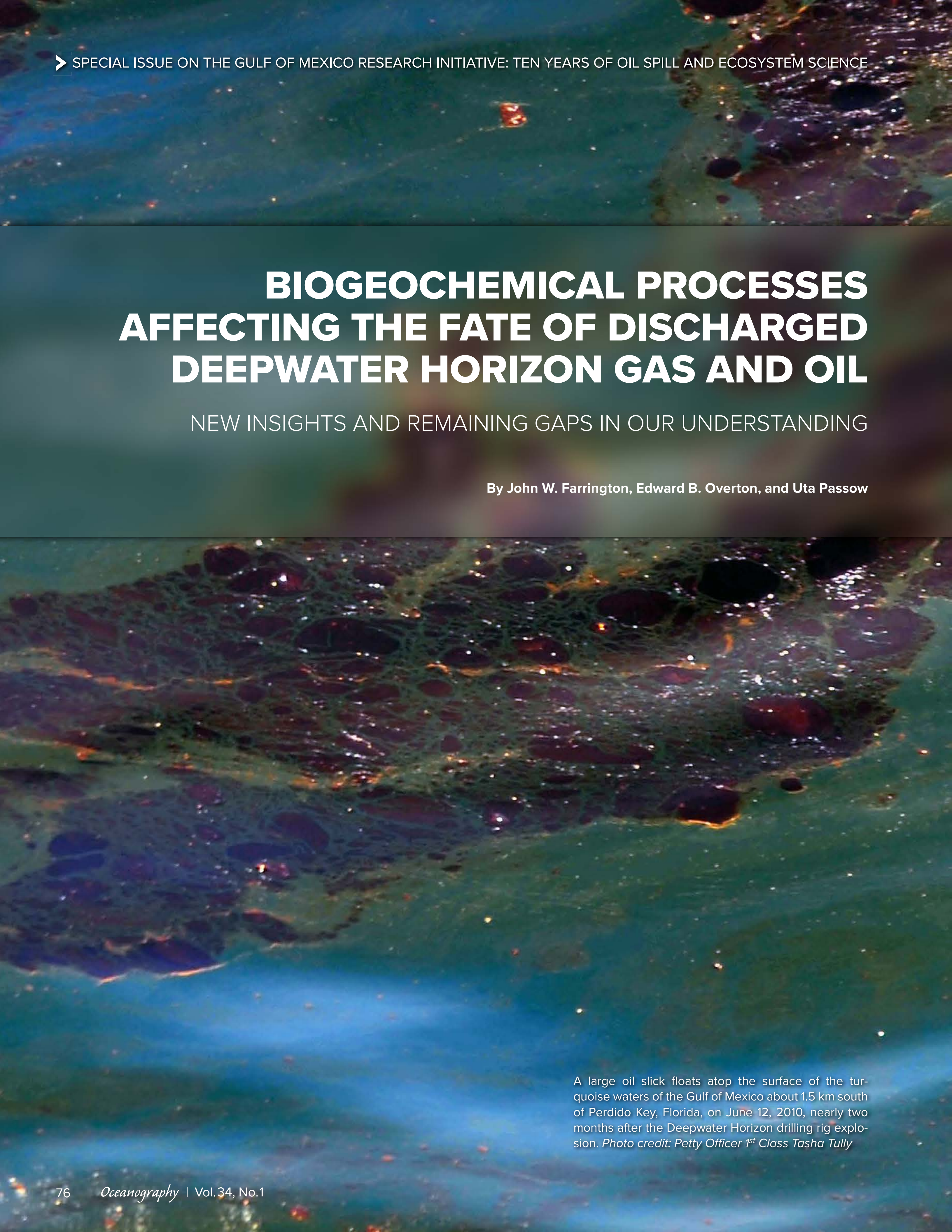
SPECIAL ISSUE ON THE GULF OF MEXICO RESEARCH INITIATIVE: TEN YEARS OF OIL SPILL AND ECOSYSTEM SCIENCE

BIOGEOCHEMICAL PROCESSES AFFECTING THE FATE OF DISCHARGED DEEPWATER HORIZON GAS AND OIL

NEW INSIGHTS AND REMAINING GAPS IN OUR UNDERSTANDING

By John W. Farrington, Edward B. Overton, and Uta Passow



A large oil slick floats atop the surface of the turquoise waters of the Gulf of Mexico about 1.5 km south of Perdido Key, Florida, on June 12, 2010, nearly two months after the Deepwater Horizon drilling rig explosion. *Photo credit: Petty Officer 1st Class Tasha Tully*

ABSTRACT. Research funded under the Gulf of Mexico Research Initiative provided new insights into the biogeochemical processes influencing the fate of petroleum chemicals entering the Gulf of Mexico from the Deepwater Horizon (DWH) accident. This overview of that work is based on detailed recent reviews of aspects of the biogeochemistry as well as on activities supported by the US Natural Resource Damage Assessment. The main topics presented here are distribution of hydrocarbons in the water column; the role of photo-oxidation of petroleum compounds at the air-sea interface; the role of particulates in the fate of the DWH hydrocarbons, especially marine oil snow (MOS) and marine oil snow sedimentation and flocculent accumulation (MOSSFA); oil deposition and accumulation in sediments; and fate of oil on beaches and in marshes. A brief discussion of bioaccumulation is also included. Microbial degradation is addressed in a separate paper in this special issue of *Oceanography*. Important future research recommendations include: conduct a more robust assessment of the mass balance of various chemical groupings and even individual chemicals during specific time intervals; seek a better understanding of the roles of photo-oxidation products, MOS, and MOSSFA and their relationships to microbial degradation; and determine the fates of the insoluble highly degraded and viscous oil residues in the environment.

INTRODUCTION

This article provides an up-to-date overview of some of the important research findings of the past five years related to the biogeochemical processes influencing the immediate (minutes to months) and longer-term (years to a decade or longer) fate of chemical constituents from the Deepwater Horizon (DWH)–Macondo accident that took place April 20, 2010. Our intention is to guide general ocean science researchers and marine policy and management practitioners through the highlights of research funded by the Gulf of Mexico Research Initiative (GoMRI) and the US Natural Resources Damage Assessment (NRDA), although we hope this overview will be helpful to oil research specialists as well. Specifically, this article updates the informative 2016 papers by Passow and Hetland, Passow and Ziervogel, and Tarr et al. in the last GoMRI special issue of *Oceanography*. Our effort here is informed by the more detailed, recent reviews that provide a holistic accounting of the biogeochemistry and fate of the DWH gas and oil chemicals (Burd et al., 2020; Kostka et al., 2020; Kujawinski et al., 2020; Quigg et al., 2020; Ward and Overton, 2020; Passow and Overton, 2021, and recent work of authors Edward Overton and Uta Passow). While our effort focuses primarily on GoMRI-funded research, it also attempts to place that research, where appropriate, within a wider context of other DWH-related research and assessments such as the NRDA activities, which were published in the peer-reviewed scientific literature after the settlement of the NRDA case in the US federal courts.

It is not possible in this synopsis to cite, present, and discuss all the relevant research pertaining to the fates of gas and oil hydrocarbons connected with the DWH accident. The relevant literature is voluminous. More than 400 papers have been published on GoMRI-funded research, all focusing in some measure on the fate of Deepwater Horizon gas and oil under the category fates/biogeochemistry (see https://research.gulfresearchinitiative.org/gomri-publications/). Our apologies to those researchers whose important papers are not cited and discussed.

The major areas of research in need of updating include: (1) water column hydrocarbon measurements during and after the spill; (2) photo-oxidation of oil compounds and their water versus oil solubilities; (3) marine oil snow (MOS), marine oil snow sedimentation and flocculant accumulation (MOSSFA), and oil-mineral aggregates (OMAs); (4) long-term fate of oil deposited in deep-sea sediments (aerobic and anaerobic); (5) fate of oil stranded on beaches (mostly aerobic); (6) oil that came ashore in marsh areas (aerobic and anaerobic); and (7) microbial degradation of DWH oil chemicals. Microbial degradation will only be briefly raised because there is a very informative discussion in this issue by Weiman et al. about microbiology from the perspective of genomics/proteomics, ecology, and ecosystems.

First, we will set the scene with a brief history of oil pollution in the Gulf of Mexico.

> “But regardless of any alleged toxicity to oysters, two facts should be borne in mind. First, oil is quickly taken up by oysters, imparting an oily taste to the flesh which renders the meat unsalable. Second, the effect of oil pollution will last over a long period, for oil is carried to the bottom by suspended mud particles and released from time to time by storms, tonging, or dredging.”
>
> — *Galstoff et al. (1935)*

The quote and the paper/report from which it is drawn introduces the long history of oil pollution fates and effects studies in the Gulf of Mexico coastal areas that progressively moved to deeper waters as oil and gas exploration and production moved offshore to the continental shelf (e.g., NRC, 1985, 1993; Transportation Research Board and National Research Council, 2003; Boesch and Rabalais, 1987). The quote also highlights two aspects, among the many now known, of the fates of oil discharged to the marine environment: (1) bioavailability to various organisms and their food webs, and back to humans, and (2) the role of particulate matter in deposition to sediments, resuspension, and the longer-term fate of oil chemicals in various types of sediments.

Fortunately, much illuminating research has been conducted worldwide since the Galstoff et al. (1935) pioneering report. The variety of physical transport and biogeochemical processes acting on the gas and oil chemicals and their fates after discharge to the environment has been the subject of research over the past several decades (e.g., see NRC, 1975, 1985, 1999; Transportation Research Board and National Research Council, 2003; Royal Society, 1980; K. Lee et al., 2015, among several others).

Our understanding of the fate of gas and oil inputs to the marine environment has evolved within the framework of progress in understanding the biogeochemistry of natural biosynthesized organic matter in the marine environment and all human-mobilized and synthesized organic chemicals of environmental concern (e.g., Bianchi and Canuel, 2011; Farrington and Takada, 2014: Wakeham and Canuel, 2016; Takada and Karapanagioti, 2019; Wakeham and Lee, 2019; Steen et al., 2020). Fundamental physical chemistry and aquatic chemistry principles and examples for a variety of organic chemicals, including a range of hydrocarbon types and molecular weights found in the DWH gas and oil, are presented and discussed in the comprehensive textbook by Schwartzenbach et al. (2017).

Rullkötter and Farrington (2021, in this issue) review and briefly describe the complex compositions of petroleum and petroleum products in general and specifically of the DWH oil. Boufadel et al. (2021, in this issue) describe the influence of various physical processes within many temporal and spatial scales on the gas and oil discharged at the broken well riser as well as on the resulting surface oil slick. The interaction of the chemical composition with physical, chemical, and biological processes cannot be compartmentalized in a neat manner and to try and do so is to oversimplify a very complex situation.

OIL HYDROCARBONS IN THE NORTHERN GULF OF MEXICO ECOSYSTEMS PRIOR TO THE DWH SPILL

The Galstoff et al. (1935) quote notes the initial years of a continuing history of chronic human-caused petroleum inputs to the nearshore areas of the northern Gulf of Mexico. As noted by several assessments, there are numerous natural oil seeps in the Gulf and in several other areas worldwide (e.g., Transportation Research Board and National Research Council, 2003; MacDonald et al., 2015; Kennicutt, 2017). As a generalization, these seeps, estimated to leak in excess of 42 million gallons (160 million liters) annually, have been ongoing for thousands of years or more, and some discharges can be episodic (Kennicutt, 2017, and references therein). It is reasonable to expect, as noted in Weiman et al. (2021, in this issue), that microbial communities in and around natural seeps have evolved or developed to take advantage of the leaking gas and oil hydrocarbons as a source of carbon and metabolic energy.

Assessments of fossil fuel hydrocarbon compounds in northern Gulf of Mexico sediments and some benthic organisms were made as part of a Deep Gulf of Mexico Benthos Program from 2000 to 2002: "The purpose was to provide a better understanding of how oil and gas exploration and production might affect the ecosystem and its natural inhabitants" (Rowe and Kennicutt, 2008; Kennicutt, 2017). Sample analyses and data interpretation for the potentially toxic polycyclic aromatic hydrocarbons (PAHs) in surface sediments (Wade et al., 2008) and a population of ampeliscid amphipods (Soliman and Wade, 2008) were part of this effort. We note this as one example of studies of fossil fuel hydrocarbons in northern Gulf of Mexico ecosystems prior to the DWH accident.

In addition to chronic inputs from land sources and offshore platforms, there have been numerous small and medium size spills in the coastal areas of the Gulf (Transportation Research Board and National Research Council, 2003). As with many developed and industrialized coastal areas, there are numerous oil processing, refining, and storage facilities in those coastal areas. Severe storms inundate some of these areas and cause spillage of various amounts of oil. For example, in 2005 during Hurricane Katrina, oil spilled into the Louisiana coastal area from various facilities (e.g., Pine, 2006). A baseline of petrochemical pollution in coastal Louisiana assembled from 3,240 surface sediment samples by Iqbal et al. (2007) provides one view of the influence of the various inputs discussed above.

Another example of oil inputs is the leakage that has resulted from the toppling of Taylor Energy's Mississippi Canyon Block 20 site production platform following a regional upslope seafloor failure on September 15, 2004, caused by Hurricane Ivan. This slow, variable leakage of inputs predates DWH, is still in progress, and has attracted more attention in the past few years (Bryant et al., 2020).

Some individual chemicals in the group of aromatic hydrocarbons, particularly PAHs, are of concern from the perspective of effects on organisms and also on human health (NRC, 1985; Transportation Research Board and National Research Council, 2003; Dickey and Huettel, 2016; Farrington, 2020a). Petroleum is not the only source of many of these PAHs. Combustion of fossil fuels and wood for energy, and natural grass and forest fires, all contribute these types of compounds to the environment (e.g., see Lima et al., 2005).

Adding to the issue of biogenic/early diagenesis sources for low concentrations of PAHs, it has been known for many decades that marine organisms biosynthesize a limited number of *n*-alkanes and *n*-alkenes as well as highly branched alkanes and transform the phytol portion of the chlorophyll molecule to pristane. Basking sharks accumulate squalene in their livers (e.g., NRC, 1985; Valentine and Reddy, 2015, and references therein). Notably, Lea-Smith et al (2015) reported pentadecane, heptadecane, and 8-heptadecane biosynthesis by *Prochlorococcus* and *Synechococcus* (depending on the strain cultured), the most abundant marine cyanobacteria. The authors calculated that this results in a biosynthesis each year of between 269 and 539 million metric tons of these hydrocarbons for *Prochlorococcus*, and between 39 and 232 million metric tons of these hydrocarbons for *Synechococcus* for the world ocean. This synthesis has important implications for the potential long-term presence of bacteria capable of degrading *n*-alkanes in the marine environment (Weiman et al., 2021, in this issue), and this biosynthesis adds to the biogenic/methanogenic production of methane from biological and diagenetic processes (Reeburgh, 2007).

Thus, when tracking the fate of the DWH spilled oil, it has been important to be cognizant of the other sources of hydrocarbon/oil inputs to the same Gulf of Mexico area and to use analytical methods and interpretation of data that can successfully distinguish inputs from the spill, especially over longer periods of time and at low concentrations. It can be helpful to identify the specific chemical composition of the DWH oil and the relative compositions of specific structures of molecules known as petroleum biomarkers (molecular biomarkers to some organic geochemists—different from what are now commonly considered biomarkers in molecular biology; Rullkötter and Farrington, 2021, in this issue, and references therein). The ratios of these petroleum biomarkers to other chemicals in DWH oil, such as the alkylated PAH homologues, become important in distinguishing the presence of DWH oil from other oil sources as well as from other aliphatic hydrocarbons and PAH sources. The papers referenced in Stout and Wang (2018) provide a thorough discussion, with several examples that include some from the DWH spill. Boehm et al. (2018) provide a recent assessment of the difficulties encountered in and the limitations of the application of ratios of PAHs in terms of identifying initial sources of some, most, or all of the PAHs in given samples.

IMPORTANT FACTORS TO CONSIDER REGARDING THE RELATIONSHIP BETWEEN THE CHEMICAL COMPOSITIONS OF DWH GAS AND OIL AND THEIR BIOGEOCHEMISTRY FATES

Figure 1 depicts the biogeochemical fates of gas and oil; key biogeochemical processes are listed in Box 1. Another diagram of the environmental weathering of crude oil that has proved helpful is Figure 1 in Tarr et al. (2016), in the earlier *Oceanography* special issue about GoMRI research. These figures are both simplified schematics of a complex set of interacting processes. Some of the important processes have been the subjects of reasonably robust numerical modeling efforts in recent years as discussed in Boufadel et al. (2021) and Westerholm et al. (2021), both in this issue. One key point to reemphasize here is that a complex mixture of chemicals with a wide range of molecular weights and specific chemical structures (see Rullkötter and Farrington, 2021, in

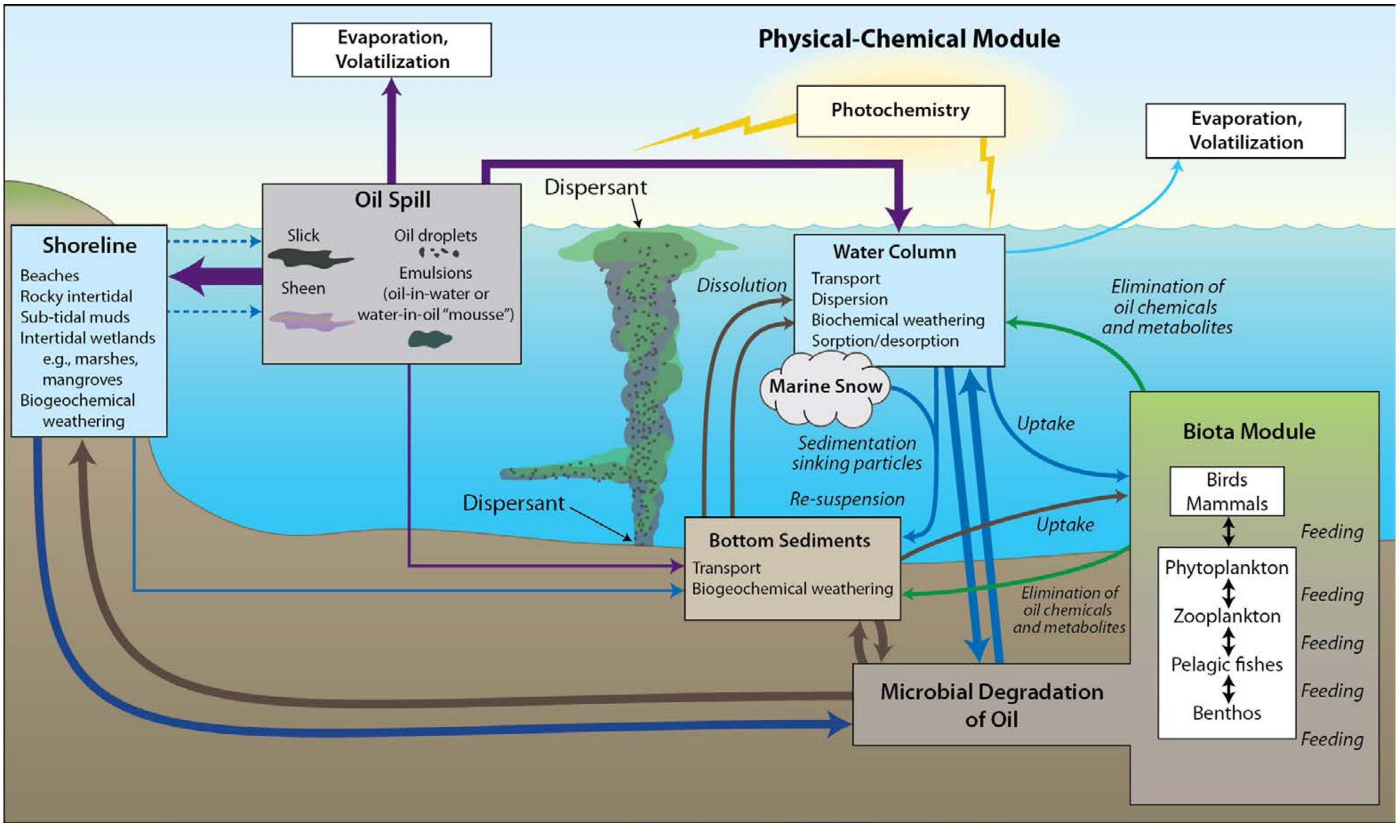


FIGURE 1. Schematic summarizing the fate of Deepwater Horizon gas and oil, including physical-chemical and biological modules with relevant processes. *From Farrington et al. (2016)*

Box 1. Key Biogeochemical Processes Controlling the Fate of DWH Gas and Oil Inputs

Not in temporal order or order of importance.

- Gas-oil-water partitioning and dissolution
- Gas-oil-water to atmosphere volatilization
- Water-oil emulsification
- Photo-oxidation at sea surface and on shorelines/beaches
- Sorption/desorption to/from particulates of various types, including transparent extracellular polymer and marine snow particles
- Emulsion formation at the sea surface, mainly water-in-oil emulsions
- Oil stimulation/instigation of formation of transparent extracellular polymer leading to more marine snow formation
- Aggregation and disaggregation of particulate matter
- Deposition of particulate matter with associated oil chemicals to sediments
- Resuspension of recently deposited material, transport, and redeposition
- Microbial degradation during all of the above
- Uptake by marine organisms, metabolism, excretion, food web transfer of oil compounds and/or metabolites

Note that the importance of any of these processes for any gas or oil group of compounds or individual compound is a function of their molecular weights and chemical structures because they govern solubility, vapor pressure, sorption/desorption, microbial degradation, and uptake/metabolism/excretion/food web transfer by marine organisms.

this issue) move through the pathways outlined in Figure 1.

Passow and Overton (2021) succeeded in constructing an estimated rough mass balance budget for the released oil and gas as a whole, even though the effort was complex. Based on the literature they consulted regarding the total input of gas and oil and post-spill field measurements in various places by numerous assessments and research efforts, they found that about 25% was recovered, 5%–15% was burned (volatile organics and oil in the surface slick), and 60%–70% was spread and weathered within the Gulf of Mexico. It was impossible to accurately budget the individual weathering processes that included: dilution in the water column (soluble, low molecular weight compounds and dissolved organic matter), volatilization and aerosol formation of some of the compounds to the atmosphere, photo-oxidation and oil/water solubility of photo products, sorption to and incorporation into particles and deposition to sediments, microbial degradation in the water column and sediments, and stranding ashore on beaches and marshes (see Tarr et al., 2016, for a very helpful and concise discussion of weathering of oil).

In this context, it is important to remember that in the strictest sense, each individual chemical within DWH gas and oil has its own mass balance, that is, its own relative distribution among various compartments in the environment (air, oil, dissolved in water, particulates in water, sediments, and biota). Thus, not all areas or ecosystems in the northern Gulf of Mexico were contaminated by all compounds of the crude oil. For example, oil reaching shorelines was largely weathered by photo-oxidization and removal of volatile compounds. Certain compounds, less susceptible to weathering, accumulated in various ecosystems (e.g., on shorelines, at the seafloor), reaching concentrations above background or detectable levels for varying periods of time. These compounds included some of the chemicals, such as PAHs of concern for known or potentially adverse effects, as discussed in other papers in this issue (Rullkötter and Farrington. 2021; Murawski et al., 2021; Halanych et al., 2021).

There are two other points worth mentioning. First, several of the papers concerning the fate of DWH oil in fact describe the analyses of oil *residues*. In those papers, the term "oil" does not refer to the crude oil at the time of discharge, but rather it means the portion of original oil chemicals that remain in the sample at the location and time of sample collection. Weathering/biogeochemical processes continuously alter the composition of oil in the environment. We make this point, because the term "residue" could be interpreted by some to mean a minor or trace amount, although chemists use the term to refer to the altered state of the spilled oil, which may be present in some samples at very high concentrations. The key is to assess the actual concentrations of specific hydrocarbons.

Second, another term found in the relevant scientific literature we cite is *target analytes*. Petroleum, or oil such as that in the DWH spill, is composed of many thousands of individual chemicals. In many cases, there has been agreement to analyze quantitatively a subset of important and abundant hydrocarbons as being representative of those compounds of greatest concern in the composition of the whole oil. In fact, many analyses report no more than 200 individual petroleum compounds. These target analyte compounds are also those for which there are well-established analytical methods and whose qualitative identifications and quantitative detection limits have been verified by the use of Standard Reference Materials from the US National Institute of Standards and Technology (or other similar agencies worldwide) and by the analysis of round robin quality assurance/quality control samples.

For example, a set of specific alkanes and specific aromatic hydrocarbons are measured frequently, usually identified in tables presented as supplementary materials, and reported as total concentrations of target analytes in the main body of a paper. Typical target analytes include normal alkanes (*n*-alkanes from C_{10} to C_{30} or C_{40}), pristane, phytane, two- to six-ringed PAH compounds and their alkyl homologues, and the "petroleum biomarkers" hopanes, steranes, and tri-aromatic diagenetic steroid compounds.

Compared to analyses from earlier decades, significant achievements have been possible using these methodological advancements. However, as noted in Rullkötter and Farrington (2021, in this issue), analytical chemistry methodology has advanced to the point where quantitative data on as many as a thousand or more oil chemicals is feasible, although expensive, and may become routine in the not-too-distant future. Thus, in many cases there has been agreement to analyze a subset, for example, a set of PAHs, and on occasion report the total of that subset as the concentration of the "target PAH analytes," or total target PAHs, as opposed to "total PAHs." The latter term implies that it includes analysis of all PAHs in the sample.

SHORTER-TERM FATE: WATER COLUMN PROCESSES

The dynamic processes of importance for the fate of the gas and oil are: (1) initial gas-oil-water partitioning between gas and oil bubbles and water in the water column; (2) progressive partitioning over time between oil in slicks at the surface, in the water column, and in air; (3) stranding on shorelines; and (4) deposition to sediments. A review of the physics and physical chemistry of these processes by Socolofsky et al. (2016) is updated by Boufadel et al. (2021, in this issue). There was a paucity of actual measurements of petroleum chemicals in the immediate vicinity of the well site and the vertical plume in the earlier days of the spill due to ongoing spill response activities and safety concerns. Thus, a more detailed scientific understanding, as presented and discussed in Socolofsky et al. (2016) and Boufadel et al. (2021, in this issue), is dependent on the interaction of various scaled laboratory experiments and modeling exercises that incorporate fundamental principles. Note that compounds in their gaseous phase form bubbles, whereas the term droplets refers to liquid oil compounds. Oil droplets in water are sometimes also referred to as particles or particulate oil because they are retained on filters. When released at depth and under high pressure, compounds that are gaseous at atmospheric pressure may be liquid and thus shift from their liquid to their gaseous phase during their ascent.

Oil entering the bottom waters from the DWH well was observed visually as a cloud of seawater containing mixtures of natural gas and oil droplets of various sizes, combined with brine from the well, resulting in a complex, uneven, interwoven brownish, tan, and yellowish plume (see image in Figure 5 of McNutt et al., 2012). At times, when drilling mud was being injected to attempt to reduce or stop the flow, an admixture of drilling mud became part of the plume. There were also reports that some gas hydrates formed, which is consistent with the temperatures and pressures of the bottom waters receiving the release. The public was treated for a period of time to live video camera feeds shown on various TV news outlets and web-based sources (authors' personal observations).

The separation of hydrocarbon gases from oil occurred prior to or shortly after exit from the broken riser pipe and broken blowout preventer (as noted in Boufadel et al., 2021, in this issue); as the gases separated from oil and began to rise through the water column, the water-soluble gas components such as methane, ethane, and propane dissolved into surrounding waters. The vertical plume transported gas and oil chemicals to surface waters from about 1,500 m depth. During that process, gas bubbles dissolved, oil droplets became smaller, and the more soluble components of the oil went into solution, with partitioning between the oil droplets and the surrounding seawater despite the old adage that oil and water do not mix. Table 1 illustrates the range of PAH solubilities, which span several orders of magnitude and are but one illustration of the range of physical-chemical parameters of individual chemicals that constitute gas and oil.

Ji et al. (2020) provide a detailed review of formation, detection, and modeling of the DWH submerged oil. In addition to the vertical plume, a significant horizontal plume, centered about 1,100 m depth, also evolved in the water column, and there were several smaller plumes at intermediate depths (Ji et al., 2020; Boufadel et al., 2021, in this issue). Modeling estimates and observations note the extent of the horizontal plume (often designated as the deep intrusion layer) to be 200 km to 400 km to the southwest and at other times in varying directions such as the northeast, depending on the variable

TABLE 1. Solubility of some aromatic/polycyclic aromatic hydrocarbons. From Table 4.3 in Transportation Research Board and National Research Council (2003), showing examples taken from the much larger data set by MacKay et al. (1992).

COMPOUND	MOLECULAR WEIGHT (Daltons)	SOLUBILITY (mg L^{-1})
Benzene	78	1,700
Toluene	92	530
Ethylbenzene	106	170
p-Xylene	120	150
Naphthalene	128	30
1-Methyl-naphthalene	142	28
1,3-Dimethyl-naphthalene	156	8
1,3,6-Trimethyl-naphthalene	170	2
Phenanthrene	178	1
Fluorene	202	2
Dibenzo-thiophene	184	1.1
Chrysene	228	0.002

water circulation processes (e.g., Ji et al., 2020; Passow and Overton, 2021). Early observation using UV-fluorescent colored dissolved organic matter measurements clearly indicated some type of horizontal plume; detector responses were consistent with its being composed of oil droplets and dissolved PAH. A few more detailed water samples were extracted and analyzed for PAHs by laboratory-based gas chromatography-mass spectrometry (Diercks et al., 2010). Within a few weeks after the Diercks et al. cruise, Camilli et al. (2010) used both UV-fluorescence and an innovative, novel, in situ mass spectrometer mounted on the autonomous underwater vehicle *Sentry*. Additional samples collected using a water column rosette were analyzed in order to define the horizontal plume. A less pronounced plume signal was detected to the northeast of the well site during the same research cruises by the same authors. The chemicals they measured included the gases methane (C_1) to butane (C_4) and the low molecular weight liquids benzene, toluene, and xylenes. The plume to the northeast "collided" at times with the continental slope, in some areas resulting in oil chemicals contaminating surface sediments (e.g., Passow and Overton, 2021, and references therein). There were indications at various times, as noted in the above-mentioned references, of other smaller horizontal plumes.

A few years later, a master's thesis (Watson et al., 2013; Watson, 2014) and detailed PAH data published by Boehm et al. (2016) evaluated results from gas chromatography and GC-mass spectrometry measurements of a large number of water samples from the vicinity of the well site collected as part of the US government and BP NRDA effort. Figure 2 replots data from Watson (2014), which compares data for BTEX (benzene, toluene, ethylbenzene, and xylenes) concentrations, total of the target PAHs, and total of target alkanes. Payne and Driskell (2018) discuss the difficulties in sampling, quality control, and quality assurance, and the challenges of sampling truly dissolved compounds, compounds in oil droplets or associated with particulates for PAHs, or other hydrocarbons.

The processes that control the water column distributions of oil compounds in time and space include complicated gas and oil bubble dynamics within turbulent flow, as well as horizontal and vertical flow and mixing (see Boufadel et al., 2021, in this issue). These processes result in the dilution of the input, potentially in microbial degradation of gas and oil hydrocarbons (Weiman et al., 2021, in this issue), and in sorption-desorption to various particles in the water column. Association with particles may be followed by biodegradation, ingestion, or deposition, and after deposition, continuing biodegradation and/or resuspension and redeposition.

If there were an ideal, soluble, nonbiodegradable gas or oil compound that did not partition with particles, we might expect it to behave and dilute as did the CF_3SF_3 tracer introduced to the deep Gulf of Mexico to study physical dynamics processes of the water column (Ledwell et al., 2016). Of course, there is no such ideal inert and soluble gas or oil chemical in petroleum. In addition, the DWH input lasted longer than one day, was composed of multiphase gas and oil comprising thousands of chemicals, and was greater on amount and spatial extent than the tracer. Nevertheless, the tracer experiment does provide important insights. As Ledwell et al. (2016) explain, the dilution is not uniform in time and space; mixing was much more rapid in the continental slope region compared to the deeper

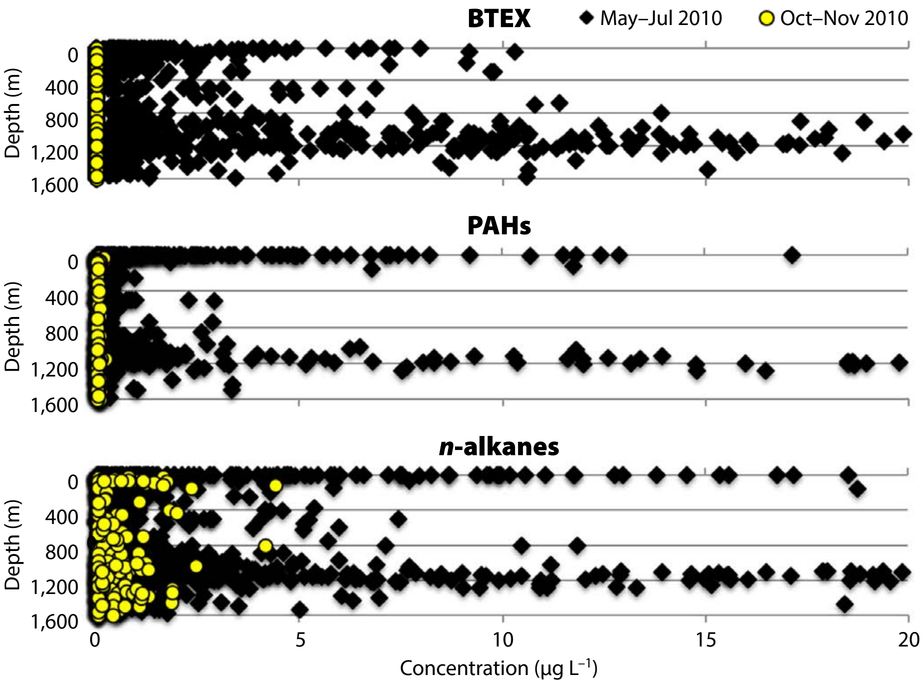


FIGURE 2. Concentration profiles for all water samples collected within 50 km of the wellhead where the water depth was ≥1,000 m. BTEX = benzene, toluene, ethylbenzene, and xylenes. PAHs = polycyclic aromatic hydrocarbons. Total PAH concentrations were the sum of the following 44 PAHs: naphthalene, C1-naphthalenes, C2-naphthalenes, C3-naphthalenes, C4-naphthalenes, acenaphthylene, acenaphthene, fluorene, C1-fluorenes, C2-fluorenes, C3-fluorenes, anthracene, phenanthrene, C1-phenanthrenes/anthracenes, C2-phenanthrenes/anthracenes, C3-phenanthrenes/anthracenes, C4-phenanthrenes/anthracenes, dibenzothiophene, C1-dibenzothiophenes, C2-dibenzothiophenes, C3-dibenzothiophenes, C4-dibenzothiophenes, benzo(b)fluorene, fluoranthene, pyrene, C1-fluoranthenes/pyrenes, C2-fluoranthenes/pyrenes, C3-fluoranthenes/pyrenes, C4-fluoranthenes/pyrenes, benzo(a)anthracene, chrysene, C1-chrysenes, C2-chrysenes, C3-chrysenes, C4-chrysenes, benzo(b)-fluoranthene, benzo(j+k)fluoranthene, benzo(a)fluoranthene, benzo(e)pyrene, benzo(a)pyrene, perylene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene, benzo(g,h,i)perylene. The compounds used to measure total *n*-alkane* concentrations were C9-40, pristane, phytane, 2,6,10 trimethyldodecane, 2,6,10 trimethyltridecane, and norpristane. (*The correct term is total designated alkanes). *Replotted from Watson (2014) with permission*

interior waters of the Gulf. Maximum concentrations of the tracer found in their surveys were measured at dilutions of 10^4, 10^7, and 10^8 at one-week, four-month, and 12-month survey times, respectively.

It is clear from the sampling and analyses reported that there was a period of significant contributions of DWH gas and oil to the nearby deep waters of the Gulf of Mexico and in the immediate region of the Macondo well site. Once the well was capped, the concentrations in the water column rapidly diminished to below detection limits in areas sampled. However, the elevated concentrations of DWH oil compounds collected in sediment traps many months after the capping of the well demonstrated that DWH oil was still present in the water column (Giering et al., 2018; Passow and Stout, 2020). Weiman et al. (2021, in this issue) describe microbial processes that were involved in biodegradation of the DWH oil, and Murawski et al. (2021, in this issue) discuss what biological effects may have ensued due to the period of elevated concentrations in the water column.

Concentrations of petroleum hydrocarbons with clear DWH molecular characteristics spread into continental shelf surface and then bottom waters off Louisiana (Turner et al., 2019; see Figure 3 for sampling locations). Sampling began in May 2010 and continued initially once a month, and at greater intervals later. Turner et al. present field observations and logical inference that the initial May 2010 samples were already influenced by DWH spilled oil. Concentrations increased markedly from May through June, July, August, and September of 2010, decreased relatively rapidly until 2015, and then continued to decrease slowly from July 2015 through 2019. Data for the total target analyte aromatic hydrocarbons in the water showed 153 $\mu g\ L^{-1}$ in August 2010 and an increase to 323 $\mu g\ L^{-1}$ in September 2010, followed by a decrease over time until 2018 when concentrations were in the range of 0.01 $\mu g\ L^{-1}$. The water samples contained a higher proportion of three-ring aromatic compounds (e.g., phenanthrene and alkyl phenanthrenes) than the initial DWH oil, which had a higher proportion of lower molecular weight aromatic compounds (e.g., the two-ring aromatic hydrocarbon naphthalene and alkylnaphthalenes). It is likely that a combination of volatilization, dissolution from the droplets, and biodegradation of some of the naphthalene and alkyl naphthalenes occurred during transport from the DWH site to the sampling location. Data for the adjacent inshore marsh areas are discussed in a later section.

FATE OF OIL AT THE AIR-SEA INTERFACE: THE IMPORTANCE OF PHOTO-OXIDATION

Substantial amounts of oil rose to the sea surface and formed oil slicks and sheens. In short order, the more volatile components of the surfaced oil evaporated. Mixing due to wind and waves promoted formation of a water-in-oil emulsion that exhibited many bright to creamy colors (e.g., orange). These emulsions, termed "mousse" years ago because of their resemblance to the dessert chocolate mousse (e.g., NRC, 1985), have been reported as important and studied extensively with previous oil spills.

Photo-oxidation of oil at the sea surface had been recognized for decades, as noted by reviews in Payne and Philips (1995), Ward and Overton (2020), and Ward et al. (2020). Although the Transportation Research Board and National Research Council (2003) report stated that "photo oxidation is unimportant from a mass balance consideration," we can find no substantive discussion or references that support this statement. That same 2003 report acknowledged that products of photo-oxidation of oil chemicals can produce toxic reaction products of concern for both immediate and longer-term impacts. There was also recognition that photo-oxidation is an important process in the fates of oil chemicals evaporated from oil slicks into the atmosphere.

Research focused on the DWH oil spill provided important results that require revision of the assertion from the Transportation Research Board and National Research Council (2003) report, at least for oils spilled in tropical

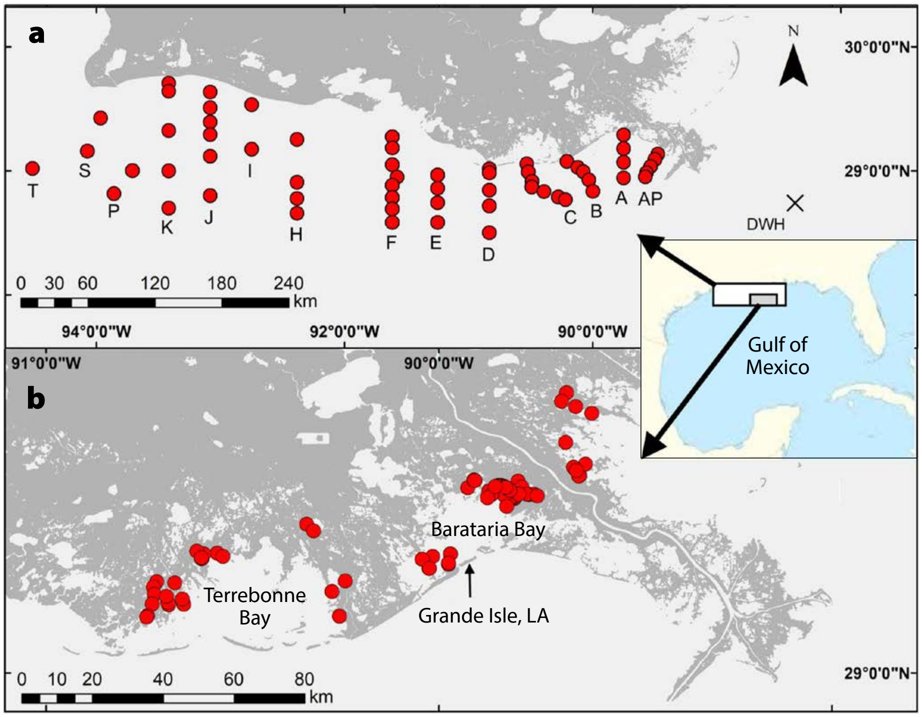


FIGURE 3. Gulf of Mexico sampling locations in (a) offshore waters, and (b) marsh sediments. The Deepwater Horizon (DWH) site is indicated by the X in (a). *Reproduced from Turner et al. (2019) with permission*

and subtropical regions, or at higher latitudes during the summer. The results of a GoMRI-funded synthesis workshop focused on photochemistry and photo-oxidation are summarized in Ward and Overton (2020). The meshing of results from field observations and field sample analyses, laboratory-scale flasks experiments, and mesocosm experiments has been key to significant progress in our knowledge about photo-oxidation associated with surface oil slicks. In reviewing all of this research, Ward and Overton (2020) and Ward et al. (2020) provide an interesting comparison of the relative importance ascribed to photo-oxidation compared to other oil slick weathering processes (evaporation, emulsification, and biodegradation) pre- and post-DWH research (Figure 4a).

Numerous experiments and analyses of field samples have tied photo-oxidation to known photochemistry reactions. These include both direct and indirect photochemical reactions, as discussed by Ward and Overton (2020). Their Figure 5 incorporated here as Figure 4b is a simplified representation of both direct and indirect photo-oxidation. Many, if not most, of these findings would not have been possible without the utilization of new analytical chemistry methods, as discussed in Rullkötter and Farrington (2021, in this issue). In particular, analyses by ultra-high-resolution FT-ICR-MS (Fourier transform-ion cyclotron resonance-mass spectrometry) have provided extensive data that challenge our ability to identify the myriad reaction pathways and chemical structures of thousands of photo-oxidation-induced reaction products (Rullkötter and Farrington, 2021, in this issue).

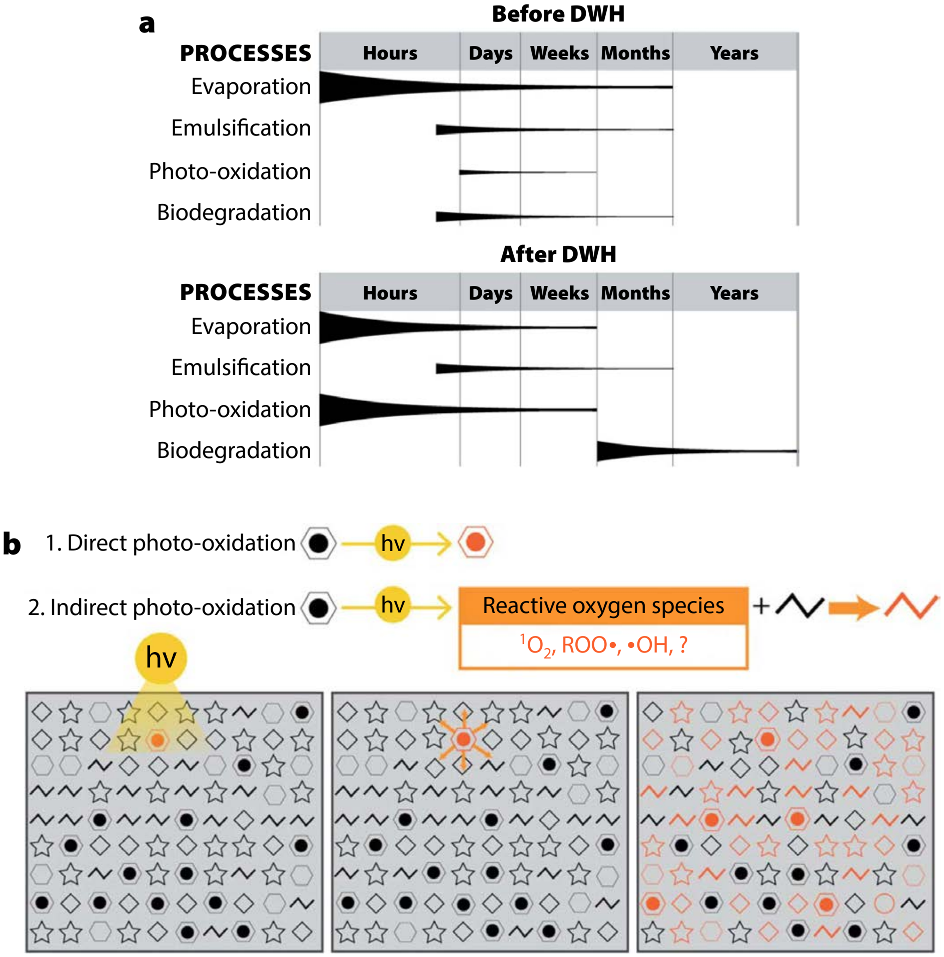


FIGURE 4. (a) The relative importance of floating surface oil weathering processes as understood prior to and after the Deepwater Horizon spill of 2010. (b) A conceptual model depicting direct and indirect photo-oxidation. In direct photo-oxidation (left panel), a light-absorbing molecule (depicted as a black aromatic ring) is partially oxidized into a new molecule (depicted as an orange aromatic ring). Indirect photolysis occurs when the absorption of light leads to the production of reactive oxygen species (middle panel), such as singlet oxygen, peroxyl radicals, and hydroxyl radicals. These reactive intermediates can oxidize a wide range of compounds, not just the compounds that directly absorb light (right panel). hv = light energy. *(a) and (b) reproduced from Ward and Overton (2020) with permission*

Ward and Overton (2020) note an additional important aspect of these findings: the technological advances in remote sensing that allow acquisition of information on oil film extent and thickness (MacDonald et al., 2015) permit photochemical rate modeling to be applied to the DWH spill. However, even better quantitation of film thickness over space and time is needed to improve the models designed to estimate the extent of photochemical/photo-oxidation reactions in any given oil spill.

Already, these new findings have allowed photo-oxidation/photochemistry to be incorporated in conceptual models to reflect more accurately the role photo-oxidation plays in the fate of oil at the sea surface or in surface waters (NASEM, 2020). Results from this work have important implications for response to oil spills. For example, Ward et al. (2018) discuss how photochemical oxidation of oil changes the oil's solubility in dispersant solvent, which has the potential to reduce the effectiveness of aerial dispersant application.

A brief summation of the three key findings as set forth by Ward and Overton (2020) are as follows (quoting the initial sentences):

1. "The rate and extent of photochemical weathering was much greater for DWH surface oil than expected based on early conceptual models of oil weathering."
2. "Indirect photochemical processes played a major role in the partial oxidation of the floating surface oil."
3. "The extensive and rapid changes to the physical and chemical properties

> of oil by sunlight may influence oil trajectory at sea and the selection of response tools."

In addition to potential implications for response strategies, photo-oxidation adds oil-soluble, oxidized chemicals to the oil mixtures. These oil-soluble oxy products, in essence, become a part of, for example, stranded oil residues, with properties similar to the oil's resin and asphaltenic semi-solid/solid components stranded on beaches and marshes (see later section).

OIL-PARTICLE AGGREGATES, MARINE OIL SNOW, AND MARINE OIL SNOW SEDIMENTATION AND FLOCCULENT ACCUMULATION

According to the Transportation Research Board and National Research Council (2003) review and recommendations, "Understanding the distribution of petroleum hydrocarbons between the dissolved phase and the variety of aquatic particles is important for determining the fate of hydrocarbons in the sea and the bioavailability of these chemicals to marine biota."

The importance of the association of oil chemicals with mineral particles and with organic matter in sediments—called oil-particle aggregates or OPAs (formerly known as oil-mineral aggregates or OMAs; Burd et al., 2020; Passow and Overton, 2020)—was known as an important biogeochemical phenomenon for decades prior to the DWH spill (e.g., NRC, 1975, 1985). OPAs are particularly important in nearshore regions or in regions where land runoff or river discharges carry mud and silt particles into the ocean. This was described as a major phenomenon governing the fate of oil chemicals as early as the 1969 Santa Barbara spill (Kolpack, 1971).

It is also important to keep in mind that during the DWH accident there were attempts to shut down the well by pumping in drilling mud. The efforts failed, resulted in discharge of drilling mud mixed with DWH gas and oil chemicals near the sediment-water interface, and likely led to the formation of OPAs, perhaps of a special type (Passow and Hetland, 2016, and references therein).

Marine snow has long been acknowledged as important in the ecology of marine environments (Silver, 2015). The involvement of the marine snow phenomenon in all biogeochemical cycles would likely be obvious to anyone with the privilege of viewing marine snow in situ. This was the case for author Farrington when he observed marine snow and easily resuspended floc in the deep ocean at the sediment-water interface out of a DSRV *Alvin* viewport during one 1976 dive and consequently changed his entire approach to a significant portion of his research effort (Farrington, 2020b).

Marine snow is defined as particles >0.5 mm in size and may consist of aggregations of smaller organic and inorganic particles, including bacteria, phytoplankton, microzooplankton, zooplankton fecal pellets and feeding structures (e.g., larvacean houses), biominerals, terrestrially derived lithogenic components, and detritus (Alldredge and Silver, 1988; Silver, 2015). Early in the research and assessments for the DWH oil spill, the issues of marine snow interacting with oil and becoming marine oil snow, or MOS, and then accumulating, flocculating, and sinking to the seafloor in the MOSSFA process were identified as important subjects for extensive research because of their apparent major roles in the biogeochemistry and fate of oil chemicals in the water column (Passow and Ziervogel, 2016; Daly et al., 2016). A GoMRI MOSSFA Working Group was formed in May of 2013 to facilitate interdisciplinary research and interactions among research groups and individuals conducting research connected with MOSSFA. The work of these scientists has culminated in several reviews summarizing MOSSFA-related results and the role of MOSSFA in the overall fate of the DWH oil chemicals (e.g., Burd et al., 2020; Daly et al., 2020; Kujawinski et al., 2020: Quigg et al., 2020; Passow and Overton, 2021).

Burd et al. (2020) pointed out three earlier references that mention detritus of the marine snow type being present in oil spills. It seems clear that, prior to the DWH spill, with a few exceptions, studies focused mainly on interactions of mineral or sediment particles with oil chemicals in shallow-water environments (i.e., the *Tsesis* oil spill in 1977–1978; see Johansson et al., 1980, and references therein). These studies drew attention to the importance of biological detritus, particulate matter, and fecal pellets, such as those from zooplankton, in the water column biogeochemistry of petroleum hydrocarbons and deposition to sediments. In addition, mesocosm experiments using No. 2 fuel oil to mimic chronic oil inputs to shallower estuarine water columns recorded the accumulation of several millimeters of organic detritus-oil chemical accumulations at the sediment-water interface (Gearing et al., 1979).

The post-DWH lexicon regarding the fates and biogeochemistry of oil chemicals in the water column now includes consideration of MOS and MOSSFA in oil spill response, modeling, and research. An important finding of DWH research and assessments is the partitioning of chemicals between oil and particulate matter or the incorporation of oil chemicals in particulate matter such as marine snow that is followed by protracted deposition of oil-associated marine snow to the seafloor. During deposition, desorption/adsorption of the more soluble/less soluble oil chemicals continues along with microbial degradation of some of the oil chemicals. Reviews by Daly et al. (2016), Passow and Hetland (2016), Passow and Ziervogel (2016), Burd et al. (2020), Passow and Overton (2020), and Quigg et al. (2020 and 2021, in this issue)—and references therein—offer a comprehensive and up-to-date review of the state of knowledge about marine snow in oil spill situations and also offer suggestions for important next stages of research. These reviews also delve into important research findings from a combination of laboratory and mesocosm experiments, placed within the context of field observations, concerning the interaction of oil hydrocarbons and Corexit dispersants with phytoplankton and bacteria. Of note are the interactions that stimulate phytoplankton and bacteria to exude extracellular organic matter such as biofilms or transparent exopolymeric particles, a subgroup of extracellular polymeric substances.

Burd et al. (2020) present and discuss evidence that MOS and MOSSFA were associated with the DWH oil spill. Their key points include:

1. **Visual observations** noted large, mucus-rich marine snow particles of about 10 cm in the surface water during May 2010. These marine snow particles seemed to contain oil and were observed near surface oil layers. They were not observed during a June cruise in the area.

2. **Sediment traps and camera systems** provided samples and observations documenting sedimentation events involving MOS in the water column during and after the spill (Diercks et al., 2018). Interestingly, well before the DWH spill, Diercks and Asper (1997) had used a similar trap and camera system to measure settling velocities of aggregates and marine snow in the Gulf of Mexico's Mississippi River plume area. A Shadowed Image Particle Profiling Evaluation Recorder (Remsen et al., 2004) was also used to observe marine snow particles and MOS (Daly et al., 2020). We note that recovery of flocs from the tops of carefully collected cores and from slurp guns (e.g., Stout et al., 2016) also provided key samples of OMAs, MOS, and MOSSFA type events.

3. **Evidence from laboratory and mesocosm experiments** confirm field observations in general and provide greater insights into what most likely occurred in the field during and after the DWH spill.
   a. Marine snow-sized bacterial oil aggregates (BOAs) that result from exopolymer production by bacteria were present. Passow and Overton (2020) noted that photo-oxidation in surface waters may have enhanced the formation of BOAs.
   b. Formation/sorption of exopolymer matrices on the surfaces of small oil droplets resulted in micro-BOAs.
   c. Phytoplankton cells and detrital particles formed MOS aggregates with oil droplets in the aggregate matrix. These can sink rapidly.
   d. Although zooplankton contributions to MOS have not been as well studied (Almeda et al., 2016), it has been known for decades that zooplankton can ingest oil droplets or particles in the water column and then produce oil-containing fecal pellets that sink to the seafloor (e.g., Conover, 1971). This process was also observed in laboratory experiments with the zooplankter doliolid (*Dolioletta gegengaurai*) (R.F. Lee et al., 2012), and it is more than likely that this occurred during DWH.

   Burd et al. (2020) provide an important observation: "Mesocosm experiments revealed that in the presence of oil and marine particles, aggregate formation was faster, and aggregates were colonized by higher densities of heterotrophic bacteria, than those formed in incubations without added oil (Quigg et al., 2016; Doyle et al., 2018)."

4. **Possible effects on deep-sea corals.** The deposition of MOS on some deep-water corals via what was most likely a MOSSFA mechanism was noted in a few areas of the deep Gulf of Mexico (e.g., see Fisher et al., 2016). The MOS or floc material was sampled, analyzed, and shown with reasonable certainty to be composed of weathered DWH oil with some dioctyl-sodium sulfosuccinate (DOSS) from dispersant also present (see Fisher et al., 2016, and White et al., 2012, 2016, and references therein).

The **Figure 5** schematic from Burd et al. (2020) summarizes the various MOS and MOSSFA processes discussed above.

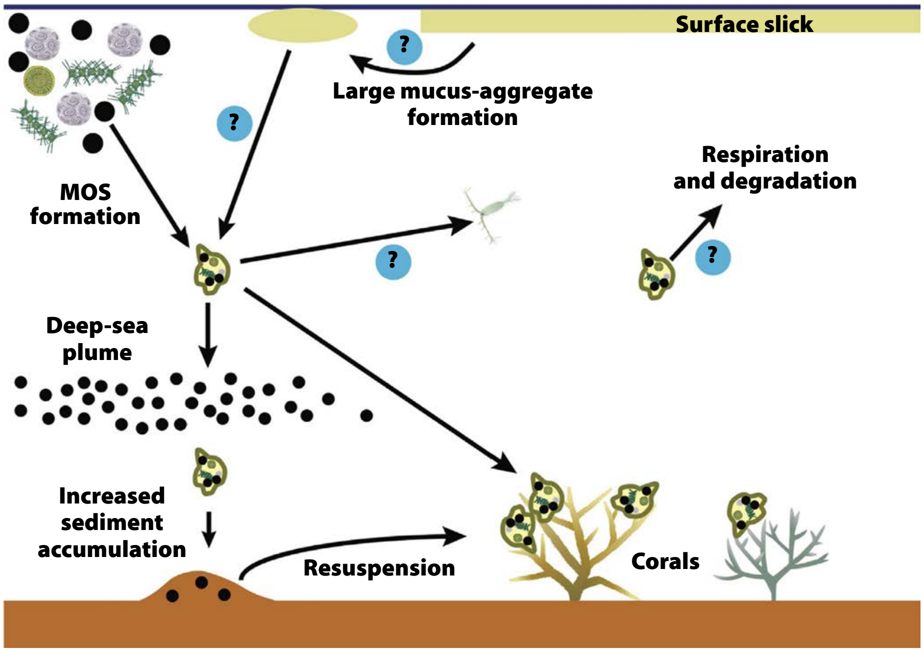


FIGURE 5. A schematic of the processes involved in the formation of marine oil snow (MOS) and marine oil snow sedimentation and flocculent accumulation (MOSSFA) events, as well the impacts of MOS and MOSSFA on marine systems. Black dots depict oil droplets, the yellow rectangle shows the surface oil slick, and the yellow ellipse represents large mucus aggregates. Question marks indicate connections that scientists suspect occur, but for which few data have been collected. *Reproduced from Figure 4 in Burd et al. (2020) with permission*

The question marks indicate processes that these authors suspect occur but for which little data have been collected, and their paper discusses questions raised, including "what remains unknown?" We summarize by paraphrasing key points.

- What are the conditions during an oil spill that can lead to MOS and MOSSFA? Discharges from nearby rivers, individually or together, seem to be concomitant with suspended sediment, nutrient, and particulate organic carbon loads. Plankton blooms occur in the more open-ocean areas and appear to accompany or cause natural marine snow events.
- We need to know more about where in the water column marine snow becomes MOS as a result of the various mechanisms of sorption, scavenging, and incorporation of particles. During DWH, it appeared not only to be a surface water phenomenon but also to occur throughout the water column and especially in the subsurface plume(s).
- How is biodegradation of oil impacted by inclusion of oil into MOS?
- Interactions between oil chemicals and particles result in transforming the oil's composition.
- How can the densities and shapes of various MOS sizes be incorporated into models to provide computation of vertical and horizontal transport velocities?

DEPOSITION AND LONG-TERM FATE IN OFFSHORE AND DEEP-SEA SEDIMENTS

Estimates of the amount of DWH weathered petroleum hydrocarbons deposited onto sediments of the northeast Gulf of Mexico, and of the area involved, vary depending on the sampling grid and the type of analysis, as summarized by Passow and Hetland (2016). They note that an estimated 2%–15% of the spilled oil was deposited after compositional change due to weathering, and that this could be considered a lower limit. Later estimates suggest 21% ± 10% (Romero et al., 2017). The deposited material was weathered by dissolution and microbial degradation of oil residues originating from the subsurface plumes and by volatilization, photooxidation, and microbial degradation of oil that reached the sea surface.

There were several different assessments of DWH oil chemicals in surface sediments collected in deep water in the immediate region of the DWH well site during and after the spill, and also further afield in the northeast Gulf of Mexico. Sampling was largely supported by federal agencies via the NRDA process, by BP, and by GoMRI. Resulting data are all available online (https://www.diver.orr.noaa.gov/deepwater-horizon-nrda-data/ and https://data.gulfresearchinitiative.org/; also see Zimmermann et al., 2021, in this issue). In addition to contributing to continuing studies of the DWH spill, we expect these data may be useful in the future, perhaps to test new hypotheses originating from laboratory or mesocosm studies, or to compare with results of future accidental oil inputs.

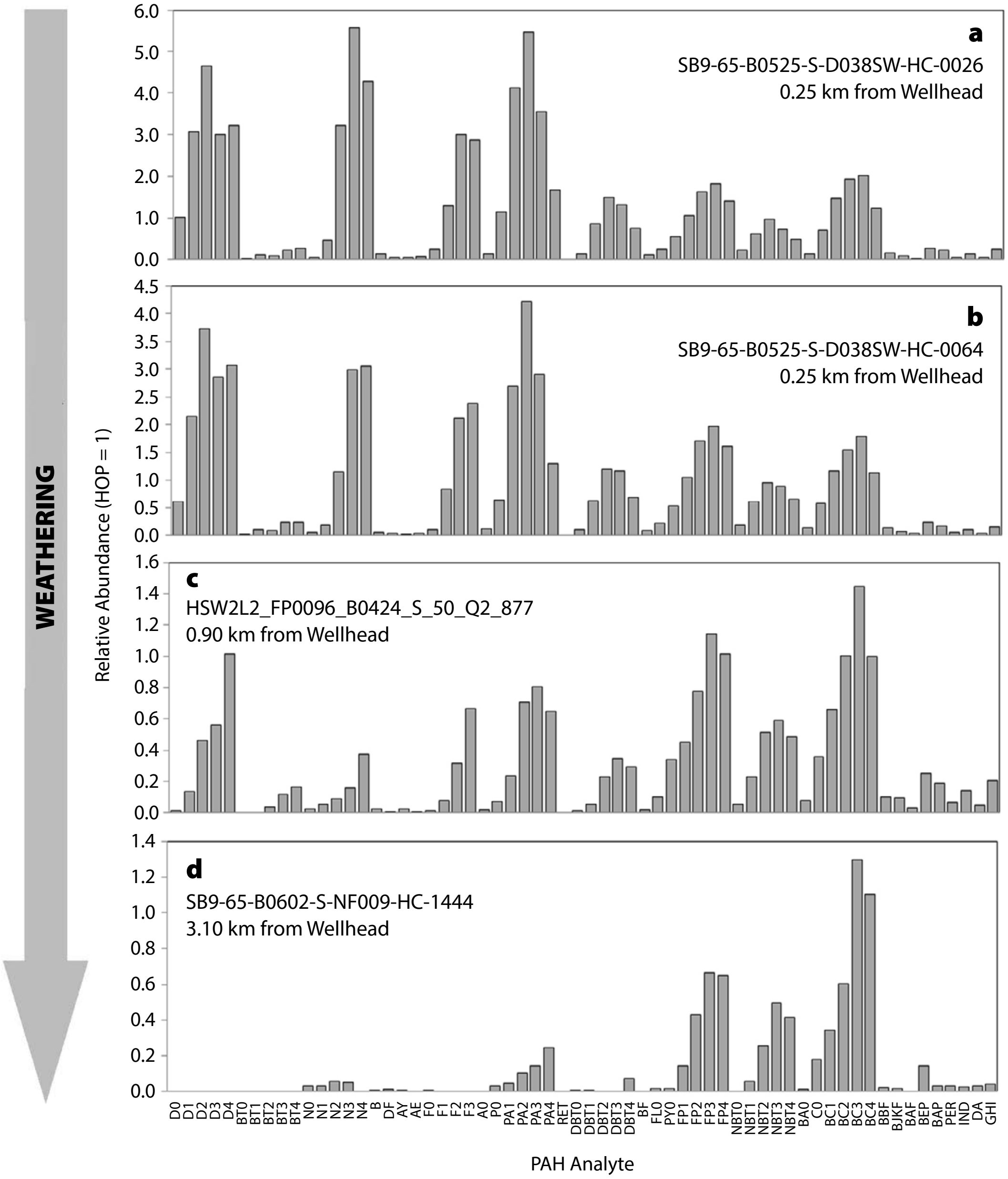
Sediment cores were collected with care to retain the floc (if present) at the sediment-water interface and within 8 km of the well site. Stout and Payne (2016a) report an important set of data from detailed chemical analyses of hydrocarbons in the upper 1 cm of sediment cores as well as of some deeper sections down to 10 cm; **Figure 6** provides the typical PAH composition of weathered oil residues they found in bottom surface sediments collected near the wellhead in 2011. Both the target alkanes (not shown here) and PAH compositions were significantly degraded in these oil residues, with some depleted by over 90%. Weathering of oil residues mainly occurred before deposition onto the seafloor and was mostly affected by dissolution and biodegradation in the submerged plumes and during vertical transport to the seafloor. Oil residues were least weathered near the well head and got progressively more weathered with distance from it, further suggesting that most weathering occurred before deposition on bottom sediments. Deep time series sediment trap data are in accord with these results (Passow and Stout, 2020).

The data in **Figure 6** illustrate a significant aspect of the changing composition of the DWH aromatic hydrocarbons over time as the various biogeochemical processes influence their composition. Chrysene and alkyl chrysenes, and aromatic hydrocarbons of similar or greater molecular weight, become the dominant aromatic hydrocarbons in the oil residues even though they were not the dominant aromatic hydrocarbons in the original DWH oil spilled. This has implications for the assessment of aromatic hydrocarbons for long-term effects on organisms. Understandably, the past focus for testing short-term effects has been on the lower molecular weight aromatics, such as naphthalenes and phenanthrenes, that have been assayed and shown to have adverse effects, depending on the concentrations, types of exposure, and the organisms (e.g., NRC 1985; Transportation Research Board and National Research Council, 2003).

The vast majority of DWH oil residues in sediments were completely depleted of low and medium molecular weight hydrocarbons (e.g., carbon numbers below ~n-C_{24}) after three to four years (Bagby et al., 2016; Babcock-Adams et al., 2017). These represent oil residues with weathering losses of over 90% of their target hydrocarbon content when compared to the content of the Macondo oil when it was spilled into the Gulf. However, it should be noted that, in addition to mineralization and CO_2 production, some of the hydrocarbon compounds lost during weathering were converted into oil-soluble oxidized compounds (White et al., 2016; Aeppli et al., 2018), which are generally not detected by target compound GC-MS analyses. Thus, the 90% loss does not mean that 90% of the original oil compounds were fully oxidized to CO_2 (i.e., removed).

To frame sampling, measurements, and estimates of DWH oil deposition, Brooks et al. (2015) provide the various sediment types known in the northern Gulf of Mexico region for the continental shelf, slope, and canyons. These authors and Romero et al. (2015) document a depositional pulse extending about 100 nautical miles (~185 km) from the DWH site to the northeast in the DeSoto Canyon area for water depths ranging from about 300 m to 1,500 m. Romero et al. (2017) depict oil and MOS deposition extending 270 nautical miles (500 km) to the southwest of the spill site with an area of 110,000 km^2. After the leak was closed, Yan et al. (2016) deployed a deep time-series sediment trap in that area above the sediment-water interface at 1,538 m water depth between August 2010 and October 2011. They reported deposition of DWH spill-related oil chemicals, drilling mud chemicals (presumably from the failed attempt to shut the well with drilling mud), and black carbon particles from the in situ burning of the oil slick, which was one of the response mechanisms (Rullkötter and Farrington, 2021, in this issue).

Daly et al. (2016) provide a detailed and informative review of the vari-



D0	cis/trans-Decalin
D1	C1-Decalins
D2	C2-Decalins
D3	C3-Decalins
D4	C4-Decalins
BT0	Benzothiophene
BT1	C!-Benzo(b)thiophenes
BT2	C2-Benzo(b)thiophenes
BT3	C3-Benzo(b)thiophenes
BT4	C4-benzo(b)thiophenes
N0	Naphthalene
N1	C1-Naphthalenes
N2	C2-Naphthalenes
N3	C3-Naphthalenes
N4	C4-Naphthalenes
B	Biphenyl
DF	Dibenzofuran
AY	Acenaphthylene
AE	Acenaphthene
F0	Flourene
F1	C1-Flourenes
F2	C2-Flourenes
F3	C3-Flourenes
A0	Anthracene
P0	Phenanthrene
PA1	C1-Phenanthrenes/Anthracenes
PA2	C2-Phenanthrenes/Anthracenes
PA3	C3-Phenanathrenes/Anthracenes
PA4	C4-Phenanthrenes/Anthracenes
RET	Retene
DBT0	Dibenzothiophene
DBT1	C1-Dibenzothiophenes
DBT2	C2-Dibenozthiophenes
DBT3	C3-Dibenzothiophenes
DBT4	C4-Dinenzothiophenes
BF	Benzo(b)fluorene
FL0	Flouranthene
PY0	Pyrene
FP1	C1-Flouranthene/Pyrene
FP2	C2-Flouranthene/Pyrene
FP3	C3-Flouranthene/Pyrene
FP4	C4-Flouranthene/Pyrene
NBT0	Napthobenzo thiophenes
NBT1	C1-Napthobenzo thiophenes
NBT2	C2-Napthobenezo thiophenes
NBT3	C3-Napthobenzo thiophenes
NBT4	C4-Napthobenzo thiophenes
BA0	Benz(a)anthracene
C0	Chrysene/Triphenylene
BC1	C1-Chrysenes
BC2	C2-Chrysenes
BC3	C3-Chrysenes
BC4	C4-Chrysenes
BBF	Benzo(b)flouranthene
BJKF	Benzo(jk)flouranthene
BAF	Benzo(a)flouranthene
BEP	Benzo(e)pyrene
BAP	Benzo(a)pyrene
PER	Perylene
IND	Indeno[1,2,3-cd]pyrene
DA	Dibenz[a,h]anthracene
GHI	Benzo[g,h,i]perylene

FIGURE 6. Histograms showing the hopane-normalized concentrations in surface sediments (0–1 cm) from four cores collected near the DWH wellhead in 2011 that demonstrate the progression of weathering of Deepwater Horizon oil (Macondo well). (a) Partially weathered and wax-rich oil. (b) Intermediately weathered and wax-rich oil. (c) Highly weathered and wax-rich oil. (d) Severely weathered and wax-rich oil. Wax-rich oil contains a high concentration of *n*-alkanes, also called normal paraffins. The x-axis shorthand notations for aromatic hydrocarbons analyzed are listed at right with full compound names written out in the order they are shown left to right on the x-axis. *Figure and compound names and abbreviations (with some modifications) reproduced from Stout and Payne (2016a) with permission*

ous origins of sinking OPAs, MOS, and MOSSFA, and factors that might or did control their deposition to the seafloor. Sediment cores provided a multi-proxy record of MOSSFA events, the intensity of the flux of oil chemicals to the seafloor, and the spatial extent of such deposition and post-depositional events.

Bagby et al. (2016) examined 125 aliphatic (saturated hydrocarbons), aromatic, and biomarker compounds (Rullkötter and Farrington, 2021, in this issue) in 2,908 sediment samples collected within four years of the spill. The data they interrogated are available from the NRDA website and in the supplementary materials for Bagby et al. (2016). They demonstrate the importance of chemical structure, physical chemical form (e.g., large and small OMA and MOS particles), and hydrocarbon persistence for sample locations containing higher initial concentrations at the time of deposition.

Romero et al. (2017) combined their own samples with a large, archived data set in order to interpret 158 hydrocarbon compounds in 2,613 sediment cores, several of which overlapped the data set accessed by Bagby et al. (2016). Romero et al (2017) assessed the chemical signature of DWH oil in surface sediments to determine the amount, distribution, and areal extent of DWH oil residues deposited on the seafloor from coastal, continental shelf, and deep-sea areas of the northern Gulf of Mexico. The total residual hydrocarbon concentrations deposited at each site based on the 2010–2011 sampling that they found is depicted on the spatial chart in Figure 7 and grouped in coastal, continental shelf, and deep-sea stations in Figure 8. Their work revealed relatively large deposition of weathered oil chemicals in the coastal and deep-sea areas and very little deposition on the continental shelf. Large spatial heterogeneity of deposits is a consequence of spatial variability in sedimentation rates, resuspension of deposited material, and lateral transport.

Giering et al. (2018) measured sedimentation rates of polycyclic aromatic hydrocarbons with time-series sediment traps at three contrasting sites in the northern Gulf of Mexico: a station near the DWH site (1,660 m water depth), a natural seep site (1,380 m water depth), and a reference site (1,160 m water depth). They summarized sedimentation rates of organic carbon and other proxies for marine particles as well as hydrocarbon compounds for the period 2012 to 2016. They concluded that the quality and quantity of sedimentation at each site were very different and ascribed this to differences in relative riverine and oceanic influences as well as inputs from natural seepage and combustion product PAHs—the latter most likely from land sources via atmospheric transport and/or runoff. Modeling efforts comparing two of the traps provide clear documentation and mechanistic explanations of the complex variability of vertical fluxes due to "mesoscale circulation and seasonal cycle of primary production, which in turn are linked to riverine inputs, wind forcing and the seasonal cycle of the mixed layer" (Liu et al., 2018).

Diercks et al. (2018) discuss observations and accompanying interpretations

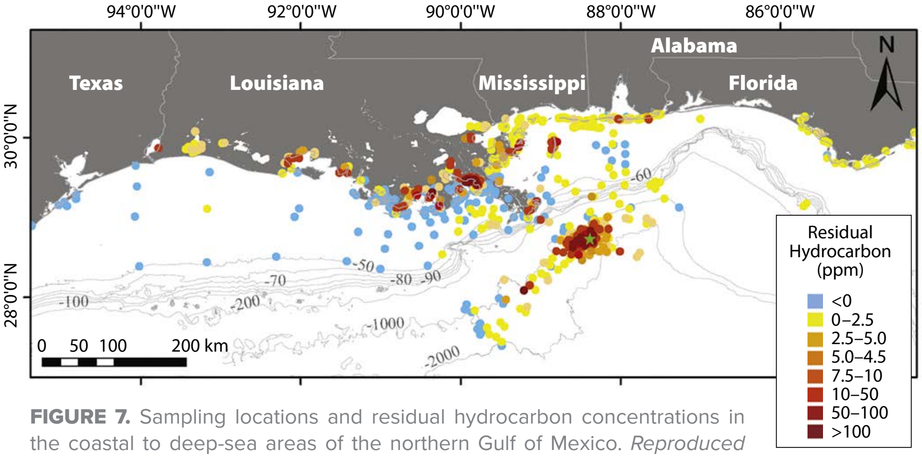


FIGURE 7. Sampling locations and residual hydrocarbon concentrations in the coastal to deep-sea areas of the northern Gulf of Mexico. *Reproduced from Romero et al. (2017) with permission*

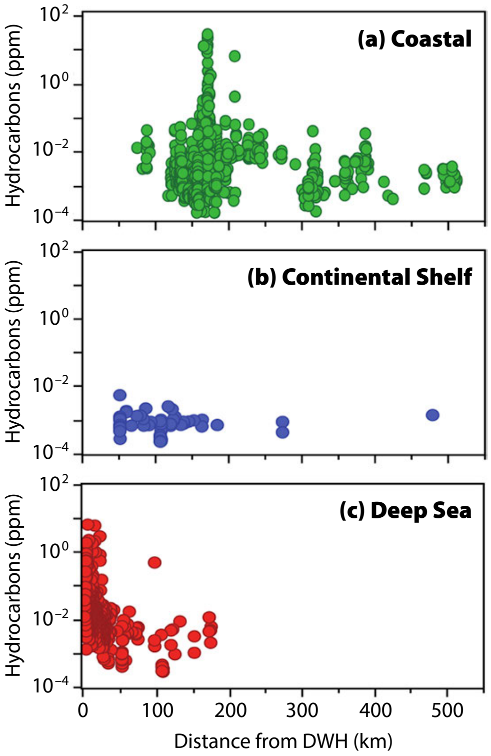


FIGURE 8. Spatial extent of contaminated sediments found in the northern Gulf of Mexico after the Deepwater Horizon spill. Data are shown for (a) coastal, (b) continental shelf, and (c) deep-sea areas. Contaminated sediments contain higher ∑Hydrocarbons in the surface layer (post-spill) compared to down-core layers (background, pre-spill) of the sediment cores analyzed. The cores were collected in 2010–2011. ∑Hydrocarbons refer to the sum of aliphatics (*n*-alkanes C_{10-40}, isoprenoids, branched alkanes), polycyclic aromatic hydrocarbons (2–6 ring, including alkyl homologues), hopanoids (C_{27-25}), steranes (C_{27-29}), and tri-aromatic steroid compounds (C_{26-28}). *Reproduced from Romero et al. (2017) with permission; details of sampling locations are therein*

of resuspension of deposited MOS using a rich set of data from moored flux cameras, a profiling camera, current meters, and sediment trap sampling from fall 2012 to summer 2013, including the period of Hurricane Isaac. They concluded that while hurricane resuspension events are large scale, they become part of the averaged long-term background signal. Their observations and interpretations led them to suggest that small-scale resuspension events play an important role in redistributing sediment on the seafloor. This did not include the separate and rarer issue of hurricane-induced turbidity flows of unstable slope sediments as noted for the Taylor Energy Platform briefly discussed earlier (Bryant et al., 2020).

Physical oceanography observations and models (Boufadel et al., 2021, in this issue) indicate it is likely that DWH oil chemicals in the deep plume were transported horizontally by currents until they contacted sediments on the continental slope, where they were deposited and incorporated into surface sediments or were subject to resuspension and redeposition events elsewhere on the slope.

The potential deposition of oil residues remaining after in situ burning, which was used as a response measure to reduce oil mass in the slicks (see Rullkötter and Farrington, 2021, in this issue), is not well described, although Stout and Payne (2016b) did explore how much of the burn residue was deposited to the seafloor. They sampled a few burn residues from the sediment-water interface and provided a rough estimate that between 26,800 kg and 37,800 kg of PAHs (they measured concentrations of 51 PAHS) were deposited with the burn residues. They also stressed that the in situ burn process had reduced by 89% the mass loadings of PAHs that otherwise would have been contributed to Gulf of Mexico ecosystems.

The immediate and longer-term fate of the synthetic-based drilling mud (SBM) used in attempts to stop the DWH accident's oil and gas release and its input to surface sediments near the wellhead was examined by Stout and Payne (2017). They tracked the distribution of SBM-derived C_{14}–C_{20} olefins in space and time. In summary, they found these compounds, mixed with DWH oil chemicals, in surface sediments as deep as 10 cm and extending for 6.5 km^2 around the well site. They noted a decrease in concentrations of the olefins in most of the sediments by a factor of 10 between 2010/2011 and 2014, most likely due to biodegradation. Based on their own and other data, they projected that weathered SBM olefins released during the DWH disaster would likely persist in detectable concentrations in the deep-sea sediments of all or parts of this area for up to 13 years.

FATE ON SHORELINES: BEACHES AND MARSHES

Standardized surveys were instituted early in the spill to assess where DWH oil came ashore along the coastal areas of the northern Gulf of Mexico. Michel et al. (2013) reported 1,773 km of the 7,058 km of beaches and coastal marshes from Florida to Texas received DWH oil at various stages of weathering. Louisiana accounted for 60.6% of the oiled shoreline, and 38% of that shoreline remained visually oiled after two years. Past experience suggested that there were no effective methods for cleaning oil from marshes; those tried had resulted in large adverse effects to the marshes (NRC, 1985). However, cleaning of oil deposited on beaches had developed into an acceptable practice, and extensive efforts were made to remove the visible oil from beaches fouled by the weathered oil.

Beaches

A total of 925 km of beaches were polluted by DWH oil (Huettel et al., 2018, and references therein). Most of the oil came ashore as a floating water-in-oil emulsion, for example, as "mousse." It was known from research conducted after other oil spills that heavily weathered oil residues buried in beaches could persist for years to decades (Huettel et al., 2018, and references therein). Thus, there was a relatively rapid and significant response effort to remove the clearly visible oil from affected beaches.

Despite these efforts, normal movement of sand due to wind, waves, and human activities resulted in burial of oil sheets and sand-oil aggregates (SOAs) of various sizes. The initial cleanup response was followed by Operation Deep Clean, which involved digging and sifting for SOAs, and the resulting removal of most of the large ones (Huettel et al., 2018, and references therein). Despite these efforts, small SOAs or surface residual balls (SRBs), depending on the authors' designations, remained hidden in the beach sand. In some locations there were "tar patties" on the sand and buried layers of SOAs and submerged oil mats (SOMs) nearshore. Storm waves mixed the remaining SOAs and tar patties into the beaches or resurfaced and even resuspended them, leading to the reappearance of oily sand on cleaned beaches (Hayworth et al., 2015; John et al., 2016). This was still happening at a reduced rate as of September 2017 (Huettel at al., 2018; Bociu et al., 2019).

Because a variety of approaches was used for field sampling along the coast, comparisons were challenging and required that syntheses of data and interpretations take temporal and spatial variations into account. Nevertheless, field studies that included sampling and analyses of SOAs and tar patties for oil chemicals and reaction products along with microbial ecology/omics have yielded substantive new knowledge about fates of oil residues on/in beaches (John et al., 2016; White et al., 2016; Bostic et al., 2018; Huettel et al., 2018; Bociu et al., 2019). In addition, experiments explored the effects of light exposure (John et al., 2016) or the weathering of aging buried SOAs over several years (Bociu et al., 2019). The latter experiments suggested that SOAs buried deep in beach sand can be decomposed relatively rapidly by aerobic microbial degradation. The key enabler is the tidally ventilated permeable beach sand. Despite this process, given the high molecular weight constituents in the residual oil and the addition of photochemically or microbially generated oxygenated reaction products, Bociu et al. (2019) estimated that complete decomposition of SOAs buried in sand may take as long as three decades. Besides removal by mechanical means, microbial degradation, photo-oxidation (most likely mainly before stranding), and the loss by water washing/dissolution governed the fate of oil chemicals as well as microbial degradation and photo-oxidation reaction products within SOAs and tar patties.

It is important to consider the findings of Aeppli et al. (2018), who discuss emulsions/slicks that come ashore containing substantially weathered oil or oil that has been subjected to photo-oxidation. Between 2011 and 2017, the alkane and aromatic hydrocarbon fractions of the oil residues in the sand patties were depleted by 79 ± 2% compared to original DWH oil. The analyses done by Aeppli et al. (2018) document that the loss of alkanes and aromatics was partly compensated by a simultaneous increase in the production of the oil soluble OxHC fraction. Thus, the overall decrease of oil-derived chemicals in sand patties was only ~42% ± 12% between 2011 and 2017 when compared to the composition of original DWH oil. Further experiments demonstrated that the water-soluble fraction of the OxHCs was relatively small, for example, on the order of 0.1% to 1%, indicating that the OxHCs retained significant hydrophobicity, thereby promoting sorption or association with the resin-like or asphaltene-like residues in the sand patties. Bostic et al. (2018) demonstrated that microbes were utilizing either residues from DWH spilled oil or the OxCHs as a source of carbon by measuring the depletion of ^{14}C in phospholipid fatty acids.

Challenges for the future include establishing the exact reaction pathways for both microbial and photochemical reactions, the products of these reactions, and the potential for environmental effects of these reaction products. A potential human health concern is the ingestion by toddlers on beaches of very small SOAs (and their associated chemicals) missed by beach cleaning response efforts or generated from nearshore sand-oil mixtures brought ashore after the beach cleaning response (Sandifer et al., 2021, in this issue, and references therein).

Marshes

The DWH spill extensively oiled portions of northern Barataria Bay, Louisiana, marshes. Atlas et al. (2015) analyzed samples from 20 marsh sites for the years 2011, 2012, and 2013 and documented both spatial and temporal variability in the presence of DWH oil and the response of the microbial community to its residues. The 2011 marsh samples exhibited significant oil losses due to weathering and biodegradation, which may have occurred in transit to the marsh site or shortly thereafter. The lower molecular weight alkanes (below n-C_{15}) and aromatic hydrocarbons (below the three-ring phenanthrene/anthracene and their alkylated homologues) that were present in the discharged oil were not present or were detectable only in trace amounts in samples from the marshes. The chemical compositions of the hydrocarbons indicate that both weathering (volatilization and dissolution) and microbial biodegradation are responsible for the losses. This work by Atlas et al. (2015) is one of the few studies to date of the fate of DWH oil in marshes that examines microbial community composition and species abundance in parallel with analyses for alkanes and aromatic hydrocarbons. Examples of other such studies are Engel et al. (2017) and Tatariw et al. (2018). See Weiman et al. (2021), in this issue, for a discussion of microbial genomics and related matters.

Atlas et al. (2015) further reported that between 2011 and 2013, loss of oil chemicals proceeded in the upper 0–2 cm of their sampling sites. Biodegradation and/or dissolution to pore waters or overlying waters due to tidal and storm flushing led to significant decreases in concentrations of the higher molecular weight C_{15} to C_{40} alkanes and of higher molecular weight phenanthrene to alkylated chrysene aromatic hydrocarbons. Similar results of patchiness and weathering/biodegradation of DWH oil in transit or shortly after arrival in the marsh were reported for five sites in the subtidal and intertidal area of Barataria Bay sampled 18 months after the spill (Kirman et al., 2016). Using oil chemical signature or "fingerprinting" techniques, Meyer et al. (2018) observed redistribution of oil buried below the upper 0.5 cm in Bay Baptiste, Louisiana, marsh after Hurricane Isaac.

Over eight years, Turner et al. (2019) pursued a more comprehensive study of the fate of oil and oil residues in marsh sediments of Barataria Bay as part of the multi-year Coastal Waters Consortium effort funded by GoMRI (see Figure 3 for sampling locations). The concentrations of 28 individual alkanes and 43 polycyclic aromatic hydrocarbons and their respective alkyl homologues (i.e., 18 parent PAHs and 25 alkyl homologue groups) were analyzed. Initially, the higher concentrations of oil alkanes and aromatics were found in the samples nearest to marsh edges (i.e., 1 m into the marsh from the shoreline compared to 10 m from the shoreline), and the oiling was uneven overall. As time progressed, the uneven nature of oiling was replaced by more uniform distribution of oil residues in the marsh sediments, presumably by tidal and stormwater actions.

The total concentrations of alkanes and the aromatic hydrocarbons as a function of time over the period 2010 to 2018 are plotted in Figure 9. There are significant decreases in concentration over the first few years, in the range of 70% to 90% losses, depending on the specific compound. Thereafter, loss rates decreased, and concentrations leveled. In 2018, concentrations were at least an order of magnitude higher than initial concentrations, when there were no DWH oil residues. These elevated concentrations are of concern in the longer term, for example, with respect to their effects on marsh grass roots and subsequent erosion and their effects on the behaviors of marsh animals (e.g., fiddler crabs), as discussed by Turner

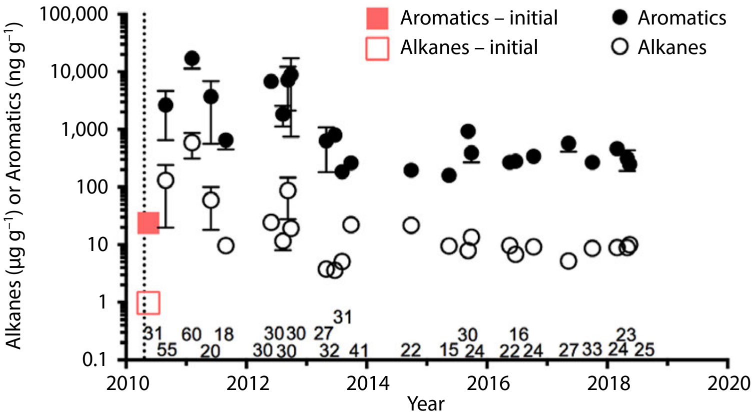


FIGURE 9. The concentrations of total aromatics (filled symbols, ng $g^{-1} \pm$ SE) and total alkanes (open symbols μg $g^{-1} \pm$ SE) in marsh sediments for each sampling trip from May 2010 to May 2018. The red symbols indicate samples taken before oil reached the marshes. The vertical dotted line is the beginning of the Deepwater Horizon oil spill offshore. The average number of samples taken for individual trips appear below each sampling symbol (along the x-axis) and are the same for alkanes and aromatics. *Reproduced from Turner et al. (2019) with permission*

et al. (2019, and references therein).

We know that the higher molecular weight resins and asphaltenes were part of the water-in-oil emulsions that came ashore (see earlier discussions this paper). Chen et al. (2016) conducted detailed analyses of extracts from Barataria Bay marsh surface sediments using FT-ICR-MS, a powerful analytical chemistry method (Rullkötter and Farrington, 2021, in this issue, and references therein for a description). They reported the presence of some of the higher molecular weight compounds found in DWH resins and asphaltenes. These are among the first, if not the first, of these types of measurements for oil-contaminated marshes. They documented incorporation of carboxylic acid into the parent DWH hydrocarbons. Furthermore, there was a significant increase, over 48 months, in high molecular weight oxygenated compounds containing four to six oxygens, compounds not found in the resins and asphaltenes of the DWH oil. The combined results of these analyses, which used two-dimensional gas chromatography with both a flame ionization detector and a mass spectrometer detector, and ultra-high-resolution FT-ICR-MS indicate that both biodegradation and photo-oxidation caused molecular modification of the oil residues in the marsh. There was accumulation of some higher molecular weight oxy-generated products in the resin and asphaltene extracts of the marsh sediments. The asphaltenic-like material in shoreline mats hampers vegetative regeneration of marsh shorelines for at least several years (Lin et al., 2016). Furthermore, observations note that less weathered oil resides in fiddler crab burrows and in packets under vegetated tar mats, suggesting the existence of conditions that retard degradation of oil residues.

BIOAVAILABILITY OF OIL CHEMICALS IN THE GULF ECOSYSTEMS

The term *bioavailability* refers to a chemical being in a physical or chemical form (e.g., sorbed to particles, incorporated into marine oil snow, or dissolved) that can be either ingested by marine organisms or taken up across cellular or membrane surfaces (e.g., marine animal gills). Prior to the DWH accident and spill, there was a growing understanding of the general processes and factors governing the bioavailability, uptake, metabolism, excretion, and food web transfer in marine organisms for specific constituents of oil in the molecular weight range between n-C_{14} and n-C_{35} alkanes and branched alkanes, and polynuclear aromatic hydrocarbons in the range of naphthalenes to dibenzophenanthrenes. Most of this knowledge was gained from a combination of field observations, modeling exercises, and laboratory and mesocosm experiments in estuarine, coastal, and continental shelf ecosystems (e.g., NRC, 1985; Transportation Research Board and National Research Council, 2003; Mitchelmore et al., 2020).

During DWH, there was a significant effort to assess the safety of seafood that might be contaminated to the extent that it was unsafe for human consumption. More than 8,000 samples of common seafood fish and bivalves were analyzed for a specified group of aromatic hydrocarbons (Ylitalo et al., 2012; reviewed in Dickey and Huettel, 2016). Understandably, because of the urgency of protecting public health while not adversely impacting the fishing economy, the study focus was on PAHs. Unfortunately, this meant that analyses of other DWH hydrocarbons were not done. Such a broader analysis might have provided an assessment of oil biomarker compounds over a wide geographic area, which could have provided more clues about oil uptake by these organisms.

Mitra et al. (2012) report measurements of several PAHs in mesozooplankton sampled in August and September 2010 in the northern Gulf of Mexico. The data indicate contamination of the zooplankton by petroleum PAHs and are consistent with contamination by DWH oil residues. Oil droplets were also present in fecal pellets of zooplankton (Almeda et al., 2016).

Murawski et al. (2014) and Snyder et al. (2015) conducted an extensive study of offshore demersal fishes in 2011–2013 with assays for naphthalene and benzo(a)pyrene metabolites. There was evidence of an episodic increase and then decrease for naphthalene metabolites in red snapper and kingsnake eel. Golden tilefish exhibited the highest concentrations of naphthalene metabolites, concentrations that persisted for the study period. The benzo(a)pyrene metabolites were the same for all species and were low when compared to data from studies reported in the literature for other spills.

A pioneering study by Romero et al. (2020) measured PAHs in deep-sea cephalopods in the northern Gulf of Mexico. They analyzed samples from 2001 (pre-spill), 2010, and 2015–2016, and reported episodic exposure to petrogenic hydrocarbons in 2011 and continuing through 2015–2016. This is consistent with the presence of DWH oil in these waters and on particulate matter, as reported above.

It was beyond the scope of our review to consider all of the Natural Resource Damage Assessment studies and reports relative to organism contamination by DWH oil chemicals. However, we direct readers' attention to an important study of deep-sea benthic red crabs (*Chaceon quinquedens*) that were sampled at several stations near the DWH site, at oil seeps, and at historic sites by Douglas et al. (2018).

Isotopic signatures of carbon, $\delta^{13}C$ and $\Delta^{14}C$, in petroleum can be used as rough tracers of DWH chemicals, as they were taken up, biodegraded, and metabolized as they passed through Gulf of Mexico ecosystem food webs. As with other chemical analyses, a consideration is that there may be other petrochemical sources contributing to the samples being analyzed. That said, Graham et al. (2010), Chanton et al. (2012), Quintana-Rizzo et al. (2015), and Wilson et al. (2016) collectively traced isotopic signatures consistent with DWH oil residues in some of the planktonic, coastal, and mesopelagic food webs.

In summary, field measurements reporting concentrations of PAHs or PAH metabolites in several species in the northern Gulf of Mexico are consistent with the presence of DWH oil residues in the region's water, particulate matter, and surface sediments. Isotopic signatures of $\delta^{13}C$ and $\Delta^{14}C$, also consistent with DWH oil residues, have been detected within some northern Gulf of Mexico ecosystems. Future studies might also consider research that assesses the efficacy of measuring biomarkers.

The bioavailability of the higher molecular weight components of crude oils (e.g., resins and asphaltenes) and reaction products of photo-oxidation and microbial degradation, as well as combinations of the two processes, have yet to be the subject of concerted research efforts.

SUMMARY

A wealth of new information on the fate of oil injected into the ocean from a well blowout at 1,500 m water depth was gained with funding from the Gulf of Mexico Research Initiative, the Natural Resource Damage Assessment for the Deepwater Horizon spill, BP, and government agencies, including the US National Science Foundation. This research has documented that photo-oxidation was a significant process acting on the surface oil slick very early in the spill, and that it played a significant role in the fate of the spilled oil. Photo-oxidation had been downplayed for decades despite earlier research in the 1970s and 1980s suggesting that it would be an important research topic.

Although marine snow and the process of sorption of oil chemicals onto particulate matter have long been recognized as important in marine biogeochemical cycles, the term marine snow was not mentioned in oil spill fate and effects literature in any meaningful manner until the DWH oil spill, when it became a topic of interest almost immediately as a result of field observations. The term marine oil snow and marine oil snow sedimentation and flocculent accumulation have now become prominent in the oil spill fate and effects scientific literature. MOS and MOSSFA are recognized as important components of the fate and effects processes post spill and especially in delivering oil residues to seafloor sediments and into the food webs of water column ecosystems.

Deposition, resuspension, and redeposition moved sediment contaminated with weathered and biodegraded DWH oil among benthic ecosystems. Little, if any, long-term accumulation took place on the continental shelf due to resuspension and transport to the continental slope, where several areas were contaminated by MOS deposition from overlying waters, deposition of resuspended and horizontal/vertical transported material, or impingement of the subsurface plume in a few cases. Contamination of continental slope surface sediments was uneven but measurable in several places, and detectable oil residues lasted in some deep sediment areas for at least three years.

Despite extensive cleaning of oil from beaches as part of oil spill response activities, small amounts of residual oil remained on beaches as sand oil aggregates, surface-residual balls, and small tar patties. Combinations of photo-oxidation and microbial degradation proceeded, depending on environmental conditions (e.g., exposure to light, availability of oxygen). Analyses of the higher molecular weight resins, resin-like material and asphaltenes, and asphaltene-like material indicated small residues containing microbial degradation and photo-oxidation products continue to be present in beach sands and will most likely last for years to decades.

Studies of the oiled marshes in Barataria Bay, Louisiana, documented that initial oiling at the edges of marshes would soon be spread by tides and storms. Due to this dilution and to weathering, concentrations of oil residues decreased markedly for the first few years until they were about a factor of 10 more than background and were still at that level when last sampled in 2018. Analyses of a few samples using advanced analytical chemistry methods (FT-ICR-MS) documented the presence of higher molecular weight, resin-like and asphaltene-like material being added over time by a combination of photo-oxidation and microbial degradation. Less weathered DWH oil residues exist under vegetative mats and in fiddler crab burrows in impacted marsh environments.

Lastly, the development of relatively easily accessible and extensive data archives have proven to be helpful for follow-on research by the scientific community at large. We believe that this will continue to be the case for years into the future.

CHALLENGES FOR THE FUTURE

Here are a few important challenges that have arisen from DWH research:

- Successfully incorporating the knowledge gained regarding photo-oxidation, MOS, and MOSSFA into models of the fates and effects of spilled oil, including response models. There are indications that this has begun already (e.g., Ward et al., 2018, and as noted by Westerholm et al., 2021, in this issue).
- Understanding and documenting the influence of mitigation measures/techniques, such as aerial dispersant applications and in situ burning, on the movement of weathered oil into MOS and into the water column and to deep sediments by MOSSFA events (Quigg et al., 2021, in this issue).
- More extensively applying the advances in analytical chemistry to samples from various components of the ecosystem to better document reaction pathways for the fates of various oil chemicals.
- Continuing to advance understanding of the important photo-oxidation reaction pathways and rates for oil on the sea surface and oil residues on beaches and in marshes.
- Simultaneously applying advanced analytical chemistry techniques and advanced genomic/proteomic analyses to samples from field observations and laboratory and mesocosm experiments in order to maximize rich data sets that will lead to new discoveries with respect to the fates of oil inputs (e.g., biodegradation) and responses of specific biological processes to specific oil chemicals.
- Understanding the long-term weathering, persistence, impacts, and fates of high molecular weight resin and asphaltenic and oxyhydrocarbon residues in deep-sea, coastal, beach, and marsh environments.
- Developing useful and accurate ways to budget the fate of spilled oil over time. We recognize that initial responses to oil spills need early estimates of fates of spilled oil. However, as time progresses in specific oil spill situations, there is a need to recognize that oil budgets are inherently compromised as each specific oil compound has its own fate, theoretically requiring its own budget. Bulk oil budget estimates not based on compound-specific analysis are thus problematic. Moreover, any one compound may have successively different fates: for example, compounds that are dissolved or dispersed likely later biodegrade, but should not categorized into both fates within the same budget. Due to the dynamic nature of spilled oil, any budget can only reflect a specific point in time. Combining estimates of processes measured in different units or spanning different timescales will generate budgets of questionable relevancy.

DEDICATION. To David Hollander (1959–2020) of the University of South Florida, whose enthusiasm for research was infectious and who made numerous important contributions to oil spill research. David is shown aboard R/V *Justo Sierra* during sampling in 2015 near the site of the 1979 Ixtoc 1 oil well blowout in the southern Gulf of Mexico.

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AUTHORS

John W. Farrington (jfarrington@whoi.edu) is Dean Emeritus, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Edward B. Overton** is Professor Emeritus, Department of Environmental Sciences, Louisiana State University, Baton Rouge, LA, USA. **Uta Passow** is Canada Research Chair in Biological Oceanographic Processes, Ocean Sciences Centre, Memorial University, St John's, NL, Canada.

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A Decade of GoMRI Dispersant Science

LESSONS LEARNED AND RECOMMENDATIONS FOR THE FUTURE

By Antonietta Quigg, John W. Farrington, Sherryl Gilbert, Steven A. Murawski, and Vijay T. John

ABSTRACT. Dispersants are among a number of options available to oil spill responders. The goals of this technique are to remove oil from surface waters in order to reduce exposure of surface-dwelling organisms, to keep oil slicks from impacting sensitive shorelines, and to protect responders from volatile organic compounds. During the Deepwater Horizon response, unprecedented volumes of dispersants (Corexit 9500 and 9527) were both sprayed on surface slicks from airplanes and applied directly at the wellhead (~1,500 m water depth). A decade of research followed, leading to a deeper understanding of dispersant effectiveness, fate, and effects. These studies resulted in new knowledge regarding dispersant formulations, efficacy, and effects on organisms and processes at a broad range of exposure levels, and about potential environmental and human impacts. Future studies should focus on the application of high volumes of dispersants subsea and the long-term fate and effects of dispersants and dispersed oil. In considering effects, the research and applications of the knowledge gained should go beyond concerns for acute toxicity and consider sublethal impacts at all levels of biological organization. Contingency planning for the use of dispersants during oil spill response should consider more deeply the temporal duration, effectiveness (especially of subsurface applications), spatial reach, and volume applied.

A US Air Force C-130 aircraft from the 910th Airlift Wing dropped oil dispersing chemicals into the Gulf of Mexico as part of the Deepwater Horizon response effort, May 5, 2010. *US Air Force photo by Tech. Sgt. Adrian Cadiz*

INTRODUCTION

The use of chemical dispersing agents (dispersants) is one of several options available to responders during an oil spill. Dispersants are typically used on larger offshore spills when environmental conditions preclude mechanical recovery, in situ burning, or allowing natural processes to control the fate and effects of the oil. In the case of the Deepwater Horizon (DWH) oil spill in 2010, surface dispersant application was used, and for the first time, subsea dispersant injection (SSDI). The latter approach was undertaken with the objective to reduce the emergence of crude oil at the surface and hence the volume of oil transiting to sensitive coastal and estuarine habitats. Further, SSDI may have provided safer working conditions for first responders and others on scene by reducing occupational exposures to volatile organic compounds. SSDI, however, had an inevitable environmental cost and added chemically dispersed oil (i.e., oil plus dispersant) to the deep Gulf of Mexico. Thus, it is critical that the efficacy of SSDI be considered going forward.

In the September 2016 special issue of *Oceanography* on the DWH oil spill, John et al. (2016) provided a rationale for the use of dispersants in oil spill remediation. The authors reported on the basic science of dispersants and the creative design of newer dispersants that were offering great promise. Today, there continues to be a need to understand the efficacy of dispersants. This article builds on the earlier synthesis, bringing together new information regarding the fate of dispersants and their effects on ecosystems and humans and, further, summarizes the grand challenges for the future. This review is not intended to be a comprehensive treatise on dispersant research in the last decade. Rather, given that few topics have aroused more public concern than the utility of dispersants to combat an oil spill, this is an effort to bring together the best available science from Gulf of Mexico Research Initiative (GoMRI) researchers within the context of work conducted by all scientists, irrespective of the source of funding. Excellent reviews on dispersants, their effectiveness, and ecological impacts prior to the DWH incident are found in the National Research Council reports (NRC, 1989, 2005), while information gathered since the DWH incident is available in Judson et al. (2010), Prince (2015), Kinner et al. (2017), CRRC (2010, 2018), John et al. (2016), Stroski et al. (2019), and NASEM (2020). GoMRI has generated a significant body of knowledge in this arena (Box 1). This review expands on some of the GoMRI-related research cited in the National Academies of Sciences, Engineering, and Medicine publication entitled *The Use of Dispersants in Marine Oil Spill Response* (NASEM, 2020). In addition, it sets the scene for a forthcoming report from a November 2020 workshop where a synopsis of GoMRI-funded research and other research and assessments was presented and discussed.

ROLE OF DISPERSANTS IN OIL SPILL RESPONSE

The goal of dispersant use is to rapidly remove floating oil, a known hazard to diving birds and mammals and the ecosystem as a whole, as well as to reduce the volume of weathered oil that could be transported long distances and affect sensitive nearshore areas, beaches, and marshes. Surface application of dispersants from planes and vessels requires special regulatory approvals that evaluate whether dispersion is possible and beneficial and if the volume of oil transported shoreward into uncontaminated areas can be reduced (IPIECA-IOGP, 2014). In this regard, dispersant application as a tactic in oil spill cleanup has been a well-established intervention method since the 1970s (IPIECA-IOGP, 2014; IPIECA, 2018; NAESM, 2020). Worldwide, there are stockpiles of carefully formulated dispersant products that can be applied rapidly in preapproved areas, for example, United States, United Kingdom, Australia (Carter-Groves, 2014; Global Dispersant Stockpile [https://www.oilspillresponse.com/services/member-response-services/dispersant-stockpiles/global-dispersant-stockpile/]).

BOX 1

GoMRI Dispersant Publications Summary*

There were 205 recent publications in the Gulf of Mexico Research Initiative (GoMRI) database with "dispersant" in the abstract or that identified it as a key word. Of those publications, 176 were relevant to this GoMRI dispersant synthesis.

TYPE OF STUDY

128	lab-based studies
14	mesocosm-based studies
18	studies based on field measurements/observations
18	modeling studies (various)

STUDY TOPIC

54	physics (mostly new dispersants and modeling)
53	ecology/exposure employing WAF and/or CEWAF
35	chemistry (some using WAF and CEWAF, some new dispersants)
16	MOSSFA (many using WAF and CEWAF)
9	review papers (various)

EXPERIMENTAL FOCUS

65	organism-focused (26 bacteria, 19 plankton, 10 invertebrate, 6 vertebrate, 4 human health)
35	new dispersant formulations
30	droplet and dispersion focused
10	chemical degradation, photodegradation

WAF = water accommodated fractions of oil.

CEWAF = chemically enhanced WAF.

MOSSFA = marine oil snow sedimentation and flocculent accumulation.

*Effective October 6, 2020. Available at https://research.gulfresearchinitiative.org/gomri-publications/.

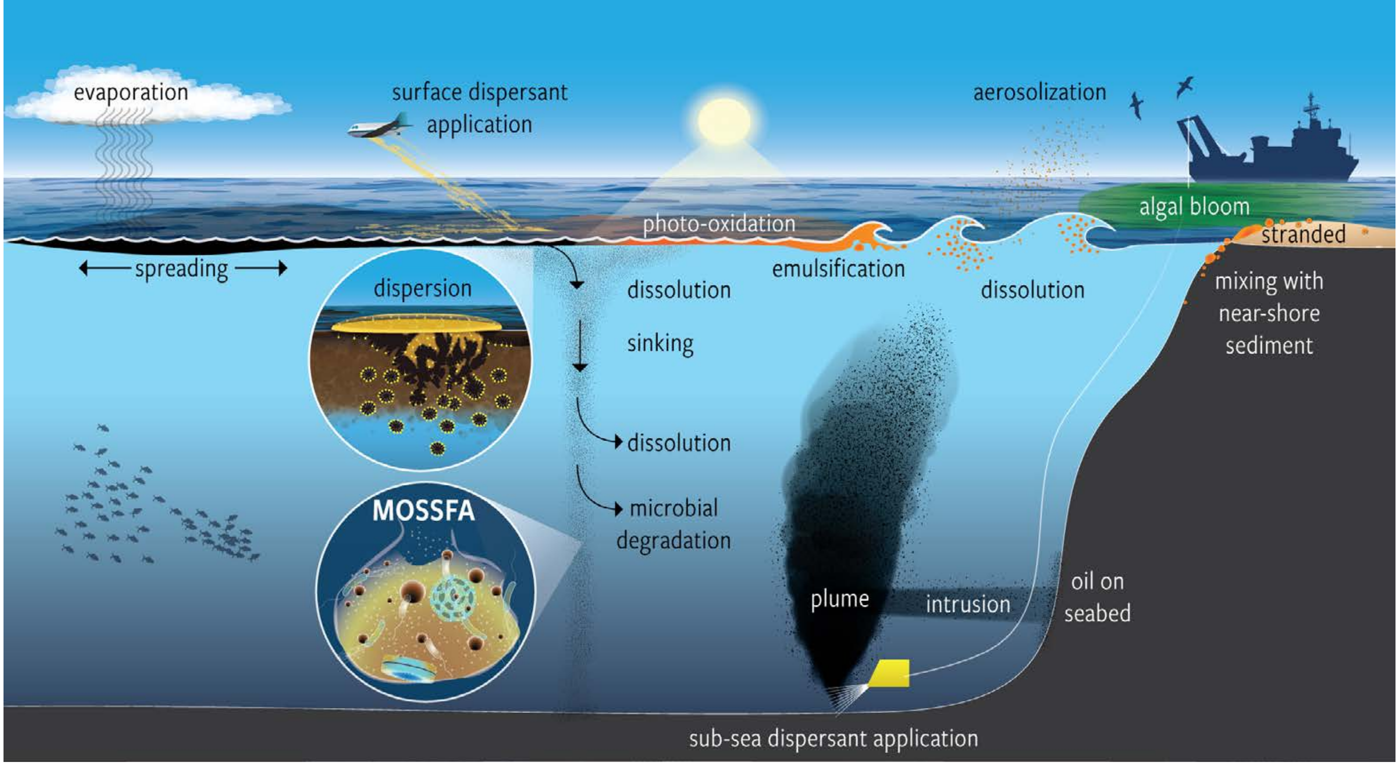

FIGURE 1. Surface and subsea dispersant injection results in the formation of oil droplets that then undergo a plethora of physical, chemical, and biological reactions. MOSSFA = marine oil snow sedimentation and flocculent accumulation.

Prior to the 2010 DWH spill, dispersants had been applied 213 times at the sea surface (Steen and Findlay, 2008). Over the course of the DWH oil spill, 4.1 million liters of the Corexit dispersants 9500 and 9527 were applied at the sea surface (Figure 1) and an additional 2.9 million liters at ~1,500 m water depth at the wellhead (Figure 1; USCGNRT, 2011; Place et al., 2016). The Corexit class of dispersants used during the DWH oil spill are complex mixtures of surfactants (dioctyl sodium sulfosuccinate [DOSS], Span, Tweens) and solvents such as propylene glycol and petroleum distillates (Brochu et al., 1986; Brandvik and Daling, 1998; Riehm and McCormick, 2014). Surfactants are typically formulated from chemicals used as food additives and/or cosmetics, similar to those found in common shampoos and cleaners, including those used to clean oiled seabirds (USFWS, 2003; Hemmer et al., 2011; Word et al., 2015; DeLorenzo et al., 2018). Because of these uses, adverse effects were considered to be minimal. However, recent research has raised questions about these assumptions.

The objectives of using SSDI as a response strategy were to reduce vertical oil transport to the sea surface and subsequent formation of surface slicks, and to reduce the exposure of responders to volatile organic compounds (VOCs) that could be harmful to their health and negatively affect operations (Kujawinski et al., 2011; Gros et al., 2017; Paris et al., 2018; Murawski et al., 2019, 2020; NASEM, 2020). Under SSDI, dispersants reduce the ejection turbulence of oil emanating from the wellhead (Figure 1), allowing the formation of tiny neutrally buoyant oil droplets in the deep sea that can be more readily biodegraded (Hazen et al., 2010; Prince et al., 2013; Prince and Butler, 2014). This was also accompanied by a large-scale, horizontally spreading subsea plume of small oil droplets and dissolved hydrocarbons during the spill, in addition to the plume already present prior to the use of SSDI (Camilli et al., 2010; Diercks et al., 2010; Paris et al., 2012; Zhao et al., 2014; Socolofsky et al., 2019). In retrospect, plume formation was predicted as an outcome from ultra-deep blowouts (Transportation Research Board and National Research Council, 2003) but had never been addressed to any significant degree in pre-spill contingency planning. Consequently, detailed monitoring protocols were not preplanned and had to be created de novo during the response. These ad hoc protocols did not include the types of measurements necessary to understand fundamental aspects of well dynamics such as the physics and chemistry of multiphase flows with and without the addition of dispersants and the sizes of oil droplets exiting the well. While information was available on biodegradation rates of dispersant components, long-term fate and transport of the more resistant components was not well known. Modeling and experimental work has been undertaken since the spill in an attempt to understand the effects of SSDI on both the quantity of surfacing vs. subsurface oil and whether SSDI reduced the concentration of VOCs around the ship that was drilling a relief well to intercept and kill the blown-out well (e.g., Paris et al., 2012; Gros et al., 2017; French-McCay et al., 2018). At present, there is conflicting evidence as to the efficacy of the use of SSDI (Nedwed et al., 2012; Nedwed, 2017; Gros et al., 2017; Paris et al., 2018; Murawski et al., 2019; Pesch et al., 2018, 2020).

FATE OF DISPERSANT AND CHEMICALLY DISPERSED OIL

Dispersants partition the oil-water interface to reduce the interfacial (surface) tension sufficiently to create oil droplets (<70 μm) that then stay colloidally suspended in the water column (Figure 2) as they are essentially neutrally buoyant (Brakstad et al., 2015; John et al., 2016). Larger droplets do rise and can (eventually) reach the surface. Partitioning into droplets also allows the chemically dispersed oil to be diluted to very low concentrations for biodegradation by microbes naturally present in seawater (NRC, 2005; Lee et al., 2013; Prince et al., 2013; Aeppli et al., 2014; McFarlin et al., 2014; Prince and Parkerton, 2014; Prince and Butler, 2014; Prince, 2015; Bejarano et al., 2016; Bejarano, 2018). It should be recognized that the enhanced surface area, which is often cited as a major justification for using dispersants, is associated with a surfactant-populated interface rather than a native oil-water interface (Figure 2). In 2010, the US Environmental Protection Agency tested eight of the 14 dispersants listed on the National Contingency Plan Product Schedule, including those used during the DWH incident. Results of these tests showed that a mixture of dispersants and oil was no more toxic than the oil alone (Hemmer et al., 2010). Further, laboratory studies demonstrated that dispersants may be less toxic than the tested oils based on a variety of toxicity protocols (e.g., Barron et al., 2003; Hemmer et al., 2011; Claireaux et al., 2013) where the oil toxicity is primarily shown or thought to be associated with the polycyclic aromatic hydrocarbon (PAH) content.

Dispersed oil biodegradation rates varied from those identified by Hazen et al. (2010), who measured half-lives of *n*-alkanes in samples that had spent a few days in the dilute (2–442 ppb), dispersed submarine plume created by the DWH spill at 1,100–1,220 m depth (and at 5°C). Very similar results were reported for a broad array of individual hydrocarbons studied at low concentrations in New Jersey seawater at 8°C, in a flume in Trondheim, Norway, at 30°–32°C, and in water collected off the Penang, Malaysia, shore at 27.5°C. The approximate biodegradation half-life of the total measurable hydrocarbons was 11–14 days, both at low oil concentrations with indigenous nutrients (2.5 ppm and 43 ppm oil, respectively) and at slightly higher concentrations (100 ppm oil) with added nutrients. Even the four-ring aromatic PAH chrysene and its methyl-, dimethyl-, and ethylalkylated forms had half-lives on the order of a month (Hazen et al., 2010; Zahed et al., 2011; Bælum et al., 2012; Prince et al., 2013; Prince and Butler, 2014; Prince and Parkerton, 2014; Brakstad et al., 2015; Prince, 2015). However, smaller oil droplets were also found to result in increased dissolution

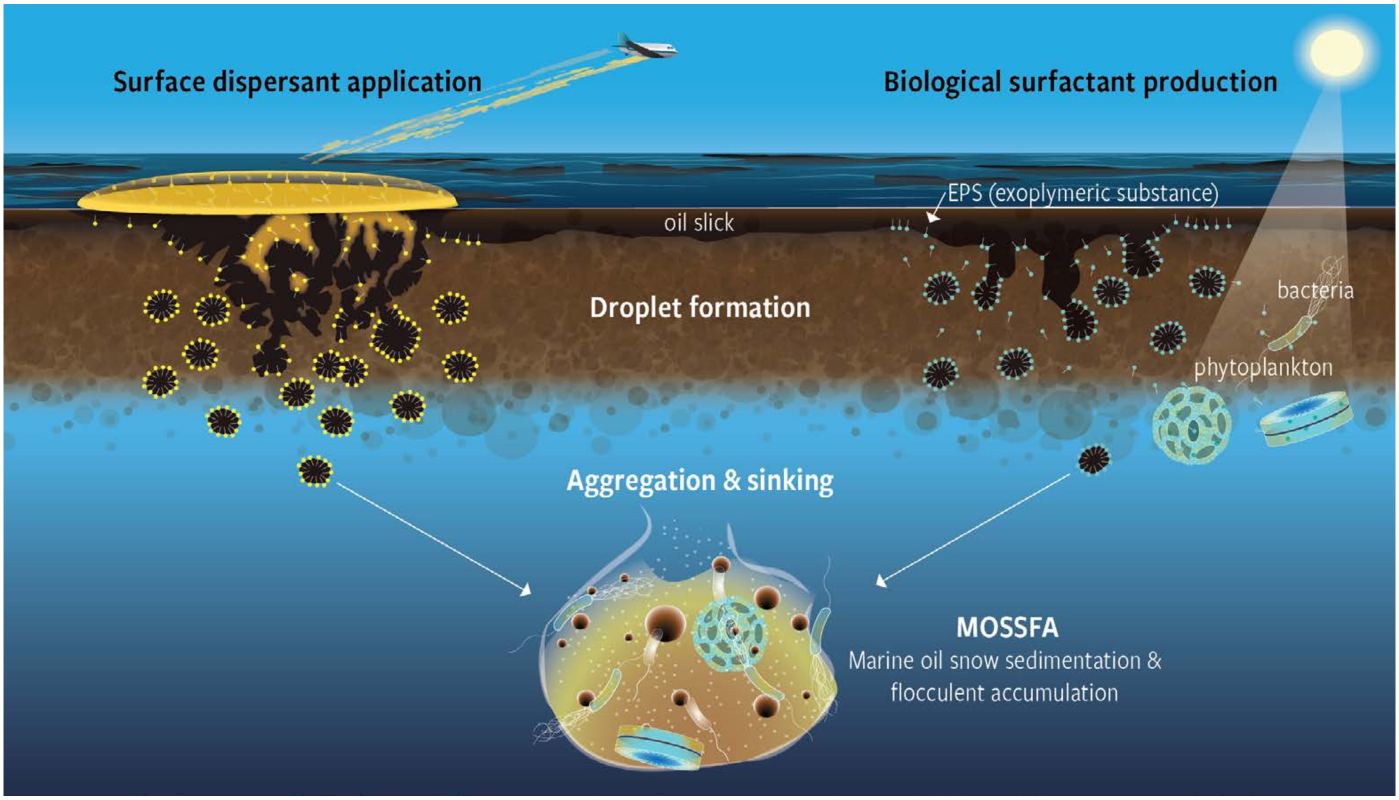

FIGURE 2. The application of dispersant on the surface slick coats the oil and leads to formation of droplets that are readily dispersed as a result of a range of chemical and physical processes (left side of figure). Microbes (bacteria, phytoplankton) release exopolymeric substances (EPSs) in response to a variety of environmental stressors, including oil and dispersants. An EPS is a biological surfactant that coats oil droplets and chemically disperses them to form marine oil snow (MOS), which aggregates below the surface (MOSSFA) and ultimately leads to the deposition of these materials on the seafloor. (For details, see Daly et al., 2016; Quigg et al., 2016; Burd et al., 2020; Ross et al., 2021).

of potentially toxic oil components and exposure to aquatic organisms (NRC, 2005; Seidel et al., 2016). The fate and transport of the oil and its components is reviewed in detail by Passow and Overton (2021) and by Farrington et al. (2021) in this issue.

Some studies, especially those conducted at higher chemically dispersed oil concentrations, found that dispersants have no effect on microbial biodegradation rates while others show they do (Fingas, 2008; Camilli et al., 2010; Hazen et al., 2010; Kleindienst et al., 2015a,b; Joye and Kostka, 2020; Rughöft et al., 2020). Although some dispersant components are easily metabolized, others may persist for long periods in the environment (Kujawinski et al., 2011; White et al., 2014; Place et al., 2016). After dispersant application during the DWH spill, water samples collected at the sea surface and below showed low (or undetectable) concentrations of DOSS (a biomarker used for Corexit), while water collected in the oil-derived plume contained appreciable amounts of DOSS (Gray et al., 2014). Near the wellhead during the blowout and after SSDI, concentrations of DOSS in the subsurface plume were correlated with dissolved methane concentrations and fluorescence-based measurements of hydrocarbons (Kujawinski et al., 2011). As the plume traveled farther from the wellhead, DOSS concentrations decreased, presumably via dilution (Kujawinski et al., 2011) rather than by biological degradation. DOSS was also entrained in oil that eventually rose to the surface, sank into sediments, or was deposited on corals near the damaged wellhead (White et al., 2014). Subsequent experiments showed that DOSS does not degrade appreciably under the cold and dark conditions of the deep ocean (Campo et al., 2013; Perkins and Field, 2014). Further, the breakup rate of a surface slick ultimately becomes limited to the rate at which surfactants (dispersants) are able to populate the new surfaces (Riehm and McCormick, 2014). Only a small fraction of the surfactants contained in the dispersant is necessary to saturate the oil-water interface of a droplet. By definition then, the remaining surfactant has to partition to the bulk phases: the water-soluble Tween to the water phase and the oil-soluble DOSS and Span to the oil phase.

An interesting set of experiments by Reichert and Walker (2013) indicated potential irreversibility of surfactant adsorption at the oil/water interface (Figure 2). Using Tween 80 as a model surfactant, the authors gradually introduced the surfactant in solution to a stationary drop and monitored the decreasing rate of oil-water interfacial tension. Subsequently, there was a shift from a surfactant-containing to a surfactant-free solution, and interfacial tension was monitored to observe the possible desorption of surfactant from the interface. Interestingly, the interfacial tension does not increase significantly, implying a partial irreversibility of adsorption to the interface. This observation has implications for oil-spill remediation using dispersants. Surfactant-coated oil droplets, and excess surfactant in the aqueous phase consisting of swollen micelles, travel in plumes, and dilution into the vast water column may not be as rapid as intuitively expected. There could be exchange of surfactant between the aqueous phase and the droplet interface during such transport. The implication is that if there is a degree of irreversibility in surfactant adsorption, oil droplets will typically contain surfactants at the interface. The two- or threefold increase of interfacial area as droplets form with dispersant application does not necessarily translate to a similar increase in biodegradation rates, as this is a new interface containing surfactants. Indeed, Abbasi et al. (2018) found that surfactant-covered droplets have a strong inhibitory effect on the attachment of the alkane biodegrading organism *Alcanivorax borkumensis* on the oil-water interface. The hydrophobic effect of surfactant tail insertion into biomembranes is a possible interpretation of such inhibition of attachment. These authors also found that *Alcanivorax borkumensis* readily attaches to oil-water interfaces in the absence of surfactant and initiates prolific growth of biofilm (Figure 3), an observation verified by Omarova et al. (2019). The presence of particles to stabilize oil-water emulsions further leads to sequestration of *Alcanivorax borkumensis* and significant biofilm growth (Omarova et al., 2018). Thus, there are a number of fundamental mechanisms that support the observations in some experiments of dispersant-induced reduction of biodegradation.

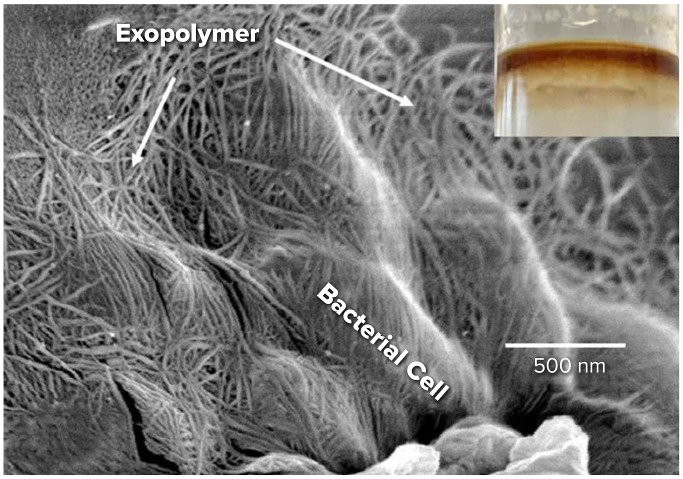

FIGURE 3. The alkane degrader *Alcanivorax borkumensis* forms a prolific biofilm under oil. This biofilm is composed most likely of bacterial released exopolymers, often referred to as EPSs (exopolymeric substances or extracellular polymeric substances). *Image from Omarova et al. (2019)*

DISPERSANT EFFECTS ON MARINE LIFE

After an initial decline, benthic animals, mostly invertebrates, in the area around the spill site began to recover and then to increase in biomass and diversity with time (e.g., Wise and Wise, 2011; Montagna et al., 2013; Fisher et al., 2016; Schwing and Machain-Castillo, 2020; Schwing et al., 2020). The usefulness of field-derived information for understanding the impacts of dispersants on mobile marine wildlife is limited because these chemicals are never used in the absence of crude oil. As a result, what we know about the toxicity of dispersants is generally from controlled, and mostly acute (e.g., 96-hour), toxicity test results (Bejarano, 2018; NASEM, 2020). In their evaluation of eight commercial dispersing agents used during the DWH incident, Hemmer et al. (2011) concluded they were almost non-toxic to mildly toxic to the fish species inland silverside, *Menidia beryllina*, and the mysid shrimp, *Americamysis bahia*, at the concentrations and exposure durations evaluated. In the aftermath of DWH, a considerable number of laboratory-based studies of the toxicity of dispersants alone, crude oil alone, and the combination of the two were undertaken (see the meta-analysis in NASEM, 2020). Concerns with previous toxicity testing are that such studies were not applicable to field-relevant species, especially deepwater forms, and that there may be a synergistic effect between oil and dispersants not accounted for in binary studies (Murawski et al., 2019; NASEM, 2020). The NASEM committee attempted to conduct a meta-analysis of studies to test several hypotheses regarding the toxicity of oil and dispersants by examining study characteristics including the duration of exposure, exposure concentrations, experimental conditions, species being tested, and whether the combination of dispersants and oil was more toxic than the individual ingredients. This analysis proved extremely difficult because water accommodated fractions were manufactured in a variety of ways, chemically enhanced oil concentrations varied, analytical chemistry was not always conducted to verify exposure concentration, and exposure durations differed. Despite these limitations, NASEM (2020) did not find compelling evidence that at low to moderate oil concentrations, chemically dispersed oil was any more toxic than oil alone. At high concentrations, however, the combination appeared more toxic.

There is some indication from field sampling that fishes and other animals were exposed to dispersants, although the evidence is somewhat circumstantial. Ylitalo et al. (2012) conducted extensive monitoring of shellfish and finfish species used for human consumption in a wide area surrounding the DWH site. They determined that the concentrations of both PAHs and the Corexit component DOSS in fish and shellfish muscle samples were generally low. However, as DOSS is also a common component of pharmaceuticals and laxatives, the presence of DOSS cannot be definitively considered evidence of dispersant exposure, but rather only indicates that DOSS is persistent in the environment. If dispersants applied in SSDI were in fact effective at increasing oil droplet and dissolved oil concentrations in deepwater plumes (Figure 1), then they may also account for the elevated exposure levels seen in mesopelagic fishes (Romero et al., 2018) and evident in extensive sampling of the fauna of continental shelves of the Gulf of Mexico (e.g., Snyder et al., 2019, 2020; Pulster et al., 2020a,b). The severe declines of mesopelagic nekton in the region surrounding DWH since the spill (Sutton et al., 2020) is consistent with toxic exposures of this community of invertebrates and fishes to PAHs (and perhaps other toxic chemicals in the weathered crude oil, including reaction products from photo-oxidation and microbial degradation).

DISPERSANT EFFECTS ON HUMAN HEALTH

There were several main pathways for human exposure to dispersants (Figure 4) during the DWH oil spill: (1) handling (loading, packaging for spraying from planes, vessels, and subsea dispersal), (2) application (vessel staff spraying dispersants or working on source control vessels monitoring VOCs), (3) passive (e.g., exposure to vessel staff in areas where dispersant was sprayed from airplanes), (4) passive air (e.g., dispersant injected into the atmosphere at the sea surface from treated oil slicks), and (5) indirect (exposures while shutting down or capping the well). In these scenarios, the main pathways for uptake are dermal and

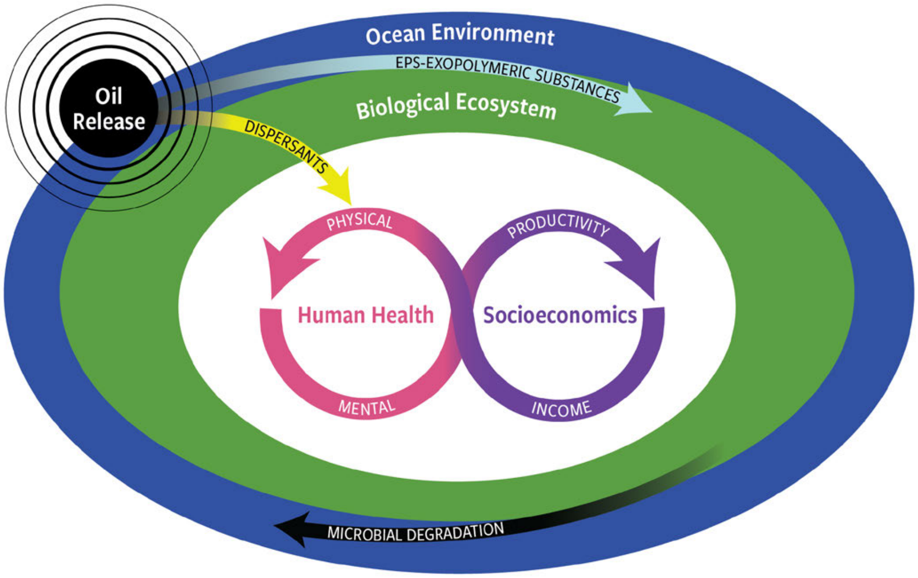

FIGURE 4. This whole ecosystem view of the Deepwater Horizon oil spill effects and consequences includes impacts beyond the ocean environment and its biological components. Specifically, human health and socioeconomics are key for responding to future spills. For details, see Solo-Gabriele et al. (in press).

respiratory (McGowan et al., 2017). For surface applications, VOCs and airborne fine particulate matter posed the greatest health risks as a result of dispersant application on oil slicks, increasing the total mass burden (Afshar-Mohajer et al., 2018, 2019, 2020). Future studies will, however, be required to determine the applicability of lab findings to natural conditions where other factors are known to modify oil-dispersant mixtures. Further, epidemiological studies found that occupational exposure to dispersants during the response resulted in adverse acute health effects that were still being reported up to three years later (McGowan et al., 2017). In the case of SSDI, less is known about the direct impacts to humans. However, Gros et al. (2017) concluded—based on modeling studies—that SSDI increased the entrapment of VOCs in the deep sea and thereby decreased their emission to the atmosphere by 28%, including a 2,000-fold decrease in emissions of benzene, which ultimately lowered health risks for response workers.

In terms of human health and dispersant application, certainly the mental and social welfare of those who live and work in the region requires more critical investigation (CRRC, 2010; IPIECA-IOGP, 2015; Singer and Sempier, 2016; NASEM, 2020; Solo-Gabriele et al., in press). The adverse health effects for communities of people in coastal areas adjacent to where the large quantities of dispersants were applied well away from land included psychosocial and economic impacts (**Figure 4**; Solo-Gabriele et al., in press). As summarized by Eklund et al. (2019), studies found dispersant application to be associated with human health concerns, including obesogenicity, toxicity, and illnesses from aerosolization of the agents. Those heavily reliant upon natural resources for their livelihoods were found to be vulnerable to high levels of life disruptions and institutional distrust. Going forward, actions taken to improve disaster response (i.e., media, education, and outreach) can be expected to reduce stress-associated health effects.

DISPERSANTS AND MOSSFA

In the weeks after the DWH oil spill, phytoplankton and associated microbes encountered high concentrations of oil and chemically dispersed oil. As a result, these communities formed large-scale exudates of a sticky material rich in proteins and polysaccharides. This material then accumulated cells, oil, and surface inorganic particles into gelatinous flocs that, when combined with clay particles from riverine runoff, sank to the seafloor in considerable amounts (**Figures 1 and 2**). This abundant marine oil snow (MOS) formed at the sea surface (Passow et al., 2012; Ziervogel et al., 2012; Passow, 2014; Passow and Ziervogel, 2016), and some reports also suggest formation in the subsea plume at 1,100–1,220 m depth (see Burd et al., 2020; Passow and Stout, 2020; Ross et al., 2021). This complex mixture of organic matter, oil, and microbially produced extracellular polymeric substances (EPSs) and transparent exopolymer particles (TEP; Quigg et al., 2016). EPSs facilitated access to oil components (**Figure 2**) and concurrently served as a metabolic substrate for a diverse community of bacteria (e.g., α- and γ-Proteobacteria, Bacteroidetes, and Planktomycetales) and phytoplankton (diatoms, dinoflagellates, phytoflagellates) (e.g., Lu et al., 2012; Baelum et al., 2012; Gutierrez et al., 2013; Arnosti et al., 2016; Doyle et al., 2018, 2020; Kamalanathan et al., 2018; Bretherton et al., 2020; Finkel et al., 2020). These observations raise further questions about the effects of dispersant application on microbial activities and microbially catalyzed degradation of oil.

MOS formed in the presence of dispersant appeared to contain more *n*-alkanes than the oil-only aggregates (Fu et al., 2014; Genzer et al., 2020). EPSs trap oil droplets (see Figure 6 in Quigg et al., 2016) and increase the bioavailability of oil components to microbial communities (McGenity et al., 2012). In this respect, EPS properties are similar to those of surfactants as they reduce the interfacial tension between oil and water and thereby enhance dispersion and potential solubilization and biodegradation processes (Lewis et al., 2010; Gutierrez et al., 2013), including pathways that emulsify petroleum hydrocarbons (Head et al., 2006). EPSs with entrained oil droplets form networks that act as energy and carbon sources for members of the microbial community. This process allows microbes to build biomass. Further, biodegradation does not need to occur exclusively with oil-degrading bacteria directly attached to the oil-water interface (**Figure 2**). It is quite possible for microbe communities sequestered in EPS films to consume dissolved oil and thus serve as a driving force for oil to partition from droplets to a bulk state. Biosurfactants generated by the microbes can also incorporate oil to form swollen micelles that are more accessible for their metabolism. More work, however, is needed to understand the underlying mechanisms and driving factors for these processes.

Dispersants alter the metabolic pathways of organic matter biodegradation and hence biogeochemical pathways in the ocean. Given that marine snow serves as food for other organisms, this may result in its being repackaged in fecal material that sinks to the seafloor. Via this pathway, marine oil snow sedimentation and flocculent accumulation (MOSSFA) could transfer oil and other chemicals to the food web (**Figure 2**; Passow and Ziervogel, 2016; Burd et al., 2020). Estimates of the total spatial extent of MOSSFA on the seafloor of the northern Gulf of Mexico range from 1,030 km^2 to 35,425 km^2 (Passow et al., 2012; Passow, 2014; Daly et al., 2016; Burd et al., 2020; Quigg et al., 2020; Passow and Overton, 2021; Ross et al., 2021). Thus, MOSSFA accounted for a significant fraction of the oil returning to the deep ocean (Valentine et al., 2014; Brooks et al., 2015; Chanton et al., 2015; Yan et al., 2016; Romero et al., 2017; Xu et al., 2018a,b). Recent reviews identify the gaps in knowledge about MOSSFA, focusing on the science (Burd et al., 2020), operational response strategies (Quigg et al., 2020), and oil spill responder and policy decisions (Ross et al., 2021).

How dispersants influence the formation of MOS and ultimately the fate and transport of MOSSFA remains poorly understood. Collective studies conducted under GoMRI revealed the rich complexity of reactions and responses of oil-droplet-dwelling microbial communities with and without dispersants through transcriptomic, metabolomic, proteomic, and concurrently ultrahigh resolution mass spectrometry; these techniques collectively revealed that we are only at the tip of the iceberg in our understanding of the complexities of MOS and MOSSFA (Box 1; Figure 2). Given that the effects of dispersant on MOS formation and sedimentation depend largely on the relative concentrations and surface characteristics of the dispersant, marine particles, oil residues, and exudates, future studies might consider how and if novel dispersant formulations will produce the MOSSFA effect. In addition, potential impacts of different combinations (e.g., based on types, formulations) of oil and dispersant on MOS/MOSSFA require investigation as well as the effects of location (e.g., Arctic versus the Gulf of Mexico) as drivers for these impacts. Toxic effects on corals that appear to result from their exposure to oil and dispersant carried by sinking MOS (DeLeo et al., 2016) is little studied and also needs attention. Together, all of this information is critical in order to advance numerical modeling of a simulated oil spill and the trajectories of resulting surface and subsurface flows coupled to satellite mapping. These analyses will provide responders and NRDA trustees information for predicting where MOS may pose significant risk, to whom injury will occur, and how to plan for a spatial and temporal sampling of natural resources at risk (see Ross et al., 2021, for more details). In this way, the NRDA process and other findings can leave a legacy of enhanced preparedness in advance of the next oil spill.

WHAT ARE SOME OF THE GRAND CHALLENGES IDENTIFIED BY GoMRI SCIENTISTS?

GoMRI research has significantly expanded understanding of deep oil spills and the use of dispersants in response to them, but do we know all that is needed to make a scientifically valid response decision for the next major oil spill? Specific to the research conducted by GoMRI scientists, we have identified the following grand challenges in relation to dispersants.

Subsurface Dispersant Injection (SSDI) Application

Use of SSDI was unique to the DWH incident and, consequently, has changed the way in which dispersants will be used in future deepwater blowout scenarios. As part of GoMRI efforts, we learned that SSDI affects transport, biodegradation, flocculation, and sedimentation processes as oil enters and is distributed in a deep ocean environment (e.g., Paris et al., 2012; Zhao et al., 2014; Kleindienst et al., 2015b; Lee et al., 2015; Daly et al., 2016; Socolofsky et al., 2019;). Murawski et al., (2020) identified six important questions regarding the use of dispersants and particularly those delivered as SSDI: (1) How toxic are commonly used dispersants for field-relevant species? (2) Are dispersants + oil more toxic than oil alone or dispersants alone? (3) How effective is SSDI in creating subsurface plumes of small droplets vs. plume effects due to natural processes? (4) Do dispersants increase or decrease biodegradation? (5) Does SSDI reduce the presence of VOCs at the sea surface, thus potentially reducing inhalation exposure to humans and wildlife? (6) What are the trade-offs of sequestering oil in the deep sea by the use of SSDI (subject to the efficacy question) vs. allowing more oil to surface and potentially come ashore? Others (e.g., Prince, 2015) have compared the potential hazards and environmental fate of floating slicks and dispersed oils. We need to determine the best science to address these and other questions.

The difficulty in understanding processes associated with the effervescing "live" oil from a broken well are numerous (NASEM, 2020). No reliable contemporaneous measurements of droplet size diameters at or near the wellhead were obtained during the accident. Furthermore, while some measurements of VOCs at the surface were obtained (Nedwed, 2017), they were not systematic or from fixed locations, nor were the observations controlled for method. Finally, prior to the spill, no high-pressure experimentation had ever been done with a combination of crude oil saturated with natural gas to emulate the actual multiphase flows from a real blowout (see Brandvik et al., 2016). Given the importance of this issue, these data should be revisited, accompanied by new modeling and assessment information.

To help resolve the issues of droplet size formation with and without SSDI, and to determine partitioning of oil into its constituents, GoMRI supported the development of high-pressure jet modules and other experimental set-ups (e.g., Figure 5; Jaggi et al., 2017; Malone et al., 2018; Pesch et al., 2018, 2020). Importantly, these experiments included the use of methane-saturated surrogate oils to evaluate the dynamic processes associated with the physical and chemical mechanisms present in an uncontrolled blowout. Chief among the mechanisms investigated were (1) the effect on "live oil" of the over 80 bar, virtually instantaneous, pressure drop at the blowout preventer that led to rapid-degassing, droplet breakup, and the creation of smaller oil droplets; (2) the effects of simulated obstructions in the blowout preventer (such as the partially closed-shear rams) on turbulent kinetic energy and particle size distributions; (3) the decrease in static pressure leading to further outgassing, enhanced buoyancy, and faster droplet rising velocities; and (4) the effects of temperature and pressure on the partitioning rates of various oil-related compounds. Results of all of these experiments support the conten-

FIGURE 5. Scientists and engineers evaluate droplet size distributions from oil and gas jet experiments using a surrogate (pink stained) oil. For more information, see Pesch et al. (2020). *Left photo courtesy of Michael Schlüter, TUHH, Hamburg, Germany*

tion that in actuality the distribution of droplet diameters from the uncontrolled, broken well were much smaller than has been projected from sea level experimentation (Brandvik et al., 2019; NASEM, 2020). Furthermore, even in the absence of SSDI, a substantial fraction of the oil droplets from the well would have been naturally dispersed (Aman et al., 2015; Lindo-Atichati et al., 2016), thus contributing to lateral intrusions of hydrocarbons (Diercks et al., 2010; Kessler et al., 2011) trapped by density stratification of seawater, as described earlier by Socolofsky and Adams (2005). This is supported by the detection of deep oil plumes at the beginning of the oil spill before any significant SSDI use had occurred (Diercks et al., 2010; Paris et al., 2018).

As noted in NASEM (2020) and by Murawski et al. (2019), resolving the questions surrounding the efficacy of the use of SSDI is imperative if it is ever again to be included in operational oil spill response. There have been three different suggestions for additional research to more definitively resolve the question of SSDI efficacy, including (1) the use of much larger-scale, high-pressure facilities capable of using live oil, (2) the use of field-scale controlled releases of oil and gas, and (3) waiting for a "spill of opportunity" (e.g., the next deepwater blowout) and employing new measurement technologies and conducting experimentation with and without SSDI (see Murawski et al., 2019). For a variety of reasons, scaling up experimental facilities seems the most practical. As this is inherently an issue of public resource management, support for such a facility should be funded by the oil industry and the government, with appropriate independent scientific oversight.

Experimental Design

Conclusions regarding the relative toxicity of oil compared to chemically dispersed oil are not only species dependent but also influenced by the experimental design (short vs. long term, in vivo vs. in situ) and the chemical exposure measurement unit used to determine the outcome (Coelho et al., 2013; Bejarano et al., 2016; Bejarano, 2018; Mitchelmore et al., 2020; NASEM, 2020), as well as the use of different methods in the preparation of water accommodated fractions of oil (WAF) and, when working with Corexit or other dispersants, a chemically enhanced WAF (CEWAF; see Halanych et al., 2021, in this issue). While some authors used oil and dispersants directly, others worked with WAF and CEWAF fractions. For the former method, a small, but ecologically important, fraction of the oil dissolves in the water and behaves differently than the bulk oil (Liu et al., 2020). We know less about the factors affecting the fate and transport of crude oil water soluble fractions (WSF) in marine ecosystems, despite evidence suggesting that this fraction is enriched during weathering and is more toxic to aquatic organisms than the parent oil (Shelton et al., 1999; Barron et al., 2003; Melbye et al., 2009; Bera et al., 2020). For the latter method, it is difficult to maintain the total concentration of hydrocarbons in the test media due to differential dissolution and dilution of the microdroplets in a WAF preparation, unless these are removed a priori, which few studies do (e.g., Redman and Parkerton, 2015; Kamalanathan et al., 2018; Bretherton et al., 2018, 2020). The toxicity of chemically dispersed oil can be up to an order of magnitude higher than oil that has not been dispersed (Gardiner et al., 2013; Bejarano et al., 2014; NASEM, 2020). These issues impact not only experimental design (variable loading versus variable dilution) but also interpretation of the findings and their relevance to in situ conditions; they are discussed in detail in NASEM (2020).

New Dispersants

Over the decades, exact chemical formulations for dispersants have changed in response to new findings. For example, there were concerns about the adverse health effects in some responders as a result of prolonged exposure to 2-butoxyethanol in Corexit 9527 during the *Exxon Valdez* accident (NRC, 2005). This solvent is not present in Corexit 9500A, the preferred dispersant for surface applications. In addition, the hydrophobic solvent in Corexit has shifted over the years from hydroformed kerosene to NORPAR (mainly normal alkanes, also called paraffins, therefore the NORPAR), then to ISOPAR (mainly branched or isoalkanes, sometimes referred to as isoparaffins, therefore ISOPAR). Thus, formulations have changed, even if only slightly. Synthetic dispersants enhance dispersion of the oil by natural processes such as wind and wave action (Chapman et al., 2007). The role of new dispersants that work in synergy with Corexit EC9500A, Finasol OSR 52, and Dasic Slickgone NS—the dispersants of choice by the oil industry—remains an area for future studies.

A major challenge to the use of liquid dispersants is the drift of the dispersant spray when aerially applied. Also, liquid dispersants can be washed off when applied to heavy or weathered oils (Nedwed et al., 2008; Nyankson et al., 2014; Owoseni et al., 2014). The use of gel-like dispersants has been proposed to overcome such limitations (Nedwed et al., 2008). Design characteristics for gel dispersants would include a close adherence to oil, a degree of buoyancy that would allow increased encounter with surface spilled oil, and high surfactant concentrations to enable efficient dispersion (Nedwed et al., 2008). Owoseni et al. (2018) showed that polyoxyethylene (20) sorbitan monooleate (Tween 80) can be incorporated into a gel-like phase formed by phosphatidylcholine (lecithin) and DOSS. Inclusion of the food grade, environmentally benign lecithin reduces the need for DOSS, and the system can be translated into a gel when the surfactants are dissolved into approximately equal amounts of water and alkane. The microstructure of the gel as studied through small angle neutron scattering and cryo scanning electron microscopy is one of sheet-like lamelli (sheets of thin membranes) that are rolled up into cylindrical lamelli. These systems are naturally buoyant and break down on contact with oil to release surfactants and reduce interfacial tension to as low as 10^{-2} mN m^{-1}, producing oil-in-water emulsions with an average droplet size of 7.8 µm. Hence, gels that are buoyant may increase encounter rate with surface oil spills (Owoseni et al., 2018).

Other interesting new concepts in dispersant science include the formulation of dispersants from food grade emulsifiers such as Tween and lecithin, which have been found to be more effective at stabilizing emulsion droplets than Corexit (Athas et al., 2014; Riehm et al., 2015) and the use of engineered particles at the oil-water interface (Omarova et al., 2018). Synergistic aspects of both particles and surfactants have been reported in the design of novel tubular clays (halloysite) containing surfactants within their tubes (Farinmade et al., 2020). Here, the clays act to stabilize the oil-water interface and release surfactant that reduces interfacial tension and decreases droplet size. While the energy of wave action may be insufficient for surface spills, the turbulence at the well head in deep-sea oil spills will allow the formation of particle-stabilized emulsion droplets. Such armored (encapsulated) droplets will not spread as a sheen when they surface but rather will spread as dispersed droplets with hydrophilic exteriors that may possibly be skimmed effectively.

THE FUTURE

Given that dispersant application has been an important component of oil spill response since the early 1970s and that dispersants have been used at least 20 times in the United States (NOAA, 2018), it is important to continue to develop a comprehensive understanding about the fate and effects of dispersants and chemically dispersed oil. This understanding will inform updating of the American Petroleum Institute's Net Environmental Benefit Analysis for Effective Oil Spill Preparedness & Response (API, 2016; IPIECA-IOGP, 2015), the Spill Impact Mitigation Assessment protocols (IPIECA, 2018), as well as the Consensus Ecological Risk Assessment and the Comparative Risk Assessment (see NASEM, 2020). All of these approaches are used by the oil spill response community and key stakeholders to determine what combination of mitigation techniques, including dispersants, offer better protection of environmental and socioeconomic resources. They integrate ecological, biological, socioeconomic, and cultural considerations into assessment strategies. They also encourage stakeholder involvement in selecting the best response options. As the oil and gas industry moves further offshore, deeper and higher-pressure wells are being drilled. A spill would produce new challenges—what shape might these take?

It will also take time and research to determine whether the dispersants themselves, used in such high volumes and at subsea, are in fact effective at what they are intended to do and whether they have any longer-term detrimental effects on marine life and/or public health. Along with the grand challenges identified above, there are further topics that require additional attention. Last, but not least, during GoMRI, as noted above, research has been undertaken to explore alternatives to the established dispersants (e.g., Corexit 9500A) in the United States. As more knowledge is gained about alternative formulations, and perhaps a much more effective and less harmful dispersant is discovered/formulated, there is the pragmatic issue of Corexit 9500A and other dispersants currently listed on the National Contingency Plan Product Schedule that are already purchased and stockpiled in key locations (https://www.epa.gov/emergency-response/ncp-product-schedule-products-available-use-oil-spills). There remains a paucity of information on the long-term consequences of dispersants in the marine environment, as little is known about the fate of household cleaners and products such as shampoos and dishwashing liquids. Thus, the use of these dispersants enters the realm of the interfaces of science-economics-policy management. We submit that the current existence of a stockpile of prepositioned dispersants should not hinder research that could lead to more efficient and potentially less harmful dispersant formulations.

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AUTHORS

Antonietta Quigg (quigga@tamug.edu) is Professor, Department of Marine Biology, Texas A&M University at Galveston, Galveston, TX, USA. **John W. Farrington** is Dean Emeritus, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Sherryl Gilbert** is Assistant Director, C-IMAGE Consortium, University of South Florida, St. Petersburg, FL, USA. **Steven A. Murawski** is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Vijay T. John** is Professor, School of Science & Engineering, Tulane University, New Orleans, LA, USA.

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CONSIDERATIONS FOR SCIENTISTS GETTING INVOLVED IN OIL SPILL RESEARCH

By Kenneth M. Halanych and David G. Westerholm

Oil that reaches the water's surface has already been altered in chemical composition since leaving the well head. Researchers collecting and working with oil should be cognizant of how the environment promotes chemical modifications. *Photo courtesy of Georgia DNR*

ABSTRACT. From the outset of the Deepwater Horizon (DWH) oil spill, scientists from many different sectors (e.g., government, industry, academia, independent) sprang into action to establish appropriate experimental procedures, collect essential samples, and gather meaningful data. The scale of the spill and the unprecedented use of dispersants challenged scientists familiar with oil spill research, but also drew in many scientists new to hydrocarbon studies. The response to DWH, as with other oil spills, was centered on environmental and human safety concerns as mandated by the US Clean Water Act, the Oil Pollution Act of 1990, and the National Contingency Plan, which defines roles and responsibilities of multiple parties. These roles, however, are usually carried out by government, industry, or government-contracted researchers and, until DWH, have included limited input from academic investigators. In studying the DWH spill, most researchers also had to navigate the logistics and liability issues that can be associated with an oil spill event, including the formal government response processes that can be unfamiliar to academic researchers. In particular, biological researchers had to rapidly educate themselves on the nuances and complexity of the hydrocarbons and dispersants throughout the water column. Nonetheless, biological studies were hampered by the lack of controls or challenges with employing experimental approaches in the field. DWH spill research also highlighted challenges and opportunities that arose due to the interactions of researchers from the academic, government, and industry sectors. The objective of this article is to provide some perspective and to highlight issues that researchers new to the area should consider when approaching oil spill and dispersant studies.

INTRODUCTION

Scientific response to and study of an oil spill can be a daunting task. It requires a variety of scientific approaches and inclusion of associated response and remediation efforts as well as assessment of impacts across the complex network of biological systems and different hierarchical levels. In the torrent of biological studies after the Deepwater Horizon (DWH) spill, the importance, relevance, and applicability of a given study proved to be dependent not only upon the quality of the biological aspects of the research but also in many instances on how oil spill chemistry and physics were incorporated into the experimental design and interpretation. At the time of a catastrophic event like the DWH spill, the initial urge of many researchers is to immediately start collecting samples or data to understand impacts to the environment. Although sampling habitats prior to encountering oil is invaluable for pre-spill baselines, preparation for and careful thought about collection schemes and experimental design can significantly improve the prospects of producing *meaningful* scientific products. Additionally, in the case of DWH, initiating research with limited planning resulted in a lack of coordination and communication among researchers and created considerable duplication of effort and confusion among the community. Research groups that were more exacting with their inclusion of chemical and physical parameters early in DWH research tended to produce more consequential products that helped shape knowledge of oil spill impacts. Here, we highlight some considerations so that researchers tackling future spills or other disaster events can benefit from wisdom gained during the DWH research efforts.

With an emergent catastrophic event, there may be limited time or opportunity to prepare for data collection or experimental design. This could not have been more true in the case of the DWH spill. Connecting with the response and restoration community *before* an event can help identify opportunities and limitations efficiently and effectively. As a result, science will be improved and frustration reduced. There are several salient aspects of a major spill that may be unfamiliar to most researchers. Although some of these aspects are obvious, preparing for and embracing them is different than just recognizing they exist.

CONSIDERATIONS

Consideration 1: Once the event occurs, researchers must work within a command structure, so it is advisable to build collaborations prior to events.

Conducting research in a dangerous, harmful, or uncontrolled environment is a game changer. DWH was unprecedented in its duration and scope. As such, scientists were trying to collect samples at the same time responders were still trying to control or mitigate the spill. Researchers, especially academic researchers, are accustomed to being independent. However, human safety and mitigation of the spill are the first priorities for the command structure overseeing the incident, not research. During the summer of 2010, there were 47,000 response personnel and approximately 7,000 vessels engaged in spill response (Ramseur and Hagerty, 2013). Dispersant applications, in situ burning, oil spill boom deployments, as well as sampling associated with the response and the Natural Resource Damage Assessment (NRDA) process made site access and logistics for independent research difficult and, in some locations (e.g., near the wellhead), impossible.

During this crucial time, a few researchers had access or approval for collecting in restricted areas, whereas most did not. Moreover, the scale of the spill and the extensive use of dispersants drew in many scientists new to this type of research. Being a researcher with access was not a chance process, and potential researchers need to do their best to be prepared for future opportunities. As expected, researchers who were invited in, and thus had access, offered direct relevant experience with Gulf of Mexico organisms and ecosystems or experience with oil spills, or they were US federal agency researchers charged with environmental stewardship or protection

FIGURE 1. Admiral Thad Allen provides a briefing to the Unified Area Command in New Orleans, Louisiana, on Monday, June 28, 2010. Admiral Allen was the National Incident Commander for the BP Deepwater Horizon oil spill in the Gulf of Mexico. *Photo credit: US Coast Guard photo by Petty Officer 3rd Class Ayla Kelley*

(e.g., those affiliated with agencies such as the National Oceanic and Atmospheric Administration or the Environmental Protection Agency). From the outset of the DWH oil spill, scientists from many different sectors (e.g., government, industry, academia, nongovernmental organizations, and independent scientists) were involved in collecting relevant samples and establishing appropriate and meaningful experimental procedures. For an academic researcher, having numerous and strong collaborative ties with scientists in different sectors who know the relevance of proposed research improves chances for access to critical samples or areas. For agencies, promoting openness and transparency can stem some of the mistrust or tension felt by those researchers on the outside looking in.

Understanding the federally mandated response structure provides context for what may or may not be possible. The Oil Pollution Act of 1990 (33 U.S.C. 2701-2761) was enacted in the wake of the *Exxon Valdez* spill and outlines roles and responsibilities in terms of prevention, response, liability, and compensation for oil spills. This act, in conjunction with federal regulations found in the National Oil and Hazardous Substance Pollution Contingency Plan (NCP; 40 CFR Part 300) establishes response procedures and structures when the federal government responds to an oil spill. Unlike most disaster responses under the US Federal Emergency Management Agency (FEMA) where the federal government often assists local and state responses, under the NCP, the federal On-Scene Coordinator (usually from the Coast Guard or the Environmental Protection Agency) has certain federal authorities. If the On-Scene Coordinator shows that the discharge poses or may present a substantial threat to public health or welfare of the United States, he or she shall direct all federal, state, or private actions to remove the discharge or to mitigate or prevent the threat of such a discharge.

In such a case, the On-Scene Coordinator establishes an Incident Command System, sometimes headed by a Unified Command that employs multiple command posts to oversee containment and response to an incident and guides response at multiple levels (federal, state, local). During the response (Figure 1), a scientific advisor can contribute to the Incident Command System primarily in two ways, as a Scientific Support Coordinator or by working within the "Environmental" Unit. In the case of marine spills, Scientific Support Coordinators will be provided to the On-Scene Coordinator by the National Oceanic and Atmospheric Administration (NOAA). Although they work for NOAA, the Scientific Support Coordinators are to be objective advisors to the On-Scene Coordinator. They have special training and skills and often have established networks of personnel with specific scientific expertise to bring the "best" science to the response. The Environmental Unit, on the other hand, is responsible for executing environmental duties in an Incident Command System structure. It can have numerous personnel assigned with varying expertise. The Scientific Support Coordinator and Environmental teams are necessarily limited in terms of personnel and have specific responsibilities, so most scientists engaged in research on the spill will not be part of these teams. However, if these science advisors are aware of how one's tools or expertise are relevant, chances for access to critical areas or at critical times will be improved. Importantly, Incident Command System personnel work on a timescale much shorter than most researchers. Their first concern is to control the spill with safety in mind. The Oil Pollution Act of 1990 also established the liability framework for the responsible party, including removal costs and damage. In cases like DWH, where the responsible party mobilized and funded the response to remove the oil, industry personnel and resources become part of the Incident Command System structure. This may include industry scientists or contracted scientists with specialties related to the incident. In addition, and often simultaneous to the response, work is done to evaluate the natural resource damage and to determine whether the responsible party must compensate the public for damages from the incident and the response (see Consideration 2).

Importantly, one must be qualified to work in such areas when the time comes. In hazardous situations, this often requires certifications and knowledge of legal and safety protocols that are best obtained prior to the event. Once the event happens, there can be confusion about where and how to be trained for working in hazardous situations, and even a backlog of requests for training. An excellent primer for academic researchers has been developed by NOAA's Sea Grant (Sea Grant Programs of the Gulf of Mexico, 2020).

Consideration 2: Source of research support.

During a response, limited sampling (water, air, sediment) may be conducted by the Unified Command/Incident Command if it is directly related to the response. If alternative countermeasures are going to be utilized, Special Monitoring of Applied Response Technologies (SMART) protocols and monitoring are employed. For example, during in situ burning or dispersant operation, rapid, real-time sampling and reporting provides the Unified Command/Incident Command with data for decision-making. Although SMART is not a regulatory requirement, scientists assist with reporting and evaluating the data collected.

In concurrence with DWH response efforts, a number of researchers were also mobilized to conduct a Natural Resource Damage Assessment. NRDA is a legal process under which designated natural resource trustees (from federal, state, and tribal governments with jurisdiction) determine the appropriate type and amount of restoration needed to offset impacts and lost use to fisheries, wildlife, habitats, and human uses from oil spills, hazardous waste sites, and vessel groundings. NRDA occurs in phases that include (1) assessment of the injury (which may include a preliminary assessment), (2) planning the restoration, (3) holding polluters accountable (via settlement or court action), and (4) restoring the environment to the extent practicable. This work is usually done by government scientists and specialized contracting firms or institutions that conduct NRDA studies. However, for the DWH spill, the government turned to academic researchers more than usual because of the scale of the spill and because government scientists, consultants, and industry researchers had limited knowledge of deep-sea environments. In such a situation, the academic researchers are formally contracted and typically must sign a non-disclosure agreement. In some cases, this fostered tension between academic researchers. Such non-disclosure agreements should be vetted carefully by the parties involved (including university lawyers), as publication of results may be prohibited for some length of time, impacting the research outputs of principal investigators and, importantly, early career scientists in their laboratories. Fortunately, in the case of DWH, the government realized that the peer-review process bolsters the integrity of a scientific study, making findings more likely to hold up to scrutiny in a court of law.

Unlike the response effort, which may be of relatively short duration, NRDA can often take years to complete. In the case of DWH, the NRDA settlement was approved nearly six years after the historic event, and restoration efforts will continue until 2032. Researchers may be involved throughout this process. At the same time, the responsible party will also independently evaluate damages, a process that may be done with designated

BOX 1. The Benefits of Industry-Academia Interaction in Oil Spill Research

During the DWH spill, interactions between researchers in different sectors were typically positive and productive, but several interactions, especially between industry and academia, were initially challenging. Industry scientists often have knowledge of considerable research that is not available to the general community. This situation can cause tension, as in some cases industry researchers can be dismissive because they think the work was already completed, and academicians are skeptical about the quality of non-peer reviewed, or privately reviewed, work. As was clear in the case of research on dispersants, considerable insights and knowledge were gained from a fresh perspective that academic researchers brought to the table, and academic researchers benefited from industry's knowledge. Moreover, all researchers who participate in spill response must be open and realistic about their biases and motives versus the biases and motives of others. In most cases for DWH research, once researchers interacted in a neutral setting, a collaborative mindset ensued. For example, larger research consortia that comprised much of the Gulf of Mexico Research Initiative's (GoMRI's) effort included industry representatives who served on their advisory boards. The interaction between sectors can help industry scientists see beyond there company-driven perspective and can help academic scientists from repeating research efforts already carried out by companies. Transparency and communications are fundamental to facilitating such interactions. Funders of oil spill response and research can serve a critical role in developing these interactive relationships, as was done in the GoMRI research model.

national trustees in a cooperative manner (i.e., joint research and sharing of data, with each party conducting independent evaluations) or, if not, the responsible party may choose scientists or contracted researchers. Because this is a legal process, chain-of-custody protocols and limitations on researchers will often apply until the process is complete.

To help mitigate conflict-of-interest issues, most NRDA science is contracted to companies that specifically support the government or those that specifically support the industry responsible parties, and not to independent sources. This model also includes sample analysis, where specialized and certified laboratories can meet the legal requirements. A nuance is that if data are publicly available, such as those published by a researcher, the government and/or industry may choose to use that information as it relates to potential injuries to natural resources. A poignant example is the discussion of flow rates from the wellhead during the spill, which sparked disagreements among NRDA-contracted researchers, federal agencies, and industry representatives regarding damages wrought by the spill. In extremely rare cases, for example if the case were to go to trial, researchers may be requested to provide depositions or asked to be witnesses if their material is particularly germane. Such material may include field samples, cruise logs, laboratory notebooks, instrument data files, and email correspondence.

> “Focusing on the oiled communities and environment, rather than other objectives or priorities relevant to specific research sectors, is the best way for all to benefit from research efforts.”

Although the NRDA covers damages incurred to public resources, it does not get involved with commercial claims. The responsible party usually sets up a claim process for third parties. In large-scale or unusual events, there may be an opportunity for specific research associated with those commercial claims, either to support those claims against the responsible party or to refute the claims on behalf of the responsible party.

DWH was unique in that there were significant research funds available spread out over many years. Examples include US National Science Foundation Rapid Response Research (RAPID) grants and Gulf of Mexico Research Initiative (GoMRI) funding (a 10-year program that was not required by law or settlement), as well as Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act and National Academies funding that continue today. Future spill events may provide similar opportunities for academic research funding. Congress can also play a role by providing federal funding and mandating research from certain agencies, which usually occurs post event. Of course, there is unassociated research that may link to an event, such as fisheries stock research, seafood safety research, and long-term environmental studies that now have oil introduced to their study area and that may have long-term implications for resource management.

Lastly, one overarching issue concerning support for DWH research was that those who had baseline data or ongoing studies were targeted by research agencies and the NDRA process. As mentioned below, having before and after comparisons is essential for understanding environmental impact.

Consideration 3: Liability.

Academic researchers understand that there is liability with field research or sample collection, but the focus is usually on an individual’s well-being or equipment used in the field. In the case of an oil spill, there are several other aspects to liability as well. Under the Oil Pollution Act of 1990, the company that caused the spill is the financially responsible party for impacts caused by the spill *including any impacts that may have been caused by response to, or assessment of, the spill.*

In other words, if a researcher is somehow injured in response to the spill, exposed to toxicants, or causes further harm to the environment, including causing delays in the response, the responsible party for the spill may incur additional liability. Likewise, research results may either directly or indirectly inflate assessments of damages caused by the spill. For example, findings that are publicly vetted and cause further damage to local economies (e.g., by reducing beach tourism or reductions in recreational fishing) may incur additional third-party claims or additional NRDA injuries. In either of these cases, the responsible party may seek to attribute such damages to researchers or their institutions and seek third-party compensation. In this vein, how findings and results are reported should be considered. Peer-review publications have been vetted by qualified individuals and the language focuses on accurate and scientifically supported statements. In contrast, a university press office or a public media outlet may try to reduce statements to more simple or catchy language that may be interpreted in unintended ways. Understanding these potential liabilities can be critical for making sure the proper steps are taken to ensure actions or reported findings are done in a manner that reduces the exposure of the researchers and their institutions.

Consideration 4: Design research to fit into an appropriate comparative framework.

The importance of controls for comparison is well known to researchers, but during the DWH spill studies were hampered by the limited availability of baseline data or appropriate control samples to ensure proper experimental design. Biological systems, from organism to ecosystem, are subject to multiple stressors (e.g., Carmichael et al., 2012; Weinnig et al., 2020). This especially is true in the Gulf of Mexico, a system known for variability (e.g., Morey et al., 2005; Kolker et al., 2011; Xue et al., 2013; Muller-Karger et al., 2015). Without sufficient resources to appropriate governmental agencies and other stakeholders, obtaining a baseline understanding of the contaminant burden of the ecosystem and the degree of underlying variability will remain elusive.

Baseline data prior to DWH was remarkably scarce with respect to important issues such as background levels of polycyclic aromatic hydrocarbons (PAHs), organism health of important species, or even variations in community structure and biodiversity. In some cases, data that were available were not easily discoverable. When baseline data were available, the collection method or frequency may have been different from what was needed after the event, compromising the utility of such data. Although several studies focusing on DWH used comparative baseline data, interpretation of impacts may have been hindered due to the difficulty of elucidating influences of multiple simultaneous stressors (Chagaris et al., 2020). The more meaningful studies that used baseline comparisons were largely either continuations of previous studies or they took advantage of previously collected samples (e.g., Pulster et al., 2020).

Without baseline data, many researchers employed a modified before-after-control-impact (BACI) experimental design (Conner et al., 2016; Smokorowski and Randall, 2017). In the case of DWH, this mainly focused on the control versus the impact of the experimental design because "before" data were limited or lacking. One challenge of this particular spill was that the scale was so large that finding appropriate controls (i.e., sites that were not impacted) in close proximity and with similar parameters was difficult.

Consideration 5: Experimental design should account for the chemical complexity, and environmental state, of oils and dispersants.

Oil is a complex mixture of hydrocarbons and the result of multifaceted geological processes. As such, the composition of oil varies significantly depending on its source. The sizes of oil molecules emanating from a wellhead may range from small ones such as methane (CH_4) and ethane (C_2H_6) up to larger asphaltenes, whose molecular masses can be as much as 1,500 u (Rullkötter and Farrington, 2021, in this issue). Oil can be composed of hydrocarbon chains or molecules that form rings and can be saturated or unsaturated. Because of this complexity, the exact molecular composition of a particular oil sample is very difficult to know. Oil fingerprinting depends on identification using a combination of key hydrocarbon compounds that are uniquely tied to the oil's source. Importantly, some molecules in oil are labile and others recalcitrant, meaning that the composition of oil changes over time. For example, in the case of DWH, much of the methane found in the oil mixture emanating from the wellhead on the ocean floor never made it to the ocean surface, as it was absorbed into the water column. Likewise, once the oil reached the photic zone, photo-oxidation of hydrocarbon molecules began changing the nature and composition of the oil. As a result, oil that has undergone modification in the environment, that is, "weathered oil," can be compositionally very different than oil released at the wellhead.

In contrast, the chemical formulations of dispersants are known and can be reproduced. However, because they are proprietary, the researcher conducting experiments may not have knowledge of the precise formulas used during the spill response. Although we suspect that molecular components of dispersants also change under environmental conditions, we have much less understanding of the longevity of such molecules in the environment and how they degrade or are catalyzed into subsequent entities. Tracking them in the environment can be more difficult than tracking hydrocarbons (Quigg et al., 2021, in this issue).

Biological researchers need to do a better job of considering the chemical and physical properties of molecular components of oil and dispersants to gain a more accurate and thorough understanding of hydrocarbon and dispersant impacts on biological systems. For example, differences in hydrocarbon composition can impact carbon assimilation rates by microbes that feed on the oil deep in the water column versus on the surface (Weiman et al., 2021, in this issue; see photo on this article's opening page). Such differences in carbon utilization are important, as carbon from DWH oil was directly taken up into food webs (Graham et al., 2010; Chanton et al., 2012;

FIGURE 2. Scientists monitored mobile animals such as dolphins, which experienced wide variation in toxicant exposures. *Photo credit: Consortium for Advanced Research on Marine Mammal Health Assessment*

Quintana-Rizzo et al., 2015). Using similar logic, DWH sourced oil may have limited applicability to some questions addressed in oil pollution studies due to compositional differences in oil chemistry.

Immediately following the DWH spill, many researchers scrambled for access to Macondo well oil, or similar surrogates, to use in experiments. Fresh or "pristine" oil was used in experiments for shallow and nearshore water and for terrestrial organisms, even though these animals were only exposed to weathered oil that was reduced in several of the smaller volatile hydrocarbons (Rullkötter and Farrington; 2021; Farrington et al., 2021, both in this issue). Critically, different compounds in oil and dispersants have differential toxicity and can produce various secondary compounds. Healthy skepticism is warranted when assessing how well a particular study has replicated the hydrocarbon or dispersant environment of the biological system under study.

Thus, when conducting research, investigators should consider (1) the composition of oil and/or dispersants that the organismal system was exposed to, given modification by "weathering," and (2) which of the hundreds to thousands of chemical compounds found in oil and dispersants are likely responsible for the observed organismal response. Because accurate assessment of oil and dispersant composition is beyond the scope of most biologists, a researcher should consider collaborating with an appropriate chemist, preferably one with mass spectrometry experience. Because many previous studies have treated oil (and/or dispersant) as a singular entity, many of the molecular mechanisms that actually cause harm or insult to biological systems remain unknown.

Consideration 6: The scale and magnitude of parameters and results to be measured should be carefully considered.

Major catastrophic events have considerable lethal impacts that are often quicker and easier to measure than sublethal and long-term effects. In the case of DWH, oil and dispersants were distributed over hundreds of square kilometers, and concentrations of specific hydrocarbon molecules or dispersant components varied spatially and temporally on scales that spanned several orders of magnitude. Although much of this was driven by the movement of oil, organisms also moved in and out of impacted areas. For example, pelagic organisms characterized by diel vertical migrations (Sutton et al., 2020) and highly mobile mammals (Figure 2) likely moved through different concentrations of the oil.

In designing experiments and reporting results, researchers should be as explicit as possible in replicating environmental conditions of interest. Also, for results to be more robust and meaningful, researchers should consider experimental designs that encompass a broad range of dosages for the pollutant in question. For example, if a nearshore fish species is being examined in a mesocosm, is the experimental design trying to replicate pollutant conditions observed at the edge of a large slick, or conditions where the oil has been broken into small droplets suspended midwater, or something else? In these cases, the organism may have been exposed to varied pollutant concentrations, and the exposures may have been more episodic than constant in nature. If such differences in exposure are not considered during interpretation of the data, extrapolation to impacts of the spill on the health of individuals or populations may be flawed.

The remainder of this article focuses on some of the lessons learned and approaches that have continued to be refined over the 10-year course of DWH research.

RESEARCH LOGISTICS

Research related to an oil spill has some unique considerations. Although government, industry, and academic investigators may have similar reasons for doing research (i.e., to understand how the spill impacted the environment), their uses of data can be very different (e.g., peer-reviewed publications, industry reports, governmental assessments, or court proceedings). Many scientists may contribute to NDRA research to inform damage assessments that will be critical to settlement negotiations or court cases. Some researchers became involved in the DWH spill due to a sense of civic duty or because it was a logical extension of ongoing work, and for some, it presented a funding opportunity. Regardless of the motivation for conducting the work, how the research is to be used can impact logistical considerations. For example, research under the NRDA umbrella requires a strict accounting of the chain of custody for samples and more rigorous standards of laboratory documentation than may be customary for academic scientists. Some of the logistical considerations are outlined below.

Logistical Consideration 1: Chain of custody and documentation.

If the research is part of an NRDA process, then chain-of-custody documentation for samples is usually required. However, even if the research is not part of the damage assessment, using a chain-of-custody approach may be advisable. Environmental disasters caused by human activity attract multiple stakeholders (e.g., industry, governments, environmental groups, local residents), some of whom may attack a given research finding based on their interests rather than the quality of science. Additionally, even if researchers are not initially involved in damage assessment, they may possess unique samples or results of interest to formal proceedings at a later date. Alternatively, the responsible parties may seek compensation if they feel research inappropriately contributed to their liability exposure. Thus, the work may need to be defensible in a legal, in addition to a scientific, framework. As such, a researcher wants the work to be as defensible as possible, including verifying explicit details of procedures used in the lab and who had access to samples at all times. This may require signed research logbooks or having samples under lock and key in one's own lab.

Logistical Consideration 2: Plastic is a hydrocarbon.

The use of plastics is ubiquitous in biological research settings, largely because they are durable and convenient, but components used in making plastic containers and Eppendorf tubes, for example, may be similar to the hydrocarbons found in oil. If measurements are to be made of hydrocarbon concentrations in tissue, items used in the transport and storage of samples, or housing of live organisms, should be considered. Plastics may not be appropriate, and containers made of glass or foil may be preferred. This consideration is particularly relevant for eliminating contamination in experimental design where measurements for sublethal exposure to oil products may be in the parts per billion, or in working with dispersants where contamination is possible from similar compounds that can be found in a working laboratory setting.

Logistical Consideration 3: Replicating environmental parameters will determine the experimental setting and scale.

Because both oil and biological systems are exceedingly complex, and dispersants are somewhat of an unknown quantity, the number of parameters to manage when conducting oil-spill research is potentially unwieldy. Much of the success of DWH research was facilitated by using a tiered approach to handle and replicate biological complexity. A combination of lab, mesocosm, and/or field experiments was used to relate parameters that could be clearly defined in a controlled setting to more realistic environmental settings (Coull and Chandler, 1992). In the case of oil spill research, experiments in the field are not only difficult because of the number of parameters that are free to vary, but the introduction of pollutants that exceed regulatory thresholds (e.g., oil sheen) is often unethical and usually prohibited by law.

In the laboratory, experiments can focus in on impacts of oil and dispersants by holding all other parameters constant. Although this works well for specific questions regarding individual organisms, this approach usually is too restrictive to deal with how oil impacts ecological connections between organisms. Thus, to provide a more complex but controlled environment, mesocosms have been very helpful as they allow for a greater, but still manageable, number of parameters to vary or be subject to manipulation. The questions driving the research, along with careful consideration of the environmental conditions to be examined, will help determine how lab, mesocosm, and field experiments should be employed.

Logistical Consideration 4: Toxicity and waste management.

Just like the handling of any other toxic substance used in an experimental setting, disposing of hazardous waste must be considered. Many DWH researchers were innovative in their experimental designs, which in some cases required new solutions to hazardous waste management. Regardless of whether one is using a 250 mL flask in the lab or a 20,000 L mesocosm, water treated with pollutants must be disposed of properly and equipment used must be properly cleaned. Although this may be a minor issue for small aquaria, cleaning and hazardous waste protocols can be expensive both in terms of time and money for larger facilities. Before hastily starting an experiment because samples are available or there is a need to act quickly, researchers should make sure they have adequately planned for disposal of waste and wastewater and for how equipment will be cleaned or detoxified. Because biosafety, chemical safety, and other safety offices have their own schedules, planning and contingencies are best done before crisis hits, if at all possible.

Logistical Consideration 5: Delivery and dosing of organisms with oil and dispersants is not a trivial procedure.

As indicated above, over the course of the 10-year GoMRI program, researchers have learned a considerable amount about the best ways to study the impacts of oil spills. Because oil and dispersants are complex chemical mixtures, and because oil and water don't mix (to use an age-old phrase), delivering oil and dispersants to organisms in the desired quantities can be a challenge. For example, if oil is added to an aquarium containing a crab, the oil will likely float. In that case, determining which components and what concentrations of the oil may leach into the water and reach the crab at the bottom of the tank requires additional measurements and understanding of chemistry. Similarly, the water-oil interface in a plexiglass versus a glass tank can be different. Such factors can alter organismal interactions with toxicants.

Methods for delivering oil and dispersants to study organisms have been refined over many years. Water accommodated fractions (WAFs) for hydrocarbons and chemically enhanced water accommodated fractions of oil (CEWAFs) have been used for the combination of hydrocarbons and the Corexit dispersant that was used during DWH. The techniques used for dosing oil and dispersants, including which chemicals in those mixtures are released, need careful consideration and can present myriad challenges (e.g., Wade et al., 2017; Bera et al., 2018; Hodson et al., 2019; Colvin et al., 2020; NASEM, 2020).

CONSIDERATIONS FOR INTERPRETATION

Consideration for Interpretation 1: Disentangle effects due to different molecules.

A significant challenge during the DWH research effort was separating impacts due to hydrocarbon exposure versus dispersant exposure. One issue was that good estimates of exposure concentrations of dispersants in animals were largely unknown (NASEM, 2020; Quigg et al., 2021, in this issue). However, in the laboratory, many researchers quickly gravitated to experimental setups that exposed different cohorts to either oil, dispersant, or a combination of dispersant and oil (with appropriate controls; Figure 3). Due to the complexity of these mixtures and ongoing physical-chemical processes during the experiment, determining which chemicals within oil or dispersants are likely to be mechanistically responsible for causing an observed change in organismal state can be very difficult.

During analyses and interpretation, researchers should take care to clearly articulate the resolution at which interpretations can be drawn. For example, based on how a given study was conducted, can we say that the impact was due to hydrocarbons in general, PAHs, or a single specific chemical?

Consideration for Interpretation 2: Recovery is not just a function of time but of processes.

As mentioned, oil and dispersants are a complex cocktail of molecules, many of which can be degraded or metabolized, thus changing the "cocktail" over time,

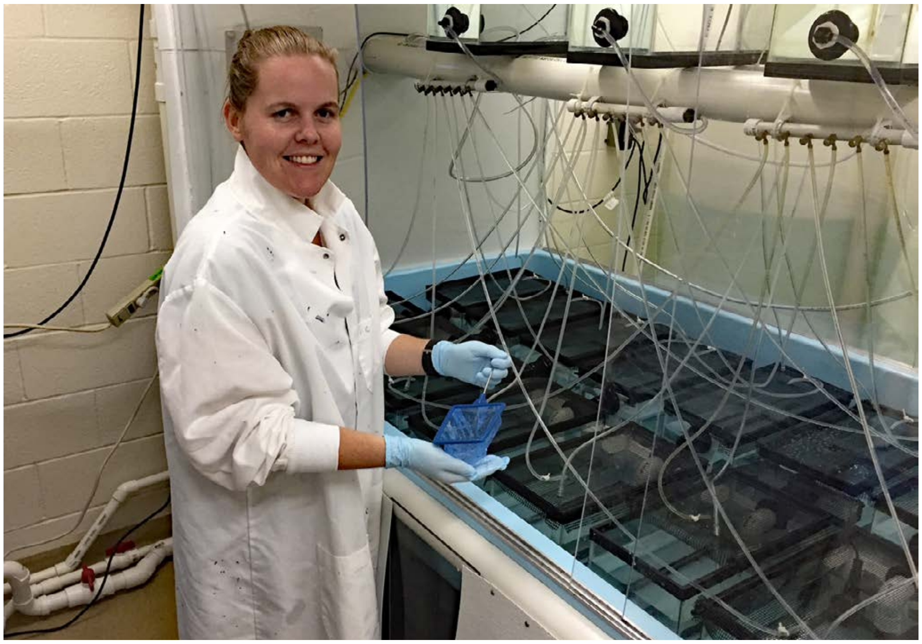

FIGURE 3. Working with oil in a controlled setting offers many challenges in terms of replicating organismal exposure, chemical modification, and disposal of hazardous substances. Here, a researcher works at an aquarium designed to replicate marine animal oil exposure and multiple environmental stressors. *Photo credit: Milton Levin*

even in some laboratory and mesocosm experiments (Farrington et al., 2021, in this issue). Therefore, when looking for responses of biological systems over time, focusing on a single indicator or marker may not be sufficient. Importantly, toxicants can have sublethal impacts that take time to manifest. Chemical components of hydrocarbons and dispersants can be metabolically active and produce secondary compounds. The initial indicator molecule measured in the environment may have been transformed into compounds that are more or less detrimental.

For sublethal or long-lasting impacts, rates of processes that control cellular metabolism may be much better indicators of recovery than time since event. For example, PAH metabolites measured in the tilefish *Lopholatilus chamaeleonticeps* increased over time following the DWH event (Snyder et al., 2019; Figure 4). These PAH metabolites were positively correlated with decline in fish health and appear to have been taxing the energy budgets of individuals, particularly of adult females, and ultimately impacting fitness. Additionally, the reproductive lifespan for many deep-sea and larger nearshore organisms is typically much longer than the duration of the NRDA process or other research programs, including the GoMRI effort that lasted 10 years. The example of metabolite load in tilefish resulting from the initial toxicant is illustrative, as that study included five years of sampling. Thus, referring to a rate of degradation or the accumulation of a metabolite, rather than measuring the amount of a particular toxicant, may be more useful for tracking recovery.

CONSIDERATIONS FOR FUTURE ENGAGEMENT

Academic researchers who want to be involved in spill research may find funding more difficult after time has elapsed from a major event. However, engaging with the response and planning community may still provide insight and opportunity. Federal agencies that are engaged in spill response are part of the Interagency Coordination Committee for Oil Pollution Research (ICCOPR), which reports to Congress on funded research projects as well as unmet needs. Additionally, for the marine environment, the Coast Guard has Area Committees comprised of federal, state, and local officials whose responsibility is to prepare an Area Contingency Plan for a response to a discharge of oil or hazardous materials. For many academic researchers, the most appropriate intersection with oil spill response may be through open meetings held by Area Committees. In addition to governmental agencies, numerous individuals from oil spill response organizations, industry, academia, and environmental groups participate in these committees' planning processes. Understanding what is planned for a major spill can bring focus to research areas and familiarity with those who will be leading the response. This is a process where academic researchers can share insights with colleagues from other sectors and collectively bring the latest knowledge of a particular research area to the framework of response, NRDA, and restoration planning as well as identify ongoing or new needs for advancement of knowledge. Connecting to these groups can be facilitated by NOAA and the US Fish and Wildlife Service as well as the Coast Guard and NOAA Sea Grant.

Importantly, current laws and regulations mandated by the Clean Water Act, the Oil Pollution Act of 1990, and the National Contingency Plan undervalue the importance of the academic sector to the science and remediation of large-scale oil spills. Without modification or changes based on the DWH experience, the next major event will likely see similar confusion and inefficient use of resources at the outset. Government agencies and universities must engage with legislatures to explain the insight and potential that academicians bring to the table. At the same time, revisiting and revising laws to promote positive and progressive interactions among industry, academic, and government sectors during such an

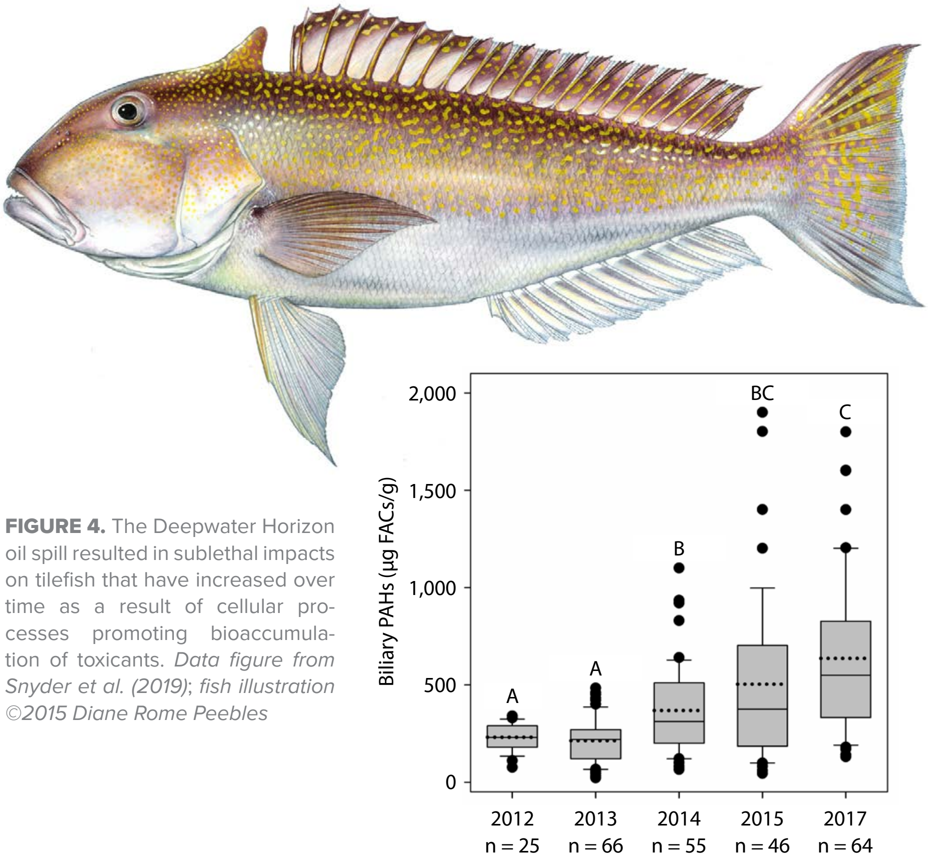

FIGURE 4. The Deepwater Horizon oil spill resulted in sublethal impacts on tilefish that have increased over time as a result of cellular processes promoting bioaccumulation of toxicants. *Data figure from Snyder et al. (2019); fish illustration ©2015 Diane Rome Peebles*

event would provide a substantial benefit for response, mitigation, and restoration of future disasters.

The need for an efficient communication infrastructure by the Incident Command System and responding agencies should be a critical consideration for future events. Well-established lines of communication that promote transparency and have sufficient capacity will only benefit all involved. DWH was so massive compared to previous incidents that established channels of communication could not handle the large volume of information and communications needed. These limitations sowed confusion and, in some cases, distrust. The lack of sufficient bandwidth impacted researchers, but more importantly, increased and promoted anxiety for some sectors of the public. Mandates for expanding the team of science advisors, as well as specialists to engage the public, should be explored.

One last consideration: expect the unexpected, as there will be unforeseen processes, and every spill is different. The great thing about research is that there are always new discoveries and surprises. Be open to and prepared for unexpected findings, including some that do not fit preconceived models or ideas. Early in the DWH spill there were, of course, comparisons to the other major spill in US waters, the *Exxon Valdez*. However, that was a surface spill of heavy crude oil, in contrast to the DWH spill, which consisted of a sweet light crude that occurred at great depth below much warmer surface waters. Comparatively, the oil and associated chemicals from DWH were metabolized relatively quickly by microbes (Weiman et al., 2021, in this issue). The 1979 Ixtoc 1 spill in the Bay of Campeche in Mexican waters, also a prolonged major spill in the Gulf of Mexico, was more similar in many ways to DWH. However, several factors relating to funding, accessibility in Mexican waters, and decisions about how research finding would be disseminated limited the impact on scientific knowledge that resulted from Ixtoc 1. All three of these major North American spills were important for advancing understanding of the environmental impacts of spills. Oil spills differ in a number of ways, and thus there will always be some degree of unpredictability.

SUMMARY

Although the target audience of this article is largely those new to oil spill research, there are several points that apply to a broad cross section of investigators. A major oil spill causes a complex cacophony of interactions, not only in the environment, but among response teams and investigators. Being prepared to work efficiently in such an environment is no accident, and preparatory steps can be taken to improve the possibility of conducting meaningful research in such a situation. Successful participation in that cacophony requires being able to work with, and learn from, individuals in other research sectors. Investigators in government, industry, or academic positions all have their own strengths and perspectives. Focusing on the oiled communities and environment, rather than other objectives or priorities relevant to specific research sectors, is the best way for all to benefit from research efforts. Lastly, oils spill research is exceedingly interdisciplinary. To address even a simple question in a specific and thorough manner, researchers need help from other disciplines, especially chemistry. All of the issues discussed here developed and matured over the course of DWH research, and the hope is that the knowledge gained during 10 years of Gulf of Mexico Research Initiative efforts can jumpstart research on the next spill.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

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AUTHORS

Kenneth M. Halanych (ken@auburn.edu) is Professor, Department of Biological Sciences, Molette Biology Laboratory for Environmental & Climate Change Studies, Auburn University, Auburn, AL, USA.
David G. Westerholm (retired) was Director, Office of Response and Restoration, National Oceanic and Atmospheric Administration, Silver Spring, MD, USA.

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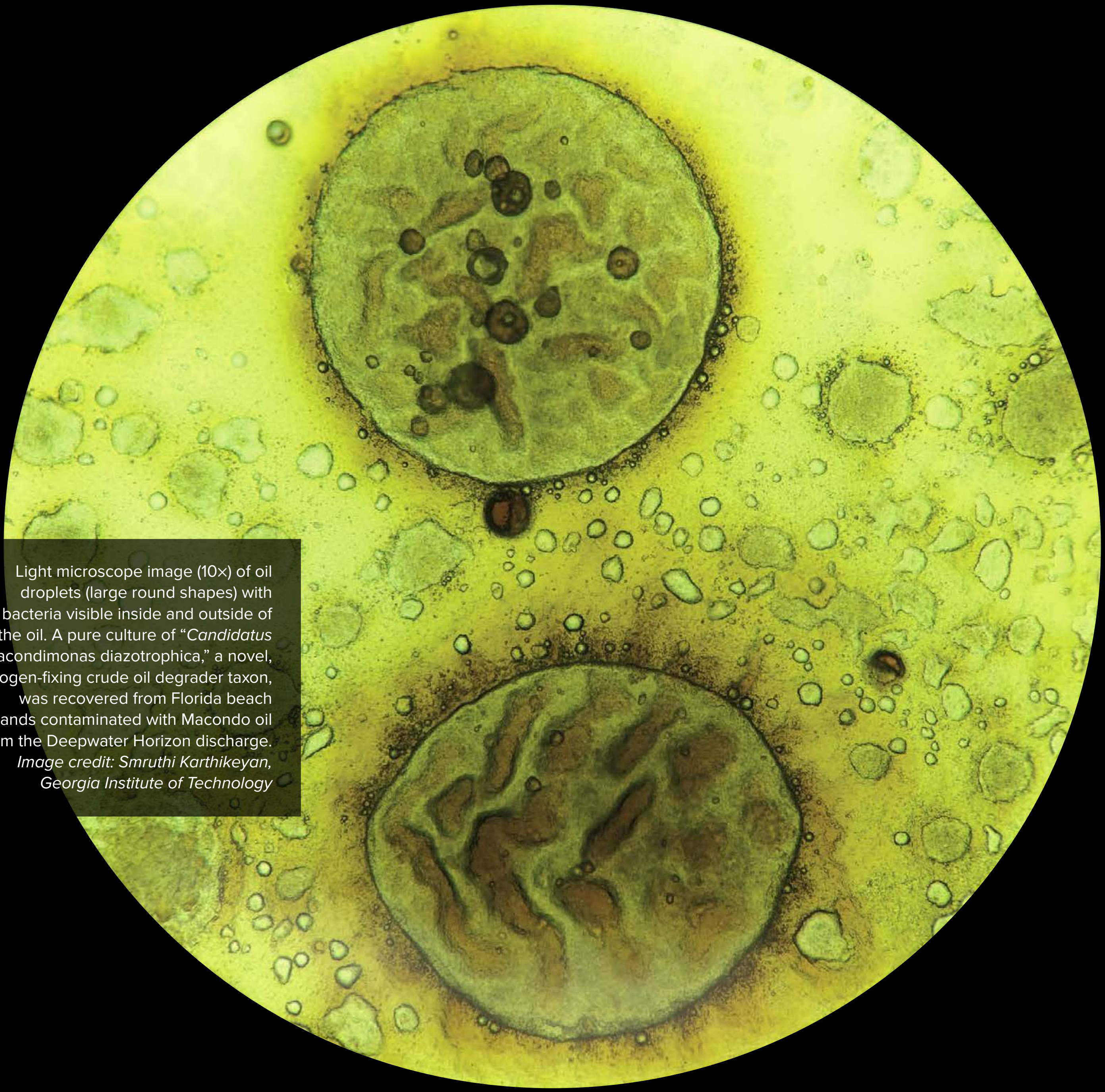
GoMRI Insights into Microbial Genomics and Hydrocarbon Bioremediation Response in Marine Ecosystems

By Shannon Weiman, Samantha B. Joye, Joel E. Kostka, Kenneth M. Halanych, and Rita R. Colwell



Light microscope image (10×) of oil droplets (large round shapes) with bacteria visible inside and outside of the oil. A pure culture of "*Candidatus* Macondimonas diazotrophica," a novel, nitrogen-fixing crude oil degrader taxon, was recovered from Florida beach sands contaminated with Macondo oil from the Deepwater Horizon discharge. *Image credit: Smruthi Karthikeyan, Georgia Institute of Technology*

ABSTRACT. The Deepwater Horizon oil spill represents one of the most damaging environmental catastrophes of our generation. It contaminated vast areas of the open ocean, the deep sea, and the shoreline of the Gulf region and disrupted its ecosystems, with both residual and long-term impacts. At the core of all of these ecosystems are microbial communities that perform essential biogeochemical processes and ecosystem services such as carbon and nutrient cycling. Despite their importance, relatively little was known about marine microbes that degrade hydrocarbons in the Gulf of Mexico prior to the Deepwater Horizon spill, nor the effect of hydrocarbons on the microbiology of the Gulf region. Research carried out through the Gulf of Mexico Research Initiative (GoMRI) revealed cooperative microbial communities operating at the heart of bioremediation services with highly adaptive and complex dynamics. In addition, these efforts established new methods for assessing and monitoring ecosystem health, whereby microbial population genetics can serve as indicators of biogeochemical disruptions and/or restoration status in marine and coastal environments. Although much research is still needed to fully understand and engage microbially mediated bioremediation services, GoMRI constructed a strong foundation of methods, discoveries, and overarching principles to build upon. These insights and tools will help scientists better prepare for, and respond to, future environmental catastrophes, from oil tanker spills to long-term disruptions of climate change.

INTRODUCTION

One of the most damaging environmental catastrophes of our generation, the Deepwater Horizon (DWH) oil spill discharged 4.9 million barrels of oil and 250,000 metric tonnes of natural gas into the Gulf of Mexico and contaminated vast areas of the open ocean, the deep sea, and the shoreline. Its disruption of ecosystems carries residual and long-lasting impacts.

At the core of all ecosystems are microbial communities that constitute the foundation for all life by performing essential services such as carbon and nutrient cycling, as well as other core biogeochemical processes. Microbes are Earth's first responders, and by rapidly reacting and adapting to changing conditions, they restore balance and stability to the entire ecosystem. In the context of oil spills, microbes serve as emergency cleanup crews by feeding on hydrocarbons and contributing other fundamental remediation services.

Despite their importance, relatively little was known about hydrocarbon-degrading marine microbes resident in the Gulf of Mexico prior to the DWH spill or about the effects of hydrocarbons on the microbiology of the Gulf region. The Gulf of Mexico Research Initiative (GoMRI) was established to provide resources for advancing understanding of marine hydrocarbon microbiology among other Gulf biological, physical, and chemical components. The microbiology research included development and application of genomic and bioinformatics tools that enabled scientists to examine hydrocarbon-degrading microbes in the context of complex microbial communities and in unprecedented detail. With an array of transformational "omics" tools, scientists gained valuable insight into how microbes respond to hydrocarbon infusions and restore ecosystem health. This research discovered novel species, genes, metabolic pathways, and community dynamics that are instrumental to hydrocarbon degradation and related ecosystem functions. In combination, the findings revealed an extensive and intricate natural capacity of microbes in the Gulf of Mexico to catalyze bioremediation of petroleum hydrocarbons. This new information will guide future mitigation and restoration strategies to harness the natural bioremediation capabilities of microorganisms without further disturbing sensitive ecosystems.

Broadly, the GoMRI researchers have provided an outline of core ecological and evolutionary principles regarding microbial response and ecosystem functions that is widely translatable to other systems. Lessons learned from GoMRI research form a foundation for understanding how microbes in various ecosystems around the globe respond to diverse environmental disturbances. From the Arctic to the equator and the deep sea to coastal shores, these principles apply to describing how microbes maintain and restore ecosystem balance. These insights will help scientists better understand and prepare for future catastrophes, from a tanker spill to the long-term disruptions of climate change.

In summary, the research carried out by GoMRI investigators led to new methods for monitoring and assessing ecosystem health using microbial populations as ecosystem indicators in marine and coastal environments. Scientists can now deploy omics tools to take the pulses of microbial communities, identify disturbances, and guide mitigation strategies—notably at early stages before widespread damage occurs. Although much work is still needed to fully understand and engage microbially mediated biogeochemical processes that underpin ocean systems and their resilience, GoMRI research has prepared future generations to better protect and restore invaluable habitats by guiding disaster preparedness and response in the face of diverse environmental stressors and natural disasters around the globe.

OMICS TECHNOLOGIES ENABLE NEW BIOGEOCHEMICAL DISCOVERIES

Discovery of New Oil-Degrading Microbial Species, Genes, and Enzymes

A powerful toolbox of omics technologies and bioinformatic methods, including genomics, transcriptomics, proteomics, metabolomics, and metagenomics, is now available that allows scientists to probe the structures and functions of microbial communities that form the foundation of marine ecosystems (Grossart et al., 2020). These technologies provide researchers with the tools to comprehensively examine microbial dynamics in real-world situations (Mason et al., 2014a,b; Rodriguez-R et al., 2015). The advanced techniques and bioinformatics methods used generated discoveries and impacts far beyond what was previously thought possible (Karthikeyan et al., 2019).

GoMRI researchers discovered many new microbial taxa that thrive in oil-contaminated marine environments, along with novel genes and metabolic pathways they use for hydrocarbon degradation (see image on opening page of this article; Hazen et al., 2010; Kostka et al., 2011; Mason et al., 2014a; Crespo-Medina et al., 2014; Rodriguez-R et al., 2015; Kleindienst et al., 2015a; Yang et al., 2016; Karthikeyan et al., 2019). In addition, major known classes of microbes, for example, *Bacteroidetes*, were found to harbor a previously unrecognized potential for hydrocarbon biodegradation (Liu and Liu, 2013). However, the many major players and ecotypes discovered represent only a fraction of all the microbes involved in hydrocarbon degradation (Gutierrez et al., 2018).

Oil-Degrading Microbial Collaboration and Community Dynamics

Oil-degrading microbes are ubiquitous in marine and estuarine environments around the world, but their abundance is low when oil is absent. As part of the "rare biosphere," they harbor metabolic potential of ecological significance; they act as first responders in the event of an oil spill, providing critical ecosystem cleanup and stabilization functions that impact the fate and environmental distribution of hydrocarbons.

When oil spills occur, microorganisms sense and respond to the oil, using innate mobility to pursue oil via flagella-based motility and chemotaxis. They are stimulated to express hydrocarbon degradation genes that enable metabolism of various hydrocarbon compounds as energy sources. These hydrocarbon utilizers reproduce rapidly in the presence of oil to dominate the microbial ecosystem in contaminated waters and sediments, creating a microbial bloom (Kostka et al., 2011; Doyle et al., 2018, 2020; Karthikeyan et al., 2019). Many oil-degrading microbes possess multiple pathways for hydrocarbon degradation, and which metabolic pathway is induced may depend on environmental conditions and type of exposure (Karthikeyan et al., 2020a).

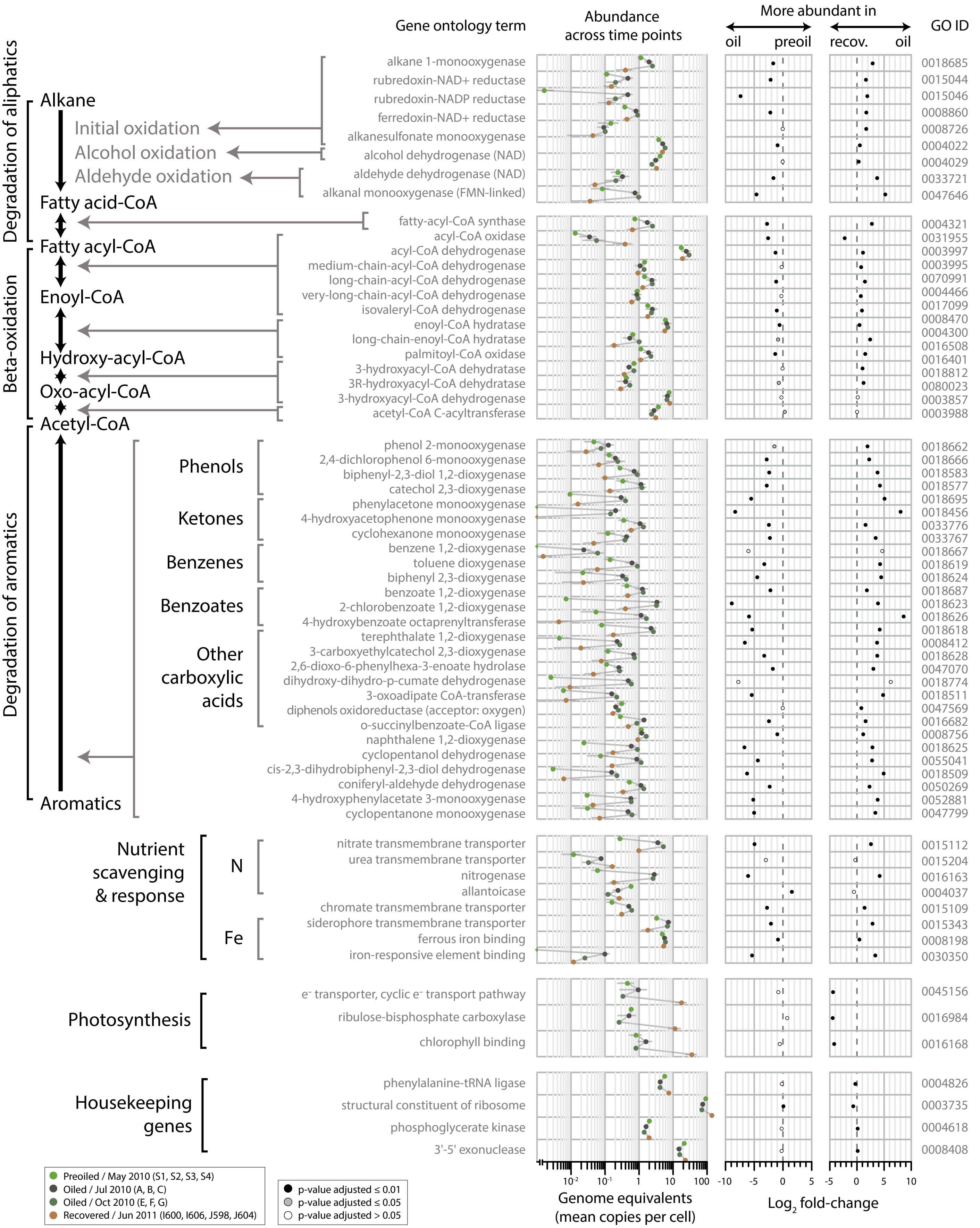
Microbes often exhibit cooperative metabolism by partitioning metabolic pathways among community members (Zengler and Zaramela, 2018). These microbial partnerships or collaborations are critical to microbial community functions and processes, including hydrocarbon degradation (Joye et al., 2016). Microbes can also create new catabolic pathways by shuffling hydrocarbon degradation genes between and among community members via lateral gene transfer, generating novel combinations of enzymes and metabolic capabilities in new hosts.

GoMRI research led to the discovery of metabolic partnerships for oil degradation. Metagenomic analysis revealed that genes within a single metabolic pathway may be distributed throughout the community, rather than contained within a single microbial species or strain. In some cases, different bacterial species were found to specialize in specific metabolic steps, but because they shuttled metabolites among species, collaborative networks were created that together completed the oil degradation process. In other cases, researchers determined that certain species specialize in breaking down the byproducts that are generated by other species. Together, these microbial networks can accomplish far more, with greater efficiency, than any single species could. Taking such a holistic approach, the research done by the GoMRI scientists has illuminated collective metabolic pathways and ecosystem functions that would have been overlooked by examining only individual species (Mason et al., 2012; Doyle et al., 2020).

In short order, the DWH spill caused major shifts in microbial ecosystem structure and function. Rare biosphere species capable of degrading hydrocarbons rapidly outgrew neighbors, ultimately accounting for up to 90% of the community (Kleindienst et al., 2015a; Karthikeyan et al., 2019, 2020a). At the same time, microbes that typically dominate healthy environmental systems, such as ammonia oxidizers and other autotrophs and heterotrophs, declined in relative abundance. Coastal nitrifier populations in offshore pelagic waters underwent alteration in species composition for at least a year, returning to normal only after the oil had dissipated. (Newell et al., 2014; Huettel et al., 2018)

Community composition shifted over time as hydrocarbon oxidizing bacterial blooms consumed available hydrocarbons, and then declined, being replaced by microbial species capable of degrading the residual metabolic byproducts (Figure 1; Kostka et al., 2011; Rodriguez-R et al., 2015; Kamalanathan et al., 2020). Such microbial succession patterns have

FIGURE 1 (NEXT PAGE). Microbial community functional shifts in coastal sediments in response to oil from the Deepwater Horizon discharge. Genes coding for selected molecular functions related to hydrocarbon degradation, nutrient scavenging and response, photosynthesis, and housekeeping genes are listed (left), with mean genome equivalents per group of samples (middle), and log2 of pre-oil/oiled and oiled/recovered (recov.) fold changes (right). Gene abundance was assessed as the average genome equivalents (mean copies per bacterial cell) at each sampling period. The log2 fold change was estimated as the log2 of the ratio of normalized counts between pre-oiled samples (S1 to S4) and oiled samples (A to G) and between oiled samples and recovered samples (I600, I606, J598, and J604). P values were estimated using a negative binomial test. Interesting patterns were the succession of genes related to easily degradable, light-hydrocarbon fractions, followed by genes specializing in polycyclic aromatic hydrocarbons (PAHs) and complex aromatics, and an increase in nitrogen fixation genes that denote nitrogen limitation for the microbial communities during crude oil biodegradation. CoA = coenzyme A. *Figure from Rodriguez-R et al. (2015)*


Gene ontology term
Abundance across time points
More abundant in
oil
preoil
recov.
oil
GO ID
Degradation of aliphatics
Alkane
Initial oxidation
Alcohol oxidation
Aldehyde oxidation
Fatty acid-CoA
Fatty acyl-CoA
Beta-oxidation
Enoyl-CoA
Hydroxy-acyl-CoA
Oxo-acyl-CoA
Acetyl-CoA
Degradation of aromatics
Aromatics
Phenols
Ketones
Benzenes
Benzoates
Other carboxylic acids
Nutrient scavenging & response
N
Fe
Photosynthesis
Housekeeping genes
alkane 1-monooxygenase 0018685
rubredoxin-NAD+ reductase 0015044
rubredoxin-NADP reductase 0015046
ferredoxin-NAD+ reductase 0008860
alkanesulfonate monooxygenase 0008726
alcohol dehydrogenase (NAD) 0004022
alcohol dehydrogenase (NAD) 0004029
aldehyde dehydrogenase (NAD) 0033721
alkanal monooxygenase (FMN-linked) 0047646
fatty-acyl-CoA synthase 0004321
acyl-CoA oxidase 0031955
acyl-CoA dehydrogenase 0003997
medium-chain-acyl-CoA dehydrogenase 0003995
long-chain-acyl-CoA dehydrogenase 0070991
very-long-chain-acyl-CoA dehydrogenase 0004466
isovaleryl-CoA dehydrogenase 0017099
enoyl-CoA hydratase 0008470
long-chain-enoyl-CoA hydratase 0004300
palmitoyl-CoA oxidase 0016508
3-hydroxyacyl-CoA dehydratase 0016401
3R-hydroxyacyl-CoA dehydratase 0018812
3-hydroxyacyl-CoA dehydrogenase 0080023
acetyl-CoA C-acyltransferase 0003857
0003988
phenol 2-monooxygenase 0018662
2,4-dichlorophenol 6-monooxygenase 0018666
biphenyl-2,3-diol 1,2-dioxygenase 0018583
catechol 2,3-dioxygenase 0018577
phenylacetone monooxygenase 0018695
4-hydroxyacetophenone monooxygenase 0018456
cyclohexanone monooxygenase 0033776
benzene 1,2-dioxygenase 0033767
toluene dioxygenase 0018667
biphenyl 2,3-dioxygenase 0018619
benzoate 1,2-dioxygenase 0018624
2-chlorobenzoate 1,2-dioxygenase 0018687
4-hydroxybenzoate octaprenyltransferase 0018623
terephthalate 1,2-dioxygenase 0018626
3-carboxyethylcatechol 2,3-dioxygenase 0018618
2,6-dioxo-6-phenylhexa-3-enoate hydrolase 0008412
dihydroxy-dihydro-p-cumate dehydrogenase 0018628
3-oxoadipate CoA-transferase 0047070
diphenols oxidoreductase (acceptor: oxygen) 0018774
o-succinylbenzoate-CoA ligase 0018511
naphthalene 1,2-dioxygenase 0047569
cyclopentanol dehydrogenase 0016682
cis-2,3-dihydrobiphenyl-2,3-diol dehydrogenase 0008756
coniferyl-aldehyde dehydrogenase 0018625
4-hydroxyphenylacetate 3-monooxygenase 0055041
cyclopentanone monooxygenase 0018509
0050269
0052881
0047799
nitrate transmembrane transporter 0015112
urea transmembrane transporter 0015204
nitrogenase 0016163
allantoicase 0004037
chromate transmembrane transporter 0015109
siderophore transmembrane transporter 0015343
ferrous iron binding 0008198
iron-responsive element binding 0030350
e⁻ transporter, cyclic e⁻ transport pathway 0045156
ribulose-bisphosphate carboxylase 0016984
chlorophyll binding 0016168
phenylalanine-tRNA ligase 0004826
structural constituent of ribosome 0003735
phosphoglycerate kinase 0004618
3'-5' exonuclease 0008408
10⁻²
10⁻¹
1
10
100
Genome equivalents (mean copies per cell)
-10
-5
0
5
-5
0
5
10
Log₂ fold-change
Preoiled / May 2010 (S1, S2, S3, S4)
Oiled / Jul 2010 (A, B, C)
Oiled / Oct 2010 (E, F, G)
Recovered / Jun 2011 (I600, I606, J598, J604)
p-value adjusted ≤ 0.01
p-value adjusted ≤ 0.05
p-value adjusted > 0.05

been documented across many different ecosystems, each with unique species and dynamics, driven by abundance of different hydrocarbon fractions and related environmental factors and at different time points. Thus, conclusions can be drawn from integrating data across time and localities but must be contextualized when making broader observations (Crespo-Medina et al., 2014).

In the deep-sea plume, methane, and potentially propane, butane, and ethane, fueled the early microbial response (Valentine et al., 2010; Joye et al., 2011; Crespo-Medina et al., 2014). Methane was a major driver in the DWH spill, spawning the emergence of *Methylomonas* species with methane oxidation capabilities (Figure 2; Crespo-Medina et al., 2014). Although Archaea are known generally to play important roles in anaerobic methane oxidation and anaerobic hydrocarbon (oil) degradation, they were not major players in pelagic or benthic oil or gas degradation during DWH. Immediately after the spill, when *n*-alkanes and cycloalkanes were more abundant, *Oceanospirillaceae* and *Pseudomonas* spp. were dominant (Figure 3; Hazen et al., 2010). These species were later supplanted mainly by *Colwellia* spp. and, to a lesser degree, *Cycloclasticus* and *Pseudoalteromonas* spp., which peaked when linear and simple aromatic hydrocarbons were abundant (Dubinsky et al., 2013; Kleindienst et al., 2015a). Employing metagenomics, scientists confirmed that the different hydrocarbon degradation genes and pathways present at different time points corresponded with abundances of different substrates within the plume (Mason et al., 2012; Redmond and Valentine, 2012).

Meanwhile, in beach sands, succession of microbial populations also paralleled the chemical evolution of petroleum hydrocarbons (Rodriguez-R et al., 2015). Early responders were mostly *Gammaproteobacteria* (*Alcanivorax* and *Marinobacter* spp.), microbes known to degrade aliphatic hydrocarbons, and

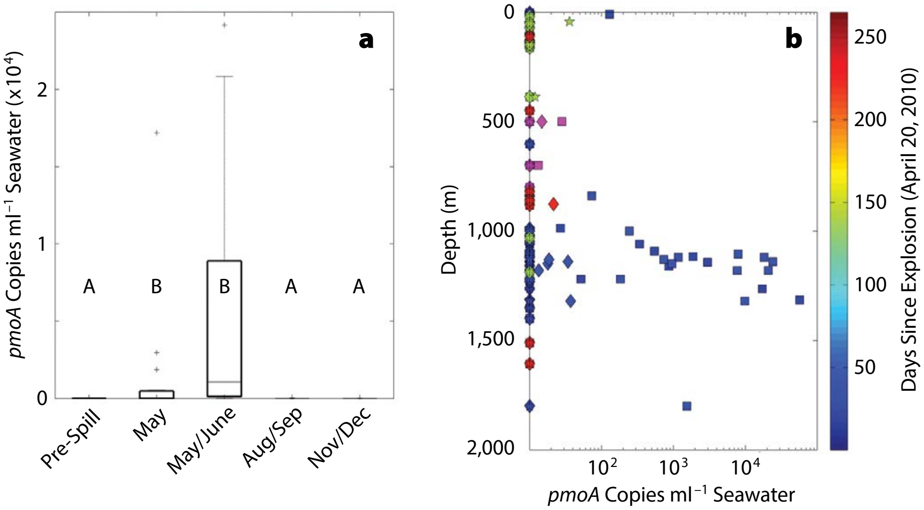


FIGURE 2. Abundance of *pmoA* genes following the Deepwater Horizon discharge. (a) Abundance of methanotrophic bacterial *pmoA* genes. Data are binned by time period. (b) Abundance of *pmoA* gene copies over time (pre-spill samples are magenta). Stars = OPU1. Diamonds = OPU3. Squares = New phenotype. Data in the two time periods marked with asterisks in panel (a) are different from those collected at other times, with a statistical significance of a P value of <0.05. Plus signs denote extreme data outliers. *Figure from Crespo-Medina et al. (2014)*

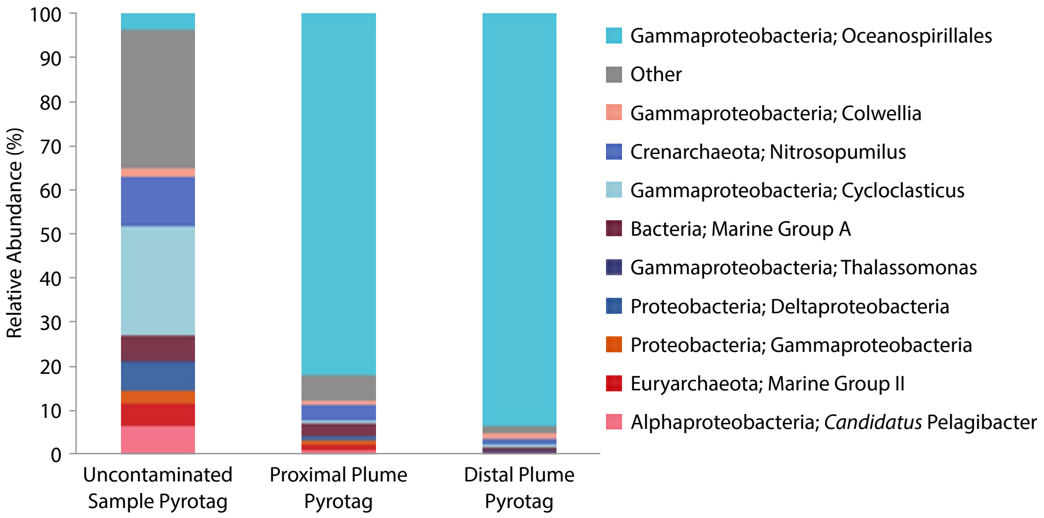


FIGURE 3. Microbial community structure and function change drastically in response to hydrocarbons. Community structure, function, and succession patterns varied depending on location and time of sampling. *Figure modified from Mason et al. (2012)*

their bloom coincided with a drastic decline in community diversity (Kostka et al., 2011). These were replaced after three months by *Alphaproteobacteria* (*Hyphomonas* and *Parvibaculum* spp.), capable of aromatic hydrocarbon decomposition. This shift coincided with the disappearance of alkanes and persistence of aromatics in field samples (Huettel et al., 2018). Nearly all of the oil on Pensacola Beach was degraded after one year, and microbial communities returned to a state that resembled the pre-oil condition, with nearly all known hydrocarbon degraders and genes coding for degradation functions exhibiting only low or undetectable levels (Rodriguez-R et al., 2015). However, significant differences were observed between the pre-oiled and recovered communities. Taxonomic diversity remained elevated in recovered communities, above that of the pre-oiled community, while functional diversity was lower in the recovered compared to the pre-oiled. Such differences could be due to unrecognized long-term effects of disturbance, such as the emergence of new taxa, and stochastic environmental events such as changes in nutrient or carbon input (Kostka et al., 2020). This return to a "baseline" state remains an open question that is actively being pursued as a legacy DWH issue.

In salt marshes, the microbial diversity of aerobic and anaerobic sediments decreased, favoring microbes capable of degrading alkanes and aromatics as weathered oil and residues accumulated (Atlas et al., 2015). In anoxic sediments, sulfate-reducing bacteria, for example, *Desulfococcus* spp., increased in parallel with oil contamination. Interestingly, marsh sediments maintained a high percentage of hydrocarbon degraders whose growth was driven periodically by storm surges that redistributed weathered oil from the anoxic sediment. These lingering shifts in microbial community diversity and function have the potential to impact the overall marsh ecosystem, particularly marsh vegetation and fishery health.

In anoxic environments (e.g., the seafloor and salt marsh sediments), biodegradation occurs much more slowly so that most of the oil persists. (Liu et al., 2012; Chanton et al., 2015). Yet, seafloor sediments near the DWH wellhead showed some enrichment, notably in anaerobic respiration and anaerobic hydrocarbon degradation genes and associated species such as *Deltaproteobacteria* (Mason et al., 2014b). Novel anaerobic polycyclic aromatic hydrocarbon (PAH) degradation pathways were also discovered (Shin et al., 2019b), potentially mediated by yet undiscovered sulfate-reducing bacteria along with their fermentative syntrophic partners. Hexadecane-degrading microbes, closely related to the *Desulfobacteraceae*, and phenanthrene-degrading microbes related to *Desulfatiglans* spp. were also discovered.

Biogeochemical Processes

Microbes play fundamental roles in basic biogeochemical cycles of marine and coastal ecosystems, including interconnected carbon, nitrogen, and phosphorus cycling—and also in hydrocarbon degradation. Omics analyses of these pathways revealed how these ecosystem functions were impacted by the DWH spill.

Nitrogen Fixation

Like all microbes, oil degraders require substantial amounts of nitrogen for growth, but nitrogen is present only in limited amounts in marine environments. Although nitrogen fertilizers have been added to accelerate microbial growth and biodegradation following some oil spills, such as the *Exxon Valdez* spill in Prince William Sound, Alaska (Pritchard et al., 1992), microbes can generate their own fixed nitrogen through biochemical fixation of dinitrogen gas (Foght, 2010). Nitrogen fixation pathways are well known in soil microbes that support crop growth and in oceanic microbes such as *Trichodesmium* cyanobacteria (Bergman et al., 2013), but nitrogen fixation by oil degraders in response to raw oil exposure is a new discovery (Quigg et al., 2016).

Researchers studying the DWH spill discovered that nitrogen fixation is a key ecosystem function of microbial communities in response to oil (Rodriguez-R et al., 2015; Fernández-Carrera et al., 2016). In the offshore and coastal ocean ecosystems where nitrogen is limiting, nitrogen fixation function increases in response to oil contamination (Scott et al., 2014; Rodriguez-R et al., 2015; Gaby et al., 2018; Shin et al., 2019a), and then dissipates once the hydrocarbons are significantly reduced (Shin et al., 2019a).

Fixing nitrogen provides a strong selective advantage for those species capable of fixation in the presence of oil, allowing them to utilize hydrocarbon energy sources without restriction. Although species with such dual capabilities are uncommon under pristine conditions, they thrive in oil-contaminated environments. This explains the niche dominance of keystone oil-degrading organisms such as *Candidatus* Macondimonas diazotrophica (Karthikeyan et al., 2019).

Microbial genes involved in carbon, nitrogen, phosphorus, sulfur, and iron cycling were also enriched in oil-contaminated ecosystems (for additional information, see Mason et al., 2012; Rodriguez-R et al., 2015). Understanding these biogeochemical interdependencies could inform fertilization strategies to enhance natural biodegradation.

Marine Oil Snow (MOS)

Phytoplankton and hydrocarbon-degrading microbes that assemble around oil droplets in large communities produce transparent exopolymers (TEPs) that entrap oil. These dense macroscopic assemblages of carbohydrates and biomass behave like "snow" as they sink to the seafloor. Marine oil snow (MOS) effectively transfers hydrocarbons from the water column to the seafloor as sediment (Vonk et al., 2015). Although MOS formation was observed during previous oil spills, including the 1977 Baltic Sea *Tsesis* spill (Johansson et al., 1980) and the 1979 Ixtoc I spill in the southern Gulf of Mexico (Patton et al., 1981), it was first thoroughly studied after the DWH spill, which triggered MOS formation in unprecedented quantities (Joye et al., 2014).

Oil degradation and deposition that takes places in MOS impacts the fate of spilled oil (Figure 4). MOS particles are hot spots for oil degradation, exhibiting high levels of lipase activity (Gutierrez et al., 2018) and distinct microbial communities that specialize in breaking down oil. In particular, *Colwellia*, *Marinobacter* spp., and *Alteromonas* spp. are prevalent because they have the unique capacity to degrade oil relatively rapidly in cold, deep marine environments (Gutierrez et al., 2018).

MOS particles sink quickly, reaching the seafloor within ~10 days (Passow, 2016). MOS formation is triggered by water column elements that include detritus, fecal matter, minerals, and chemical dispersants, as well as such living cells as diatoms, microalgae, and bacteria, and the polymers they secrete.

The question remains, however, whether MOS is good or bad as an oil spill bioremediation mechanism. MOS could have negative consequences for the water column as well as the seafloor where it is ultimately deposited. These larger particles can trap and remove planktonic animals from the water column. MOS particles can also effectively seal off the sediment surface, potentially suffocating fauna, while addition of organic content to the benthos could stimulate respiration, with negative consequences for filter-feeding fauna. Understanding the consequences of MOS in the water column and the benthos requires further investigation.

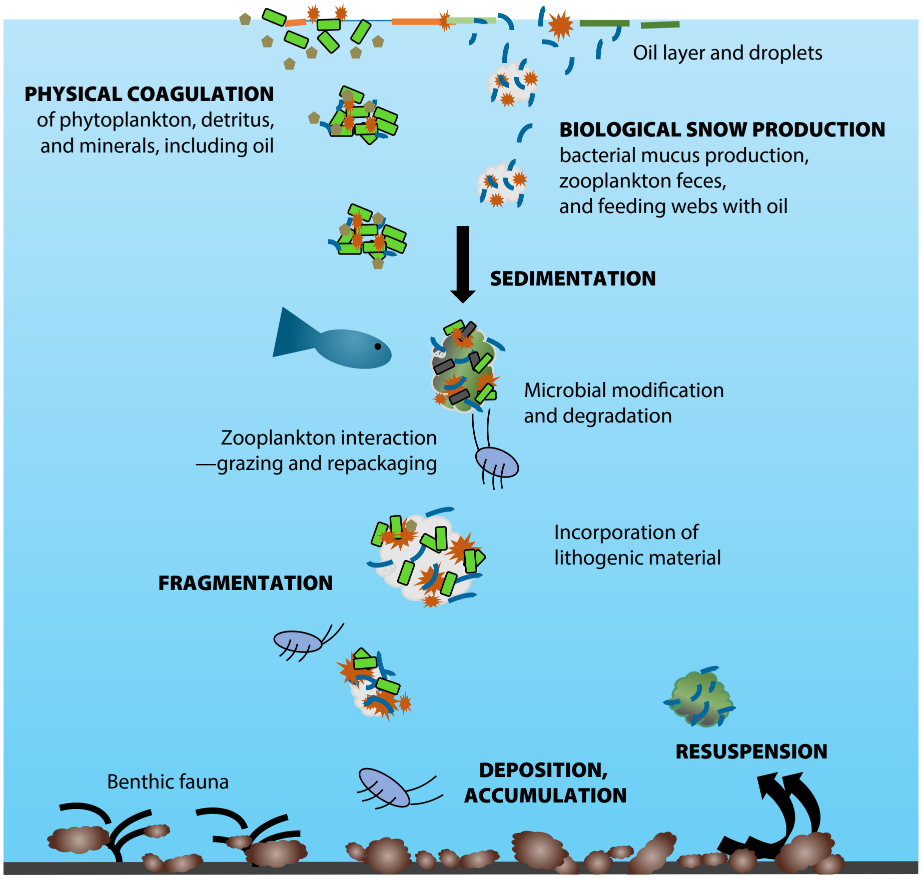


FIGURE 4. The formation, sinking and loss of marine oil snow, which consists of exudates, biotic, and abiotic particles. Marine oil snow is a common food source that removes hydrocarbons from the water column as it sinks to the seafloor. *Image credit: Uta Passow, Memorial University of Newfoundland*

SIGNIFICANCE AND APPLICATIONS OF GoMRI RESEARCH

Ultimately, scientific and technological advances derived from GoMRI research provide a foundation for new research that will improve strategies for predicting and mitigating ecosystem perturbations and have impacts across broad scientific disciplines and far beyond the Gulf of Mexico.

Broad Lessons in Microbial Hydrocarbon Response

As the examples cited above show, GoMRI research has revealed ecological, evolutionary, and biogeochemical principles that underlie microbial community composition and response to disturbance across diverse environments and contexts.

The hydrocarbon-degrading microbes and genes that code for hydrocarbon degradation and utilization discovered by GoMRI scientists are present in oil-contaminated waters and coastal regions around the world, and thus are available everywhere as first responders. However, while oil-degrading microbes are globally distributed, regional variables can significantly influence microbial community composition and metabolic capabilities prior to and during a spill.

Physical, chemical, and biological environmental conditions, including temperature, salinity, hydrostatic pressure, oxygen supply, nutrient availability (particularly N and P), water currents and stratification, MOS presence, and sea ice can influence microbial species composition and rates of hydrocarbon degradation, activity, and dispersal from the deep sea to intertidal marsh ecosystems (Head et al., 2006; Edwards et al., 2011; Redmond and Valentine, 2012; Rodriguez-R et al., 2015; Fernández-Carrera et al., 2016; Huettel et al., 2018; Sun and Kostka, 2019). Furthermore, the type of oil spilled, how it weathers, and the extent of sunlight exposure can alter the chemical composition of oil and/or induce MOS formation, all of which act to drive different microbial responses

(Bacosa et al., 2015; Shin et al., 2019a). The DWH spill provided a unique opportunity to study many of these environmental factors because it affected a wide variety of open-water and coastal ecosystems with large variations in physical and chemical conditions.

Microbial communities in the Gulf of Mexico are considered to have been uniquely primed for rapid response to oil spills due to the prevalence of natural hydrocarbon seeps and drilling operations that constantly discharge oil into the Gulf. The background levels of hydrocarbons sustain a higher proportion of oil-degrading microbes that are also typical of many other regions with natural seepage and/or hydrothermal venting, for example, the Gulf of California, the Bay of Bengal, the Black Sea, and the Arctic Ocean. In addition, shipping lanes in open waters and ports are primed for oil response because of long-term industrial and human activities. In some cases, hydrocarbons produced by phytoplankton or cyanobacteria can prime microbes for hydrocarbon degradation through low level exposure (Guiterrez et al., 2014; Love et al., 2021).

Oil spills are particularly threatening to Arctic regions where climate change is already wreaking havoc. It is therefore critical to understand the environmental risks and develop mitigation strategies before a major spill occurs in these delicate ecosystems. Interestingly, GoMRI research has proven pertinent to this region; preliminary results of these studies reveal microbial responses and community succession similar to those reported for the Arctic marine environment (Sun and Kostka, 2019). However, sea ice and extremely low temperatures can alter degradation properties of both oil and microbial communities, which may significantly impact biodegradation and need to be considered. The Canadian government is actively engaged with the GoMRI community to build on GoMRI discoveries, methodology, and technology in efforts to prepare for a spill in the Canadian Arctic.

Informing Oil Spill Response

GoMRI research provides a foundation of knowledge and tools that will enable scientists to play key roles in guiding future oil spill response and mitigation planning using data-driven strategies. Evidence-based interventions informed by evaluating ecosystem responses and recovery status will improve the success of future emergency responses by replacing previous trial-and-error approaches.

Specifically, by examining the presence of oil-degrading species, genes, and biogeochemical pathways, scientists can assess the natural bioremediation potential of a community, providing insight into whether and how its metabolic capabilities can be augmented. One example is addition of nitrogen fertilizers, which has been proposed by GoMRI and other investigators to accelerate microbial bioremediation (Edwards et al., 2011; Kleindienst et al., 2015b; Fernández-Carrera et al., 2016). Additionally, enhancement of microbes that produce exopolymeric substances, which emulsify oil and act like dispersants, could preclude addition of man-made dispersants such as Corexit (Ziervogel et al., 2019). Strategies to promote growth of native microbial species or utilization of genetically engineered microbes for natural surfactant production would provide responders with biodegradable, nontoxic surfactant alternatives. Natural microbial surfactants may also prove effective as nontoxic dispersants with fewer environmental concerns (Bacosa et al., 2018).

Mounting an effective microbial oil spill response will require analysis of microbial communities not only during a spill but also before and after. Documenting the "normal" or "baseline" state of an ecosystem prior to a crisis is essential for planning intelligent mitigation strategies aimed at restoring native microbial communities and their ecosystem functions (Joye, 2015). In addition, it can indicate whether an ecosystem is compromised by previous environmental stress and therefore in need of additional protections, for example, limiting oil drilling or tanker traffic (Sun and Kostka, 2019). After a spill, monitoring mitigation and restoration efforts should be undertaken to assess whether response actions work as predicted or if alternative plans should be implemented.

In summary, with application of omics tools, scientists can assist first responders in determining potential environmental impacts of a spill, as well as actions to be taken, on what time frames, and in which locations to minimize risks and damage.

Assessing Ecosystem Health in the Context of Environmental Disturbance

By developing basic principles of microbial ecosystem function and response along with techniques to study them, GoMRI scientists have provided a basis for understanding diverse marine and terrestrial ecosystems in order to address natural and man-made disasters, from chemical spills to algal blooms, and even gradual and long-term stressors, including climate change. Understanding microbial ecosystem dynamics and function in response to climate perturbations will be essential for predicting long-term impacts and for preparing mitigation plans.

Documentation of indigenous microbial communities in diverse marine and terrestrial ecosystems around the world is necessary for assessing ecosystem changes and restoration goals in the context of any perturbation. Baseline metagenomic analyses require sampling over vast timescales to account for daily, monthly, and seasonal community variations, as well as interannual and even decadal shifts. Such studies are underway to catalogue Earth's microbiome (Gilbert et al., 2018). From deepwater benthic regions to coral reefs, beach sands, marshes, and associated terrestrial ecosystems (Magnuson, 1990, 1995), different ecosystems each have unique microbial baselines that require individual documentation so that significant or problematic changes can be detected and measured.

Microbial Indicators of Ecosystem Health and Disturbance

GoMRI researchers identified microbial indicators of ecosystem disturbance in the context of the DWH spill that will help scientists assess ecosystem health across various contexts.

Low microbial diversity can be a red flag, signaling ecosystem disruption and declining ocean health. A healthy microbial ecosystem is composed of a variety of species that provide diverse ecosystem functions and maintain system stability. Environmental disturbances such as the DWH spill disrupt the balance, favoring a limited number of species that is able to adapt to new conditions. These few species thrive over the others, often reflected in low overall species diversity. A community with low diversity may be more sensitive and less resilient to further disturbances.

The presence of a single species or genus in very high numbers indicates a recent ecosystem disruption, even if the original composition of the community is unknown. For example, during the DWH spill, rare species with hydrocarbon degradation potential and/or nitrogen fixation capabilities were poised to take advantage of new energy sources. Under novel conditions, these species outcompete their neighbors and can grow to one-third or more of the population.

The emergence of different and novel genes, metabolic pathways, and ecosystem functions within microbial communities reflects adaptation to environmental change. When microbes respond to environmental disturbance, organisms may express different genes and metabolic pathways as they adapt to new sources of energy (hydrocarbons), nutrients, physical/chemical limitations, and other factors in order to take on novel and adaptive ecosystem functions.

These genetic and metabolic indicators of ecosystem disruption can also provide critical clues as to how the environment has changed, and therefore how it might be restored.

THE FUTURE OF GENOMICS IN THE STUDY AND MANAGEMENT OF ECOSYSTEM HEALTH

In the future, scientists hope to identify microbial "biomarkers" of ocean health, as detectors of ecosystem disruption and risk predictors in the face of diverse threats, including man-made and natural disasters as well as climate change. For example, how might microbiologists help fisheries or oyster farms recover after an oil spill or hurricane? Similar to ways that medical biomarkers help doctors diagnose diseases and identify appropriate treatments, researchers could "take the pulse" of the ecosystem with microbial biomarkers to identify atypical functioning and direct strategies to correct these problems.

Biomarkers might be used in various ways to assess and support ecosystem health:

Predictive biomarkers. Disruptions in microbial communities can often be perceived before ecological consequences or impacts are apparent. Thus, microbes can serve as the "canary in the coal mine" to warn of impending consequences of a disturbance. For example, microbial community restructuring or functional changes might indicate a slow oil leak or gradual warming due to climate change. This can trigger early action to better prevent or mitigate potential damages from natural and man-made disasters in the ocean, as well as other ecosystems, by alerting scientists to changes before they are irreversible, and/or identifying areas that need extra protections.

Diagnostic biomarkers. The presence of specific indicator species and genes might be used to "diagnose" certain disturbances, which could indicate what has gone awry within an ecosystem. For example, overgrowth of a species and emergence of novel genes, metabolic pathways, and ecosystem function can all assist scientists in identifying biogeochemical disruptions.

Therapeutic biomarkers. Indicator species and genes might also point scientists and managers toward solutions by providing information about how an environment has changed and, therefore, how its ecosystem might be restored. Therefore, in addition to informing mitigation and restoration strategies, these indicators can help to identify action plans during a crisis event. For example, the emergence of a nitrogen-fixing species might indicate nitrogen as a limiting factor in bioremediation, suggesting that the addition of nitrogen fertilizers would accelerate recovery.

To assemble a complete picture of ecosystem health will require the use of multiple, diverse biomarkers, each of which will provide a piece of the puzzle. For example, genomic biomarkers may provide insight into hydrocarbon degradation, toxin accumulation, hypoxic conditions, or other environmental disturbances. Meanwhile, metatranscriptomics might reveal immediate adaptations, whereas meta-community restructuring suggests long-term consequences.

Ideally, such biomarkers will be able to inform scientists and first responders on site and in real time as an essential component of an environmental emergency response toolkit. This will require robust, portable (i.e., hand-held devices), cost-effective, and integrative analytic instruments, such as the small mobile DNA sequencers designed for the rigors of field research.

Predicting Environmental Impacts with Biomarkers and Models

Biomarkers can be paired with biogeochemical models to predict important outcomes, including when oil will be removed from a system, how long would it take for an ecosystem to recover, whether responders should intervene to speed ecosystem recovery, and other aspects of biogeochemical responses and timelines. Models can also reveal which factors may have the greatest impact on damage or recovery, enabling responders to tailor mitigation strategies rather than relying on one-size-fits-all approaches that may or may not work.

Biogeochemical models can help scientists answer questions, including:

- Should oil spills be seeded with microbes with hydrocarbon degradation capabilities? If so, which ones and in what quantity?
- Should dispersants and/or fertilizers be added? If so, in what quantity? How will such interventions impact ability of indigenous microbes to degrade oil?
- What environmental impact can be avoided with an intervention? What are potential unintended consequences of intervention?
- Will leveraging natural microbial processes be more successful than alternative approaches such as burning or vacuuming the oil?

> “Using the powerful and constantly evolving tools of genomics, GoMRI researchers discovered novel [microbial] genes, pathways, organisms, communities, and partnerships associated with oil decomposition and spill remediation.”

Current biogeochemical models are limited and, in general, unable to answer such complex questions. To achieve more realistic models will require significant advances in understanding physical, chemical, and biological processes and their interactions in the ocean, as well as active and effective collaborations among oceanographers, microbiologists, computational scientists, and many other disciplines.

The greatest hurdle in developing predictive biogeochemical models is translating omics data to metabolic functions. While metagenomics informs metabolic potential, it may not always reflect microbial activity. There are many novel microbial species, genes, and proteins to be discovered and identified, and their biogeochemical functions characterized, most probably with inferences from taxonomic and sequence similarities to reference species and their metabolic profiles. In reality, metabolic capabilities can differ dramatically from predicted activities and currently must be defined through cultivation, biochemical assays, or gene knockout experiments. Machine learning/artificial intelligence is likely to be of great value in overcoming this obstacle.

To better link omics data with functional rates of activity at the enzymatic and cellular levels will require new strategies, such as stable isotope probing (SIP) and biorthogonal noncanonical amino acid tagging (BONCAT). These tools track metabolic activity of individual microbes and consortia within their natural environments. They can assign specific paths to specific microbes, elucidate cross-feeding partnerships, and identify novel metabolic steps and pathways.

Facilitating Advances Through Open-Access Resources and Multidisciplinary Collaboration

The omics and environmental data sets collected by GoMRI investigators are accessible via the open-access platform https://data.gulfresearchinitiative.org/. In the event of a new spill or disaster, this resource can be mined to predict consequences and inform response.

Specifically, GoMRI researchers created the Genome Repository of Oil Systems (Karthikeyan et al., 2020b), a comprehensive, searchable database that documents microbial populations in natural oil ecosystems and oil spills, along with available underlying physicochemical data, geocoded via the geographic information system to reveal their distribution patterns. Provided as an independent project through the Microbial Genomes Atlas (MiGA) web server (http://microbial-genomes.org/), the repository contains over ~2,000 genomes, more than 95% of which represent novel taxa, though representation of cultured organisms from oil-contaminated and oil reservoir ecosystems in this database is limited. The database allows researchers to classify unknown genomes by reference to known genomes, thereby facilitating the predictive understanding of microbial taxa and activities that can control the fate of oil spills.

CONCLUSIONS

Microbiology and omics tools have proven instrumental in providing an understanding of the impacts of the Deepwater Horizon oil spill on marine and coastal ecosystems. The new omics-based technologies and strategies enabled a comprehensive investigation of Gulf microbial communities and their biogeochemical functions in unprecedented detail.

Using the powerful and constantly evolving tools of genomics, GoMRI researchers discovered novel genes, pathways, organisms, communities, and partnerships associated with oil decomposition and spill remediation. Key shifts in community structures that dictate essential ecosystem functions and bioremediation services were documented. Altogether, GoMRI studies have revealed new insights and core lessons about microbial community responses to environmental disturbances, as well as their roles in maintenance and restoration of ecosystem stability during and after an oil spill. The lessons learned inform a scientific understanding of how oil spills impact various ecosystems, from deep waters to beach sands to tidal marshes, and will allow improved prediction and mitigation of damage in the event of future spills.

RESOURCES

- http://www.taraoceans-dataportal.org/
- https://data.gulfresearchinitiative.org/
- http://www.mg-rast.org/
- http://enve-omics.ce.gatech.edu/

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AUTHORS

Shannon Weiman (sweiman@nasw.org) is a freelance science and biomedical writer/editor located in Boulder, CO, USA. **Samantha B. Joye** is Professor, Department of Marine Science, University of Georgia, Athens, GA, USA. **Joel E. Kostka** is Professor, School of Biology and Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA. **Kenneth M. Halanych** is Professor, Department of Biological Sciences, Auburn University, Auburn, AL, USA. **Rita R. Colwell** is Distinguished University Professor, University of Maryland, College Park, MD, USA.

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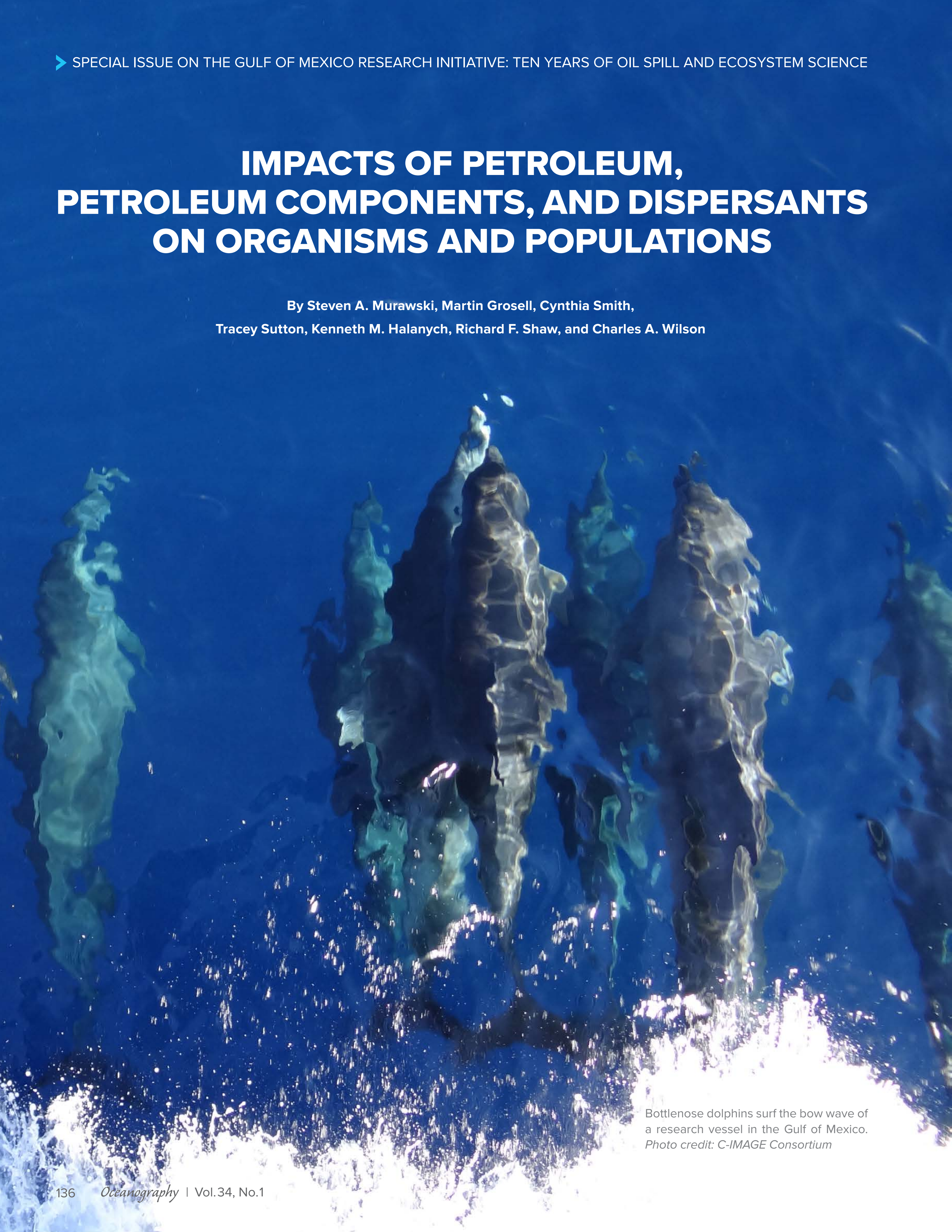
SPECIAL ISSUE ON THE GULF OF MEXICO RESEARCH INITIATIVE: TEN YEARS OF OIL SPILL AND ECOSYSTEM SCIENCE

IMPACTS OF PETROLEUM, PETROLEUM COMPONENTS, AND DISPERSANTS ON ORGANISMS AND POPULATIONS

By Steven A. Murawski, Martin Grosell, Cynthia Smith, Tracey Sutton, Kenneth M. Halanych, Richard F. Shaw, and Charles A. Wilson



Bottlenose dolphins surf the bow wave of a research vessel in the Gulf of Mexico. *Photo credit: C-IMAGE Consortium*

ABSTRACT. Following the Deepwater Horizon blowout, oil, degraded oil, oil mixed with dispersants, and management responses to the spill affected a variety of Gulf of Mexico organisms. This review provides examples of various documented impacts, common patterns, and trends across organisms and/or their environments, and discusses future implications as well as directions for future research. Organism effects are generally characterized as lethal and sublethal. Sublethal can be short term, long term, or permanent and multigenerational. We present individual examples of effects on behavioral response, olfaction, vision, cardiac function, and gene shift, based on research done in laboratories, mesocosm settings, and the field. Future research should emphasize collection and analysis of routine toxicological baselines and examine how and if molecular impacts cascade up to populations. This research will require development of rapid molecular tools and testing procedures to determine exposure compared to field-relevant exposure levels and to be able to extrapolate laboratory results to the field, especially given the mosaic of differing contaminant concentrations (below, at, or exceeding critical concentrations that result in lethal or sublethal effects) occurring in the environment. Recent chemical studies have identified a detectable suite of polycyclic aromatic hydrocarbon metabolites for which there are no toxicity data; further research is needed to determine their impacts on food webs.

INTRODUCTION

Approaches for assessing impacts of significant oil spills on the natural world, and oil spill research generally, lurch forward rapidly but unevenly in the wakes of infrequent large spills in a "punctuated equilibrium" of sorts. For example, in the decades following the 1989 *Exxon Valdez* spill, a new appreciation for the secondary effects of oil on predator-prey dynamics and the effects of both oil pollution and response measures on the integrity and productivity of affected habitats and populations emerged as a paradigm shift in oil spill science (Peterson et al., 2003). Of course, each large spill is idiosyncratic, and the mix of topical issues associated with each does not necessarily move the field forward in any predictable path. Likewise, because of the lack of sustained funding during long periods when large spills do not occur, agencies find it challenging to proactively fund science consistent with the matrix of emerging threats or to keep pace with innovations and trends in the oil and gas production industries (ICCOPR, 2015; Murawski et al., 2020). Such is the case with the Deepwater Horizon (DWH) oil spill in the Gulf of Mexico, the first and largest ultra-deepwater (≥1,500 m water depth) well blowout in global history (Lubchenco et al., 2012). While originating in the deep sea, spilled oil and oil dispersing chemicals from DWH eventually polluted ecosystems ranging from the meso- to the epipelagic water column; the deep-sea benthos; the continental shelves; and inshore habitats, including beaches, marshes, and estuaries (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016; Murawski et al., 2021). Impacts to marine and estuarine species and habitats resulted from direct exposure to fresh, weathered, and fresh and chemically dispersed oil, and indirectly from degraded habitats and as a result of response measures intended to mitigate spill effects.

A unique feature of the DWH spill was the significant involvement of the academic community both in response to the ongoing spill and especially in documenting and evaluating impacts to biota. This community of scientists was rarely involved in oil spill response prior to DWH except in narrowly prescribed contracting roles with response agencies. One consequence of the funding largesse available to independent scientists, through grants from the Gulf of Mexico Research Initiative (GoMRI, which spent $500 million) and other funders, has been to infuse this research with a broad array of advanced tools, technologies, and approaches originally developed for use in other fields, and to involve a science community not usually invested in oil spill applications (e.g., Murawski et al., 2018; Grosell et al., 2020; Kostka et al., 2020). This research has included, for example, the application of advanced genomic tools to quantify bacterial community change, as well as the application of a host of genomic, morphological, physiological, and immune system tools to determine how oil exposure affected organisms at the subcellular to organismal levels (Figure 1). Understanding toxicological effects and their implications for survival, growth, and reproduction permits an evaluation of changes in the overall fitness of populations (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016; Beyer et al., 2016; Grosell and Pasparakis, 2021). Definition of the cascade of effects from subcellular to population and ecosystem levels reflects an increasing appreciation for the modes of action of pollutants as they sequentially affect organs, body systems, and outcomes (Figure 1), leading to both lethal and sublethal endpoints.

Traditional assessments of environmental impacts of oil spills have often been based on evaluating concentrations of pollutants required to kill 50% of subject (and standardized) test animals in short-term laboratory-based studies to estimate lethal concentrations or other effective concentrations (i.e., LC_{50}/EC_{50}; Bejarano et al., 2014; Bejarano and Barron, 2014; Grosell et al., 2020; NASEM, 2020). These levels typically are then extrapolated to concentrations of pollutants in the environment to project population-level impacts of a particular spill (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016; Barron et al., 2020). During and subsequent to the DWH oil spill, considerable research was conducted to assess traditional biomarkers of biological endpoints (e.g., Mitchelmore et al., 2020) and to develop and apply suites of sublethal indicators of aquatic biota health in order to understand the induction of health effects involving immune responses, genomic changes, reproductive success, growth effects, and impairment of various organ systems in affected species (e.g., Whitehead et al., 2012; Sherwood et al., 2017; Grosell and Pasparakis, 2021; Rodgers et al., 2021). Rather than focusing only on direct mortality outcomes for individuals and populations, these studies have emphasized the importance of understanding mechanisms of induction and regulation of organism homeostasis in the presence of oil and dispersed oil at sublethal concentrations. Field-level research combined with controlled laboratory analyses revealed how organismal response mechanisms can be used to explain symptomology observed in areas and species affected by the spill (Deak, 2020; Raimondo et al., 2020). Additionally, longitudinal studies over the ensuing decade since DWH have documented changes in populations and communities of species potentially affected by the spill and by a host of simultaneous co-stressors (Schwing et al., 2020; Murawski et al., 2021b). Ascribing post-spill decadal changes in populations to oil spill impacts is challenging, but some obvious population and community changes point to the spill as a likely suspect.

Here, we highlight examples of exposure effects on behavioral responses, olfaction, cardiac function, disease progression, and other morphological and physiological consequences and findings from laboratory experiments and mesocosm settings and from field data. Further, we describe in general terms how various habitats affected by the DWH spill and species populations inhabiting them have fared, particularly emphasizing longitudinal monitoring of abundance and demography over the decade subsequent to the DWH spill, which is in itself unique for oil spill impact monitoring. Assessments of impacts of future oil spills will be guided by discoveries made as a consequence of a decade of post-DWH oil spill research funded by the Gulf of Mexico Research Initiative, the Natural Resource Damage Assessment Trustees, and the parties responsible for the DWH accident.

EVOLVING PERSPECTIVES FROM DWH-RELATED RESEARCH ON THE MEASUREMENT AND ASSESSMENT OF ECOTOXICOLOGICAL EFFECTS

Toxic effects of crude oil and derivative products on marine life have long been appreciated and assessed as significant negative consequences of oil spills

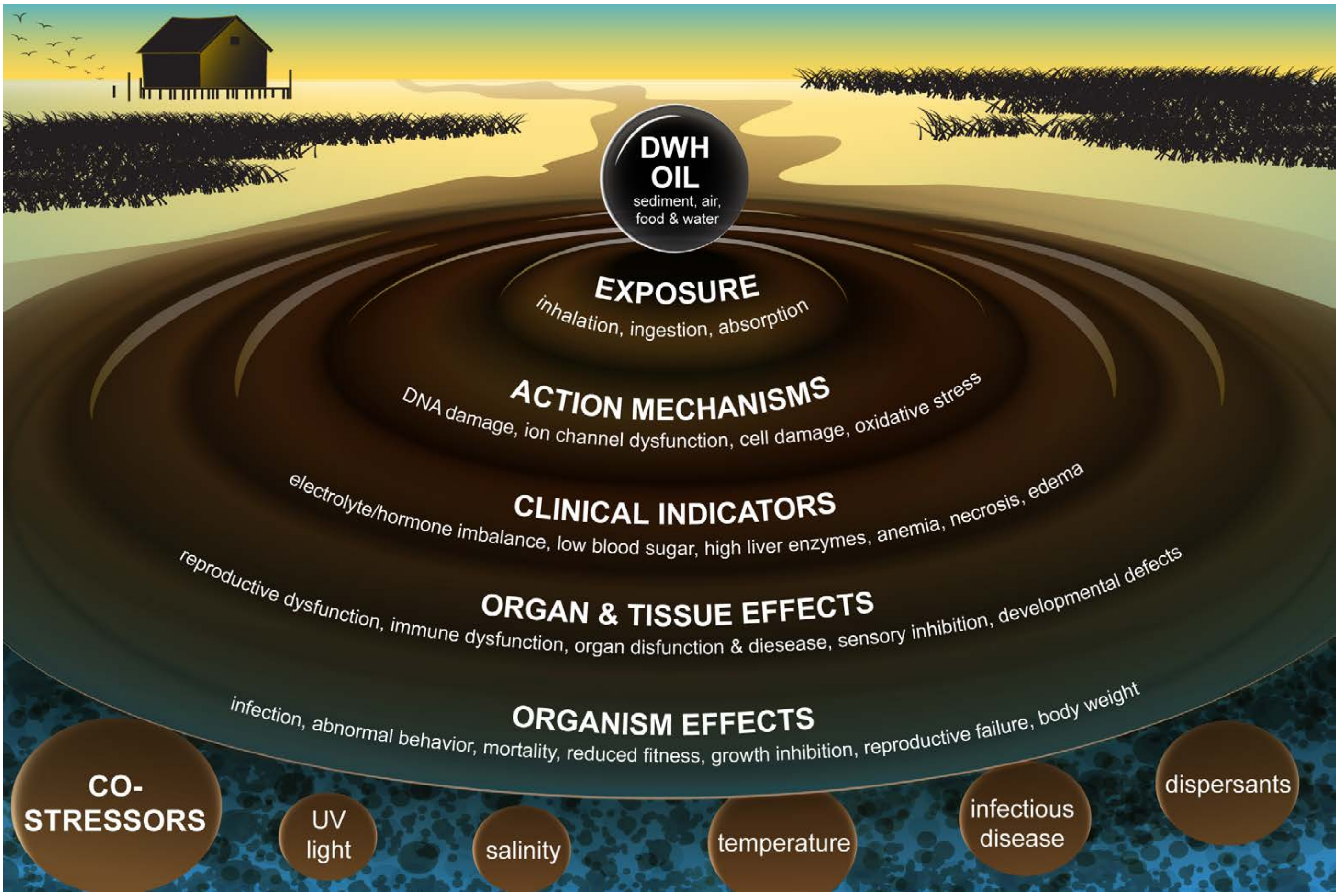


FIGURE 1. Toxicological effects on aquatic life of exposure to oil and dispersed oil. The successive rings define the routes of potential exposures and cascading series of symptomology leading to effects at the organism level, eventually leading to population and ecosystem level effects *Figure recrafted from a similar diagram in Deepwater Horizon Natural Resource Damage Trustees (2016)*

(NRC, 1985; Transportation Research Board and National Research Council, 2003; NASEM, 2020). While the fields of cellular biology and mutagenesis held promise for understanding the pathways of injury short of lethality (i.e., NRC, 1985), most studies of oil pollution up to the time of the *Torrey Canyon* tanker spill in 1967 were directed primarily to physicochemical aspects and associated analytical methods (see review in NRC, 1985). Toxicity studies were primarily conducted in highly artificial laboratory settings and focused on critical oil concentrations that induced lethality (Capuzzo, 1981; Boesch and Rabalais, 1987; Capuzzo et al., 1987). A number of pioneering studies developed techniques for assessing exposure of aquatic wildlife to oil constituents, and, in particular, toxic polycyclic aromatic hydrocarbons (PAHs). Working on chronic pollution effects in urban estuaries from the 1970s to the 1990s, Usha Varanasi and her colleagues at the Northwest Fisheries Science Center (NOAA) examined exposures of benthic organisms, including flatfishes, to PAHs and other toxic chemicals and determined the biochemical pathways that lead to liver cancers and symptoms of other diseases (e.g., Varanasi et al., 1979; 1987; Krahn et al., 1986; Collier and Varanasi, 1987; Stein et al., 1990). This era was also the subject of intensive oil-related toxicology research in Europe and elsewhere. Subsequent to *Torrey Canyon,* and particularly in response to the 1989 *Exxon Valdez* tanker spill (Rice et al., 1996), a variety of sublethal effects of exposure to oil and especially to PAHs were correlated with adverse effects on resource populations of salmon, birds, marine mammals, and other species (Rice et al., 1996; Peterson et al., 2003).

Discovering pathways by which exposure to PAHs induces various pathologies was aided by the finding that in the presence of various PAH compounds, the aryl hydrocarbon receptor (AhR) transcription factor is activated, inducing the expression of the cytochrome P450 1A (CYP1A) gene by binding to the AhR (for a review of the history of the discovery and use of AhR, see Okey, 2007; Stegeman et al., 2001; Incardona, 2017; and Grosell and Pasparakis, 2021). The elevated expression of the CYP1A gene is commonly measured by the presence of ethoxyresorufin-*O*-deethylase (EROD) activity as a biomarker of PAH exposure. While elevated EROD activity does indicate exposure, it does not, alone, indicate the effects PAH exposure may have; activation of gene activity does indicate that the vertebrate organism is attempting to metabolize the PAHs into more polar compounds for eventual excretion (Meador et al. 1995; Grosell and Pasparakis, 2021).

The presence of DNA adducts (chemicals binding to DNA sequences) formed subsequent to PAH exposure is not only indicative of the activation of the CYP1A gene but also implies alterations to the transcriptome that may or may not be harmful to the animal. With the mapping of gene sequences to their particular function (e.g., growth, wound healing, osmoregulation), it is then possible to evaluate the differential expressions of all genes (e.g., through the production of RNA sequences as DNA is replicated) to assess which are up- and down-regulated in the presence of PAHs or any xenobiotic chemical (Harrill et al., 2019). If there is a map of the gene sequences with functional annotations, it may be possible to determine which of the organism's homeostatic mechanisms may be positively or negatively affected.

By far, most of the work to date has focused on transcriptomics (changes in genome-wide gene expression) rather than on changes in the genome itself. The state of the field on transcriptomics today is to link the phenotypes (physiology and behavior) to gene expression, which permits the use of gene expression data to infer effects (Xu et al., 2016, 2017a,b; Diamante et al., 2017).

Most often, studies of pollutant effects on gene expression are conducted with "model" organisms (e.g., those species wherein the gene sequence is mapped and the relationships between specific genes and their functions are understood) such as zebrafish (*Danio rerio).* Subsequent to the DWH accident, a number of studies evaluated transcriptomics of oil exposure in a wide range of Gulf-specific organisms, including blue crab (*Callinectes sapidus*; Yednock et al., 2015), dolphinfish (*Coryphaena hippurus,* aka mahi-mahi; Xu et al., 2016), tilefish (*Lopholatilus chamaeleonticeps)* and red snapper (*Lutjanus campechanus*) (Deak, 2020), Gulf killifish (*Fundulus grandis*; T.I. Garcia et al., 2012; Whitehead et al., 2012; Dubansky et al., 2013), red drum (*Sciaenops ocellatus;* Hollenbeck et al., 2017; Xu et al., 2017b; Khursigara et al., 2017), southern flounder (*Paralichthys lethostigma*; Sherwood et al., 2017; Rodgers et al., 2021), and seaside sparrows (*Ammodramus maritimus*; Bonisoli-Alquati et al., 2020), among others. Because of the lack of appropriate a priori gene sequence information for any of these species, researchers reconstructed gene expression profiles from short sequences based on RNA using a process known as de novo assembly (akin to solving a two-billion-piece jigsaw puzzle) and differential gene expression.

While relative gene expression varied among species and experimental conditions, immune system responses and sequences involved in responses to xenobiotic exposure were commonly up-regulated (Yednock et al., 2015; Deak et al., 2020; Rodgers et al., 2021), as were indicators of antioxidant production. Conversely, down-regulated functions included lipid production and expression of genes supporting reproduction (Deak, 2020) and nervous, muscular, and cardiovascular system functions (Xu et al., 2016, 2017a,b, 2021; Diamante et al., 2017). These studies have led to a better understanding of the complex array of physiological mechanisms activated or suppressed in the presence of oil pollution and provide a biochemical basis for evaluating critical functions affecting organism and population health. These studies also point to the fact that traditional biomarkers of PAH exposure may not sufficiently characterize longer-term impacts to the organism. For example, Rodgers et al. (2021) conducted chronic exposure studies over 35 days, followed by a 30-day "recovery" period. Their results showed alteration of a number of system functions, including cholesterol metabolism even 30 days post exposure, far longer than would be indicated by the presence of elevated PAH biliary metabolites or EROD activity from a single oiling event. Transcriptomic dynamics of oil-exposed organisms not only predict which individual and cross-linked genes may be differentially expressed but also generally correlate with symptomology discovered in morphological, developmental, and physiological assessments of impacts to non-model species. Below, we highlight a number of studies conducted post-DWH that show the toxicological impacts of oil exposure as related to critical functions in species that may lead to reductions in the overall fitness or survival of individuals and ultimately their populations.

In multispecies exposure trials conducted at the Mote Marine Laboratory post-DWH, Pulster et al. (2017) exposed red drum, Florida pompano (*Trachinotus carolinus*), and southern flounder to intraperitoneal injections of DWH crude. Although fishes have a high capacity for metabolizing PAHs, their ability to metabolize subsequent metabolites is poorly understood. The study documented differential responses among the species and the potential for "metabolic fatigue" through the post-exposure presence of hydroxylated metabolites. Florida pompano (a high metabolic rate pelagic species) had higher rates of biotransformation for naphthalene and phenanthrene than the other two, suggesting pompano may have lower susceptibility to adverse effects. Results for these three Gulf of Mexico species demonstrated species-specific vulnerability to adverse outcomes for fishes exposed to identical crude oils—clearly indicating that extrapolation of oil effects from model species to environmentally relevant species is fraught. Although the response was different across the three species, with Florida pompano exhibiting more rapid biotransformation, the long-term consequences of previously unstudied metabolites that may persist in fishes remains poorly understood and is a prime subject for future research. Vast sensitivity differences (>2 orders of magnitude) among species exposed to water accommodated fractions (WAFs) of DWH oil have also become evident since 2010 (Pasparakis et al., 2021).

Other studies of oil exposure with non-model fish species demonstrated additional important sublethal effects. Dose-dependent growth inhibition was demonstrated in southern flounder (Brown-Peterson et al., 2015) and for larval and juvenile spotted seatrout (*Cynoscion nebulosus*; Brewton et al., 2013). Oil exposure can also induce tissue histopathology in livers and gills and decreased lymphocyte and granulocyte densities in southern flounder (Brown-Peterson et al., 2015), alligator gar (*Atractosteus spatula*; Omar-Ali et al., 2015), and menhaden (*Brevoortia* spp.; Bentivegna et al., 2015).

In addition to effects noted above, a variety of studies conducted post-DWH have emphasized broader physiological, metabolic, and behavioral impacts of oil exposure on a wide range of non-model species. These effects include, among others, changes in central nervous systems (behavior), peripheral nervous systems (olfaction, vision), cardiovascular function, respiration, swimming performance, prey capture, immune response, stress response, reproduction, Aryl hydrocarbon receptor activation, and cholesterol biosynthesis.

Olfactory cues (i.e., particular smells the animal associates with some state of nature) evoke behavioral responses that are crucial to survival in fishes and other animals. Receptors, including olfactory sensor neurons, are susceptible to damage from aquatic contaminants. In WAF exposure studies to crude oil, bicolor damselfish (*Stegastes partitus*) did not respond to chemical alarm cues that would normally lead to predator avoidance. Hence, sublethal WAF exposure modified detection of chemical cues for up to eight days, suggesting at least short-term reduction in predator avoidance (Schlenkler et al., 2019a; Figure 2). In a similar experimental setup at the University of Miami, mahi-mahi avoided oiled water in favor of unoiled seawater, and avoidance increased in proportion to the concentration of crude oil in water. Even a short-term (24 h) oil exposure disrupted that behavior, leading to the inability of the fish to avoid oil contamination. Oil-exposed and control fish detected crude oil through an olfaction cue, although oil-exposed mahi-mahi showed no differences in physiology at the olfactory epithelium as compared to controls. Thus, observed behavioral alterations are occurring in the olfactory bulb or at higher brain centers and not at the olfactory epithelium. Results of these behavioral trials suggest that mahi-mahi may be able to sense and avoid oiled areas, but once exposed, fish will not seek clean water and will thus likely be contin-

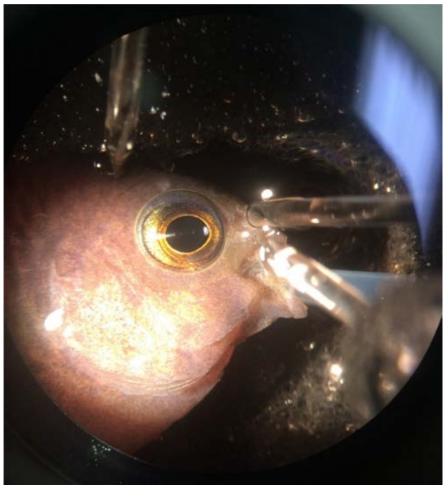


FIGURE 2. An anesthetized damselfish is prepared for recording of olfactory epithelium potentials to assess the effect of oil on olfaction. The fish is fitted with a tube passed through the mouth to perfuse the gills and ensure oxygenation, a delivery pipette to administer olfactory cues near the olfactory epithelium, a recording electrode inserted at the surface of the sensory epithelium, and a reference electrode near the skin above the eye. *Photo credit: Lela S. Schlenker*

ually exposed (Schlenker et al., 2019b).

Exposure of individuals to oil can also affect schooling behavior and modify group behavior even when not all animals are similarly exposed. Armstrong et al. (2019) exposed Atlanta croaker (*Micropogon undulatus*) individuals to crude oil and noted that schooling behavior was disrupted with exposure to 2% oil. Exposed fish groups also showed reduced voluntary movement. Not only were individual fish affected, but individual fish that were affected disrupted group behavior. Oil exposure in fish like Atlantic croaker can have adverse effects on their behavior and might lead to reduced fitness (Armstrong et al., 2019).

Perhaps one of the most important sets of studies of behavioral responses to crude oil exposure conducted post-DWH examined effects on swimming behavior, particularly of pelagic species. Swim chamber respirometry of young adult mahi-mahi demonstrated that acute exposure to a sublethal concentration of DWH crude oil elicited significant decreases in critical (14%) and optimal (10%) swimming speeds, a 20% reduction in maximum metabolic rate, and a 29% reduction in aerobic scope (Stieglitz et al., 2016a). Similar effects were observed for juvenile mahi-mahi exposed briefly during embryonic development (Mager et al., 2014) and for red drum (Johansen and Eshbaugh, 2017) and cobia (Nelson et al., 2016, 2017). For a pelagic predator species, these reductions in swimming performance have obvious implications for their abilities to avoid predation themselves, to capture pelagic prey, and to sustain long-distance migrations.

Digging deeper into the biochemical basis for impairment of swimming performance, Grosell and Pasparakis (2021) describe the cascade of biochemical and physiological changes that occur as a result of oil exposure in mahi-mahi (Figure 3). They noted in particular that impaired cardiac function, as a result of lower heart rate and especially stroke volume—leading to reduced cardiac output—may be the proximal cause of reduced swimming

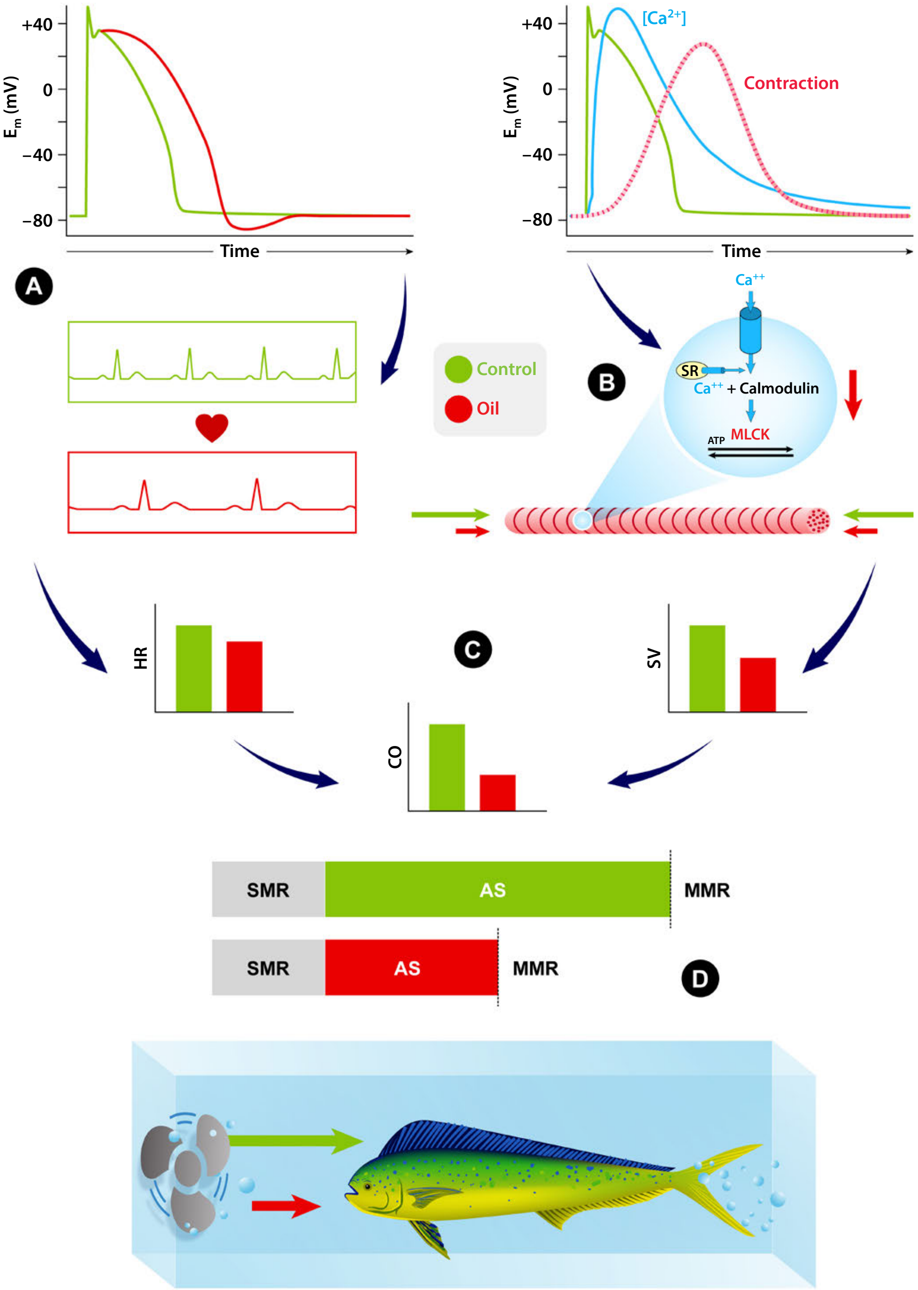


FIGURE 3. Illustration of how oil exposure (red) inhibits ion movement through the delayed rectifier potassium channel (*I*Kr), thereby prolonging action potentials in the heart cells of yellowfin and bluefin tunas (Brette et al., 2014). (A) Prolonged action potentials are likely the cause of the heart rate reduction observed in many oil-exposed fish. (B) Studies of isolated heart cells demonstrated decreased calcium movement (*I*Ca) through L-type calcium channels and impaired intracellular calcium cycling in response to crude oil exposure (Brette et al., 2014, 2017). Intracellular calcium binds to myofilaments to activate heart cell contractions, and its dysregulation results in reduction of the magnitude of heart cell contraction (Heuer et al., 2019); this explains decreased stroke volume, that is, the amount of blood leaving the heart following each contraction (Nelson et al., 2016; Perrichon et al., 2018). (C) Reductions in maximal heart rate and decreased stroke volume combine to result in impaired heart function, illustrated by reductions in the total amount of blood pumped by the heart (cardiac output). (D) Decreased cardiac output limits oxygen delivery in oil-exposed fish, which results in a reduced maximum metabolic rate, as observed in many studies (Thomas and Rice, 1987; Mager et al., 2014; Stieglitz et al., 2016b; Johansen and Esbaugh, 2017). Decreased maximal metabolic rate is likely responsible for impaired swimming abilities, such as reductions in maximum sustained swim speed (*U*crit), recorded in a number of oil-exposed fish. E_m = membrane potential. MLCK = myosin light chain kinase. SR = sarcoplasmic reticulum. *From Grosell and Pasparakis (2021)*

performance. In addition, cholesterol biosynthesis, nervous system function, stress responses, osmoregulatory function, and acid-base balance processes all were disrupted following exposure to oil. Depletion of cholesterol may be a significant contributor to impacts on cardiac, neuronal, and synaptic function as well as reduced cortisol production and release. Furthermore, impairment of intracellular calcium regulation, critical for muscle contraction and regulation of heart rhythms, may be related to cholesterol depletion in oil-exposed fish (Grosell and Pasparakas, 2021).

Defects in cardiac function and cardiac abnormalities appear to be common responses with fish embryos and larvae exposed to concentrations of PAHs between 1 μg L^{-1} and 15 μg L^{-1} (i.e., in bluefin tuna, *Thunnus thynnus*; yellowfin tuna, *Thunnus albacares*; and amberjack; Incardona et al., 2014) or between 1.2 μg L^{-1} and 30 μg L^{-1} (i.e., mahi-mahi eggs and larvae, which also exhibited decreased swimming performance). Oil exposure can cause pericardial edema (fluid buildup in the sac enclosing the heart) in yellowfin and bluefin tuna and mahi-mahi embryos, with decreased heart rate and atrial contractility resulting (Incardona et al., 2014; Esbaugh et al., 2016). Cobia exposed for 24 hours to two ecologically relevant concentrations of dissolved PAHs, similar to mahi-mahi, exhibited reduced cardiac function as measured through cardiac power output (pumping). This effect was mitigated through additional exposure to adrenergenic stimulation that may serve as a compensatory response (Cox et al., 2017; Nelson et al., 2017).

Embryonic stages of mahi-mahi displayed acute toxicity at concentrations as low as 8.7 μg L^{-1} PAHs (Esbaugh et al., 2016). Other morphological deformities such as fin fold damage, craniofacial malformations, and spinal curvatures have been observed during 48 h exposures to oil concentrations of 1.2 μg L^{-1} for embryos and 30 μg L^{-1} PAHs for larvae (Grosell and Pasparakis, 2021; Mager et al., 2014).

Impacts of oil exposure were not limited to vertebrates, and a variety of toxicology studies with non-model invertebrate species resulted in a range of toxicological effects. Sublethal exposure to realistic concentrations of crude oil can significantly decrease copepod (*Acartia tonsa*) escape swimming performance (Almeda et al., 2014a, 2016). This has implications for trophic transfer of hydrocarbons in marine food webs. Similarly, the routine swimming speeds of barnacle and copepod larvae were found to be significantly reduced when the organisms were exposed to realistic concentrations of crude oil and crude oil with dispersant; however, no change was observed in dispersant-only treatments (Almeda et al., 2014b). For planktonic copepods (*Acartia tonsa*, *Temora turbinate*, and *Pseudodiaptomus pelagicus*), low concentrations of dispersed crude oil (1 mL L^{-1}) caused a significant reduction in survival, growth, and swimming activity of copepod nauplii after 48 h of exposure (Almeda et al., 2016). UVB radiation increased toxicity of dispersed crude oil by 1.3–3.8 times (Almeda et al., 2016). In eastern oyster early life history stages, a larger proportion of veligers were inactive following WAF and CEWAF (i.e., WAF enhanced with chemical dispersants) exposure as compared to controls; the effect was greater for pediveligers, and pediveliger settlement at the highest concentration CEWAF treatment decreased by 50% compared to controls (S.M. Garcia et al., 2020). Thus, pediveligers may be particularly vulnerable to oil exposure. Significant reduction in clearance rates for adult oysters persisted 33 days after acute exposure to CEWAF (S.M. Garcia et al., 2020). For shallow-water corals (*Porites astreoides* and *Montastraea faveolata*) exposed to WAF, CEWAF, and dispersants, settlement and survival of larvae decreased with increasing concentrations, although the degree of the response varied by species (Goodbody-Gringley et al., 2013). Shallow-water corals exhibited significant changes in gene expression. Upregulation of cellular machinery associated with detoxification and depuration occurred at concentrations four to eight times lower than that for physical effects (N.R. Turner, 2020).

While all of the laboratory studies summarized above have implications for non-model populations in the wild, quantifying the effects at population and ecosystem levels (e.g., Wiesenburg et al., 2021, in this issue) requires that a sufficient proportion of the population be exposed to oil and that this exposure can be detected despite the intermittent and localized nature of field-based sampling. Given that oil concentrations during DWH were not uniform over the extensive footprint of the spill, nor consistent in time (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016), it is a particular sampling challenge to document the consequences of the spill to population outcomes. As pre-spill baselines of oil contamination were rarely collected prior to DWH, characterizing the degree and persistence of oil pollution in biota resulting from this particular spill was challenging owing to the range of other sources of oil pollution in the Gulf of Mexico (Transportation Research Board and National Research Council, 2003). Nevertheless, ongoing field-based sampling programs supported by GoMRI, some results of which are described below, generally comport well with parallel laboratory studies described above.

Monitoring Toxicological Impacts in the Field

Field-level sampling conducted post-DWH also provides important insights into toxicological responses of populations to elevated PAH exposure. Determining which individuals in a population have been exposed at what concentrations to a particular spill is extremely challenging. As noted above, the lack of pre-spill baselines of contaminant exposure often impedes the attribution of cause and effect, as does the presence of multiple simultaneous sources of contaminants such as PAHs. For example, as reported in Transportation Research Board and National Research Council (2003), a number of natural and anthropogenic sources of petroleum contribute to a diverse oil pollution budget in the Gulf of Mexico. Two important pieces of information, however, can narrow source attribution to a particular event. If, as was the case for DWH, the concentrations of PAHs in animal tissues are elevated in the region affected by the spill as compared with other areas within the ecoregion (Gulf of Mexico) that are not affected by the spill, this presents strong circumstantial support for considering a particular source, especially if the volume is large or persistent over time. Secondly, if, in post-event monitoring of the affected region, concentrations decline over time, this too presents strong evidence as to source, at least in the circumstances where residual oil is biologically unavailable to the species in question.

Field-based studies demonstrated that these two conditions were met; in addition, coincident post-DWH sampling of animal tissues revealed associated symptomology consistent with toxic exposures. Murawski et al. (2014) found elevated frequencies of external skin lesions (Figure 4) and PAH concentrations in liver and bile metabolites from red snapper and other species in 2011 as compared to those sampled in 2012. Subsequently, Snyder et al. (2015) and Pulster et al. (2020a,b,c,d) demonstrated further declines in PAHs and associated metabolites in red snapper and in king snake eel (*Ophichthus rex*) in continental shelf areas affected by DWH. They also expanded the number of species examined and, importantly, showed strong contrasting concentrations of PAHs between the northern Gulf of Mexico where DWH occurred and the rest of the Gulf (Figure 5), as did Snyder et al. (2020) for tilefish. Similarly, PAH concentrations were inversely correlated with the frequency of skin lesions (Snyder et al., 2015). Snyder et al. (2019) found increasing PAH concentrations in bile but not liver from tilefish, a benthic species, sampled during 2012–2017 in the northern Gulf of Mexico, which correlated inversely with body condition (weight for a given length) and percent liver lipid. Histopathological evaluations also indicated a decline in liver lipid storage and a coincident increase in hepatic glycogen storage (Snyder, 2020). Together, these findings suggest an association between chronic and increasing PAH exposure, altered energy storage, and reduced body condition, all of which influence the overall fitness of the individuals and, by inference, the population. The seem-

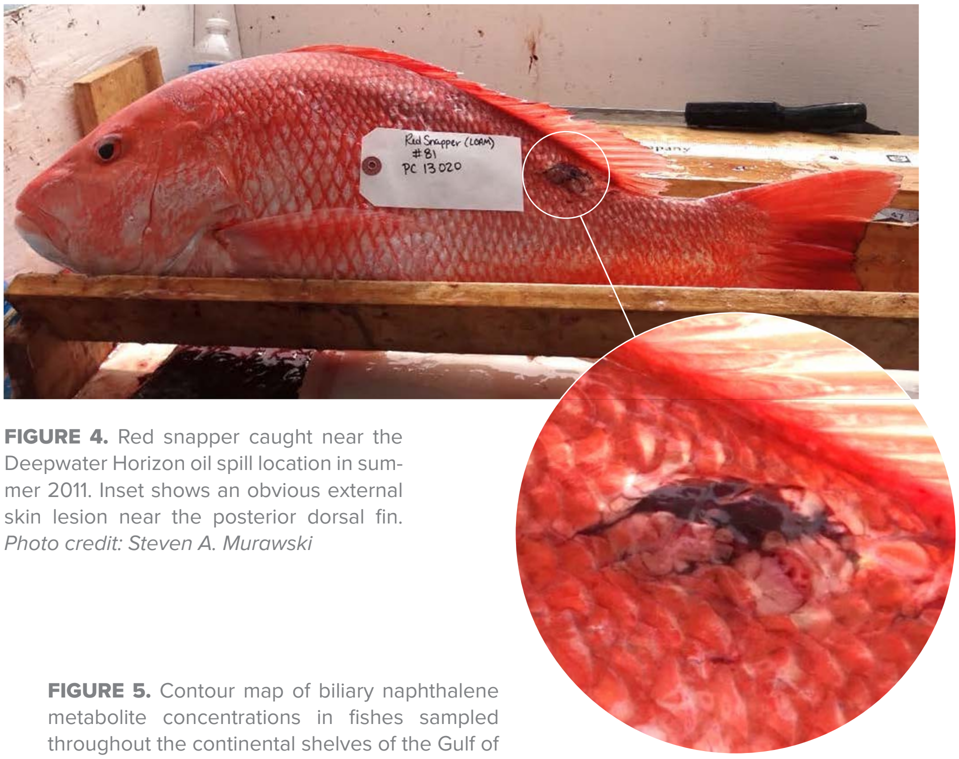
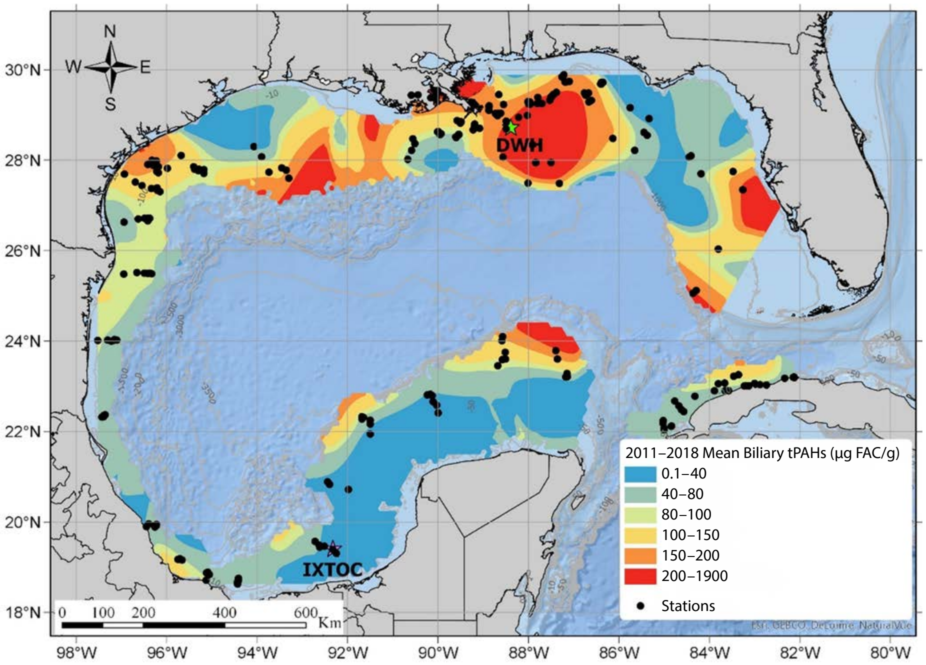


FIGURE 4. Red snapper caught near the Deepwater Horizon oil spill location in summer 2011. Inset shows an obvious external skin lesion near the posterior dorsal fin. *Photo credit: Steven A. Murawski*

FIGURE 5. Contour map of biliary naphthalene metabolite concentrations in fishes sampled throughout the continental shelves of the Gulf of Mexico, 2011–2018. Data show high concentrations in the region impacted by the Deepwater Horizon oil spill. *From Pulster et al. (2020b)*



ingly contradictory increasing trend in oil contamination for tilefish probably is a result of their burrowing into oil-contaminated sediments. Pulster et al. (2021) likewise correlated a suite of liver pathologies with PAH exposure. Importantly, in a series of laboratory experiments, Bayha et al. (2017) demonstrated that exposure to oil followed by a bacterial challenge with *Vibrio anguillarum* induced downregulation in immune response of southern flounder and ultimately the appearance of external skin lesions and other morphological symptoms consistent with bacterial infection, whereas test animals exposed only to the bacteria challenge exhibited none of these effects. These experiments thus confirmed the immunosuppressive mechanism likely responsible for the positive correlation between PAH exposure and skin lesion frequency as determined from field-sampled fishes (Murawski et al., 2014; Pulster et al., 2020c) and are consistent with a wider body of research elsewhere demonstrating that external skin lesions are correlated with PAH exposure (e.g., Myers et al., 1994).

Once the DWH oil was transported to coastal ecosystems, there were a variety of impacts on inshore species ranging from none to significant (Fodrie et al., 2014; Able et al., 2015; Powers et al., 2017; Murawski et al., 2021). Gulf killifish initially showed linkages between gene expression and gill immunohistochemistry and oil exposure within the first four months of marsh oiling, with CYP1A protein expression and gill morphological changes being symptomatic of oil exposure (Whitehead et al., 2012). Killifish larvae exposed to oiled sediments had poorer hatching success as compared with controls, and larvae showed differential gene expression in both gill and especially liver tissues (Dubansky et al., 2013). Because elevated oil concentrations in marsh sediments persisted at concentrations an order of magnitude over background levels in Louisiana marshes even eight years post-DWH (Turner et al., 2019), there is concern about long-term effects of the spill in these areas (Dubansky et al., 2013).

In marshes subjected to high levels of oiling from DWH, losses of the marsh grass *Spartina alterniflora,* particularly at marsh edges, were significant (Lin and Mendelssohn, 2012; Fleeger et al., 2015, 2018, 2019, 2020; Lin et al., 2016; Deis et al., 2017). Some infauna in oiled marshes denuded of vegetation recovered to densities equivalent to unoiled reference sites in about a year's time after the regrowth of *Spartina* began (Fleeger et al., 2015). However, epigenetic differentiation in response to oil contamination was not detected, probably due to the high levels of genetic variability inherent in the species and the fact that seed dispersal is facilitated by winds (Robertson et al., 2017). Similarly, recruitment from non-oiled patches may be responsible for the lack of long-term effects of oiling on marsh minnow assemblages (e.g., Able et al., 2015).

During and subsequent to DWH, ciliate zooplankton—major grazers of phytoplankton—were negatively affected by exposure to oil/dispersants, whereas bloom-forming dinoflagellates increased in abundance (Almeda et al., 2018). The results of this field investigation imply removal of key grazers due to oil and dispersant may disrupt predator-prey controls ("top-down controls") that, under normal conditions, would suppress blooms of toxic dinoflagellates. In subsequent laboratory studies using bacteria isolated from oil contaminated sediments from the 2014 Galveston "Y" oil spill (Park et al., 2020), the oil-degrading bacterial isolates significantly stimulated growth of dinoflagellates through the release of growth-promoting substances. Thus, impacts on low trophic levels occur not only through trophic "cascades" (e.g., Almeda et al., 2018) but also through the co-production of phytoplankton "growth factors" (Park et al., 2020), both of which have implications for natural ecosystem dynamics and human health.

The effects of oil and dispersants on coastal mesozooplankton (plankton in the size range of 0.2–20 mm) were evaluated in the field and in laboratory-based experimentation. Mortality of mesozooplankton increased with increasing oil concentration (the median lethal concentration was 32.4 mL L^{-1}). Dispersants applied at a 1:20 ratio increased toxicity by 0.3 to 3.4 times. Bioaccumulation of PAHs documented in the mesoplankton community increased by 35%. The conclusion was that oil spills negatively impact mesozooplankton (Almeda et al., 2014a) and also ctenophores (Peiffer and Cohen, 2015), and this effect increases with the use of chemical dispersants and coincident exposure to UV radiation.

For some species groups affected by the spill, a variety of logistical challenges and ethical concerns prevent direct exposure trials in laboratory settings. Such is the case for marine mammals impacted by DWH. As a result, a combination of nonlethal field sampling and laboratory studies of model species and cell lines of affected species, and comparisons with otherwise healthy animals in managed settings (e.g., Figure 6), was conducted to address priority questions related to health effects of oil exposure in common bottlenose dolphins (*Tursiops truncates*) in the northern Gulf of Mexico inshore habitats. Dolphins living within the oil spill footprint sustained a high reproductive failure rate. Capture-release health assessments focusing on fetal, placental, and maternal health of Barataria Bay dolphins, and photo-ID field studies focused on reproductive outcomes, documented a continuation of the low reproductive success rate of only 20% within the oil spill footprint. The success rate remained fairly consistent at ~20% from 2011 onward (Smith et al., 2020).

Chronic maternal illness in the aftermath of the DWH oil spill is the likely cause of reproductive failure. Normal progression of fetal development in utero (Barratclough et al., 2020; Ivančić et al., 2020) and retrospective examination of pregnancies with known failed outcomes have enabled several hypotheses as to the potential mechanisms of pregnancy failure, with maternal illness standing out unequivocally as the most important predictor for pregnancy complications (Smith et al., 2020). Various data were integrated with the complete veterinary case history for each dam (female) and the resulting fetal and placental histopathology findings to elucidate maternal, placental, and fetal predictors of pregnancy failure. Exhaustive analyses have proven pivotal for understanding of reproductive failure in dolphins and have provided a mechanistic model with which to analyze and interpret wild dolphin cases, even if only a single exam is available (Gomez et al., 2020).

Additional health assessments of Barataria Bay dolphins included pulmonary ultrasound evaluations, utilizing a standardized technique developed with managed dolphins (Figure 6), which have informed the comprehensive analysis. The prevalence of moderate to severe lung disease in dolphins that were alive at the time of the DWH spill and presumably exposed to oiling in Barataria Bay, remained elevated in comparison to dolphins outside the oil spill footprint (Smith et al., 2017, 2021). Lungs were scored as moderate to severe in 35% of dolphins in 2017 and 54% in 2018, significantly higher than the 7% in reference-site dolphins (Sarasota Bay, Florida). Overall, the prevalence of pulmonary disease is contributing to the overall poor maternal health of Barataria Bay dolphins, which in turn is contributing to the sustained high reproductive failure rate.

Based on the medical data generated, scientists do not expect the maternal reproductive failure rate to improve until the overall health of reproductive females in Barataria Bay improves. With the sustained low reproductive success rate in Barataria Bay, it is essential that maternal health be continuously monitored and addressed.

FIGURE 6. From left, Megan Tormey, Cynthia Smith, and Veronica Cendejas conduct a voluntary ultrasound examination of a Navy dolphin in San Diego Bay, California, using a heads-up display (virtual reality goggles) to view the diagnostic ultrasound image in real time. *Photo courtesy of the US Navy*

Cardiac assessment techniques never before applied in wild dolphins, including auscultation, echocardiography, and electrocardiography, were developed and performed on dolphins from both Barataria Bay and the Sarasota Bay comparison site (Linnehan et al., 2020; Barbara Linnehan, National Marine Mammal Foundation, *pers. comm., 2021*). Taken together with stranding studies, these findings suggest that there may be cardiac effects of oil exposure in dolphins either via direct effects to the heart that lead to morphometric abnormalities/lesions or via damage to the lung and secondary heart effects (Barbara Linnehan, *pers. comm., 2021*). Immunological studies demonstrated a variety of dysregulated immune system components, including the proportions and function of regulatory T cells, cytokine patterns, and inflammation markers. The weight of evidence for an association with oil exposure was enhanced by experimental laboratory studies that exposed mice to DWH oil and in vitro dolphin cells to DWH oil (De Guise et al., 2021).

Understanding toxicological impacts on deep-sea fauna presents particular challenges owing to the difficulty of sampling them, the inability to husband them in the laboratory for experimentation, and the general lack of detailed life history, behavioral, and baseline toxicological data (Sutton et al., 2020). Nevertheless, the mesopelagic is a highly diverse realm (e.g., over half of the known fish species in the Gulf of Mexico occupy these water column strata; Figure 7), and a significant quantity of DWH oil and its gas components dissolved in subsurface habitats (Deepwater Horizon Natural Resource Damage Trustees, 2016). Novel trawling activities in the mesopelagic areas of the Gulf of Mexico affected by DWH detected significant increases in PAH content post-DWH in mesopelagic fishes (Romero at al., 2018) and in squids (Romero et al., 2020). In the case of deepwater squids, increases in PAHs in squid mantle tissues were accompanied by a significant decline in percent lipid, similar to patterns found in tilefish (a deep-dwelling fish found along the outer continental shelf; Snyder et al., 2020). The exposure to toxic effects of oil appeared to be more prolonged in these organisms than in shallow-water biotic analogs (Romero et al., 2020). The significant and ongoing

FIGURE 7. Examples of mesopelagic fishes and squids captured by a MOCNESS (multiple opening and closing net environmental sampling system) in the Gulf of Mexico during post-Deepwater Horizon field activities, 2010–2018 (Sutton et al., 2020). The small fish pictured in the center is an antenna codlet (*Bregmaceros atlanticus*). Identifications for the other images, clockwise from lower left, are fangtooth (*Anoplogaster cornuta*), scaly dragonfish (*Stomias affinis*), diaphanous hatchetfish (*Sternoptyx diaphana*), eel leptocephalus larva (Ilyophinae sp. D3), clubhook squid (*Onychoteuthis banksii*), Cocco's lanternfish (*Gonichthys cocco*), Dana viperfish (*Chauliodus danae*), glass squid (*Cranchia scabra*). *Images © Dante Fenolio*

abundance decline across all major invertebrate and fish deepwater taxa (Sutton et al. 2020) that has coincided with the DWH spill and is coincident with the discovery of elevated PAH levels and other biochemical changes provides strong circumstantial evidence of a toxicological triggering event. Changes in the mesopelagic prey base were accompanied by shifts in the distribution of major marine mammal predators, including whales and dolphins (Fraiser, 2020; Fraiser et al., 2020), although seasonal movements in species such as sperm whales (*Physeter macrocephalus*) were apparent (Morano et al., 2020). While direct oil contamination may have elicited many of the toxicological impacts seen in other species, disruption of chemosensory abilities may be particularly important as an outcome for deep-sea biota. Many mesopelagic fish species have highly developed brain regions involved in chemosensing, olfaction, and light reception (Wagner, 2001). Chemical (and light) sensory signaling in mesopelagic fishes and invertebrates may be particularly important in their reproduction, given low light levels and low animal densities in this large ecosystem (Zimmer and Butman, 2000). As noted above, fishes are able to detect and discriminate oil contamination, and the effects of exposure may be long lasting. Although not studied in detail, disruption of chemosensory capabilities may be a mechanism at least partially responsible for the significant decline in these species post-DWH.

A PATH FORWARD FOR BIOLOGICAL EFFECTS ASSESSMENT OF OIL SPILLS

Few studies of the effects of oil spills track the fate and toxicity of spilled oil over timescales sufficient to capture the totality of weathering processes to near extinction. An exception has been the over 40-year study of the effects of the 1969 #2 fuel oil spill from the barge *Florida* off West Falmouth, Massachusetts (Cape Cod). Because of its location near the Woods Hole Oceanographic Institution and oil spill expertise and resources located there, the grounded oil in the West Falmouth salt marsh has been periodically monitored and its effects on biota analyzed, resulting in a number of seminal publications (Burns and Teal, 1979; Sanders et al., 1980; Teal et al., 1992; Reddy et al., 2002; Peacock et al., 2005). One of the most illuminating findings of this longitudinal study was the persistence of oil when it eventually became buried in marsh sediments to a depth where anoxic conditions exist. Similarly, prospecting for residual oil in low-energy environments, including coastal mangrove forests of the western Yucatán, revealed incompletely weathered remnants likely from the 1979–1980 Ixtoc 1 oil spill off Mexico (Radović et al., 2020). More recently, oil from the Deepwater Horizon was found to be similarly persistent in marsh sediments over eight years post-spill (Turner et al., 2019). Thus, the full impacts of spills on organisms and ecosystems cannot be completely characterized from short-duration studies following spills. In the case of significant oil spills, provisions for periodic (decadal-scale) assessments of oil persistence and ongoing impacts are therefore imperative.

This paper highlights some important developments in understanding the sublethal but nevertheless significant impacts on biota from the DWH oil spill. The advent of access to relatively powerful and cost-effective procedures and methods for evaluating changes at genomic, transcriptomic, and subcellular scales (**Figure 1**) has allowed a more complete understanding of the effects xenobiotic exposures may have on individuals, and by extrapolation to field data, on populations of marine life. Several important points, however, must be emphasized. First, the impacts of such a large and prolonged spill to long-lived populations and their communities have not ceased. Large reservoirs of partially weathered DWH oil remain in the environment (i.e., in the deep sea and in marshes; Turner et al., 2019; Schwing et al., 2020), and it may take decades to a century or more for the residual oil to decompose or be land-filled and essentially rendered biologically inert. What are the long-term consequences of these residual oil pools? Second, what kind of genetic legacy, if at all, does DWH leave? There have been very few studies of the impacts on the heritability of genetic alterations induced by prolonged and widespread oil pollution (e.g., White et al., 1999; Bautista and Burggren, 2019). While some experiments with F_1 and F_2 generations were attempted, results have so far been equivocal. Grosell and Pasparakis (2021) note that much of the biota of the northern Gulf of Mexico may have become adapted to the presence of naturally occurring and anthropogenically derived hydrocarbons, and thus the consequences of chronic pollution originating from the DWH reservoirs may be partially mitigated. They caution, however, that studies have shown that offspring from oil-polluted parents may be more susceptible to other stressors and have relatively poorer survival rates. If heritable but consequentially negative traits result from DWH pollution, the long-term prognosis for affected populations may be altered. If, however, heritable traits result in subsequent generations being more resilient to pollution, the legacy of DWH may in fact be a more positive one. Study of short-lived species (<4 years), such as the Atlantic killifish (*Fundulus heteroclitus*) commonly found in polluted urban estuaries, have provided evidence of rapidly evolved tolerances to environmental toxicants and anthropogenic pollution (Whitehead et al., 2017). However, evolutionary adaptations are rarely successful because they tend not to occur without physiological costs (e.g., reproductive fitness). In some species (e.g., longer-lived) or large populations, tolerance adaptations may not evolve fast enough to keep pace with their rapidly changing environment, and thus are not advantageous. Clearly, this is unfinished but important business to resolve.

Apart from conducting additional work on the heritability of pollution-related effects, a number of other high-priority research topics related to the toxicology of oil spills include:

- Continuing research on molecular and physiological cascades that occur during and after exposures and how they affect homeostatic mechanisms of the individual and fitness of populations.
- Collecting and analyzing routine toxicological baselines (including chemical analysis, study of sublethal biomarkers of contamination, and pathology assessments) for non-model species occurring in regions where significant oil and gas development and production are located.
- Developing rapid molecular tools and testing procedures to determine exposure, that is, greater use of semipermeable membrane devices (SPMDs), both to collect baseline contaminant data and to monitor pollution during and after spills. SPMDs are passive devices that may indicate the cumulative relative oil exposure within a parcel of water and thus can be a useful tool for determining the spatial mosaic of exposure concentrations. However, since they are inanimate objects, exposure potential is not mediated by physiology (e.g., ability to metabolize pollutants vs. accumulate them).
- Refining models for extrapolating laboratory results to the field, especially given the mosaic of differing contaminant concentrations (below, at, or exceeding critical contaminant concentrations resulting in lethal or sublethal effects) occurring in real spills.
- Updating and standardizing the protocols for the manufacture, use, and interpretation of WAFS and CEWAFs for exposure studies.
- Generating annotated gene maps for environmentally relevant, non-model organisms likely to be affected in oil spill-prone locations (e.g., Gulf of Mexico).
- Identifying and evaluating the toxicity of PAH metabolites and their metabolites.
- Evaluating sensory pathways in mesopelagic species and effects that oil pollution may cause in disrupting such mechanisms.

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AUTHORS

Steven A. Murawski (smurawski@usf.edu) is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Martin Grosell** is Professor, Department of Marine Biology and Ecology, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. **Cynthia Smith** is Executive Director, National Marine Mammal Foundation, San Diego, CA, USA. **Tracey Sutton** is Professor, Oceanic Ecology Laboratory, Halmos College of Arts & Sciences, Nova Southeastern University, Fort Lauderdale, FL, USA. **Kenneth M. Halanych** is Professor, Department of Biological Sciences, Auburn University, Auburn, AL, USA. **Richard F. Shaw** is Professor Emeritus, College of the Coast & Environment, Louisiana State University, Baton Rouge, LA, USA. **Charles A. Wilson** is Chief Scientific Officer, Gulf of Mexico Research Initiative, Fairhope, AL, USA.

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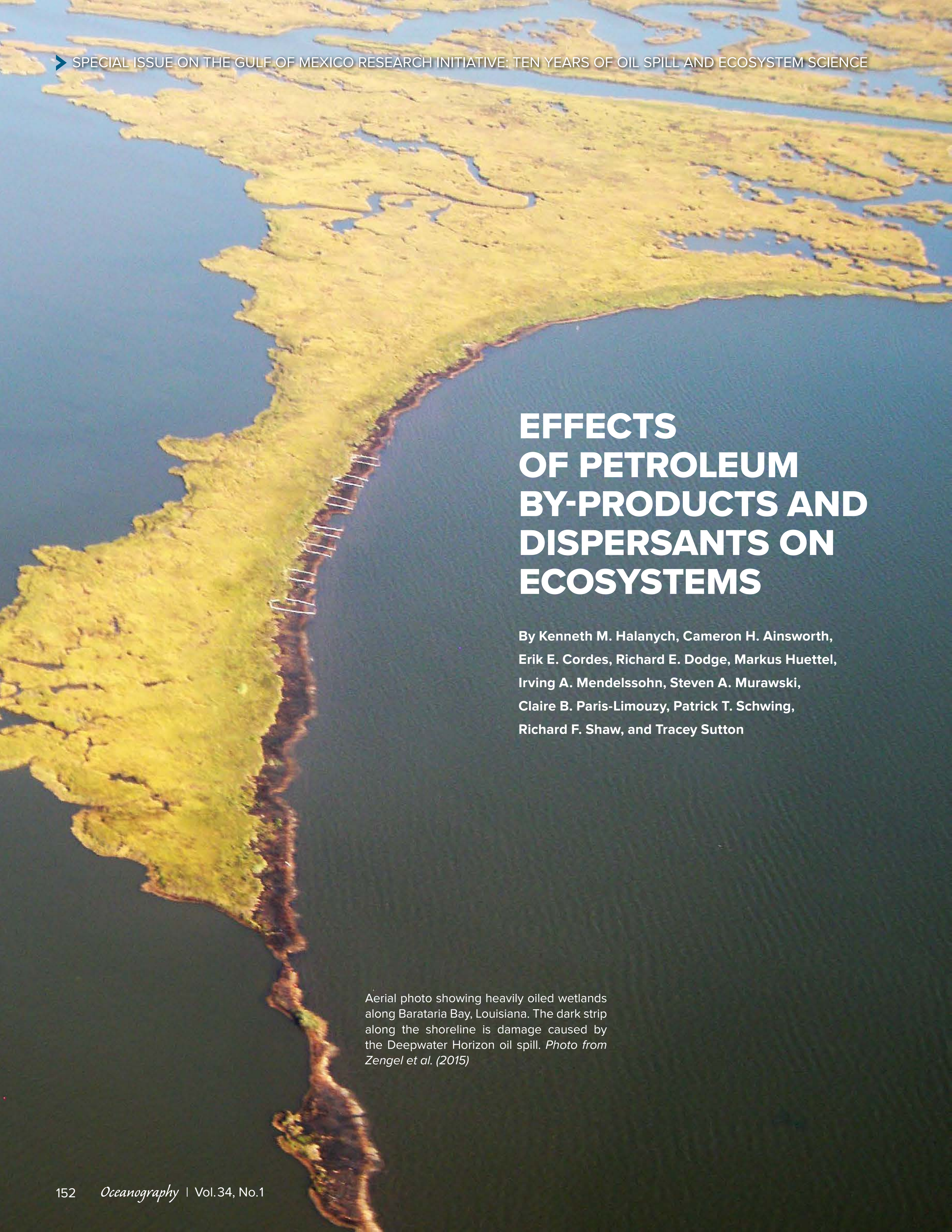

EFFECTS OF PETROLEUM BY-PRODUCTS AND DISPERSANTS ON ECOSYSTEMS

By Kenneth M. Halanych, Cameron H. Ainsworth, Erik E. Cordes, Richard E. Dodge, Markus Huettel, Irving A. Mendelssohn, Steven A. Murawski, Claire B. Paris-Limouzy, Patrick T. Schwing, Richard F. Shaw, and Tracey Sutton

Aerial photo showing heavily oiled wetlands along Barataria Bay, Louisiana. The dark strip along the shoreline is damage caused by the Deepwater Horizon oil spill. *Photo from Zengel et al. (2015)*

ABSTRACT. Gulf of Mexico ecosystems are interconnected by numerous physical and biological processes. As a result of the Deepwater Horizon (DWH) spill, some normal ecological processes including resource connectivity and trophic interactions and were damaged or broken. A considerable portion of post-DWH research has focused on higher levels of biological organization (i.e., populations, communities, and ecosystems) spanning at least four environments (onshore, coastal, open ocean, and deep benthos). Damage wrought by the oil spill and mitigation efforts varied considerably across ecosystems. Whereas all systems show prolonged impacts because of cascading effects that impacted functional connections within and between communities, deep-sea and mesopelagic environments were particularly hard hit and have shown less resilience than shallow environments. In some environments, such as marshes or the deep-sea benthos, products from the spill are still biologically accessible. Some shallow ecosystems show signs of recovery, and populations of some species show resilience; however, a return to a "pre-spill" state is questionable. Importantly, habitats in which large amounts of energy flow through the ecosystem (marshes, coastal regions) recovered more quickly than low energy habitats (deep-sea benthos). Functional interactions between Gulf of Mexico systems are more complex and widespread than generally recognized. Moreover, ecosystems in the Gulf are subject to multiple stressors that can combine to impart greater, and less predictable, impacts. To help mitigate the effects of future insults, we identify four salient areas of research that should be addressed for each of the major environments within the Gulf of Mexico: establishing monitoring systems; quantifying coupling between Gulf ecosystems; developing criteria for assessing the "vulnerability" and "resilience" of species, communities, and ecosystems; and developing holistic predictive modeling.

INTRODUCTION

Organisms and populations depend on each other. When one species is harmed or perturbed, other species can be affected, and connections that bind species together to make functional ecosystems can be stressed or broken. The Deepwater Horizon (DWH) oil spill was unprecedented in the vastness of the area impacted (149,000 km^2), duration (87 days), and amounts of pollutants added to the environment (approximately 635,000,000 liters of oil and 25,740,000 liters of dispersant; see Rullkötter and Farrington 2021, in this issue). Uncountable species were affected, profoundly altering the complex interactions that ecosystems rely upon to remain resilient. Whereas some impacts of the DWH spill on the environment and ecosystem services were easily discernible and quickly recovered, a far greater number of effects have been hard to measure, assess, and even observe. Nonetheless, one of the major endeavors of the Gulf of Mexico Research Initiative (GoMRI) effort was to elucidate how the DWH spill impacted the patterns and trends of perturbations, responses, and recoveries in the multiple ecosystems that comprise the Gulf of Mexico region. Here, we highlight some of the significant findings and questions that emphasize needs for future consideration at population, ecosystem, and community levels.

The Gulf of Mexico hosts a diverse set of ecosystems that intersect at numerous levels of scale and complexity (Paris et al., 2020). In some cases, the boundaries between habitats, communities, and ecosystems can be sharp, as is the case between high beach and intertidal regions. In other environments, transitional boundaries can be blurred, for example, between nearshore and deep benthic habitats. Here, we consolidate habitats impacted by the DWH spill into four major environments: onshore, coastal, open ocean (shallow to deep water column), and deep benthos.

Considerable research attention has been given to these systems, but the amounts of effort and types of research have varied greatly, in part because our baseline knowledge prior to the oil spill varied among habitats. In the case of open ocean or deep benthic habitats, we are still discovering which taxa are present and we have limited knowledge of species-species interactions (Schwing et al., 2020; Sutton et al., 2020). In contrast, the biodiversity of coastal and marsh areas is reasonably well known, with some understanding of ecosystem functions (Mendelssohn et al., 2017; Murawski et al., 2018, 2021, in this issue). What we have learned about various habitats is summarized elsewhere (Mendelssohn et al., 2012; Rabalais and Turner, 2016; Powers et al., 2017; Rabalais et al., 2018; Schwing et al., 2020). Here, we examine findings that transcend habitat or ecosystem boundaries and also explore significant insights gained for particular environments.

VARIABLE TIMESCALES OF IMPACTS

Consistent with previous research on oil spills (e.g., Peterson et al., 2003; Lincoln et al., 2020), available evidence suggests that impacts of the DWH spill on Gulf of Mexico biodiversity and ecosystem functions will last for many decades. In places like salt marshes and deep benthic environments, hydrocarbons persist, as removing them was impossible. In general, toxicants left systems in one of three ways: (1) hydrocarbons and dispersants, and their subsequent by-products, were metabolized, although some of them were incorporated into organismal cells; (2) weathered residues containing hydrocarbons and other products were, and are being, buried to the point that associated chemical moieties are either no longer available to organisms (assuming no disturbance) or have spatially localized impacts; and (3) toxicants were actively removed from the system either by processes such as advection (e.g., water movement, organismal transport) or human intervention (e.g., beach cleaning). Of course, some environments facilitate relatively rapid metabolic consumption or human removal (e.g., surface waters and near-

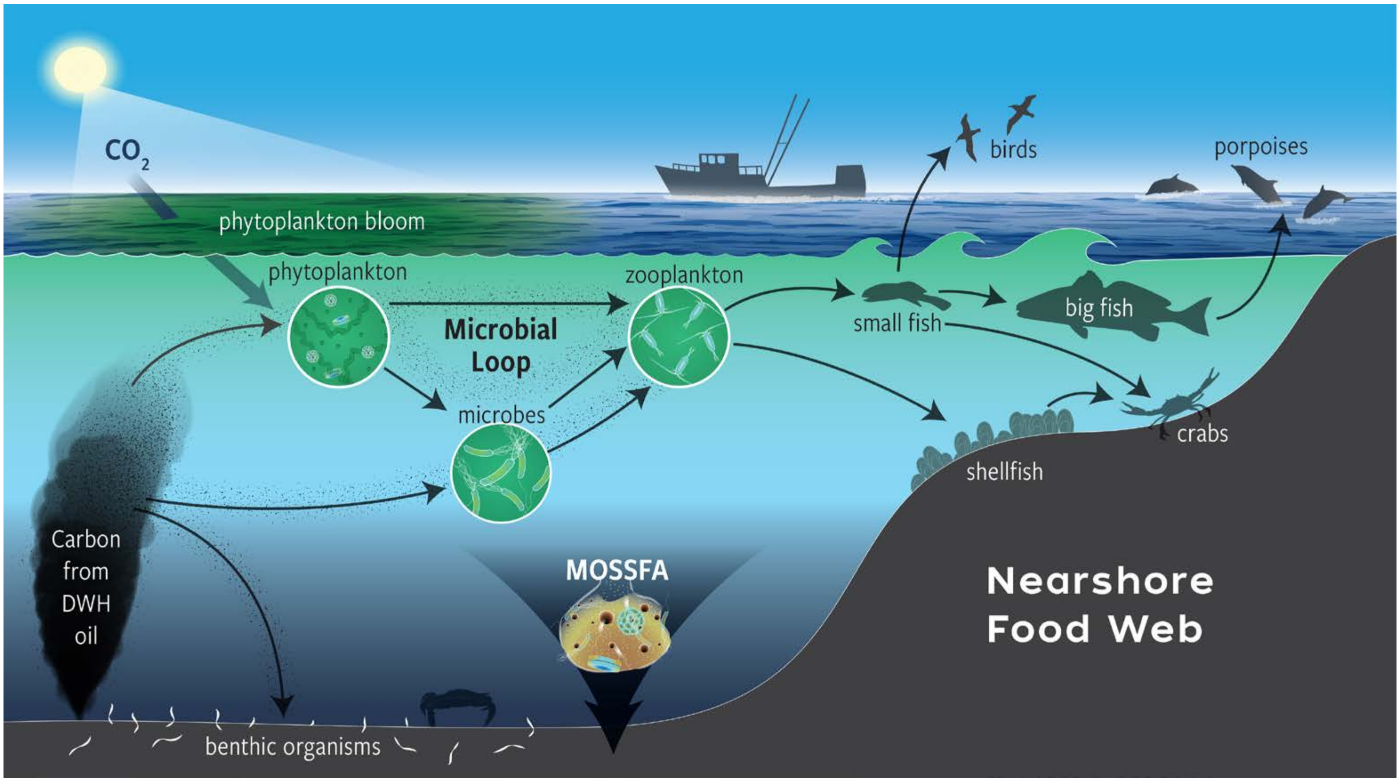

FIGURE 1. Hydrocarbons from the Macondo wellhead were incorporated into the pelagic microbial food web and subsequently passed on to eukaryotic organisms via food web interactions. Hydrocarbons moved into both coastal and deep benthos ecosystems.

shore environments), whereas deposition, burial, and negligible degradation may dominate in inaccessible deep benthic and some marsh environments. In different habitats or ecosystems, these mechanisms work on spatial and temporal scales that vary considerably, making it nearly impossible to accurately answer the seemingly simple question: how long will the DWH impacts last?

One of the first notable changes in ecosystems was the uptake of Macondo hydrocarbons into the pelagic microbial food web and subsequent uptake by eukaryotic organisms via feeding (Figure 1). This pulse of carbon energy happened in both the nearshore (Graham et al., 2010) and the open ocean (Chanton et al., 2012). Although this pulse was ephemeral in nature and waned as the carbon source was altered or exhausted, it supplied energy at the base of the food chain that was distinctly different than typical photosynthetic carbon fixation pathways to which most ecosystems are finely tuned. The initial increase in microbial carbon fixation was relatively short lived, but the movement of the carbon pulse through various trophic levels can take years, with impacts dissipating as it moves to higher levels (Patterson et al., 2020). Importantly, the spill did not just introduce pollutants, it fundamentally perturbed the base of the food web. Thus, as long as DWH hydrocarbons are present, environments have the potential to be impacted from both toxicant effects and an altered carbon cycle (Peterson et al., 2003; Lincoln et al., 2020). For example, in 2012, Hurricane Isaac resuspended previously buried DWH hydrocarbons sequestered in nearshore sediments (Diercks et al., 2018).

Variation in responses to the DWH spill by different environments was caused not only by the different amounts of oil received in any particular location but also by the duration pollutants were retained in the system and whether the system was of high or low productivity. Beaches, wetlands, and deep benthos serve as three illustrative examples of how the influence of hydrocarbon burial or removal can proceed on very different timescales (Figure 2).

DWH oil deposited on Florida sandy beaches in June 2010 was rapidly buried, contaminating the sediment down to 70 cm depth (Figure 3). Degradation rates scale with the kinetic and radiant energy present, so oil deposited on Gulf sandy beaches decomposed more rapidly than oil in the deep sea. Hydrocarbons in small (millimeter-size) sand-oil agglomerates were degraded within a year by a diverse microbial community, boosted by warm temperatures and aerobic conditions maintained by tidal pumping of oxygen through the contaminated sediment (Huettel et al., 2018). In some cases (e.g., Pensacola, Florida), excess hydrocarbons caused blooms in bacterial biomass (Kostka et al., 2011) that favored hydrocarbon-degrading microbes, leading to a drastic temporary decline in taxonomic diversity (Rodriguez-R et al., 2015; Gao et al., 2018). Chemical evolution of hydrocarbons can drive succession of microbial species, and once most of the oil was degraded, microbial communities returned to near baseline abundances, with little evidence of being enriched for hydrocarbon-degrading bacteria (Kostka et al., 2020).

In wetlands, oil impacts were generally limited to salt marshes bordering estuarine bays and barrier islands as well as low-salinity reed swamps of the Mississippi River birdfoot delta (Mendelssohn et al., 2012; Michel et al., 2013). Effects on wetland vegetation were highly variable and dependent upon oiling intensity and penetration of oil inland, among other factors. Along heavily oiled shorelines, oil frequently pooled under vegetation and often penetrated the soil more deeply through crab burrows (Zengel and Michel, 2013). Highest concentrations of oil were found in the top 2 cm of the soil profile but penetrated to 8 cm depth (Atlas et al., 2015) and possibly deeper (Natter et al., 2012). Heavily oiled marshes suffered combined effects of toxicity and smothering. In general, plant survival, growth, and recovery depended on oiling severity, duration, and species affected, with impacts decreasing with distance from oiled shorelines (Silliman et al., 2012; Zengel et al., 2015; Chen et al., 2016; Hester et al., 2016; Lin et al., 2016; Beland et al., 2017). Differential species tolerance to Macondo oil was particularly evident. For example, black needlerush (*Juncus roemerianus*) was more sensitive and less resilient to oiling than smooth cordgrass (*Spartina alterniflora*; Lin and Mendelssohn, 2012; Lin et al., 2016). Along some shorelines, recovery was likely impaired or prevented by shoreline erosion, which oiling can accelerate (Zengel et al., 2015; Hester et al., 2016; Beland et al., 2017). On a positive note, vegetation that was lightly or moderately oiled by the DWH spill showed little impact or recovered rapidly (Lin and Mendelssohn, 2012; Hester et al., 2016; Lin et al., 2016). In fact, a case study of heavy oil exposure from a pipeline rupture of Louisiana crude oil (pre-DHW) documented near complete recovery of *Spartina* after four years (Hester and Mendelssohn, 2000). Lin et al. (2016) estimated full vegetation recovery of heavily oiled marshes from the DWH spill may take five years or longer, assuming minimal shoreline retreat.

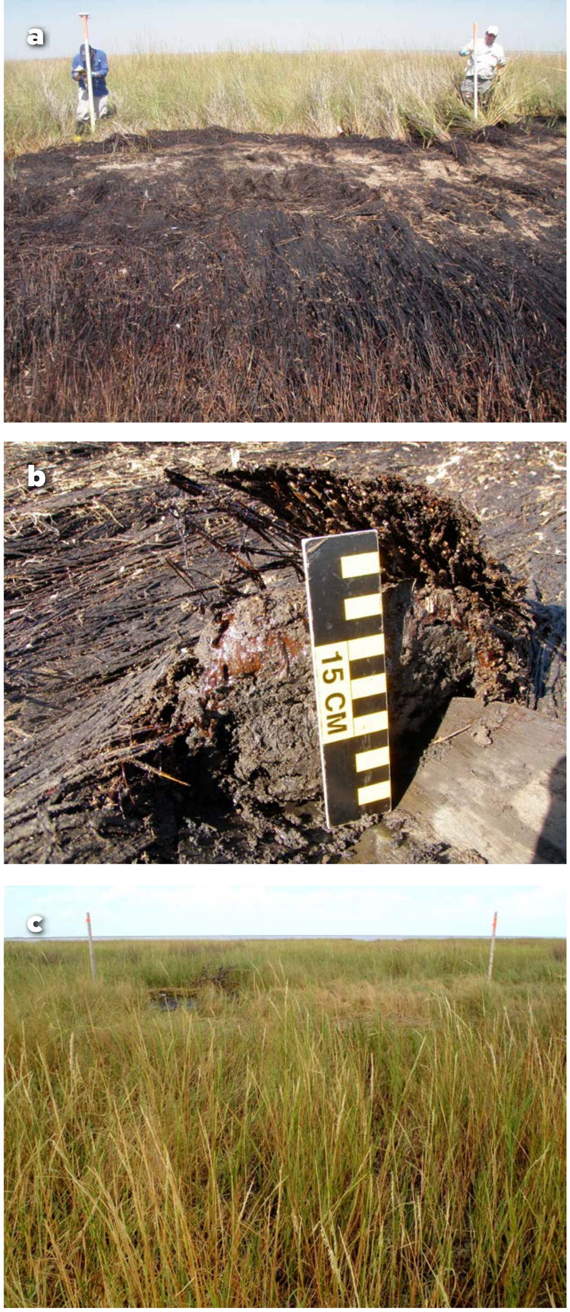

FIGURE 2. Photos of heavily oiled wetlands along Barataria Bay. See title page photo for aerial view (a) A ground-level plot exhibits the extent and ingression of bulk oiling. (b) This close-up photo reveals oil thickness on the substrate (~2–3 cm). (c) Recovering vegetation is shown about two years after manual cleanup. *Photos from Zengel et al. (2015)*

FIGURE 3. Cross section of sand at Pensacola Beach, Florida, photographed on July 25, 2010. The dark double layer produced by oil deposited during the nights of June 22 and June 23 is visible at 45–50 cm depth. Oil was buried in Pensacola Beach sands down to ~70 cm depth. Note the marker for scale. *Photo credit: Markus Huettel*

Deep-sea hydrocarbon degradation models suggest that recalcitrant residues will remain in sediments for about a decade (Romero et al., 2017). Pre-DWH spill abyssal sediment accumulation rates ranged from 0.04–0.44 cm yr^{-1} and bioturbation depths ranged from 1.75–3.25 cm (Yeager et al., 2004). Mass accumulation rates of sediment increased four- to tenfold during and immediately following the DWH spill (Brooks et al., 2015), with a concomitant decrease in abundances of meiofaunal and macrofaunal densities by as much as 90% in some areas (Schwing et al., 2015; Montagna et al., 2017). Such massive sedimentation rates, toxicant input, and fauna decreases have major impacts on ecosystem function and, importantly, will directly impact benthic-pelagic coupling of nutrient cycles and food chains. Taking all of these factors into account, 50–100 years will be needed to achieve full recovery from DWH contaminant burial below bioturbation depths (Schwing et al., 2020).

In all three of these environments, oil is being sequestered by burial. Whereas oil per se in the open water column was not retained for a long time, the bioavailable hydrocarbons and hydrocarbon pollutants have had a long-lasting impact. There is evidence that as late as 2017, DWH-derived toxicants were measurable in eggs of pelagic fishes and shrimps at levels above those known to cause sublethal effects (Romero et al., 2018). Though life histories, including longevity, of deep pelagic organisms are poorly known, extrapolation from known fauna suggests that individuals examined were several generations removed from the spill, indicating DWH-derived residues have persisted in the deep pelagic environment. These long-term elevated concentrations may be a result of food-web incorporation (Graham et al., 2010; Chanton et al., 2012; Quintana-Rizzo et al., 2015) and/or the persistence of oil residues in the water column (Walker et al., 2017) due to resuspension of contaminated sediments (Romero et al., 2017; Diercks et al., 2018), providing one possible explanation for widescale persistent declines in mesopelagic population abundances in the Gulf after the DWH spill (unpublished data of author Sutton).

PROLONGED IMPACTS VERSUS FAST RECOVERY

Impacts of environmental insults can be spatiotemporally delayed in part because biological processes (e.g., behavior, physiology, ontology, recruitment) can operate on long timescales (Peterson et al., 2003). Determining the timing and magnitude of delayed impacts, as well as the ecological mechanisms that propagate the impact, can be exceedingly difficult even for relatively simple biological systems. However, observations made since DWH confirm ecological theory as to how different trophic levels may be impacted by an environmental disturbance such as an oil spill.

Upper trophic levels can exhibit considerably delayed impacts from disasters and toxicants relative to lower trophic levels, which tend to be short-lived species with higher fecundity and abundances. Depending on the situation, life-history variables can act in concert, or independently, to moderate or exacerbate impacts from an oil spill. Factors such as body size may influence how much toxicant needs to be absorbed to produce detrimental effects, or motility may influence how often or for how long an organism comes into contact with a pollutant. Such factors will influence the rate and magnitude of toxicant damage that can lead to death, short-term sublethal impacts, or long-term persistent damage. The 1989 *Exxon Valdez* oil spill in Prince William Sound offers an instructive example of chronic exposure. It exacted a sublethal toll on the sea otter (*Enhydra lutris*) population, which failed to recover and indeed declined over a prolonged period within the oiled area (Peterson et al., 2003). In the case of the DWH spill, higher trophic levels tend to show more prolonged impacts and slower rates of recovery (this is in part due to bioaccumulation impacts of polycyclic aromatic hydrocarbons, or PAHs, in fatty tissue; see Murawski et al., 2021, in this issue). Additionally, because organisms at higher trophic levels have generally smaller population sizes and longer generation times, obtaining appropriate numbers to allow for statistically rigorous analyses on the impacts of sublethal effects can be difficult. The bottlenose dolphin (*Tursiops truncates*) exemplifies impacts on a top predator in the Gulf of Mexico system. Dolphin populations are highly vulnerable to hydrocarbon impacts and have medium to low resilience, limiting their ability to recover (Murawski et al., 2020).

In contrast, lower trophic levels tend to show more resilience because they typically have short generation times and high fecundity, allowing faster replacement of individuals, especially among species, or genotypes within species, that may be competitively superior given the altered environmental conditions. For example, many nearshore commercial shellfish communities rebounded fairly quickly in the wake of the DWH spill (Gracia et al., 2020). Presumably, their resilience is due in part to their reproductive biology. For example, penaeid shrimp (*Farfantepenaeus aztecus*, *F. dourarum*, and *Litopenaeus setiferus*) and blue crab (*Callinectes sapidus*; Figure 4) lay a larger number of eggs and mature within one to two years.

Although the speed with which a population of a given species may recover is roughly correlated with trophic level and fecundity, how quickly the overall ecosystem recovers is more closely aligned with available energy, which influences productivity. Organisms living in high productivity environments, such as salt marshes or the epipelagic water column, which both receive large inputs of solar energy, recovered faster because more energy was available for growth, repair, and reproduction. In comparison, energy is scarce in deep environments. Metabolic rates in deep benthic organisms are slower than those in the pelagic zone due to limited food resources and cooler temperatures, and thus turnover rates for larger deep benthic organisms (macrofauna, megafauna, corals) are generally slower than those of smaller, shallow benthic organisms (Rowe and Kennicutt, 2008; Montagna et al., 2017). For example, estimates of deep coral growth range from 0.03 cm yr^{-1} to 0.2 cm yr^{-1} (Prouty et al., 2016), which corresponds to centuries of growth to achieve a colony on the scale of tens of centimeters.

As is the case with complex biological systems, outcomes can vary depending upon the species and the population. How the spill affected commercially harvested fish seems to have varied depending upon multiple factors, including fecundity, trophic position, and sensitivity to accumulated PAHs. For example, some commercial fish communities recovered quickly despite stressors from the DWH spill, but changes in fishing pressures may have influenced recovery (Gracia et al., 2020). Shortly after the spill, impacts on bluefin tuna (*Thunnus thynnus*) were of concern because the DHW spill disrupted their spawning season. Fortunately, <12% of bluefish tuna larvae were in contaminated waters because their spawning grounds are broadly distributed (Muhling et al., 2012), and a large impact on that population has not been observed to date (bluefin tuna take about eight years to sexually mature). Potential impacts on red snapper (*Lutjanus campechanus*) have also been a point of concern. These fish mature at two years and have a >50-year life span. Thus, their reproductive potential augments their resilience.

ECOSYSTEM ENGINEERS AND CLONAL SPECIES

Although many attributes of ecosystem function are driven by energy availability or trophic level, ecosystem engineers can control environmental complexity through niche availability. In particular, three-dimensional structure, critical for both diversity and abundance of many species, seems somewhat limited in the Gulf of Mexico given the sandy shallow coastline and shelf that lack rocky substrate. Interestingly, in wetland, nearshore, and deep-sea regions of the Gulf of Mexico, organisms, rather than geological features, fill the role of providing three-dimensional structure. Structure relates to niche diversity and availability and thus biodiversity. In these systems, taxa responsible for engineering environmental structure tend to be clonal species, meaning that the organism has limited genetic variability and tends to be long-lived. These clonal species are being stressed in multiple ways as well. A major concern of the DWH spill recovery included whether the damage to ecosystem engineers would result in loss of three-dimensional habitat structure that would impact recovery of other species.


FIGURE 4. The blue crab, *Callinectes sapidus* (whose names means “tasty beautiful swimmer”), is an example of a species that seemed to recover quickly after the spill, in part because of its high fecundity. *Photo credit: Bree Yednock*

During the DWH spill, effort was made to keep oil away from nearshore and coastal areas in part to protect the sensitive nursery grounds of seagrass beds (e.g., *Halodule wrightii* and *Thalassia testudinum*) and saltmarsh wetlands (mainly, *Spartina alterniflora*). *Spartina* habitats, in particular, are critical as they also provide many ecosystem services, such as erosion control and surface and subsurface habitat; are an interface between the marine and terrestrial environments; and host considerable biodiversity. As a result of the intentional mitigation efforts, the offshore water column and deep benthos received large amounts of oil and dispersants. That decision doomed many deep-sea communities, including deep coral assemblages, some of which are estimated to be over 2,000 years old (Girard et al., 2019). Coral colonies themselves were covered to varying degrees in the flocculent material derived from marine oil snow produced by the DWH spill. Colonies that were lightly impacted have shown signs of recovery, while those with more extensive injury have continued to decline and have lost entire branches of their colonies (Girard et al., 2019). Reductions in the numbers and sizes of colonies at the impact sites will affect total reproductive output because their fecundity is dependent on the number of reproductive polyps in the colony. Coral growth rates are extremely slow (Prouty et al., 2016), and recruitment is sporadic (Doughty et al., 2014), suggesting that population recovery will be considerably delayed. Just as with shallow-water coral reefs, deepwater corals are critical for providing three-dimensional structure and increasing biodiversity. One of the most common and persistent associations is with the ophiuroid brittle stars, which were shown to accelerate the rate of coral colony recovery following the spill by preventing settling of or dislodging flocculate oil from the corals, although some of the brittle stars died as a result of their efforts (Girard et al., 2016; Figure 5). Octocoral colonies serve as nursery grounds for some fish species, including the chain catshark (Etnoyer and Warrenchuk, 2007) and *Sebastes* spp. (Baillon et al., 2012), as well as octopus species (Shea et al., 2018). Because of their significant role in the generation and maintenance of biodiversity through direct habitat provision and increased habitat heterogeneity (Lessard-Pilon et al., 2010), the loss of these coral structures and their associated fauna in the deep Gulf of Mexico will have repercussions for the biological and genetic diversity of these habitats on long timescales.

ECOSYSTEMS ARE INTERCONNECTED

One surprise of GoMRI research was the degree of coupling among Gulf of Mexico ecosystems. Hydrocarbons and associated toxicants showed considerable vertical and horizontal spatial connectivity in addition to having a temporal component. As mentioned in Quigg et al. (2021, in this issue), dispersants were hard to track and, unfortunately, we have few long-term data on these chemicals. Both physical and biological processes accounted for transport of spill-related toxicants. Conventional wisdom suggests that spilled hydrocarbons, weathered hydrocarbons, and dispersants were moved by physical transport mechanisms (currents, sedimentation) and that biologically modified or incorporated products were moved between ecosystems by organisms. However, this is an oversimplification of how DWH toxicants spread throughout the Gulf of Mexico. Both physical and biological processes facilitated dispersal of hydrocarbons, dispersants, and their downstream byproducts, suggesting considerably more interdisciplinary research is needed to fully understand the magnitude and mechanisms of connectivity between ecosystems. (For discussion of the physical mechanisms that initially distributed DWH products, see Boufadel et al., 2021, and Farrington et al., 2021, both in this issue).

Once hydrocarbons and toxicants had worked their way into biological systems, migration and predatory-prey relationships promoted transfer of those chemicals to other ecosystems. For example, diel vertical migrations account for movements of organisms en masse up and down the open ocean water column in search of food. Approximately half of all fish species and three-quarters of all pelagic macrocrustaceans (shrimps, krill, and mysidaceans) in the open Gulf of Mexico vertically migrate in some form (Sutton et al., 2020), including most of the biomass-dominant taxa. This upward movement from meso- and bathypelagic depths during daytime into shallow layers at night, and the concomitant descent at sunrise, constitutes the largest synchronous migrations of animals on Earth, and, through the linked process of feeding, is a key driver of the "biological pump," the primary mechanism whereby active animal movement sequesters carbon in the deep ocean. Given the presence of subsurface plumes of hydrocarbons and dispersants after the spill, vertical migrations by the deep-pelagic fauna increased their exposure to DWH spill contamination (Sutton et al., 2020). This active vertical flux also likely served as a vector for contaminant redistribution via plankton consumption near the surface and defecation at depth (Hopkins et al., 1996). Given that very little particulate organic carbon reaches the seafloor in the open Gulf (Rowe et al., 2008), tainted fecal pellets were likely consumed within the deep water column rather than being directly deposited and buried at the seafloor.

In addition to vertical migration, animals move horizontally to new regions to feed, shelter, or reproduce. As organisms carrying toxicants enter new areas, they may reproduce, defecate, be eaten, or die, thus releasing the byproducts of the DWH spill into novel areas (Figure 6). Knowledge of food web connection or migratory movements have been used in models to improve our understanding and ability to model the spread of toxicants (Larsen et al., 2016). Moreover, coupling between the benthos and the water column can serve to move chemicals among different reservoirs. Although processes such as sediment resuspension,

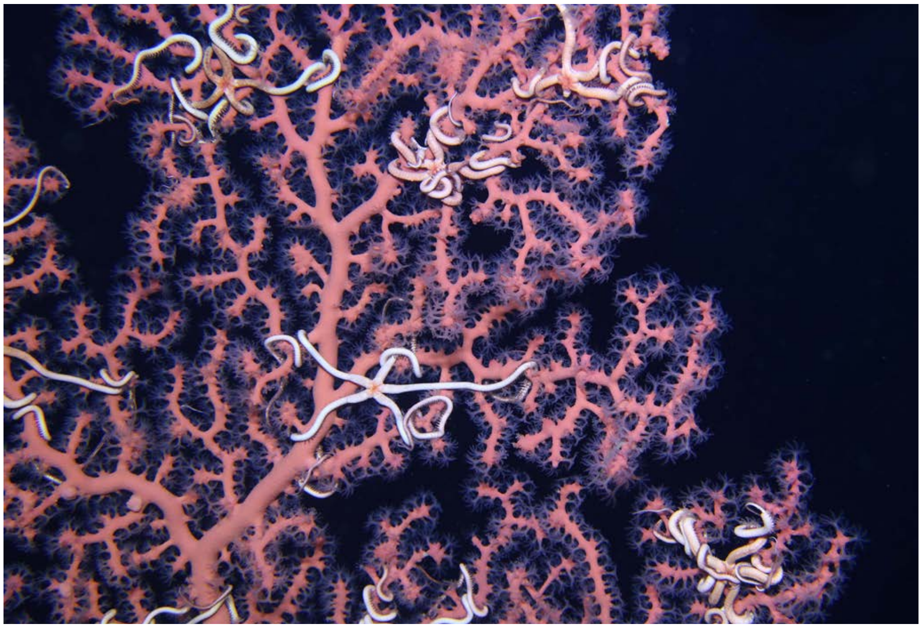

FIGURE 5. Brittle stars (*Asteroschema clavigerum*) on the deep-sea coral *Paragorgia* sp. In this image, both animals are healthy and demonstrate the intimate association between the two species. Brittle stars protected corals by preventing settling of or dislodging flocculate oil from the sessile organism. *Photo courtesy of ECOGIG*

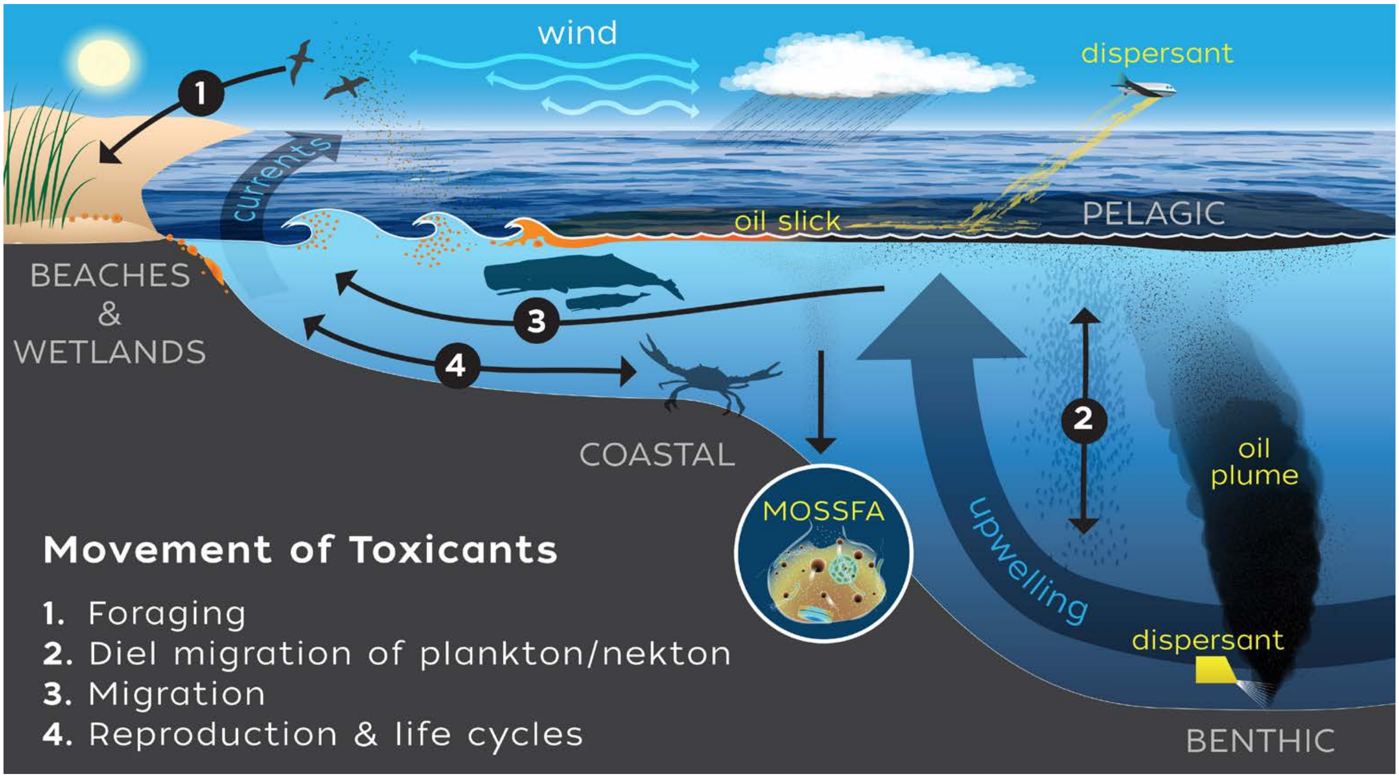

FIGURE 6. As organisms carrying toxicants enter new areas, they may reproduce, defecate, get eaten, or die and release the byproducts of the Deepwater Horizon spill into novel areas. Movements such as diel vertical migration by plankton or migration for spawning, feeding, or changes in life-history stage move toxicants to new habitats.

sedimentation (including marine snow from biological processes), predation, and bioturbation are well understood, GoMRI research has highlighted the role these processes play in facilitating the movement of hydrocarbons. The most significant of these coupling events was the large amounts of hydrocarbons and tainted marine snow sediments that were deposited on the deep benthos, mentioned above (Vonk et al., 2015).

STABLE STATES AND RECOVERY

Moving forward, great concern and effort has been focused on "recovery" of the northern Gulf of Mexico. However, different ecosystems recover at different rates. For example, the nearshore water column has largely recovered to a pre-DWH spill state, but the open ocean mesopelagic water column is still showing major declines in faunal abundance since the spill. Presumably, there are differences in ecosystem function as well, but species interactions and environmental drivers in this ecosystem are poorly understood, making assessment of ecosystem function difficult. Moreover, based on present data, these ecosystems are unlikely to return to a similar state in terms of species composition or function in the foreseeable future.

The deep-sea benthos is also unlikely to quickly return to a pre-DWH state. Schwing et al. (2015, 2020) performed decadal time-series analyses on multiple deep-benthic community size and taxa groups, including benthic foraminifera, meiofauna, and macrofauna. They found that while benthic foraminifera diversity indices and density tended to return to pre-DWH levels within three to five years, statistical analyses demonstrated that the assemblages (species present) prior to DWH were significantly different than those present following DWH, with an increase in infaunal and opportunistic taxa. They reported that an increase in opportunistic taxa was also the case for other meiofauna. However, meiofaunal assemblage changes consistent with DWH impact were superimposed on a longer-term (since the 1980s) decline in ecological quality status.

If the physical substrate of the environment has been altered or if the environment is characterized as low energy (e.g., the deep benthos), recovery to the original state will be improbable or slow. Simply put, if the habitat is no longer available or if there is limited energy for growth and repair, the community in question cannot return to pre-spill conditions. Modeling efforts that seek to incorporate biological information have improved understanding of the potential environmental impacts that may result from given oil spill scenarios (Grüss et al., 2016; Ainsworth et al., 2018; Woodstock et al., 2021). For example, one of the Schwing et al. (2020) studies produced a conceptual model of how organismal interactions in deep benthos environments changed during and following the DWH by including fluxes, increased abundance/activity/respiration, lethal and sublethal effects, and changes in community structure. Moving such models forward will be of considerable importance for identifying gaps in knowledge at all hierarchical levels. Filling these gaps will require basic research.

Even with evidence in hand and the use of predictive models, illuminating drivers that control ecosystem stability and resilience has been exceedingly difficult. One feature common to many Gulf of Mexico systems is the propensity for disturbance and recovery. Perhaps unlike any other region in the world, the Gulf of Mexico is subject to a regular procession of disturbances that include hurricanes, anoxia, and sizable salinity shifts in nearshore environments due to rain or drought. Perhaps the best recent example was the very large freshwater discharge from Hurricane Harvey emanating near Houston, Texas, in 2017. Large plumes of freshwater that lasted for months could be measured well out into the Gulf (Walker et al., 2020). In addition to these factors, several habitats are regularly affected by petrochemicals (e.g., through natural seepage, previous oil spills, and even persistent releases of small amounts of hydrocarbons due to human activities) that also likely impacted the Gulf's ability to recover from the DWH spill. When considering recovery and restoration, the fact that Gulf of Mexico communities are affected by multiple stressors, from hurricanes to anoxia to the persistent presence of hydrocarbons, should be factored into decisions that will impact the environment.

The presence of multiple stressors has presented challenges for studies in the Gulf of Mexico and can hinder restoration and recovery efforts. Scientists need to be clever in how they tease out the individual effects of multiple stressors to understand their impacts. Multiple stressors do not always work additively; stressors can combine in just the right way to cause tipping points to be exceeded. Lionfish (*Pterois volitans*) offer an illustrative case as to the difficulty of untangling the difference between causation and correlation, or how much one stressor acted as driver for ecosystem change. Immediately after the DWH spill, there were significant species shifts in northern Gulf of Mexico reef fish communities, with species richness declining 38% and Shannon-Weiner diversity declining 26% (Lewis et al., 2020). At the same time, lionfish were invading the northern Gulf of Mexico region (Kitchens et al., 2017). The environmental insult from the DWH spill may have given lionfish the opportunity to establish themselves and, subsequently, the presence of lionfish may have hindered recovery of native fish fauna. Thus, determining the impact of lingering DWH effects versus the lionfish invasion on reef fishes is challenging.

Although multiple stressors are influencing the Gulf of Mexico, research arising out of GoMRI suggests that prolonged human activities cause the greatest amount of insult to the systems. The DWH spill was a horrendous accident that will impact environments for several decades. By contrast, decades of overfishing, poor land use, and anoxia due to nutrient loading from farming practices have resulted in impacts that will take much longer to correct. In the case of seagrass communities, issues such as trawling by humans, combined with variations in salinity, combined with resuspension of toxic sediments, can make it extremely difficult to determine the impact of any one stressor. After the DWH spill, commercial fisheries were closed from January to April 2011, which included most of the spring reproductive period. These closures were successful in their intended purpose of ensuring public safety and increasing consumer confidence in Gulf of Mexico seafood, but they had little effect on the long-term recovery of fish populations because of the short duration (Ainsworth et al., 2018). Although the surface slick had a brief impact on larval populations (Chancellor, 2015), Atlantis ecosystem modeling suggests that effects on recruitment potential were short-lived and inconsequential compared to longer-lasting toxicological impacts on the breeding population (Ainsworth et al., 2018). Populations often took one or more generations to recover from the acute mortality that resulted from the spill.

WHAT ABOUT NEXT TIME?

With >1,000 active and >3,000 total oil and gas rigs sited there, the petroleum industry will continue to have a huge influence on the Gulf of Mexico. The fact that the industry continues to push into deeper waters is a concern, as the DWH spill demonstrated that the flow can be hard to stop in deeper water if safety measures fail. The DWH spill directly impacted over a third of the Gulf of Mexico, but given horizontal transport of species, impacted organisms have moved throughout the Gulf, taking toxicants with them. Decisions made at the time concerning spill mitigation had direct consequences for which environments were the most damaged. Specifically, the decision was made to try and keep as much of the oil as possible offshore and away from marshes, coastal regions, and, importantly, humans. Public perception and financial consequences of this decision should not be overlooked.

Our knowledge of organisms and ecosystem function is vastly different across ecotypes. Few data exist for deep-sea environments because getting appropriate measurements or observations is expensive and technically difficult. Comparatively, inshore and coastal environments are much better understood. This disparity of information has the potential to bias comparative risk analyses and decision-making. A more thorough consideration of management strategies for even routine practices in the oil industry should be explored (Cordes et al., 2016).

Given the likelihood of oil spills in the future, the ability to make informed decisions depends on continued considerable efforts to understand how Gulf of Mexico ecosystems function and how they are interconnected. One particularly difficult research challenge has been discerning the impact dispersants had at the community or ecosystem level. Most knowledge of the biological impacts of dispersants on biota has taken place in laboratory experiments or in controlled mesocosms (Quigg et al., 2021, in this issue). Notably, the chemical cocktails that comprise dispersants can be hard to track in natural environments even when companies are willing to disclose the contents. Dispersants were a component of the marine oil snow event that impacted the deep coral habitats (White et al., 2014). In situ studies have shown that dispersant and oil-dispersant mixtures can have physiological effects that are significantly greater than oil exposure alone (e.g., DeLeo et al., 2016; Ruiz-Ramos et al., 2017), and they can suppress oil biodegradation (Kleindienst et al., 2015). Although the exact cause and mechanism of the injury to the corals may never be known (Fisher et al., 2014), there are specific gene expression patterns of dispersant exposure that may be helpful in determining the direct cause of injury in future spills (DeLeo et al., 2018).

Moving forward, there is an opportunity to vastly improve our ability to understand and possibly mitigate oil spills (and other disasters). We present four areas of research that are particularly critical for improving understanding.

1. Establishing monitoring systems that provide essential environmental and ecosystem data. Pre-DWH spill data were very limited for some environments, making assessments of damage and ecosystem impacts difficult. Looking forward, monitoring systems will provide baseline information that facilitates assessment of the next environmental insult, be it an oil spill, hurricane, or something different. Retrospectively, monitoring is needed to help understand the long-term recovery in the wake of the DWH, especially for mesopelagic and deep-sea environments where ecosystem processes run more slowly.

2. Quantifying magnitudes and rates of exchange (i.e., coupling) between Gulf of Mexico ecosystems. We have little understanding about the rates, magnitudes, or in some cases mechanisms of processes that allow transport within and across Gulf of Mexico ecosystems. Examining, for example, benthic-pelagic coupling, mesopelagic to epipelagic coupling, and nearshore to salt marsh coupling would allow researchers to understand how toxicants can remain active and move between environments.

3. Developing criteria for assessing the "vulnerability" and "resilience" of species, communities, and ecosystems. For many organisms, we have a very poor understanding of their vulnerability to insult or injury (Murawski et al., 2021, in this issue); this is especially true for open ocean or deep-sea animals (Schwing et al., 2020). Likewise, in many cases we do not know which species are critical for maintaining ecosystem function. Criteria for defining vulnerability and resilience will vary depending upon species, community, and ecosystem and will help build more robust working parameters.

4. Developing predictive modeling that incorporates biological and physical processes. Just as biophysical models were used to predict where and when oil might disperse (Paris et al., 2012), integrative models that forecast how biological systems might behave, or what functions of the ecosystem are particularly vulnerable, would be invaluable to both scientists and resource managers.

These four areas of development are broadly applicable not just for understanding oil spills in the Gulf of Mexico but are relevant to understanding and mitigating any disaster.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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AUTHORS

Kenneth M. Halanych (ken@auburn.edu) is Professor, Department of Biological Sciences, Molette Biology Laboratory for Environmental & Climate Change Studies, Auburn University, Auburn, AL, USA. **Cameron H. Ainsworth** is Associate Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Erik E. Cordes** is Professor, Department of Biology, Temple University, Philadelphia, PA, USA. **Richard E. Dodge** is Professor, Department of Marine and Environmental Sciences, Guy Harvey Oceanographic Center, Nova Southeastern University, Dania Beach, FL, USA. **Markus Huettel** is Professor, Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, USA. **Irving A. Mendelssohn** is Professor Emeritus, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, USA. **Steven A. Murawski** is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Claire B. Paris-Limouzy** is Professor, Department of Ocean Sciences, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. **Patrick T. Schwing** is Visiting Assistant Professor of Marine Science, Eckerd College, Saint Petersburg, FL, USA. **Richard F. Shaw** is Professor Emeritus, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, USA. **Tracey Sutton** is Associate Professor, Oceanic Ecology Laboratory, Halmos College of Arts & Sciences, Nova Southeastern University, Fort Lauderdale, FL, USA.

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SPECIAL ISSUE ON THE GULF OF MEXICO RESEARCH INITIATIVE: TEN YEARS OF OIL SPILL AND ECOSYSTEM SCIENCE

PROSPECTS FOR GULF OF MEXICO ENVIRONMENTAL RECOVERY AND RESTORATION

By Denis A. Wiesenburg, Bob Shipp, F. Joel Fodrie, Sean Powers, Julien Lartigue, Kelly M. Darnell, Melissa M. Baustian, Cam Ngo, John F. Valentine, and Kateryna Wowk

Great blue heron and boom along the Louisiana coast after the Deepwater Horizon oil spill. *Photo credit: Beckie Breeding-Mims, US National Park Service*

ABSTRACT. Previous oil spills provide clear evidence that ecosystem restoration efforts are challenging, and recovery can take decades. Similar to the Ixtoc 1 well blowout in 1979, the Deepwater Horizon (DWH) oil spill was enormous both in volume of oil spilled and duration, resulting in environmental impacts from the deep ocean to the Gulf of Mexico coastline. Data collected during the National Resource Damage Assessment showed significant damage to coastal areas (especially marshes), marine organisms, and deep-sea habitat. Previous spills have shown that disparate regions recover at different rates, with especially long-term effects in salt marshes and deep-sea habitat. Environmental recovery and restoration in the northern Gulf of Mexico are dependent upon fundamental knowledge of ecosystem processes in the region. Post-DWH research data provide a starting point for better understanding baselines and ecosystem processes. It is imperative to use the best science available to fully understand DWH environmental impacts and determine the appropriate means to ameliorate those impacts through restoration. Filling data gaps will be necessary to make better restoration decisions, and establishing new baselines will require long-term studies. Future research, especially via NOAA's RESTORE Science Program and the state-based Centers of Excellence, should provide a path to understanding the potential for restoration and recovery of this vital marine ecosystem.

INTRODUCTION

When a coastal ecosystem is damaged by oil, the system can recover gradually over time without intervention, although the new state of the ecosystem may not be equal to that before the damage. Generally, mitigation efforts that are undertaken to minimize the amount of oil reaching the coast include oil collection by skimmers, burning of the oil at sea, and the application of dispersants to reduce the oil to smaller droplets, thereby increasing oil surface area and allowing natural processes to more fully and quickly interact with the oil. When oil reaches the shore and causes damage to the coastal ecosystem, restoration efforts are often used to speed the recovery of the ecosystem. Mitigation efforts following the Deepwater Horizon (DWH) oil spill included those listed above as well as release of freshwater from the Mississippi River to hopefully keep the oil offshore, and even the building of berms to protect coastal areas. Restoration efforts included mechanically sifting the oil from beaches, cleaning marine animals, and eventually planting new marsh grasses to speed recovery. This article considers the prospects for environmental recovery based on what we know from previous oil spills and from the data on the coastal ecosystem of the Gulf of Mexico collected since the DWH oil spill.

LESSONS LEARNED FROM EARLIER SPILLS

The Ixtoc 1 oil blowout in the southern Gulf of Mexico in June 1979 had many similarities to the DWH oil spill. It was a well blowout that released massive amounts of crude oil (>3.4 million barrels) into a tropical marine environment; the well leaked for over nine months and reached all the way into Texas waters. Soto et al. (2014) reviewed the environmental legacy of the Ixtoc 1 blowout. Like DWH, the impacts of the Ixtoc 1 spill were initially mitigated by physical and chemical processes and the region's local hydrological and biological conditions. However, even today, Ixtoc 1 oil residues are measurable, especially in the sediments and on shore, and some scientists suggest that the collapse of important commercial shrimp species stocks are attributable to the spill, though there is disagreement about this. Soto et al. (2014) note that the lack of adequate pre-spill information precluded a robust assessment of the Ixtoc 1 spill's damage to the ecosystem. Intense research was conducted while the oil flowed; however, when Ixtoc 1 oil stopped flowing, many research efforts funded by US agencies ceased. As a result, the total extent of environmental damage from the Ixtoc 1 oil spill is not fully understood, while the official position of the Mexican federal agencies is that no environmental damage was caused by the Ixtoc 1 blowout (Soto et al., 2014).

Before DWH, the largest oil spill in US waters came from the *Exxon Valdez* tanker accident in March 1989, where 257,000 barrels of North Slope crude oil was released into the cold, pristine waters of Prince William Sound, Alaska. The oil eventually affected 2,100 km of coastline, of which 320 km were heavily oiled. During the response, the carcasses of more than 35,000 birds and 1,000 sea otters were found, the herring fishery eventually collapsed, and two pods of killer whales have yet to recover. Mitigation techniques ranged from booms to keep the oil out of rivers and away from shorelines where salmon spawned to hot water cleaning of rocky beaches. The hot water made for great television, but it was eventually abandoned when it was realized that small coastal organisms were killed by the hot water. In the long term, fauna associated with hot water cleaned beaches recovered more slowly than those associated with beaches that were either left alone or treated by spraying nutrients on the rocky beach (Houghton, 1991). Peterson et al. (2003) concluded that because of persistence of oil in the ecosystem, the long-term population impacts are likely more important than the acute species mortality immediately following the spill. Even today, small amounts of oil can be found under rocks on the beaches of Prince William Sound (Nixon and Michel, 2018), and some species have not fully recovered. Esler et al. (2018) examined timelines for wildlife population recovery and found that for some species, the oil effects that persisted for decades had a large influence on population dynamics. These chronic effects may have been more harmful than the acute toxic effects of the oil itself. Unlike for Ixtoc 1, a legacy of post-*Exxon Valdez* research is available, as long-term research funding was made available through federal agencies and the *Exxon Valdez* Oil Spill Trustee Council; the most recent effort is the Gulf Watch Alaska Program initiated in 2012 with a 20-year lifetime (Aderhold et al., 2018). Another outcome of the *Exxon Valdez* accident was passage of the Oil Pollution Act of 1990 that established how response to future oil spills would be managed and required the responsible parties to pay for the cleanup and restoration efforts.

DEEPWATER HORIZON IMPACTS

Detailed examination of impacts on various components of northern Gulf of Mexico habitats is beyond the scope of this paper. However, the following sections include a brief review of the status of several of the more prominent habitats and species impacted by the DWH oil spill, including wetlands and mortality of fish larvae, invertebrates, sea turtles, and cetaceans. (Please see other articles in this issue for further information.) In addition, we present a more detailed review of impacts on wetland fisheries and oyster restoration.

In accordance with the Oil Pollution Act of 1990 (OPA), an assessment of damage to the environment was conducted by scientists from NOAA and their contractors as part of the OPA-required National Resource Damage Assessment (NRDA; DHNRDAT, 2016).

In general, coastal habitats were fairly well buffered from the impact of the DWH oil spill, except for those of Louisiana. Much of that impact is documented elsewhere in this issue, but in general, NRDA-identified damages that relate to the coastal zone include the following.

The DWH oil spill resulted in the oiling of 2,113 km of coastline (Nixon et al., 2016), including 763 km of coastal marsh shoreline with 135 km heavily oiled, mainly in Louisiana (Michel, et al., 2013). Many acres of wetlands were damaged, and depending on the degree of oiling, it was estimated that marsh recovery would take from two to four years for intensely treated areas and eight years for those that were untreated (Michel and Rutherford, 2014; DHNRDAT, 2016). Some residual oil is still found in the Louisiana coastal sediment. Based on the degradation rates from oil spilled in Prince William Sound, continued degradation will be extremely slow, and oil will continue to surface through erosion for the next decade or more (Lindeberg et al., 2018). From previous studies, we also learned that marsh restoration can be enhanced by the planting of *Spartina* in salt marshes and *Juncus* in the freshwater marshes (Bergen et al., 2000; Mendelssohn et al., 2012). Some efforts to restore marshes are necessary, as Zengel et al. (2015) show that in the Louisiana marsh areas not treated after DWH, most ecological parameters had not improved two years after the spill. It follows that the benthic infauna will recover fairly quickly once native vegetation is restored.

The number of fish killed was estimated during the NRDA process using biological data from NRDA-specific field studies, historical collections, NRDA toxicity testing studies, and published literature. Both direct kill and forgone production of fish and invertebrates exposed to DWH oil in the surface slick and the subsurface mixed zone were calculated. The exposure resulted in the death of between 2 trillion and 5 trillion fish larvae and between 37 trillion and 68 trillion planktonic invertebrates (DHNRDAT, 2016). Of these totals, 0.4–1 billion larval fish and 2–6 trillion invertebrates were killed in estuarine surface waters. The NRDA process also quantified the direct kill of fish and invertebrates exposed to DWH oil both in the rising cone of oil and in the deepwater plumes, as well as foregone production for a critical subset of these species. The exposure resulted in the death of between 86 million and 26 billion fish larvae and between 10 million and 7 billion planktonic invertebrates (DHNRDAT, 2016).

In general, the fish communities of the coastal Gulf of Mexico were found not to suffer long-term damage from the DWH oil spill (see below). Those communities have now recovered, and there has so far been no evidence of long-term sublethal impacts, showing the resilience of coastal fish communities (Patterson et al., 2015). As with the benthic community, once the habitat is restored, the organisms will follow.

The NRDA Trustees estimated that between 4,900 and 7,600 large juvenile and adult sea turtles and between 55,000 and 160,000 small juvenile sea turtles were killed by exposure to DWH oil. The Trustees also estimated that nearly 35,000 hatchling sea turtles were injured by response activities associated with the DWH oil spill. Likely, the most problematic impacts in the coastal zone were to higher-level vertebrates. Organisms such as birds, turtles, and marine mammals were unable to avoid the oil as it spread near the shore. Multiple recovery efforts were attempted during the spill to clean and release contaminated birds and turtles. Unfortunately, that was not possible with marine mammals. Mortalities of dolphins and turtles were documented during and immediately following the spill. Dolphin data collection funded during NRDA and continued by the Gulf of Mexico Research Initiative (GoMRI) documented dolphin fetal mortality, respiratory stress, and challenged immune responses. A variety of innovative studies conducted between 2010 and 2015 under the NRDA process documented that marine mammals experienced severe negative effects such as lung disease, reduced reproduction, and elevated death rates (see Barratclough et al., 2019). Unfortunately, restoration is not possible for this group of organisms, and it will simply take a long time for recovery to work through the system due to low reproductive success after the oil spill (Lane et al., 2015).

Eight-year study quantifies how oiling is a continuing stressor on the marsh ecosystem. Scientists measured changes in oil quantity and quality in 1,200+ samples collected over eight years at locations that Deepwater Horizon affected—the Gulf of Mexico continental shelf, estuarine waters, and marsh sediments. The concentrations in marsh sediments peaked in fall 2011 (1,000 times above May 2010 levels) then dropped to 10 times higher over eight years. The initial oiling at the marsh edge gradually affected the entire marsh within two years, suggesting that the total area oiled was larger than the visible initial oil distribution when the spill first occurred. The study authors estimated that marsh sediments will retain high levels throughout this century. *Photo credit: R. Eugene Turner, Louisiana State University*

ESTUARINE FISHERIES

The 2010 DWH oiling disaster challenged the integrity and long-term future of the Gulf of Mexico ecosystem at unprecedented scales. It led to immediate, but temporary, shutdown of fisheries harvesting and prompted serious concerns that there might be catastrophic injury to Gulf fishes and fisheries. However, nekton sampling at multiple, paired oiled and unoiled sites during 2012–2013 in Barataria and Terrebonne Bays, Louisiana, among the most heavily oiled salt marshes along the northern Gulf following the spill (DHNRDAT, 2016), documented no lasting differences in the densities, sizes, or assemblage structures of seven resident Cyprinodontiformes fishes (including the sentinel species, Gulf killifish, *Fundulus grandis*; Able et al., 2015). Similarly, catch rates of marsh-resident species, as well as overall community structure, were not different before (2009) versus after (2010–2011) oiling at impacted wetlands in Alabama (Moody et al., 2013). Likewise, settlement of blue crab, *Callinectes sapidus*, did not change in northern Gulf wetlands following the spill (Grey et al., 2015). Shrimp abundances in oil-impacted Louisiana embayments actually increased in the aftermath of the spill, perhaps due to delayed migration offshore and/or reduced harvest pressure (van der Ham and de Mutsert, 2014).

In addition to these spill-response patterns observed among marsh-associated nekton, similar patterns of stability in fish populations and communities have emerged post DWH in diverse northern Gulf settings such as seagrass-associated fishes (Fodrie and Heck, 2011), estuarine fishes throughout Mississippi Sound (Schaefer et al., 2016), and within the coastal population of Gulf menhaden, *Brevoortia patronus*, a key forage fish (Short et al., 2017).

The general resilience to unprecedented oiling exhibited by fishes, crabs, and shrimps at population levels has been surprising given what is known about the impacts of hydrocarbons on individuals within these marsh-associated taxa following DWH. In both lab experiments and field collections since 2010, individuals from these same taxa have shown negative responses to both oil constituents (e.g., polyaromatic hydrocarbons) and dispersants used to break down oil slicks. Indeed, a review of peer-reviewed studies demonstrated that in ~99% of cases (Fodrie et al., 2014), individual marsh-associated fishes exposed to even low concentrations (~1 ppb) of weathered Macondo oil and/or Corexit dispersants from the DWH oil spill demonstrated negative responses in terms of genomic expression, physiologic performance, morphological defects, and even mortality rate (Whitehead et al., 2012; Dubansky et al., 2013; Kuhl et al., 2013).

Several factors may help reconcile why these individual-level damages do not appear to manifest as losses at the population or community level for marsh-associated nekton. In addition to the fishery closures in 2010 that potentially reduced adult mortality and increased recruitment of summer/fall spawning species (Fodrie and Heck, 2011), many fishes, crabs, and shrimps may have relied on their mobility to detect and then evade oiling (Martin, 2017). In many estuaries, the distribution of oil was highly patchy and could have allowed for avoid-

Oyster populations in many areas of the north-central Gulf of Mexico were severely impacted. Researchers concluded impacts on oysters were primarily due to activities associated with response to the DWH oil spill. The summer release of large quantities of freshwater from the Mississippi River through the Caernarvon and Davis Pond diversion structures as the State of Louisiana moved to protect marsh ecosystems from the inflow of oil in 2010 resulted in the loss of 2–3 billion market-sized oysters from subtidal areas of Barataria Bay and Black Bay/Breton Sound estuaries (Grabowski et al., 2017; Powers et al., 2017b). (photo) Louisiana coastal oysters exposed at low tide. *Photo credit: Meagan Schrandt*

ance behaviors for highly mobile species, despite strong site fidelity at landscape scales (Jensen et al., 2019). Additionally, we know that many marine birds and mammals were impacted by Macondo oil, and reduced numbers of these predators might have also offset oil-related mortality on smaller fishes (Lane et al., 2015; Short et al., 2017). These are only a subset of the possible explanations that can be considered but are ultimately difficult to fully test as causal agents for observed patterns—which reinforces the complexity of ecosystem response(s) to broadscale oiling, as well as defining directions for future research. Additionally, other studies highlight the importance of identifying key taxa in the response of ecosystems to perturbations based on both their sensitivity to stressors (i.e., oiling) and their importance in the overall web of interactions (McCann et al., 2017).

OYSTER RESTORATION AND RECOVERY

Oyster populations in many areas of the north-central Gulf of Mexico were severely impacted, primarily due to activities associated with response to the DWH oil spill. During the injury assessment phase, the DWH NRDA Trustee Council directed significant resources to evaluating the impacts on oyster resources, including support of longer-term monitoring of many oyster habitats. The complexity of assessing the immediate and long-term effects of the DWH spill on oysters cannot be overstated: they were impacted both as direct consequences of oiling and response activities (e.g., freshwater diversion release, shoreline cleanup), and by the interaction of oiling and response activities. In addition, oyster resources in the Gulf region fluctuate naturally because recruitment changes in response to freshwater inflow patterns to estuaries, and because there is a legacy of different harvest regimes.

Studies in the aftermath of the DWH oil spill demonstrated that disturbances resulting from oiling and various response activities can have substantial impacts on oyster resources. The summer release of large quantities of freshwater from the Mississippi River through the Caernarvon and Davis Pond diversion structures as the State of Louisiana moved to protect marsh ecosystems from the inflow of oil in 2010 resulted in the loss of 2–3 billion market-sized oysters from subtidal areas of Barataria Bay and Black Bay/Breton Sound estuaries (Grabowski et al., 2017; Powers et al., 2017b). Mesocosm experiments funded by GoMRI indicated that exposing oysters to short periods of low salinity could help them combat oil contaminant effects; however, this must be balanced by heavy expected mortality resulting from extended periods at very low salinity (Schrandt et al., 2018). Oysters near the shoreline (fringing oyster reefs) suffered injury from direct oiling as well as from oil removal efforts (Powers et al., 2017a). While the magnitude of oysters killed in the nearshore was an order of magnitude less than in subtidal areas (34 million vs. 2–3 billion market-sized oysters), the loss of fringing oysters from the shoreline resulted in increased marsh erosion and additional loss of spawning stock biomass.

The combined effects of massive decreases in oysters in the subtidal and nearshore oyster areas likely contributed to the prolonged recovery seen in follow-up studies that were funded by GoMRI as a result of decreased oyster recruitment (from the loss of spawning stock biomass). Recent research demonstrated that the longevity of oyster shell, which is necessary to support high settlement of oysters, is limited because of bioerosion and dissolution processes in the environment (Dunn et al., 2014). Consequently, recovery from natural and anthropogenic disturbances may not be adequate if natural recovery extends beyond the lifetimes of shell resources. In such instances, active restoration will be required to restore the oyster resources of the northern Gulf of Mexico.

INFORMING AND TRACKING GULF OF MEXICO RECOVERY

To promote the recovery of the Gulf of Mexico region following the DWH oil spill, the US Congress passed the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012 (known as the RESTORE Act). This law dedicated 80% of the Clean Water Act penalties paid by responsible parties in connection with the spill to the Gulf region to promoting ecological and economic recovery activities. Two of the programs established by the Act, the NOAA RESTORE Science Program and the Centers of Excellence Research Grants Program, focus on supporting research, observation, technology, and monitoring in the Gulf of Mexico. Each program is funded by roughly $138 million plus a portion of the interest from the penalty payments.

The NOAA RESTORE Science Program's mission considers the long-term sustainability of the Gulf of Mexico ecosystem, including its fish stocks, fish habitat, and fishing industries; its work is funded directly from the trust fund of Clean Water Act penalties established by the RESTORE Act. Working in partnership with the US Fish and Wildlife Service, the Science Program seeks to accomplish two equally important long-term outcomes. One is to improve understanding of the processes and connections within the Gulf of Mexico ecosystem. The other is to apply this integrated knowledge of the ecosystem to its sustainable management and restoration (NOAA, 2015). NOAA has laid the foundation to do so by building a program that connects the capacity of the research community to the information needs of resource managers in the Gulf region. By designing its funding opportunities around the needs of resource managers, using a competitive selection process, and working closely with their funded projects, the Science Program is supporting quality research and its application.

The Science Program recognizes the importance of making long-term investments. In the fall of 2019, the Science Program made its first set of long-term awards, which may provide up to 10 years of continuous funding to teams working on long-term trends in living coastal and marine resources in the Gulf of Mexico and the processes that drive them. Such long-term awards have the potential to be transformative by providing sustained funding to promising researcher and resource manager partnerships. To further explore the relationships between trends and processes in the ecosystem and lay the foundation for ecosystem-based management, the Science Program will also support a synthesis initiative that cuts across disciplines and seeks to gain new insights from existing data.

Since its inception, the Science Program has increasingly recognized the importance of investing in research and resource management partnerships. The program has begun to emphasize the use of co-production as one way to generate actionable science. The co-production of science involves iterative collaboration between a researcher and a resource manager in all phases of a research project, and it is often centered around reducing the uncertainties around a specific decision the manager has to make. In addition to conducting competitions to fund co-produced science, the Science Program is also exploring ways to increase the capacity for co-production of science in the Gulf of Mexico region by initiating workshops, seminars, and conference sessions.

Working with priorities set by the research and application needs of resource managers, the Science Program continues to seek opportunities to support monitoring and research that can inform restoration decisions and evaluate restoration outcomes as articulated by practitioners. The key to delivering relevant research findings and products is designing and conducting experiments, models, and monitoring networks tailored to the needs of restoration managers. Rigorous science and monitoring are critical, but it will only be utilized if it is delivered at the geographic and temporal scale of the restoration action and its utility is recognized by the resource manager—ideally even before it is produced.

THE CENTERS OF EXCELLENCE RESEARCH GRANTS PROGRAM

The Centers of Excellence Research Grants Program funds research, science, technology, and monitoring with administrative and civil penalties housed in the RESTORE Act Trust Fund from the DWH oil spill. The Centers of Excellence Program, with a budget of more than $138 million, is near the beginning of its 15-year tenure, with at least one Center of Excellence established in each Gulf Coast State. Centers of Excellence are required to focus on at least one of five disciplines in the Gulf of Mexico or Gulf Coast Region: (1) coastal and deltaic sustainability, (2) coastal fisheries and wildlife, (3) offshore energy development, (4) sustainable and resilient growth and economic development, and (5) observation, monitoring, and mapping. All Centers prioritize data discoverability, accessibility, and usability by other researchers over the long term, and most Centers are housing data at the Gulf of Mexico Research Initiative Information and Data Cooperative. Although the Centers are self-directed and operate in support of separate missions, they all follow the same guidelines and regulations stipulated by the US Department of Treasury, as administrator for the Centers of Excellence Program, and funds for each Center are required to pass through a designated state entity.

Texas OneGulf Center of Excellence

Texas OneGulf is a consortium of nine top state institutions led by the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi. It has wide-ranging expertise in the environment, the economy, and human health. Texas OneGulf was established in 2015 with a mission to improve understanding of the Gulf of Mexico large marine ecosystem and its effects on human health and well-being for the betterment of both. In its initial years, Texas OneGulf supported seven research projects totaling nearly $3 million in RESTORE funding to tackle a variety of issues that directly impact Texas, the Gulf of Mexico, and its residents. These projects include establishing disaster research response infrastructure that can be deployed rapidly to assess the impacts of disasters along the Texas coast in real time, using underwater gliders to search the coast for hypoxic dead zones, and helping Texas communities build resilience and recover from Hurricane Harvey. The diversity and interdisciplinary nature of the projects helped OneGulf become a reliable source of information for Texas decision-makers and resource managers working to protect the Gulf and its coastal communities.

RESTORE Act Center of Excellence for Louisiana

The mission of the RESTORE Act Center of Excellence for Louisiana (LA-COE) is to fund research directly relevant to Louisiana's Comprehensive Master Plan for a Sustainable Coast by administering a competitive grants program and coordinating support to ensure that success metrics are tracked and achieved. The Coastal Master Plan is the guiding document for the Coastal Protection and Restoration Authority (CPRA) that was developed using the best available science and engineering to focus efforts and guide the actions needed to sustain Louisiana's coastal ecosystem, safeguard coastal populations, and protect vital economic and cultural resources. LA-COE is sponsored by CPRA and administered by The Water Institute of the Gulf. LA-COE began in 2014 and has been working with CPRA and various other advisory groups and scientists from The Water Institute of the Gulf to advance the LA-COE mission. In 2017, LA-COE granted universities nearly $3 million to support 13 research, collaborative, and graduate studentship awards. Research topics ranged from coastal restoration impacts to brown pelican nesting habitat, assessment of adaptive migration for coastal residents, and use of radar-based precipitation data sets for hydrology models.

Mississippi Based RESTORE Act Center of Excellence

The Mississippi Based RESTORE Act Center of Excellence (MBRACE) is a consortium of Mississippi's four research universities—Jackson State University, Mississippi State University, The University of Mississippi, and The University of Southern Mississippi (USM)—with USM serving as the lead institution. The mission of MBRACE is to seek sound comprehensive science- and technology-based understanding of the chronic and acute stressors on the dynamic and productive waters and ecosystems of the northern Gulf of Mexico, and to facilitate sustainable use of the Gulf's resources. Since its designation in 2016, MBRACE has dedicated more than $7 million to support oyster reef sustainability and water quality in Mississippi coastal waters, prioritizing research and modeling to inform management and restoration activities led by the Mississippi Department of Environmental Quality, the Center of Excellence pass-through entity in Mississippi, and the Mississippi Department of Marine Resources. The close partnership between MBRACE and state resource managers enables the Center to support research that both increases the state of knowledge and addresses critical management needs.

Alabama Center of Excellence

In the interest of being better prepared to respond to future disasters, the Alabama Center of Excellence (AL COE) will develop and implement a forward-looking competitive grant program that will fund up to 22 research grants and conduct hypothesis-driven, ecosystem-based monitoring focused on the development of data-driven predictions of impacts of future multi-stressors on the coastal and nearshore environments of the north central Gulf of Mexico. Lead scientists will be located at Alabama Marine Environmental Sciences Consortium's 23 member schools, and ecosystem-based monitoring will be led by resident faculty at the Dauphin Island Sea Lab. AL COE will also fund improvements to the Alabama Real-time Coastal Observing System (ARCOS), a core program administered by the Dauphin Island lab. ARCOS collects and disseminates quality-controlled hydrographic and meteorological data to a diverse and large array of stakeholders (e.g., US Coast Guard, National Weather Service, Alabama Department of Public Health) who depend on these data for a range of regulatory, commercial, and recreational activities. Partners in the evaluation of AL COE's work plan will include Mississippi-Alabama Sea Grant and the Mobile Bay National Estuary Program.

Florida RESTORE Act Centers of Excellence Program

In Florida, the RESTORE Act stipulated that the Florida Institute of Oceanography (FIO) serve as the Gulf Coast State Entity, responsible for conducting a competitive grant process to establish Florida's Centers of Excellence rather than serving as the Center of Excellence itself. FIO serves as the program headquarters for the Florida RESTORE Act Centers of Excellence Program (FLRACEP) and is responsible for administering the program's funds and evaluating the performance of each Florida Center of Excellence. Guided by the FLRACEP management team, the program seeks to engage, coordi-

Five-year study finds Deepwater Horizon negatively affected periwinkle snails. Scientists conducted a meta-analysis on marsh periwinkle snails using data spanning five years to investigate how the oil spill affected them over time. The researchers found that snails from heavily oiled sites exhibited decreased density and shell length. There were greater relative proportions of small adults and fewer large adults in heavily oiled sites compared to reference sites. These results suggest that the Deepwater Horizon spill suppressed periwinkle populations and that recovery was slowed or incomplete. (photo) Researchers sampling periwinkle snail density and size along a Louisiana marsh shoreline. *Photo credit: Scott Zengel*

nate, and establish collaborations with ocean and coastal research programs and to promote science and technology innovation among Florida's institutions of higher education, with emphasis on monitoring and supporting the health of the Gulf of Mexico and Florida's coastlines. Since 2015, FIO has established 10 Florida Centers of Excellence and allocated approximately $7 million toward the funding of 18 research projects that address multiple strategic goals identified by the FLRACEP management team.

The Centers of Excellence described here represent a next phase of science and restoration funding across the Gulf of Mexico. Early accomplishments of the 15-year Centers of Excellence program include establishment of the Centers, development of science plans to define scopes and paths forward, and creation of connections and collaborations between the various Centers and other funding agencies. Although disparate in missions, the Centers of Excellence are all ultimately working toward a resilient Gulf of Mexico ecosystem, prioritizing research to inform restoration (e.g., oyster restoration and water quality sustainability in Mississippi and coastal ecosystem restoration in Louisiana), ecosystem monitoring (e.g., the Alabama Real-time Coastal Observing System and monitoring to support healthy coastal ecosystems in Florida), and healthy communities (e.g., hurricane recovery and resilience in Texas and protecting economic and cultural resources in Louisiana). The next 10 years will be critical for research, restoration, and recovery of the Gulf of Mexico following the DWH oil spill, and the Centers of Excellence will continue to support science, technology, and monitoring to meet the needs of their state entities and work toward a healthy, resilient, and productive Gulf of Mexico.

CONCLUSIONS

Oil spills are never good news, and the DWH oil spill was both tragic and environmentally harmful. The good news is that with lessons learned from previous oil spills and the ability of scientists to rapidly undertake field studies before the oil reached the shoreline, GoMRI-funded researchers added significantly to our understanding of ecosystem impacts and were able to continue those studies for a decade following the spill. Additionally, the creation of long-term research efforts like the NOAA RESTORE Science Program and the state-based Centers of Excellence will assure development of a better understanding of ecosystem science to inform restoration efforts and assess recovery.

As expected, recovery and restoration processes of habitats and species assemblages impacted by the DWH oil spill are varied and diverse. Nearshore species with short life cycles living in stable environments recover rapidly (i.e., the Cyprinodontiformes fishes in Barataria and Terrebonne Bays, Louisiana, described above). In contrast, cetaceans and other higher-level vertebrates have suffered multiple physiological impairments, and their recovery is slow and likely to extend for decades in populations severely impacted by the spill. Anthropogenic influence intended to enhance restoration and recovery, such as described for oysters, has risk-reward consequences yet to be evaluated.

In order to correctly determine the true pace of recovery, long-term continuing studies, including monitoring, are essential. Insufficient baseline research was available when the DWH

Study finds oil impacts on fiddler crabs may also affect broader marsh health. Scientists conducted mesocosm experiments to explore how crude oil affects marsh-dwelling fiddler crabs, classified as ecosystem engineers or bioturbators. The researchers tested impacts of various oil concentrations to mimic light to heavy oiling scenarios, with fiddler crabs experiencing more acute impacts at higher oil concentrations and less at lower concentrations. The study results suggest that oil impacts on fiddler crabs may have implications for other species that depend on them for food or ecological changes from their burrowing. (left) A male fiddler crab (*Uca panacea*) sits inside an experimental mesocosm that investigated crude oil impacts. *Photo credit: M.E. Franco, University of Louisiana, Lafayette.* (right) Fiddler crabs in a marsh. *Photo credit: CWC Consortium, LUMCON*

oil spill occurred, making comparison of impacts difficult. However, the GoMRI effort has provided many starting points for long-term studies. In addition, the RESTORE Science Program and the 30-year National Academies of Sciences Gulf Research Program (NRC, 2014) will enable researchers to continue assessments well into the future. Also, the Centers of Excellence Research Grants Program is designed to extend for many years, providing support for scientists to focus on regionally important long-term investigations.

A "new normal" for habitats and impacted ecosystems is often referenced as a possibility. Again, its determination requires extended studies. With the passage of time, as recovery progresses, and anthropogenic influence is included, a return to the previous, or some new, "normal" can be ascertained.

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AUTHORS

Denis A. Wiesenburg (denis.wiesenburg@usm.edu) is Professor of Marine Science, The University of Southern Mississippi, Hattiesburg, MS, USA. **Bob Shipp** is Professor Emeritus, University of South Alabama, Dauphin Island Sea Lab, Dauphin Island, AL, USA. **F. Joel Fodrie** is Associate Professor, Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC, USA. **Sean Powers** is Chair and Professor of Marine Sciences, University of South Alabama, Dauphin Island Sea Lab, Dauphin Island, AL, USA. **Julien Lartigue** is Director, NOAA's RESTORE Science Program, Stennis Space Center, MS, USA. **Kelly M. Darnell** is Assistant Research Professor, The University of Southern Mississippi, and Director, Mississippi Based RESTORE Act Center of Excellence, Ocean Springs, MS, USA. **Melissa M. Baustian** is Coastal Ecologist, The Water Institute of the Gulf, and Director, RESTORE Act Center of Excellence for Louisiana, Baton Rouge, LA, USA. **Cam Ngo** is Assistant Director, Florida Institute of Oceanography, and Interim Program Director, Florida RESTORE Act Centers of Excellence Program, St. Petersburg, FL, USA. **John F. Valentine** is Executive Director, Dauphin Island Sea Lab, and Director, Alabama Center of Excellence, Dauphin Island, AL, USA. **Kateryna Wowk** is Senior Research Scientist, Harte Research Institute for Gulf of Mexico Studies, and Director, RESTORE Act Texas OneGulf Center of Excellence, Corpus Christi, TX, USA.

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HUMAN HEALTH AND SOCIOECONOMIC EFFECTS OF THE DEEPWATER HORIZON OIL SPILL IN THE GULF OF MEXICO

By Paul A. Sandifer, Alesia Ferguson, Melissa L. Finucane, Melissa Partyka, Helena M. Solo-Gabriele, Ann Hayward Walker, Kateryna Wowk, Rex Caffey, and David Yoskowitz

In the wake of the Deepwater Horizon oil spill, hundreds of miles of floating barriers, known as boom, were anchored in place to prevent oil from stranding on the shore and to reduce impacts to sensitive areas such as marshes and bird nesting grounds, as well as areas valued for human use like this fishing spot north of Dauphin Island, Alabama. *Photo credit: US Navy Photo by Chief Mass Communication Specialist Joe Kane, Fleet Combat Camera Group Pacific (Released)*

ABSTRACT. The Deepwater Horizon (DWH) oil spill is the only declared Spill of National Significance in US history, and it significantly impacted the health of people and communities in the Gulf of Mexico region. These impacts amplified adverse effects of prior disasters and may compound those of future traumas. Studies, both to date and ongoing, show some negative mental and physical health outcomes associated with DWH in some spill workers, as well as some coastal residents in all Gulf States. The spill was also associated with negative effects in the living resources, tourism, and recreation sectors, at least in the short term. Compared with others, people dependent on these sectors reported more health and financial concerns. Consumer concerns about the safety and marketability of seafood persisted well after data demonstrated very low risk. Parents were concerned about possible exposures of children as they played on beaches, but this risk was found to be minor. Spill-related stress was an overarching factor associated with adverse health outcomes, and some residents reported greater stress from navigating the legal and claims processes following the spill than from the spill itself. Research revealed a serious lack of baseline health, environmental, and socioeconomic data against which to compare spill effects. This finding highlighted the need for ongoing observing systems to monitor health and socioeconomic parameters and establish continuous baselines of such information.

INTRODUCTION

The Deepwater Horizon (DWH) oil spill was the largest ever in United States (National Commission, 2011) and the only Spill of National Significance. However, large oil spills, defined by NOAA (2017) as exceeding 100,000 barrels (420,000 gal) of oil are relatively rare, and very large ones even more so. Between 1969 and 2017, only 44 large oil spills (45 including the long-leaking Taylor Energy wells in the Gulf of Mexico; Mason et al., 2019) have occurred in US waters (NOAA, 2017), with about one-third of these in the Gulf.

Although they are rare, large oil spills can adversely impact the health of responders, cleanup workers, and residents, and the public welfare of affected communities (Walker et al., in press; Figure 1). The DWH spill also resulted in deaths of 11 oil industry workers. Physical and mental health effects have been reported and are closely related in disaster contexts (Aguilera et al., 2010; Palinkas, 2015; Ohrnberger et al., 2017; H.J. Osofsky et al., 2018), in part because environmental contamination results in significant stress (Hallman and Wandersman, 1992). How people adapt to repeated exposure to stress depends on an array of psychological, sociodemographic, economic, social, physical, and other variables (McEwen, 2005; Norris et al., 2008). Inhabitants of the Gulf region are particularly susceptible to oil spill health impacts due to widespread, preexisting health disparities, continuing exposure to contaminants, and location in a disaster-prone region (Lichtveld et al., 2016; Slack et al., 2020). Not surprisingly, the DWH oil spill, like Hurricane Katrina and other disasters, "had its greatest impact among those with the least" (Abramson et al., 2010).

From its beginning, the Gulf of Mexico Research Initiative (GoMRI) recognized the need for human-focused as well as environmental impact research. It sponsored a public health workshop and broadly advertised a request for research proposals focused on human health effects. Although articles explicitly focused on human health comprised only a small portion of research publications supported by GoMRI funding, they present important findings (Eklund et al., 2019). Additional health-related research was supported via the US National Institute of Environmental Health Sciences (NIEHS), in part with BP funding, some of which is summarized here.

DWH impacts on individuals, families, groups, businesses, and communities were extensive, and they compounded negative effects of previous disasters such as Hurricane Katrina in the Gulf. In turn, these effects are likely to exacerbate traumas of subsequent disasters as well as ongoing threats from chemical pollution, oil seeps, and harmful algal blooms. In this article, we describe potential, perceived, and actual impacts, beginning with the people expected to be most exposed to toxic substances—the response and cleanup workers—followed by effects on those who resided in spill-affected areas, possible hazards to children at play on beaches, seafood contamination risks, and socioeconomic effects on the Gulf's iconic fisheries and tourism industries and communities. We conclude with a discussion of the need for a human health observing system in the Gulf and a list of major findings and critical research needs for the future.

HEALTH EFFECTS ON RESPONDERS AND CLEAN-UP WORKERS

Oil spill response and cleanup workers (hereafter referred to as workers) can be exposed to a variety of hazards, including the oil and its components, burning oil, dispersants, and cleaning agents, plus mixtures of oil, dispersants, and other chemicals. Other work stressors include high heat and humidity, musculoskeletal strain, long working hours, and financial (e.g., job loss) and psychological (e.g., depression, anxiety) effects.

Between 1970 and 2009, there were 458 tanker spills greater than 700 metric tonnes (approximately 222,500 gals) of oil (IOTPF, 2009); 38 of those spills affected human populations. Of those 38 spills, only eight that occurred between 1989 and 2007 were studied in some detail for human health effects (Kwok et al., 2017a): *Exxon Valdez* (US), *Braer* (UK), *Sea Empress* (UK), *Prestige* (Spain), *Tasman Spirit* (Pakistan), *Erika* (France), *Nadhodka* (Japan), and the *Hebei Spirit* (South Korea) (B.-M. Kim et al., 2009; Aguilera et al., 2010; Jung et al., 2013).

Response to the *Exxon Valdez* oil spill led to many changes in oil spill preparedness, training, response, and worker safety and health, including use of personal protective equipment (PPE) in the United States (OSHA, 2020) and globally. Most studies of human health effects occurred in non-US countries where many workers from the community as well as volunteers engaged in oil spill cleanup with little protective gear. Studies that included pre-disaster health data were generally small, had shorter follow-up periods, and primarily investigated acute health symptoms. Acute health impacts were studied for up to one year after oil spill exposure in workers and affected community members to assess anxiety and post-traumatic stress, eye and skin irritation, and respiratory tract consequences (Palinkas et al., 1993; Zock et al., 2007; Na et al., 2012). Several studies reported longer-term respiratory symptoms in workers responding to the *Hebei Spirit* (Gwack et al., 2012) and *Prestige* (Zock et al., 2012) oil spills.

Human health studies following the DWH spill, the largest of their kind in history, are ongoing. Two epidemiological studies examine effects on the health of workers: the NIEHS Gulf Long Term Follow-Up Study (GuLF STUDY; Kwok et al., 2017a) and the US Coast Guard (USCG) Deepwater Horizon Oil Spill Cohort study (Rusiecki et al., 2018). These study teams have collaborated, and both are assessing potential long-term effects, including cancer.

The GuLF STUDY is assessing a

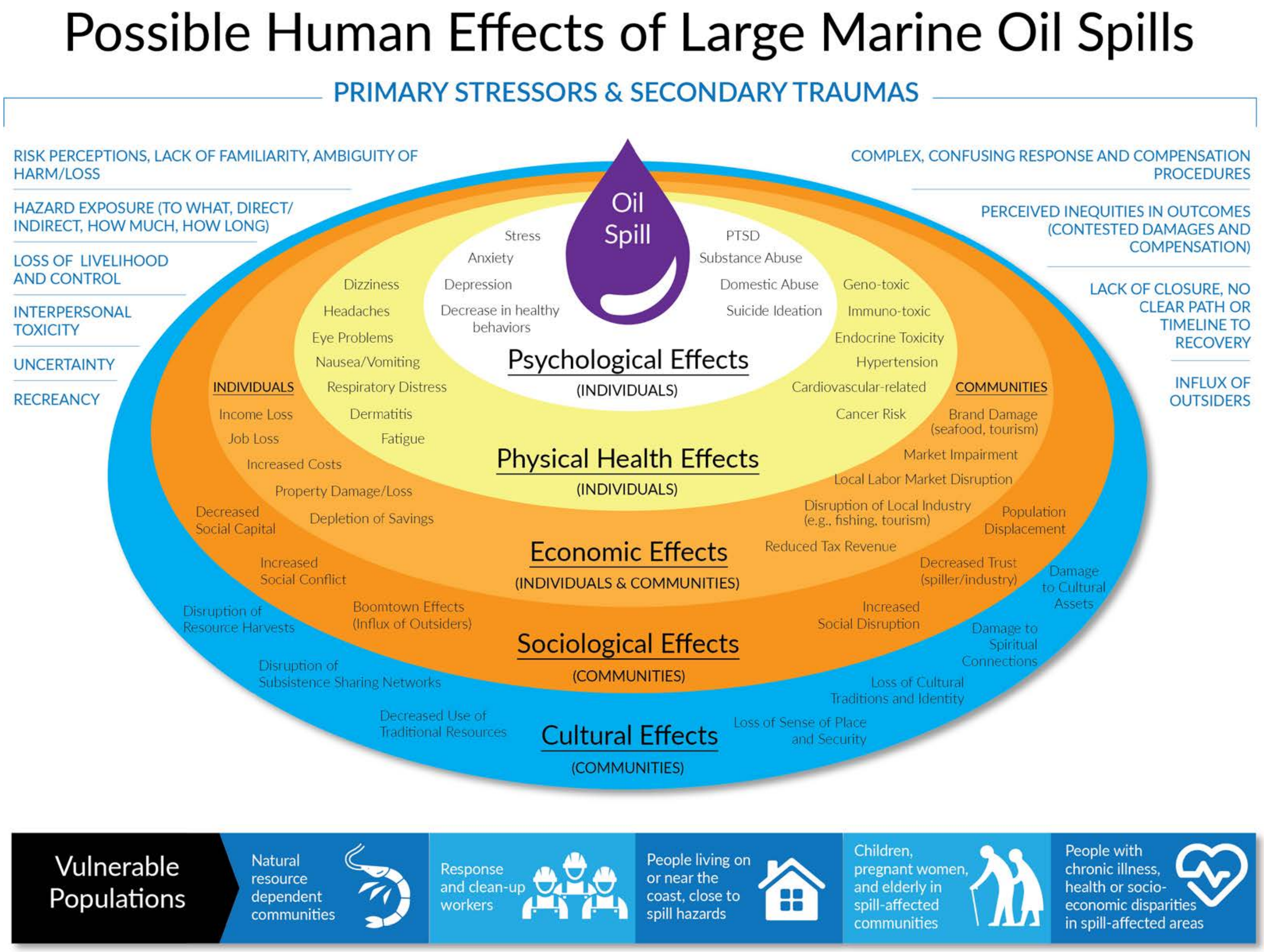

FIGURE 1. A summary of human effects research findings from studies on nine large oil spills: *Exxon Valdez* (USA), *Braer* (UK), *Sea Empress* (UK), *Prestige* (Spain), *Tasman Spirit* (Pakistan), *Erika* (France), *Nadhodka* (Japan), *Hebei Spirit* (South Korea), and Deepwater Horizon (USA). Relatively few spills have been shown to directly and adversely affect human mental and/or physical health, although many may have socioeconomic, ecological, or other effects of concern (Murphy et al., 2016). Whether any direct human effects occur from future spills will depend upon incident-specific conditions such as spilled oil type and volume, location, time of year, response actions, and safety and health protocols. Human susceptibilities to oil spill effects may be increased by pre-existing conditions, incident-specific and general life stressors, traumas, and previous disaster experience. Original concept developed by NASEM (2017) and adapted from Figure 3 in Beyer et al. (2016). Redrawn with permission from Sandifer and Walker (2018), with modifications.

range of human health effects, including worker access to mental health services (Lowe et al., 2015). It uses extensive data on actual and estimated exposures and health outcomes derived from surveys, home visits, and clinical records. Such limitations as self-reporting errors, confounding factors, and potential biases are documented in all papers and are frequently investigated with sensitivity analyses. The full cohort includes 32,608 people. Approximately 25,000 of these were actual workers, and the remainder were non-workers for comparison (i.e., people who were trained but not hired). The period of oil spill work activities was from April 20, 2010, through June 2011. Workers performed a variety of tasks with different exposure profiles under the primary categories of response, support operations, cleanup on water, decontamination, cleanup on land, and administration (Kwok et al., 2017a). The ultimate goal of the GuLF STUDY was to quantify exposures to total hydrocarbons (THC) and BTEX-H (benzene, toluene, ethylbenzene, xylene, hexane) via air measurements as a means of estimating potential toxic effects of THC and BTEX-H on workers (Kwok et al., 2017a).

The USCG cohort study consisted of 53,519 USCG personnel, 8,696 of whom responded to the spill and 44,823 who were not responders. The USCG study used health data from military medical encounters and cross-sectional survey data. Importantly, the USCG study can access a substantial amount of baseline health data for its participants, because medical data are available for all active-duty Coast Guard members from 2007 forward (Rusiecki et al., 2018). For the study, exposure levels and symptoms were based on self-reported and clinical data from the total cohort. While many health studies use self-reported information, including for toxic exposures, such data can be subject to recall and other biases (IOM, 1994; Williamson, 2007). Both the GuLF and USCG studies are continuing, with additional health effect papers expected.

Worker Exposures

To determine effects, physical health assessments evaluate elements of exposure pathways (ATSDR, 2005). THC and BTEX are generally considered to be the more toxic components of oil. THC is a composite of the volatile chemicals from the oil and was used as a surrogate for the workers' "oil experience." The exposure assessment used BP monitoring samples and agency short-term studies and accounted for oil changes due to weathering.

Kwok et al. (2017a), Rusiecki et al. (2018), and Ng et al. (2019) provided details of potential worker exposures and their measurements and estimations. Primary exposure pathways to the oil, burning oil (particulates), and oil spill chemicals are inhalation and direct contact (skin and eye). Due to the way offshore and onshore air quality measurements and exposure estimates were made, reported or observed symptoms cannot be linked to a specific crude oil chemical. From available data, it appears that total hydrocarbon exposure levels for workers likely were low compared to occupational standards (Middlebrook et al., 2012). However, an onshore study conducted from May 1 to September 30, 2010, assessed coastal ambient air quality for benzene and particulate concentrations ($PM_{2.5}$; Nance et al., 2016) using air monitoring data from the US Environmental Protection Agency (EPA) and BP. The EPA's Air Quality Index was compared prior to and during the spill. Onshore concentrations were generally higher following the spill, with benzene 2 to 19 times higher and $PM_{2.5}$ 10 to 45 times higher. Both concentrations were high enough to exceed public health criteria, with coastal areas near the spill and cleanup activities indicating measurable exposure disparities.

Worker Health Findings

GuLF STUDY findings to date have included nonfatal and fatal heart disease and reduced lung function in some workers. Reduced lung function has been documented in workers exposed to oily plants and wildlife compared to unexposed workers (Gam et al., 2018a). While Kwok et al. (2017b) linked reduced lung function with adverse mental health outcomes, Gam et al. (2018 a,b,c) found no association of depression and post-traumatic stress with lung function. Lawrence et al. (2020) reported improvements in lung function decrements four to six years after the spill, with those with the highest exposure exhibiting the greatest improvement.

When Strelitz et al. (2018) compared individual workers involved in DWH cleanup work with non-workers, they found a positive association between several oil spill related exposures and an increased risk of nonfatal heart attacks one to three years post spill. Factors associated with oil spill work, such as heat, strenuous conditions, physical exertion, and the health limitations of the individual worker, make it difficult to ascertain whether the risk of heart disease can be related directly to exposure to oil spill pollutants (Strelitz et al., 2019a). However, risk of heart disease has been associated with oil pollutants, cleanup activities, burned oil particulates, and volatile organic compounds (Strelitz et al., 2019b). The emotional stress related to the spill was also a possible cause of increased physical health risks such as heart attacks (Strelitz et al., 2018). Other analyses suggest that physical health symptoms contribute to cleanup workers' risk for mental health issues (Lowe, 2016). However, fishers who had longer periods of cleanup work and thus potentially higher work-related oil exposure also had higher income, which in turn is associated with lower anxiety and depression (Lowe et al., 2016).

The USCG study reported positive associations between exposure to crude oil, and in some cases oil and dispersant mixtures, and acute respiratory symptoms (Alexander et al., 2018); neurological symptoms including headache, lightheadedness, difficulty concentrating, numbness/tingling sensation, blurred vision, and memory loss/confusion (Krishnamurthy et al., 2019); heat stress (Erickson et al., 2018); and skin issues, as well as some gastrointestinal and genitourinary symptoms that have not previously been well evaluated (Rusiecki et al., 2018).

Dispersants

Dispersants warrant separate mention given the widespread public concern about their unprecedented use during DWH (Starbird et al., 2015; Kwok et al., 2017a). Although studied for decades by oil spill scientists, dispersants remain a controversial response option (Bostrom et al., 2015; Walker et al., 2018). Robust protocols for their application on the water surface were implemented during DWH (Houma ICP, 2010; ASTM, 2018), including monitoring for environmental effects and some air monitoring for 2-butoxyethanol, one of the components in Corexit EC9527A. Although 2-butoxyethanol had been removed from Corexit EC9500A as a result of health concerns related to the *Exxon Valdez* spill (NRC, 2005), it remained in Corexit EC9527A, which was used only in surface applications for about a month during the DWH spill (McGowan et al., 2017). Dispersants were also applied at the wellhead to mitigate impacts from surface oil slicks and to reduce levels of volatile organic compounds near the source. Because the measurements and support documentation related to the dispersants were insufficient to allow reliable estimation of exposure levels across the Gulf (Stewart et al., 2018), the GuLF STUDY used responses to survey questions to assess dispersant exposure and estimated that about 10% of its cohort could have been exposed to dispersants (Kwok et al., 2017a). Findings by McGowan et al. (2017) suggest associations between exposure to dispersants, specifically Corexit EC9527A or Corexit EC9500A, and acute adverse health effects (e.g., respiratory and eye irritation and chest tightness at the time of the oil spill work as well as symptoms that were present at the time of study enrollment one to three years after the spill). Although only 5% of the Coast Guard personnel who responded to the Deepwater Horizon Oil Spill Cohort study health questionnaire reported contact with both oil and dispersants, for example, through assignments to conduct Special Monitoring of Applied Oil Spill Technologies (Levine et al., 2011), self-reported adverse neurological health effects were worse for those workers than for those exposed only to oil, and heat exposure also exacerbated symptoms (Krishnamurthy et al., 2019). However, these authors cautioned that self-reported information can be subject to bias, and they did not have information about who was where and when in reference to possible exposures.

HEALTH EFFECTS ON NON-WORKERS

Human impacts of oil spills are much less studied than environmental impacts (Murphy et al., 2016), physical health effects are better researched among spill workers than in other populations (Laffon et al., 2016; Eklund et al., 2019), and mental health distress is better researched among community residents (Finucane et al., 2020a). Many, if not all, of the health effects noted for workers probably also apply to the general population that may be exposed, although the magnitude of the exposures may be considerably greater for workers.

Oil and associated chemical components have a wide range of known or putative toxic outcomes, including endocrine disrupting, carcinogenic, cytotoxic, immunotoxic, mutagenic, and genotoxic effects (Solomon and Janssen, 2010; Bhattacharya et al., 2016; Du et al., 2016; Laffon et al., 2016; Doctors for Environment Australia, 2019; Holme et al., 2019). Exposures can occur through physical contact with contaminants in air, water, or on materials; disruptions of routine behaviors; socioeconomic impacts; or other pathways (Hobfoll, 1991; Eisenberg and McKone, 1998; Slack et al., 2020).

Physical health problems or indicators identified with oil exposure include assorted respiratory issues; irritation of skin, eyes, nose, throat; chest pain; cardiovascular disease; gastrointestinal complaints; headaches, dizziness, fatigue, memory issues; and abnormal blood cell counts and liver and kidney function tests (e.g., Nance et al., 2016; Singleton et al., 2016; Afshar-Mohajer et al., 2018, 2019; Strelitz et al., 2019a). Laboratory experiments suggest that dispersant and dispersant-oil mixtures produce effects indicative of lung diseases such as asthma and chronic obstructive pulmonary disease (Liu et al., 2016) and mixtures may affect the gut microbiome (J.N. Kim et al., 2012).

Evidence for mental health distress associated with the DWH oil spill is mixed (Finucane et al., 2020a). Two large, population-based surveys in the Gulf Coast region suggest only modest or minimal changes in mental or behavioral health—at the aggregate level—before versus after the DWH spill (Gould et al., 2015). However, results across a range of other, more targeted studies indicate increased reports from individuals of symptoms consistent with depression, anxiety, and post-traumatic stress (Grattan et al., 2011; H.J. Osofsky et al., 2011, 2015; Buttke et al., 2012a,b; Gill et al. 2012, 2014; Morris et al., 2013; Drescher et al., 2014; Cherry et al., 2015; Fan et al., 2015; Aiena et al., 2016; Rung et al., 2016, Gaston et al., 2017; Kwok et al., 2017b). Substantial portions of coastal households (e.g., nearly 38% of an Alabama sample; Ritchie et al., 2018) were involved directly or indirectly in DWH-related claims, settlements, or litigation activity. Research on the compensation process suggests it was perceived by residents as random and lacking transparency, and resulted in additional psychological stress for individuals and corrosive effects on communities (Mayer et al, 2015; Ritchie et al., 2018; Halmo et al., 2019).

Even years after the spill, Gulf Coast residents report DWH-associated distress, but this may vary for different social groups, in part because of differing prior trauma, life disruption (especially income loss), or available support (Arata et al., 2000; Grattan et al., 2011; Morris et al., 2013, Cherry et al., 2015; Rung et al., 2016; Ayer et al., 2019; Ramchand et al., 2019; Bell et al., 2020; Parks et al., 2020). Higher levels of social support, sense of community, and perceived resiliency seem to be protective against spill-related stress. However, social support was not ameliorative for all groups, such as those with high attachment to damaged resources (e.g., fishing households; Parks et al., 2020) or nonreligious people living in highly religious areas (Drakeford et al., 2019). Ayer et al. (2019) reported that, after controlling for other traumatic experiences, individuals with higher levels of DWH exposure were not at greater risk for behavioral health problems, except for illness anxiety.

Fishers and Seafood Workers

Fishers and seafood workers are often members of tight-knit cultural communities (Picou and Gill, 1996; Marshall et al., 2007), and the cultural identity of the Gulf Coast region is intertwined with fishing (Henry and Bankston, 2002). Short-term fishing moratoria were enacted immediately following DWH (see Seafood Safety section), and even when the moratoria were lifted, uncertainty about the contamination of fishing grounds continued for fishers and seafood workers (Simon-Friedt et al., 2016). In addition to pre-existing economic pressures (Harrison, 2020), the ongoing disruption and stress from the DWH spill contributed to the unique vulnerability of these workers (Gill et al., 2012; Lee and Blanchard, 2012; Cope et al., 2013, 2016; Parks et al., 2018). While greater social support is typically helpful in bolstering mental health, it may operate differently among renewable resource communities (Freudenburg, 1992; Gill et al., 2014). Indeed, Parks et al. (2020) found that fishing households with greater social support were more susceptible to depressive symptoms six years after the DWH oil spill.

Cope et al. (2013) evaluated suites of self-reported mental and physical health issues via the Louisiana Community Oil Spill Survey, conducted in spill-affected parishes in June 2010 while the DWH oil spill was ongoing, and again in October 2010 and April 2011. A physical health index was calculated based on responses to questions about how worries about the spill manifested as physical symptoms. The index was significantly higher (indicating more health concerns) among fishing households, and while the index declined in subsequent survey waves for those not involved in the fishing industry, it grew stronger over time for people in the industry. Parks et al. (2018) used the same data source to examine disruption of routine behaviors, including sleep, following the spill. On average, respondents reported difficulty with about one-third of the activities. Again, respondents with ties to the fishing industry were more likely than non-fishers to report disruption to routine behaviors.

Women, Pregnant Women, and Children

Results of previous studies revealing adverse reproductive health effects for people exposed to petroleum hydrocarbons led to concerns about potential impacts on pregnant women in the Gulf following the DWH spill (Merhi, 2010). In the case of the DWH event, women physically exposed to the spill or who experienced negative economic impacts reported physical symptoms such as wheezing or irritated eyes and nose (Peres et al., 2016). Similarly, pregnant women who lived near the *Hebei Spirit* spill site in South Korea reported more eye irritation, headaches, and pain than those further away (B.-M. Kim et al., 2009). With regard to reproductive health, Harville et al. (2018) found little evidence of DWH spill exposure being associated with increased miscarriages or infertility in women from southeastern Louisiana, although spills in Nigeria have been linked with increased mortality rates among newborn children (Bruederle and Hodler, 2019). Among patients (predominantly African American women) seeking care at a Federally Qualified Health Center in an underserved area affected by DWH, post-traumatic stress disorder was associated with headaches, chest pains, dizziness, or trouble sleeping (Langhinrichsen-Rohling et al., 2017). However, where patients received post-disaster, integrated health services, perceptions of personal resilience increased and negative physical symptoms decreased (H.J. Osofsky et al., 2018).

Children are especially vulnerable to oil spills due to their physiology (high respiratory and metabolic rates, developing immune and hormonal systems, small stature), behavior (e.g., inquisitive play; Tipre et al., 2017; Slack et al., 2020), and poorly developed ability to estimate risk (Fischhoff et al., 2010) (see section on Beach Exposures). Children exposed to the DWH oil spill were twice as likely to have mental and physical health problems compared to those who were not exposed, and African American children and those from low-income households had higher prevalence of health effects (Abramson et al., 2010). Based on health status reports for children four, six, and eight years after the spill, general health and numbers of recent physical health problems (respiratory symptoms, eye and/or vision issues, skin problems, headaches, or unusual bleeding) were worse in households that experienced physical exposure to the spill or job/economic losses (Slack et al., 2020).

PHYSICAL HEALTH EFFECTS TO POPULATIONS FOLLOWING BEACH CONTAMINATION: CHILDREN'S EXPOSURES AS AN EXAMPLE

Health-related exposures associated with oil spills can be estimated through quantitative risk assessment of health impacts. The risk assessment process addresses hazard identification (chemicals of concern and their environmental concentrations), exposure assessment (human activities that lead to exposure through ingestion, skin contact, or inhalation), and dose-response evaluation (amounts of the chemicals likely to enter and be absorbed in the body (Figure 2; NRC, 2009; Ferguson et al., 2020a). The effect is an estimate of risk typically provided in units of probability.

Hazard Assessment

The first step in quantifying risks is to estimate the concentrations of oil spill chemicals within human exposure zones such as beaches. Thousands of chemicals can be found in crude oils. They can be broadly categorized into hydrocarbon, non-hydrocarbon, organometallic, and metallic compounds (Huba and Gardinali, 2016). Chemicals of concern in crude oil, those potentially toxic to humans, are the volatile aromatic hydrocarbons, BTEX-H, and the polycyclic aromatic hydrocarbons (PAHs) (ATSDR, 2005). Mitigation of oil spills can also include the use of dispersants, for which potential toxicities to humans are under debate (Ferguson et al., 2020a; NASEM, 2020; Quigg et al., 2021, in this issue); their use would need to be considered in risk assessments for future oil spills. Of the chemicals listed above, the PAHs and their degradation products have the most significant impacts at beaches because they weather slowly and are generally the most toxic (ATSDR, 2005). Also, toxicological profiles are not currently available for many oil chemicals and degradation products and for vulnerable populations for which information is very limited (e.g., pregnant women and children; Aeppli et al., 2012; White et al., 2016; Farrington, 2019).

Immediately after the DWH explosion, large-scale sampling efforts were initiated by the EPA, BP, and other organizations. Their measurements of oil spill chemicals were available within environmental matrices, including nearshore water and beach sediments, where beachgoers could be affected. Although these data provide snapshots of chemical concentrations, a more complete picture in time and space possibly could be obtained by using the data in oil spill models to predict oil spill chemical concentrations in nearshore environments. The General NOAA Operational Modeling Environment (GNOME) was used to help inform the Coast Guard-led response efforts about the areal extent of oil contamination. Initial efforts have been made to evaluate how well predictions from GNOME coincide with chemical concentration measurements (Montas et al., 2020; J. Xia et al., 2020, 2021), opening the possibility for future use of operational models to forecast oil spill chemical concentration distributions and provide an important first step for risk assessment.

Exposure Assessment

Different groups of humans can be exposed to oil spill chemicals at beaches, including response workers who actively engage in cleanup of contaminated shorelines and recreational users of these areas. Here, we focus on the recreational user category, and specifically on children who may be exposed to incidental residual oil that remains after beach cleaning and also to low level oiling that may occur from continuous leaks (e.g., Taylor Energy wells, seeps) and the redistribution of sunken oil. As noted elsewhere, children are a vulnerable constituency for exposures to contaminants in soil and sands, including potentially at beaches (Freeman et al., 2005; Xue et al., 2007; Beamer et al., 2012; Ferguson et al., 2019). In addition to factors noted previously, a child's mouth and nose are generally closer to the ground than an adult's, resulting in greater inhalation of pollutants that accumulate in sediments. Also, children's play habits involve intimate contact with and potential ingestion of beach sand (Shoaf et al., 2005), and they tend to dig, bury themselves, and sit in the very shallow water, which typically has the highest levels of contaminants (Shah et al., 2011; Wright et al., 2011). Although these behaviors are specific to the beach environment, they had not been quantified prior to research supported by GoMRI following the DWH. GoMRI-supported studies have quantified children's behaviors on beaches in Miami, Florida, and Galveston, Texas, through surveys (Ferguson et al., 2019), sand adherence studies (Ferguson et al., 2020b,c; Perone et al., 2020; Tomenchok et al., 2020), and videotaping of children and translating the videos to quantitative values that describe child beach play behavior (Alicia Ferguson, North Carolina Agricultural and Technical State University, *pers. comm.*, 2021). Collectively, these studies have documented child beach play behaviors that can now be utilized in risk assessment analyses.

Dose-Response Assessment

Effects from the uptake of chemicals are typically separated into two types: non-cancerous (acute and chronic) and cancerous. Non-cancerous effects are evaluated by comparing the estimated dose to minimum risk levels for chemical compounds. If the dose is greater than the corresponding minimum risk level, then non-cancerous illnesses are likely to occur. To estimate the probability of cancer, a slope factor is needed and can be obtained for some oil chemicals from

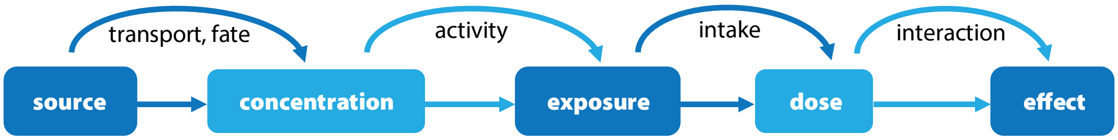

FIGURE 2. Framework for a risk assessment modeling platform.

toxicological profiles available through the US Center for Disease Control's (CDC's) Agency for Toxic Substances & Disease Registry and EPA's Integrated Risk Information System.

Risk Assessment Framework

Available information about hazard characterization, exposure assessment, and dose-response assessment has been incorporated in a risk assessment framework. Although work is currently ongoing to quantify children's activities, results to date indicate that children who play at beaches that were cleaned after oil contamination are unlikely to experience non-cancerous acute or chronic health effects. Additionally, increased cancer risks are very low, within the 10^{-6} order of magnitude (i.e., about one in a million; Black et al., 2016, Altomare et al., 2021), given toxicological information available at the time. Also, simultaneous exposure to multiple chemical contaminants was not compounded in the analysis. Moreover, mental health outcomes can manifest in physical outcomes from chemical exposures and were not integrated into the analysis.

SEAFOOD SAFETY

Oil Spills and Fisheries Closures

Following all oil spills in marine waters, the potential contamination of seafood supplies and the subsequent risks posed to human health from seafood consumption are of major concern to government authorities and community members where the spill occurred (Gohlke et al., 2011; Dickey and Huettel, 2016; Wickliffe et al., 2018). The magnitude and duration of the DWH spill posed a significant threat to the well-being of Gulf Coast communities, many of which depend upon safe and productive fisheries (Dickey and Huettel, 2016). At the time of the spill, Gulf fisheries accounted for around 16% of all US domestic landings (Shepard et al., 2013), fueling concerns of Gulf residents and non-residents about the safety of the nation's seafood supply.

In anticipation of potential contamination, surveillance testing of seafood around the periphery of the spill began on April 28, 2010. Just four days later, May 2, 2010, the first emergency fishery closure was announced. This was only the second time in US history that a fishery in federal waters was closed because of an oil spill (Fitzgerald and Gohlke, 2014). Shortly thereafter, on May 24, the federal government declared a fisheries disaster for the states of Alabama, Mississippi, Louisiana, and Florida (K. Xia et al., 2012). By early June, at the height of the spill, nearly 37% of federal waters in the Gulf of Mexico Exclusive Economic Zone were closed to fishing along with state waters extending from Louisiana to the panhandle of Florida and some public beaches (Ylitalo et al., 2012). Though federal fishing waters began to reopen as early as the end of June 2010, it was not until April 2011 that all federal waters, including those immediately surrounding the wellhead, were fully opened. Sampling of previously closed waters continued through June 2011 (Ylitalo et al. 2012). Although most fishery closures in state waters were lifted by August/September 2010, it was several more years before the most heavily impacted coastal waters in Louisiana were considered safe for fishing (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016).

Federal Response to Human Health Concerns

Higher molecular weight PAHs, like those that made up ~3.9% of the oil from the DWH well, are of particular concern for seafood safety because of their persistence in the environment, potential for uptake in aquatic species, and toxic or carcinogenic effects (Goldstein et al., 2011; Allan et al., 2012). Though the use of dispersants (Corexit 9500A and 9527) had been approved by the EPA, and they were determined to have minimal toxicity in laboratory experiments (Judson et al., 2010), their unprecedented use led to public concern about potential accumulation in seafood supplies (Ylitalo et al., 2012).

The federal response to seafood safety followed a similar approach to that used in the response to the *Exxon Valdez* spill in 1990, with minor modifications based on the difference in the nature of the Gulf oil and the environmental conditions in which the spill occurred (Ylitalo et al., 2012; Dickey and Huettel, 2016). Finfish and shellfish samples were collected from multiple seafood sources and at multiple locations and depths in areas free or cleared of oil (Ylitalo et al., 2012). Seafood samples were not collected from areas where oil was visibly present on the surface or chemically detected in the water column since these locations were closed to fishing (USFDA, 2010). Samples were screened for the presence and concentrations of 13 PAHs determined to have the most potential to harm consumers as well as dioctyl sodium sulfosuccinate (DOSS), an indicator compound for the dispersant Corexit 9500A. Levels of concern for each targeted compound were calculated based on a variety of factors that included estimated dose, mean adult body weight, and averaged seafood consumption rates for the 90th percentile of seafood consumers (USFDA, 2010). These levels were considered to be safe or associated with negligible cancer and non-cancer risk for the US population (Ylitalo et al., 2012). However, the risk level, estimated duration of exposure, and the use of national demographic values for body weight, consumption rate, and longevity were extensively scrutinized (Gohlke et al., 2011; Ylitalo et al., 2012; Wilson et al., 2015; Dickey and Huettel, 2016). There was particularly strong criticism around the adequacy of information about exposure risks and how those risks were communicated to vulnerable populations (Rotkin-Ellman et al., 2012; K. Xia et al., 2012; Sathiakumar et al., 2017), such as pregnant women and Vietnamese-American fishers and their families.

After nearly 10,000 samples and months of testing, federal and state authorities determined that Gulf seafood from reopened areas was safe for consumption (Ylitalo et al., 2012; Dickey and Huettel, 2016). While individual PAHs of the 13 considered to be most harmful and/or carcinogenic were detected in many seafood samples, the concentrations were at least two orders of magnitude below levels of public health concern (Ylitalo et al., 2012). Further, DOSS was detected in less than 1% of samples and at very low concentrations. Though heavy metals were also a concern for many, particularly for vulnerable populations (Zilversmit et al., 2017), they were not included in the federal or state testing protocols (Fitzgerald and Gohlke, 2014). However, trace metal levels in both finfish and shellfish samples did not exceed background levels as determined by independent testing (Fitzgerald and Gohlke, 2014; Zilversmit et al., 2017).

Sathiakumar et al. (2017) specifically examined additional exposure risks to children from the coastal area of Mobile, Alabama, compared to children living inland. They concluded that there was no increased risk of exposure despite higher seafood consumption rates among coastal children compared to the general population. Further, Wickliffe et al. (2018) found that, even with consumption rates of both shrimp and finfish set at highly conservative values for human health (0.7 lbs [0.3 kg] per week and upward of 8.3 lbs [3.8 kg] per week, respectively), nearly three times the rates used to calculate the federal threshold levels of concern, concentrations in seafood samples did not constitute an unacceptable lifetime cancer risk.

Widespread fisheries closures following the DWH event reduced the probability of contaminated seafood entering into commerce. However, comparisons of pre- and post-spill consumption of seafood in multiple populations found a significant decrease in consumption in the immediate aftermath of the spill (Sathiakumar et al., 2017; Zilversmit et al., 2017; Wickliffe et al., 2018). Though the federal response to the spill, including the seafood testing program, drew much public scrutiny and concern, results from independent studies largely corroborated the federal effort. While some researchers found shortcomings in the federal approach, including the narrow scope of the PAHs included in chemical screening (Andersson and Achten, 2015; Dickey and Huettel, 2016; Farrington, 2019), based on toxicity information available at the time, no studies concluded that there was an excess exposure risk from consuming Gulf seafood in the months and years after the oil spill (Gohlke et al., 2011; Dickey and Huettel, 2016; Wickliffe et al., 2018). However, it is also largely agreed that the communication of exposure risks in general, and to vulnerable populations specifically, left much to be desired (Greiner et al., 2013; Dickey and Huettel, 2016).

SOCIOECONOMIC IMPACTS ON FISHERIES, TOURISM, AND COMMUNITIES

The DWH spill resulted in numerous socioeconomic impacts, including effects on the fishing, tourism, and transportation sectors, and others that may affect community vulnerability and resilience. Similar to investigations related to human health impacts, GoMRI supported research on DWH socioeconomic effects but at comparatively modest levels, with resulting publications constituting only approximately 6% of total GoMRI-funded publications and about 4.2% of total competitive grant funds awarded (Petrolia, 2014; Finucane et al., 2020a). While much progress has been made in longitudinal monitoring of biophysical parameters, there is a lack of similarly robust efforts to monitor a suite of socioeconomic variables that could be used to assess the value of non-market resources, or identify cultural attributes, attitudes, social connectivity, or resilience in an oil spill or other disaster context (NRC, 2013; Yoskowitz et al., 2015).

Economic Impacts

In an initial study, Sumaila et al. (2012) utilized input-output analysis to estimate economic impacts for commercial fishing, recreational fishing, and marine aquaculture. They projected the highest total economic losses to commercial and recreational fishing, US $4.9 billion and $3.5 billion, respectively. The largest commercial fisher losses were predicted for shrimpers, which accounted for almost 85% of the study's projected impact to that sector. In a separate analysis, Asche et al. (2012) suggested that, due to market integration, any increase in prices (driven by spill-related reductions in supply) would not offset expected revenue losses to domestic shrimpers. Rather, imports of farmed shrimp would rapidly increase to satisfy demand, meaning that while consumers would be mostly unaffected, producers could face significant and additive supply shocks. Overall, such impacts were expected to result in significant loss of income to shrimpers, as well as in boat building or repair, restaurants, and other businesses.

Notably, analysis is still needed to confirm economic impacts to fisheries 10 years after the spill. For example, while studies alluded to significant impacts to US shrimpers, in 2011, the year following the DWH spill, the Gulf produced >216 million pounds (98 million kilograms) of heads-on shrimp at a commercial landings value of >US $421 million (NOAA, 2020), accounting for about 68% of US shrimp landings that year (NRC, 2013). For comparison, average Gulf shrimp landings for the period 1990–2009 were 236 million pounds (107 million kilograms), with a range of 181–290 million pounds/yr (82–132 million kilograms/yr). While evidence does show reduced demand and a decrease in seafood sales directly after the spill (McGill, 2011), it is not clear whether these effects persisted. For example, the total commercial landings value for all species in the Gulf (Texas, Louisiana, Mississippi, Alabama, and Florida West Coast) for the seven years following the spill (2011–2017) was US $6.8 billion (Consumer Price Index [CPI] adjusted), whereas landings for the seven years preceding the spill (2003–2009) had a total CPI adjusted value of US $5.9 billion (NOAA Fisheries data, CPI adjusted).

Using biophysical projections from the Atlantis ecosystem model (Ainsworth et al., 2018) with input-output analysis, Court et al. (2020) modeled total economic impacts for the 10 years following the spill for commercial fishing revenues and recreational fishing expenditures. Results indicate that, across both sectors, impacts could include losses totaling US $2.3 billion composed of $1.2 billion in gross regional product, $700 million in labor income, and $160 million each in federal and state tax revenues. However, more research is needed to reconcile modeled outputs and actual landings data, particularly for sectors anticipated to incur significant impacts such as the shrimping industry.

With nearly 223,000 km^2 of fishable waters and public beaches closed or showing oil spill advisories during the months-long spill event (Ylitalo et al., 2012), the tourism industry was also impacted. Misperception also contributed to tourism impacts, with one report demonstrating that the public was unaware of locations and extent of damage and believing Louisiana waterways to be closed when they remained open (MDRG, 2010). Of those surveyed, 44% believed the oil spill caused damages on par with Hurricane Katrina, and 29% of tourists canceled or postponed planned trips to Louisiana due to the spill (MDRG, 2010). Another study found that about US $147 million in tourism and recreation claims were paid between August 2010 and March 2012. While this amount only represented 2% of total claims, it spanned 23 different business types within the industry, including airlines, aquaria, entertainment, water sports, wildlife watching, and more. Claims for impacts to retail, sales, and services were about US $1.9 billion representing 31% of total claims, while those for food, beverage, and lodging amounted to US $1.6 billion and 26% of the total (Eastern Research Group, 2014). Analysis of claims across the Gulf further found significant impacts on resorts, charter fishing, and marinas/docks/ice houses, though hotels and restaurants were most impacted. Effects differed among the states, with Texas receiving a relatively small amount of paid claims, while individuals in Florida and Louisiana received US $340 million and $227 million, respectively, and businesses US $164 million and $88 million, respectively (Eastern Research Group, 2014). Though individuals and businesses clearly suffered economic losses, counties with over 1,000 employees in tourism experienced only temporary or no declines in tourism-related employment, followed by growth, though there were exceptions. For example, Hancock County, Mississippi, experienced a 7.7% decline in tourism employment compared to 2009 (Eastern Research Group, 2014).

An important finding is that consumer perception matters and is an important driver of economic impacts. A review of news articles and interviews found numerous inaccurate portrayals of conditions, with media sensationalism contributing to a perception that the entire Gulf coast was contaminated with oil (Eastern Research Group, 2014). To counter such misinformation in the future, Nelson et al. (2018) offer a spatially explicit approach for evaluating and visualizing risks to tourism or other economic sectors.

Other studies also lend insights for future research. In a case study of New Orleans, Porter (2011) argues that fishing and tourism should be viewed as a cluster of overlapping geographic space, knowledge, and impact, for example, with tourism concentrated on recreational fishing and the seafood culture. Such interdependence may limit opportunities for growth where risks of economic and environmental crisis persist, yet innovation could address some risks to external shocks. For example, a tourism subsector could focus on ecotourism and demonstrate how the city and ecosystem remained resilient to the DWH disaster, which could provide a new kind of growth (Porter, 2011). Researchers also investigated non-market impacts of the oil spill. Alvarez et al. (2014) used choice modeling to estimate compensation due to marine anglers from non-market value losses at a mean of US $585 million with a 95% confidence interval. Petrolia (2014) offers that perhaps the most prominent change for research resulting from the disaster was an expansion to an ecosystem services approach to damage assessment. The National Research Council (NRC, 2013) assessed oil spill impacts on the provisioning ecosystem service of seafood and fish-based products, as well as the cultural services provided through recreational fishing (among other case studies). Results suggested that, while fishery closures may have decreased landings in the immediate aftermath of the spill (McCrea-Strub et al., 2011; NRC, 2013), increased catch rates were later observed for a large group of regularly harvested species (Fodrie and Heck, 2011; NRC, 2013). However, impacts from the spill to fishery harvest may take years or even decades to materialize, particularly regarding cascading effects through marine food chains (NRC, 2013).

Community Resilience Impacts

Resilience is "the capacity of a system to absorb shocks and disturbance and still maintain function" (Berkes and Folke, 1998), or "the capacity of a social-ecological system to adapt to change through self-organization and learning" (Berkes et al., 2003). Finucane et al. (2020a) examined a set of adaptive capacities that may diminish impacts of an ecological disaster like the DWH, finding that although the spill resulted in differing economic impacts across fisheries, tourism, and oil and gas sectors with location, the aggregate impacts were primarily short term. However, at the household level, and particularly in poorer households, financial impacts were still being felt years later. Further, community well-being showed signals of distress related to the spill across multiple studies. Distress was expressed differently across different groups, with those tied to natural resources for their livelihoods exhibiting higher rates, including through an erosion of trust (Finucane et al., 2020a).

Similarly, Cope et al. (2016) found levels of distrust across communities regarding information provided by both BP and the federal government, with trust in state government being somewhat stable. Mayer et al. (2015) reported that, although the compensation process helped to mitigate economic impacts, apparent confusion, lack of transparency, and perceived inequality in the process eroded trust and strained community relations. In addition to those reliant on natural resources, other groups identified as having higher vulnerability to the spill included populations that exhibit disadvantages related to rural environment, dependence, older age, and socioeconomic and/or educational disparities, as well as living in mobile homes (Cope and Slack, 2017), being of minority ethnicity (e.g., Vietnamese; Patel et al. 2018), or being female (Lightfoot et al., 2020). In a case study of Apalachicola, place, heritage, and moral identity were found not to be fixed community attributes but rather to provide individuals with varying resources, which in turn impact disaster recovery (Clarke and Mayer, 2017). This has important implications for institutional recovery frameworks—often crafted by external actors—in a precarious Gulf region where resilience may vary locally. For future spills and other disasters, more attention should be given to the researcher-community relationship, where cultural norms and trust are critical for successful engagement with local residents (Lesen et al., 2019; Finucane, 2020b).

NEED FOR A COMMUNITY HEALTH OBSERVING SYSTEM

Environmental disasters of various kinds and magnitudes occur frequently in the Gulf region (NOAA, 2020; Sandifer et al., 2020; Smith, 2020), with one often following another and compounding the impacts of the previous incident. Examples include the 2010 DWH oil spill that followed the catastrophic effects of Hurricane Katrina in 2005, and the health effects of which were then compounded by subsequent disasters such as Hurricane Harvey in 2017, and others (J.D. Osofsky et al., 2014; Shultz et al., 2015; SAMHSA, 2018). Recurrent disasters take a heavy toll on human health in the region, where many people already suffer significant health and economic disparities (Lichtveld and Arosemena, 2014; Lichtveld et al., 2016). Climate change, land subsidence, and population and development pressures are all likely to increase the incidence and severity of environmental disasters in the Gulf region, along with their accompanying adverse effects on human health (Sandifer et al., 2020).

Previous studies of health effects of Gulf disasters, as well as other sections of this article, demonstrate the lack of, and critical need for, baseline health information with which to compare effects of future disasters (Sandifer et al., 2020). Ongoing health monitoring is essential to develop and maintain such a baseline and capture acute, chronic, and long-term health impacts, as well as secondary complicating events that occur in the intervals between major disasters. Recognizing the urgent need for a health observing system in the Gulf of Mexico region analogous to the kinds of atmospheric and oceanic observing systems well established for monitoring and predicting hurricanes and other extreme weather events, GoMRI commissioned a design study. The intent was to devise a framework that would provide for continuous collection of health information to ensure existence of adequate pre-, during, and post-disaster information for comparative purposes and to improve emergency planning and public health response. The resulting framework (Sandifer et al., 2020) builds upon and leverages existing ongoing national health surveys and includes new longitudinal cohort studies designed to elucidate long-term health trends and disaster-associated health effects in the five Gulf states. The system's new cohort studies must continue indefinitely, be large enough to represent the risk-prone coastal areas and populations known to be particularly vulnerable to disasters, and include mental and physical health assessments and measures of stress. In addition to collecting and providing information on direct and indirect health impacts to individuals, the system should also incorporate community data. As far as we are aware, this is the only observing system designed for a disaster-prone area and focused explicitly on disaster-related health effects.

Components of the proposed Gulf of Mexico Community Health Observing System would include: three cross-sectional surveys, the National Health and Nutrition Examination Survey (NHANES; https://www.cdc.gov/nchs/nhanes/), the Behavioral Risk Factor Surveillance Survey (BRFSS; https://www.cdc.gov/brfss/), and the National Health Interview Survey (NHIS; https://www.cdc.gov/nchs/nhis/); a proposed new Augmented BRFSS survey for the Gulf states; the new National Institutes of Health (NIH) All of Us national longitudinal study (https://allofus.nih.gov/); and proposed new Large, Small, and Disaster-Specific Gulf of Mexico longitudinal cohort studies (Figure 3). The cohort studies are designed to build upon one another and are the unique and most important parts of the observing system. Another significant strength of the system is its ability to adapt rapidly as needs arise and new biomedical and other technologies are developed.

The geographic focus of the proposed observing system is the 68 coastal counties of the five Gulf states. These are counties that either have a Gulf shoreline or are near the coast and contain Federal Emergency Management Agency (FEMA)-identified areas with high risk for tidal and/or storm surge flooding (Ache et al., 2013). A statistically representative sample of volunteers from the populations in these counties is proposed, with stratification to ensure proportionate inclusion of both urban and rural populations and with additional, targeted recruitment as necessary to enroll adequate numbers of people deemed particularly vulnerable or typically underrepresented (e.g., ethnic minorities, the underserved, and those who suffer health, health care, and economic disparities). Initially, volunteer participants are expected to be recruited using a mail-address sampling frame, followed by use of electronic communication means to the greatest extent possible.

If implemented, assessments of mental and physical health in the new cohort studies will include information obtained via detailed health questionnaires, clinical examinations, biological specimens, electronic health records, and use of wearable health devices. These will be augmented with data from secondary sources such as information from State Health Departments and the CDC, national community surveys, environmental exposure databases, social media, remote sensing, and others. Biomarker data derived from biological samples are expected to be used as indicators of health status, including for calculation of measures of chronic stress and its impacts on physical and mental health.

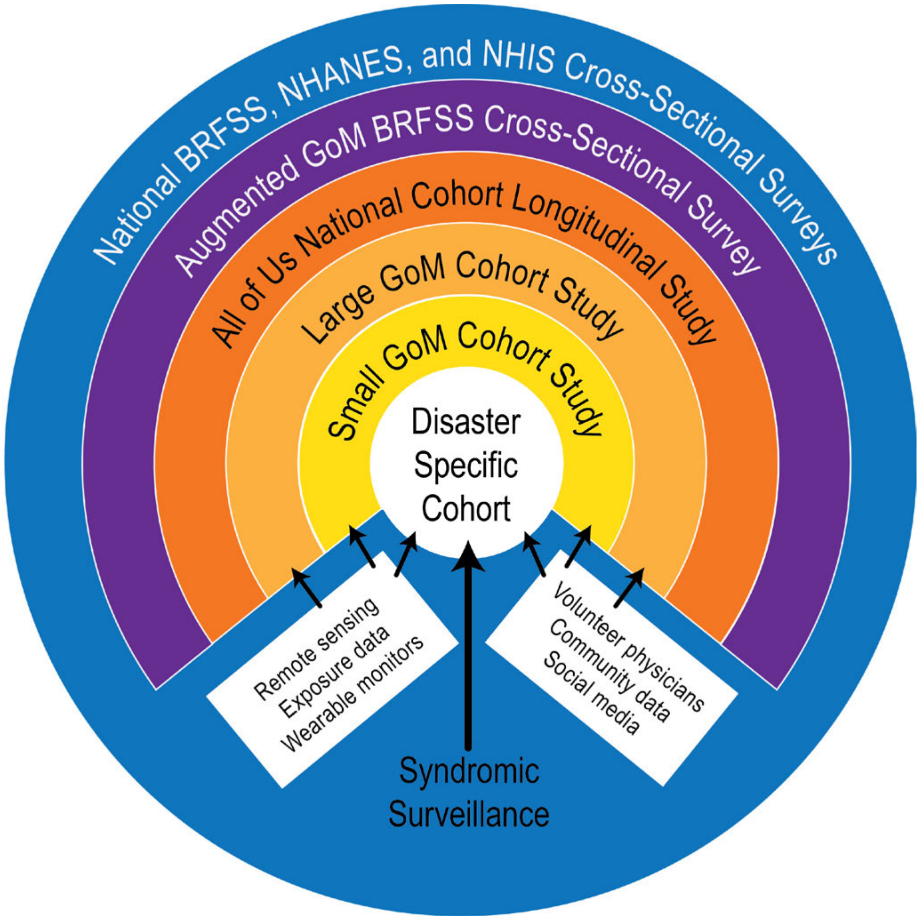

FIGURE 3. A conceptual framework for a Gulf of Mexico Community Health Observing System. *From Sandifer et al. (2020)*

Primary users of information from the health observing system will be public health and medical professionals, emergency managers and responders, and clinical and academic researchers. Secondary users are likely to include political, community, and business leaders, and many others. Data and information products are expected to be used to assess disaster-related health effects; enhance disaster planning and response; improve protection for disaster responders and workers; build individual and community resilience; and promote new clinical, biomedical, and public health research and practice.

CONCLUSIONS, GAPS, AND OPPORTUNITIES

A broad range of mental and physical health impacts has been attributed to oil spills in general and the DWH disaster in particular, but in most cases definitive cause-and-effect linkages are lacking. Overall, mental and physical health effects and their interactions are inadequately studied for oil spill workers, their families, and others who may be exposed to or affected by them. Besides spill workers, special attention is needed to vulnerable people, including individuals with chronic illness or who suffer health and health-care disparities and/or socioeconomic deprivations, lack strong social support, the elderly, and natural-resource-dependent communities.

A common theme across studies is the overarching role of stress (e.g., from physical exposure, job or income loss, compensation/litigation processes, or behavioral disruption) as an important factor associated with poor mental and physical health outcomes.

Human health findings were severely limited by a lack of baseline health data, long delays in implementing major health research activities following the spill, heavy reliance on self-reported and cross-sectional survey data, limited collection of clinical health information, and a paucity of long-term, longitudinal cohort studies. Health studies need to be initiated before, during, or immediately following a large spill and must continue long enough to identify long-term effects and secondary surges of chronic illnesses. Critically needed are cohort studies that start before a major spill and continue through it and onward for a long period after.

Considerable information about components of oil (e.g., benzene) and their potential toxicity to humans was available before the DWH spill, but many gaps in knowledge were identified, including effects of field-relevant exposures to oil components, engine exhaust, and other chemicals (e.g., dispersants and decontamination cleaners) as well as these in combination with additional stressors such as heat and humidity. Recent studies indicate that children who played at beaches that were cleaned after oil contamination are at low risk for acute or chronic health effects. However, further development of models to forecast the distribution of fresh and weathered oil is needed to predict potential human exposures and inform the common response question, "How clean is clean enough?" Also, toxicological profiles are not currently available for many oil chemicals and degradation products and for vulnerable populations for which information is very limited (e.g., pregnant women and children). A better understanding is needed of impacts from exposures to multiple chemicals, and that incorporates mental health impacts from oil spills that contribute to adverse physical outcomes.

When fisheries were reopened following closures after the spill, Gulf seafood was demonstrated to be safe for human consumption within guidelines existing at the time. However, there was much uncertainty and persistent worry about seafood safety, even years after the spill. For future large spills that affect fishing zones, thorough and rapid appraisals of seafood safety should be undertaken immediately after the spills, followed by plain language communication regarding consumption risks based on appropriate demographic information (e.g., race/ethnicity, age, sex/gender identification, pregnancy, chronic illness, weight, seafood consumption habits), and there should be regular updates. Better health advisories targeted to vulnerable populations and those who use beaches and coastal recreation areas are needed. Collaboration between government and stakeholder groups for monitoring of seafood should be enhanced, and additional social science research should be supported to improve risk communication strategies and outcomes.

There is a lack of systematic collection and integration of socioeconomic data necessary to assess near- and long-term societal impacts of oil spills. Also lacking is a concerted effort to aggregate existing data, identify and fill gaps in longitudinal data collection, and make data and information products broadly available to enhance community disaster resiliency and recovery. As an example, even 10 years after the DWH spill, the long-term psychosocial impacts resulting from the extensive fisheries closures have yet to be fully understood, although extensive data have been collected.

Major Opportunities for the Future

Establishment of the proposed Gulf of Mexico Community Health Observing System would be a major step toward improving health care planning and response and in identifying and characterizing acute, chronic, and poorly known adverse health effects of oil spills and other disasters. The system could be modified for use in other disaster-prone regions.

To inform future oil spill response protocols, findings of worker-related health effects studies should be viewed in the context of oil spill response practices, including operationally relevant exposures, worker safety and health standards, and pollutant and dispersant monitoring protocols, perhaps facilitated by an expert workshop involving researchers, preparedness and response decision-makers, and the Occupational Safety and Health Administration (OSHA) (Holliday and Park, 1993; Science and Policy Associates, Inc., 1993).

There is an urgent need for and the opportunity to develop a socioeconomic observing system. Such a system would link the most significant available socioeconomic data streams, identify additional needed information and suggest how it should be collected, and aggregate the data so as to be useful in analytical efforts to accurately estimate social and economic impacts of future large spills.

DEDICATION. This article is dedicated to the memory of Ciro V. Sumaya, MD, MPHTM, founding Dean of the Texas A&M School of Public Health and a member of the GoMRI Research Board. It was he who, in 2013, convened the GoMRI Public Health Workshop, the report from which has helped to guide GoMRI's efforts ever since on the DWH explosion's and spill's effects on human health. We mourn his tragic death and miss him very much.

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AUTHORS

Paul A. Sandifer (sandiferpa@cofc.edu) is Director, Center for Coastal Environmental and Human Health, College of Charleston, Charleston, SC, USA. **Alesia Ferguson** is Associate Professor, Built Environment Department, North Carolina Agricultural and Technical State University, Greensboro, NC, USA. **Melissa L. Finucane** is Senior Social and Behavioral Scientist, Rand Corporation, Pittsburgh, PA, USA. **Melissa Partyka** is Oil Spill Extension Specialist, Mississippi-Alabama Sea Grant Consortium, Mobile, AL, USA. **Helena M. Solo-Gabriele** is Professor, Department of Civil, Architectural, and Environmental Engineering, University of Miami, Coral Gables, FL, USA. **Ann Hayward Walker** is Principal Consultant, SEA Consulting Group, Cape Charles, VA, USA. **Kateryna Wowk** is Senior Research Scientist, Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **Rex Caffey** is Professor, Department of Agricultural Economics and Agribusiness, Louisiana State University, Baton Rouge, LA, USA. **David Yoskowitz** is Senior Executive Director, Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA.

AUTHOR CONTRIBUTIONS

P.A.S., lead author; A.F., M.L.F., M.P., H.M.S.-G., A.H.W., and K.W. contributed equally to the writing and were lead contributors for sections. R.C. and D.Y. contributed to the section on Socioeconomic Impacts.

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TECHNOLOGICAL DEVELOPMENTS SINCE THE DEEPWATER HORIZON OIL SPILL

By Nilde Maggie Dannreuther, David Halpern, Jürgen Rullkötter, and Dana Yoerger

Guillaume Novelli deploys the eco-friendly CARTHE drifters, which are designed to measure shallow-depth surface currents. *Photo credit: Cédric Guigand*

> “Although mitigation measures were planned for and ready at hand, the severity and unusual circumstances of the [Deepwater Horizon] accident called for the development of new techniques and approaches, as well as the improvement of existing methods, for mitigation and for investigations of the fate and impacts of the released material and the physical, chemical, and biological processes involved.”

ABSTRACT. The Gulf of Mexico Research Initiative (GoMRI) funded research for 10 years following the Deepwater Horizon incident to address five themes, one of which was technology developments for improved response, mitigation, detection, characterization, and remediation associated with oil spills and gas releases. This paper features a sampling of such developments or advancements, most of which cite studies funded by GoMRI but also include several developments that occurred outside this program. We provide descriptions of technological developments, including new techniques or the novel application or enhancement of existing techniques, related to studies of the subsurface oil plume, the collection of data on ocean currents, and oil spill modeling. Also featured are developments related to interactions of oil with particulate matter and microbial organisms, analysis of biogeochemical processes affecting oil fate, human health risks from inhalation of oil spill chemicals, impacts on marine life, and alternative dispersant technologies to Corexit. Many of the technological developments featured here have contributed to complementary or subsequent research and have applications beyond oil spill research that can contribute to a wide range of scientific endeavors.

INTRODUCTION

Over a 10-year period following the Deepwater Horizon (DWH) incident, the independent Gulf of Mexico Research Initiative (GoMRI) funded a variety of efforts to better understand its impacts and to be better prepared for future oil spills. GoMRI-funded studies addressed five research themes, one of which was technology developments for improved response, mitigation, detection, characterization, and remediation associated with oil spills and gas releases. The purpose of this paper is to provide a sampling of technological developments, including new techniques or the novel application or enhancement of existing techniques. Most of the featured developments cite studies funded by GoMRI, but several of them occurred outside this program (see the acknowledgments in the cited literature for funding details).

The selection of technological developments for this paper began with a decision to focus on those described in GoMRI-funded publications. We reviewed publications whose authors associated their studies with the program’s research theme of technology, and also conducted a limited review of publications associated with the four other program themes whose titles, abstracts, or methods suggested possible technological advancements. This survey yielded about 250 potential candidates, which were further reduced by the elimination of studies that broadly discussed or assessed technology, were theoretical in nature, lacked clarity of an innovation, or lacked a clear application for oil spill research. We then applied our expertise in organic chemistry, ocean physics and engineering, and oceanic-atmospheric processes to identify developments that moved oil spill science forward. We further eliminated advancements related to the tracking and analysis of oil spill components and transformation products (discussed in Rullkötter and Farrington, 2021, in this issue) and those concerned with improvements to ocean circulation modeling (discussed in Boufadel et al., 2021, in this issue). This process ultimately resulted in the 37 technological developments featured here that broadly reflect the scope of the GoMRI program. We acknowledge that the selection process and space constraints necessitated the exclusion of important and interesting innovations that have occurred since the DWH oil spill.

Brief paragraph-style summaries for each development are provided below, organized by broad topics. Each summary states what the development or innovation is or does, followed by a few details germane to its function and, in some cases, the main knowledge or insight that is intended by or that resulted from its use. In a few instances, examples are given of complementary or subsequent research that followed the innovation. We hope that by highlighting these few developments, readers will be enticed to learn more about them and seek out other technological advancements.

DEVELOPMENTS IN INVESTIGATING OIL PLUME DYNAMICS

In contrast to shallow-water or surface oil spills, a deepwater hydrocarbon blowout releases oil and gas as a buoyant jet in high-pressure, cold-temperature conditions. As the jet interacts with the surrounding marine environment, it evolves into plumes of differently sized and distributed droplets, as happened during the DWH incident. Some of these droplets move upward and form surface slicks, and others are trapped in a neutrally buoyant plume that moves beneath the ocean's surface. Any of these droplets may later form surface slicks or attach to floating marine snow and sink to the seafloor near to or at a distance from the source site.

Understanding and quantifying the factors that affect a submerged jet's evolution is critical to estimating the amount of oil released and predicting where it will go. Simulation studies investigating droplet breakup and coalescence in turbulent flows are not new, but research on the DWH incident included factors not typically accounted for, such as Macondo oil chemistry and flow rates, dispersants applied at depth, high pressure, cold temperature, and biodegradation.

Innovations featured here characterize the subsurface oil plume and droplet size distributions (DSDs) resulting from a deepwater hydrocarbon release. Also featured here are instruments that measure oil droplets and gas bubbles in laboratory and field settings, which, in the case described below, are two natural seafloor seeps at depths similar to the DWH blowout site. Natural hydrocarbon seeps provide a viable surrogate for studying the subsea plume that formed during the DWH incident because both have bubbles and droplets that are well separated in water and end up with low dissolved gas concentrations at nearly ambient temperature and pressure. Topics related to oil plume dynamics are also discussed by Rullkötter and Farrington (2021), Boufadel et al. (2021), and Farrington et al. (2021), all in this issue.

Existing technologies were applied in an innovative way to characterize the DWH subsurface oil plume, a phenomenon first discovered by Diercks et al. (2010) and linked to the DWH incident. To collect environmental data in the area of the reported subsurface plume, Camilli et al. (2010) used a Doppler water velocity log and a mass spectrometer on board the autonomous underwater vehicle (AUV) *Sentry* to record current speeds and chemical parameters and also used a ship-cabled rosette sampler to collect water samples. Results from these data indicated the presence of a continuous, neutrally buoyant plume that had not substantially biodegraded at heights up to 200 m, depths down to 1,160 m, and, in certain areas, across horizontal distances of more than 2 km. The plume was found to be moving along a southwesterly trend more than 35 km from its source, likely influenced by Lagrangian transport and topography. Later, Valentine et al. (2014) analyzed 17α-hopane concentrations (a degradation-resistant proxy for Macondo's liquid-phase oil) available in a public sediment database to assess the spatial distribution of hydrocarbons. Their analyses revealed an oblong patchwork of contamination spanning 3,200 km^2 that trended primarily to the west from the DWH site to a distance of at least 40 km, in agreement with observations reported by Camilli et al. (2010). Together, these innovative efforts characterized the plume's chemical parameters as well as significant transport and fate processes that were not originally accounted for in the DWH oil budget.

A few examples of research that followed the collection and analysis of samples from the oil plume include the work of Kujawinski et al. (2011), who corroborated findings on the fate of the Corexit component DOSS (dioctyl sodium sulfosuccinate), and Reddy et al. (2012), who extended the chemical analyses to a wider range of oil spill chemicals. Socolofsky et al. (2011) used the observations in calculations for a multiphase plume model that simulated the formation of subsurface oil intrusions. These calculations were subsequently used by Zhao et al. (2014b) as parameterizations in the jet-droplet formation model VDROP-J (see below) to simulate DSDs as oil evolves away from a jet, by North et al. (2015) in a coupled model to assess the influence of biodegradation and initial droplet sizes on subsurface oil transport, and by Aman et al. (2015) in a high-pressure sapphire autoclave apparatus to study oil-in-water dispersions.

Zhao et al. (2014b) extended the droplet formation model VDROP (Zhao et al., 2014a), developing the VDROP-J model that includes a new jet module calibrated with different orifice sizes and velocities to estimate the size distribution of droplets as they evolve from a buoyant jet stream. The VDROP-J model was validated under various conditions, such as with oil-only experiments conducted at SINTEF and with field data from the Norway offshore experiment and the DWH incident. Simulations with dispersants (10- and 1,000-fold reduction in interfacial tension) incorporated Macondo oil and gas release information and seawater conditions during the DWH spill. Both dispersant cases resulted in an increased volume of small droplets and decreased size distributions at different plume heights that correlated well with field data. These simulations indicate that droplet breakup processes mainly occurred within 50 m above the seafloor and reached a steady state at ~100 m and maintained that state to 200 m (representing the near-field upper boundary). The new jet module accounts for resistance to breakup by the oil's viscosity, which is important when dispersants are used, improving near-field simulations of DSDs from a deepwater blowout.

Research that utilized the VDROP-J model includes Zhao et al. (2015) to provide bounds on the range of droplet sizes from within 200 m of the DWH site; Zhao et al. (2017) to develop a new formulation for the simultaneous simulation of bubble and droplet size distribution; and Boufadel et al. (2018) to study the dynamics of oil and gas tumbling within the pipe from which the oil emanated, the results of which have implications for estimations of discharged oil amounts.

Dissanayake et al. (2018a) developed the Texas A&M Oil Spill/Outflow Calculator (TAMOC), a comprehensive fluid dynamics and oil chemistry model that runs scenarios with and without dispersants to assess oil and gas ejected in deepwater (~1,500 m) spills, such as occurred at the DWH platform. The suite has a discrete particle model (DPM), a Lagrangian particle model, and two plume modules: the stratified plume model (still or near-still environments) and the bent-plume model (crossflow). The DPM computes the physical, thermodynamic, and oil chemical properties to predict the evolution from live oil (with dissolved gas) to dead oil (volatile components removed). Simulations were in line with field observations (DeepSpill experiment), Macondo oil properties, and laboratory data (bubble plumes and bubbly and oily jets). TAMOC simulations confirmed that the approach used in oil spill models is often correct, but its rigorous chemistry model and well-described methods are advancements that recent response-type fluid dynamics models do not include.

The General NOAA Operational Modeling Environment in Python (PyGNOME) adopted the TAMOC for near-field subsurface oil spill modeling. Other examples of research that utilized TAMOC include Gros et al. (2017) who, in combination with the VDROP-J model, simulated the physical and chemical behavior of oil and gas rising to the surface with and without dispersants. TAMOC was utilized by Dissanayake et al. (2018b) to simulate marine oil snow formation and evolution, by Socolofsky et al. (2019) to simulate biodegradation in subsurface oil spills, by Gros et al. (2020) to explain the observed dynamics of live and dead oil droplets under deepwater conditions, and by Razaz et al. (2020) to connect the characteristics of a hydrocarbon seep to its surface footprint.

Lindo-Atichati et al. (2016) added a new oil module to the coupled Connectivity Modeling System (CMS, biodegradation included) and to the Gulf of Mexico Hybrid Coordinate Ocean Model (HYCOM) to evaluate the influence of hydrodynamic, thermodynamic, and geochemical factors on the evolution of the subsurface oil plume. The oil module incorporated hydrocarbon fractions for Macondo oil and daily oil flow rates from field measurements. Adding variable flow rates provided more realistic initial conditions and enhanced the coherence of the southwest branch of the subsurface plume. Adding biodegradation rates at high pressure resulted in estimates of droplet size and density that led to increased residence time of the oil in the water column. The model predicted a persistent subsurface plume southwest and northeast of the DWH site at 1,100–1,200 m depths consisting of droplet sizes of >50 μm (droplets in the 50–100 μm range formed shallower plumes) during the first 100 days after the spill, in agreement with observational studies.

The CMS with oil application was used, for example, by Berenshtein et al. (2020) to identify the spill exposure area that was beyond the satellite-identified boundaries of the DWH footprint and fishery closures and by Perlin et al. (2020) in case studies that investigated parameters that affect oil weathering and transport, confirming the system's robustness for simulating a deep-sea blowout.

Aman et al. (2015) employed a high-pressure sapphire visual autoclave apparatus to estimate oil droplet diameter as a function of mixing speeds (Figure 1). The apparatus provided the first visualizations of droplet breakup and coalescence at turbulent kinetic energy dissipation rates corresponding to 200–1,000 rpm mixing speed (Booth et al., 2019) and up to 120 times atmospheric pressure (roughly the pressure at 1,200 m depth). A high-speed camera enabled quantitative assessments of droplets. The data were used in DWH simulations (using the coupled CMS and Gulf of Mexico HYCOM) that showed a mean diameter size of 258 μm at speeds up to 400 rpm. When speed increased (≥500 rpm), droplet size decreased to an average of 80 μm,

FIGURE 1. A high-pressure sapphire visual autoclave apparatus was utilized to help characterize the droplet size distributions that occurred during the Deepwater Horizon (DWH) incident (Aman et al., 2015). The autoclave provided the first visualizations of droplet breakup and coalescence at dissipation rates corresponding to 200–1,000 rpm mixing speed (Booth et al., 2019) and up to 120 times atmospheric pressure (roughly the pressure at 1,200 m depth). The autoclave's well-defined shear geometry provides a unique perspective on droplet size prediction, and the data it generated helped establish a systematic approach for estimating the diameter of oil droplets dispersed in water. *Photo used with permission of Zachary M. Aman, The University of Western Australia*

suggesting a natural mechanism for oil to disperse into small droplets. The autoclave's well-defined shear geometry provides a unique perspective on droplet size prediction, and the data it generated helped establish a systematic approach for estimating the diameter of oil droplets dispersed in water.

Examples of research that utilized DSD estimations from the autoclave apparatus include Ainsworth et al. (2018) in the Atlantis ecosystem model to simulate oil spill impacts on fish guilds and their subsequent recovery and Perlin et al. (2020) in case studies investigating parameters that affect the weathering and transport of deep-sea oil spills.

Wang and Socolofsky (2015) designed, validated, and deployed a deep-sea stereoscopic imaging system, TAMU-CAM, that was mounted on the remotely operated vehicle (ROV) *Hercules* to measure and analyze gas bubbles and oil droplets flowing from natural seeps (Figure 2). The system consists of two high-speed cameras in pressure housings (rated to 1,500 m depth), lighting, subsurface power, and video monitoring over ethernet. Images are streamed onto a 12 GB RAM memory chip and transferred to a 240 GB flash drive in each camera from which the gathered information can be downloaded to a computer in the ROV, enabling almost unlimited data collection. Laboratory validation showed that the stereo view improved measurements of bubble diameters up to 90% and flow rate estimates by a factor of ~13% compared to single-camera systems. In the Gulf of Mexico, the system tracked oil droplets and gas bubbles up to ~250 m above two natural seep sites (and later up to 400 m; Wang et al., 2020). Imagery captured bubble and droplet breakup and coalescence from which size distribution, rise velocity, and methane flux were estimated, improving model parameterization for simulating deepwater spill scenarios.

Leonte et al. (2018) provide an example of research that utilized the TAMU-CAM observations, from which they established that changes in methane stable carbon isotopic ratios can be used as a tracer for methane dissolution. Their analysis using this tracer indicated that more than 90% of the methane released during the DWH spill dissolved after ascending 400 m.

INSTRUMENTATION FOR IMPROVED OIL TRANSPORT PREDICTIONS

During the DWH incident, information that was critical for response decisions was provided by remote sensing (slick locations) and by ocean circulation models (slick transport). However, a need became evident for more accurate information about how the transport of floating oil is influenced by fast-moving submesoscale near-surface currents of short duration and their interactions with the mesoscale Loop Current that moves water through and out of the Gulf of Mexico, around the tip of Florida, and into the Atlantic Ocean. This need points to an ongoing challenge in ocean circulation modeling—the limited availability of observational data to initialize predictive models. The following text describes instrumentation advancements aimed at collecting data about the ocean's near-surface currents that can be used to improve the parameterization of transport prediction models. For a discussion on the modeling of geophysical ocean transport processes, see Boufadel et al. (2021, in this issue).

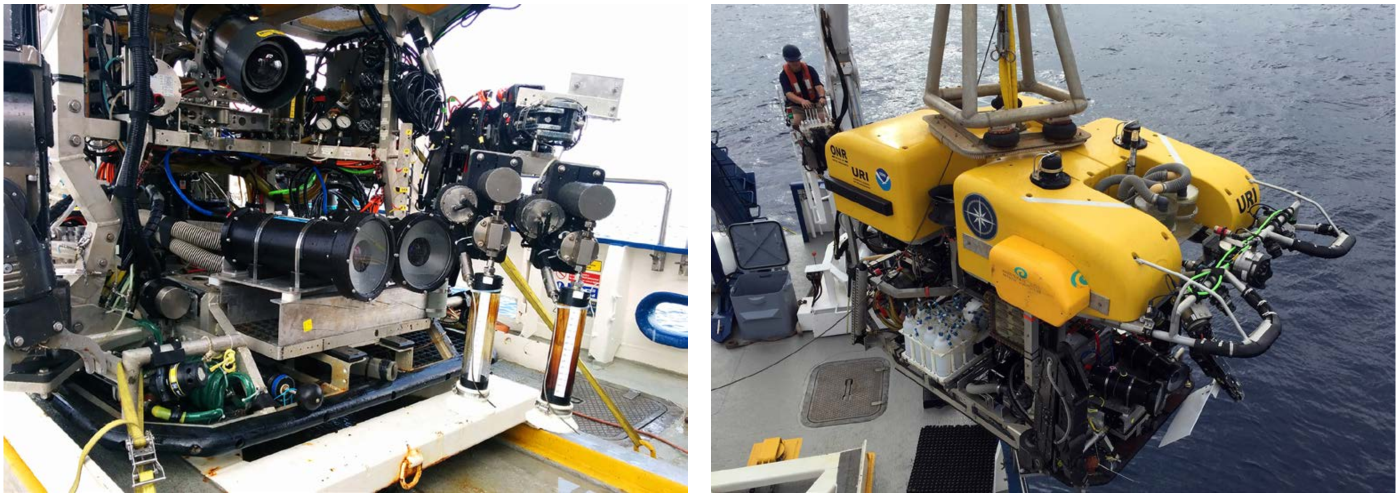


FIGURE 2. To help characterize the subsurface oil plume and droplet size distributions that resulted from the DWH incident, researchers investigated oil droplets and gas bubbles flowing from deep natural seafloor seeps, which provide a viable surrogate for studying the subsea plume that formed during the DWH incident. They used the remotely operated vehicle (ROV) *Hercules*, shown at right, to deploy the Texas A&M University stereoscopic high-resolution camera system (TAMU-CAM), pictured at left, which was developed to collect fine-scale images and measurements of oil droplets and gas bubbles rising from the seeps (Wang and Socolofsky, 2015). TAMU-CAM features two high-speed cameras within housings rated to 1,500 m depth and has its own lighting, subsurface power, and video monitoring over ethernet that can be downloaded to a computer in the ROV. *Photo on the right by and used with permission of Binbin Wang, Civil and Environmental Engineering, University of Missouri. Photo on the left by and used with permission from Scott Socolofsky, Texas A&M University*

Novelli et al. (2017) developed the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) drifter to facilitate large-scale observations of near-surface ocean currents and improve ocean model parameterization. The easy-to-assemble CARTHE drifter can be mass produced at low cost and is made from a biodegradable polymer produced by sugar-fed bacteria to reduce ocean pollution. A floating torus (**Figure 3**) houses a global positioning system and alkaline batteries, and a four-sail drogue attached with a flexible connector keeps the floater upright on waves. Without the drogue, the floater moves at wave speed; with the drogue, it moves at the underlying current speed. Tests with small-scale models were conducted in a wind-wave-current flume, and tests with full-scale models during the LAgrangian Submesoscale ExpeRiment (LASER) field campaign (http://carthe.org/laser/) validated trajectories against a well-established drifter model.

After the LASER field experiment, D'Asaro et al. (2018) reported that small fronts and vortices caused the drifters to cluster at frontal convergence zones and that larger currents distributed the drifters over a wide region later. Their results suggest that floating oil might accumulate similarly, potentially providing a window of opportunity for a targeted deployment of resources during a spill response. Results from a different field experiment using CARTHE drifters and other observational devices were reported by Androulidakis et al. (2018), who identified the influence of local and regional physical processes such as riverine fronts on the transport of surface oil from the Taylor Energy site.

Examples of research that used data collected by CARTHE drifters include Lund et al. (2018) to validate near-surface current maps generated from shipboard marine X-band radar, Barkan et al. (2019) to validate model estimations of vertical buoyancy fluxes during frontogenesis, and Gonçalves et al. (2019) to identify and follow a near-surface flow that was reconstructed by a supervised machine-learning technique using only Lagrangian data. Additionally, Novelli et al. (2020) investigated the trajectories of the DWH oil spill and the CARTHE drifters released during the LASER experiment and found that near-surface gradients controlling cross-shelf movement transported the undrogued drifters twice as fast as the drogued ones, and a higher percentage of undrogued drifters landed on the same coastline locations where DWH oil was found.

Laxague et al. (2018) employed a novel combination of instruments with complementary strengths that mitigated each instrument's blind spot to obtain the first-of-their-kind field observations in the ocean's upper layers (~10 m depth). Wind forcing and wave dynamics strongly influence motion in the upper layers, but analyses of near-surface dynamics generally treat these upper layers as the same because it is challenging to observe and measure currents within this area. As such, it is difficult to accurately predict the transport of buoyant materials such as microplastics and oil. This observation gap was addressed in a case study during the Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH) field campaign (http://carthe.org/splash/) that collected data simultaneously with several sensors and instruments, including a polarimetric camera (for wave motion and depth), a 20 MP camera attached to a drone (that tracked drifters and bamboo plates), an autonomous vehicle-mounted acoustic Doppler current profiler (ADCP) and shipboard ADCP (for currents deeper than 4 m), a mast-mounted sonic anemometer (for wind velocity), and bow-mounted acoustic altimeters (for water-surface elevation). The data revealed that wind forcing caused the current at 1 cm depth to move at twice the average speed over the upper 1 m and nearly four times the average speed over the upper 10 m. These results help account for the rapid separation of floating material of varying size or buoyancy. Incorporating these quantified dynamics into ocean transport forecasts can aid in identifying pathways along which floating material may be transported.

To improve the accuracy of ocean model parameters, Carlson et al. (2018) collected the first modern in situ observations of small-scale surface dispersion

FIGURE 3. During the DWH incident, a need was revealed for more accurate information about the influence that complex upper-ocean currents have on oil transport. To better understand these fast-moving, short-lasting currents, field experiments were conducted in the Gulf of Mexico and used the new Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) drifter, which is easy to assemble, has a low production cost, and is biodegradable (Novelli et al., 2017). The drifter is made from a polymer produced by sugar-fed bacteria. A global positioning system and alkaline batteries are housed in its floating torus, and a four-sail drogue attached to the torus with a flexible connector keeps the floater upright on waves (see photo on opening page of this article). During field experiments, the CARTHE drifters clustered along fronts, and then later dispersed, suggesting that floating oil might accumulate similarly and identifying a possible window of opportunity for a targeted deployment of resources during a spill response (D'Asaro et al., 2018). *Image by and used with permission of Cédric Guigand, University of Miami*

in a deepwater setting with the custom-outfitted Ship-Tethered Aerostat Remote Sensing System (STARSS; Figure 4). Velocities at the air/sea interface and dispersion for short-lived motions (seconds to hours) at small spatial scales (meters to hundreds of meters) are relevant to oil drift and spread, but these parameters are challenging for drifters, ships, and satellites to observe. Data were collected during the CARTHE LASER field campaign using the STARSS equipped with a 50.6 MP camera (300 × 200 m field of view) that imaged floating bamboo plates every 15 s for 4 h. A relative rectification technique enhanced image analysis by minimizing movement between frames, then custom algorithms quantified dispersion; drifter trajectories were used to connect small-scale features to the submesoscale. Results improved diffusivity estimates at the 3–40 m scale and revealed that density fronts and Langmuir circulation directed a preferred motion at small spatial and short temporal scales (Chang et al., 2019), which are difficult to reproduce in numerical ocean models.

OIL SPILL MODELING TECHNIQUES

Advancements in oil spill modeling following the DWH incident are discussed by Barker et al. (2020) in their review of operational modeling in support of oil spill response. Here, we describe two additional modeling suites, one that tracks oil from its deepwater release to landfall and another that tracks the interactions of oil with marine organisms, biochemical constituents, and sediments. We also provide additional information about an oil drift module that is included in the Barker et al. (2020) review.

Chapman et al. (2014) constructed a nested model suite to follow an oil particle from its seafloor release to shoreline arrival that includes natural rates of mixing, degradation of oil components, and processes at Gulf-wide, shelf, and bay scales. This technique addresses the need revealed during the DWH incident to have interacting systems at appropriate spatial scales and resolutions. The suite accounts for plume dynamics, including a density-stratified turbulent crossflow (with a three-dimensional Large Eddy Simulation-Reynolds Averaged Navier-Stokes model), an intrusion formation by density stratification (with an integral multiphase plume model with oil chemistry), and the behavior of discrete particles and dissolved constituents as oil ascends to the surface (with a Lagrangian particle tracking model with algorithms from the General NOAA Operational Modeling Environment). Two sets of models simulate surface transport from offshore to coastlines. The first set incorporates a base hydrodynamic model (that includes a high-resolution ocean-atmosphere model and the Weather Research and Forecasting model), the Regional Ocean Modeling System (ROMS), and the South

FIGURE 4. The complex processes in the upper ocean—which drifters, ships, and satellites have limited ability to observe—are relevant to oil drift and spread. To better understand near-surface ocean currents, the Ship-Tethered Aerostat Remote Sensing System (STARSS) was custom outfitted with a 50.6 MP camera (300 × 200 m field of view) and launched from a research vessel in the Gulf of Mexico to take images of floating bamboo plates every 15 s for 4 h. The data collected provided the first modern in situ observations of small-scale surface dispersion, and results improved diffusivity estimates at the 3–40 m scale, which can enhance the parameterization of ocean transport models (Carlson et al., 2018). *Both photos by and used with permission of Tamay Özgökmen, University of Miami*

Atlantic Bight and Gulf of Mexico model that assimilates sea surface height and temperature data from satellites. The second set comprises smaller-scale models, including the ROMS model of the Texas-Louisiana shelf that captures the interaction of mesoscale eddies with the continental slope as well as the currents on the shallower shelf and a three-dimensional nonhydrostatic coastal bay model. The nested model suite is supported by laboratory experiments (bubble and droplet formation, droplet-turbulence interaction, dissolution, evaporation, and dispersion) and field experiments (deep-sea tracer and bubble releases). Qualitative comparison with observations of the southwest-tending DWH subsurface plume showed good agreement. Simulations suggest Macondo oil released during the DWH incident may have also been transported in the subsurface to the east, but this could not be validated because sampling efforts were concentrated to the west.

Dukhovskoy et al. (2021) developed the Consortium for Simulation of Oil-Microbial Interactions in the Ocean (CSOMIO) coupled modeling system to simulate the distribution and interaction of petroleum, lower trophic level organisms, biochemical constituents, and sediment in the marine environment for assessing environmental effects of past and future oil spills. The system is based on the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al., 2010) and consists of several components. The oil plume modeling component is coupled to the ROMS hydrodynamic model, which simulates the three-dimensional movement and compositional changes (weathering) of oil as Lagrangian particles. The chemical composition of oil is described in terms of saturates, aromatics, and heavy oil (including resins and asphaltenes). The biogeochemical modeling component incorporates a microbial model based on the Genome-based EmergeNt Ocean Microbial Ecosystem (Coles et al., 2017) that was adapted for the presence of hydrocarbons. The sediment transport component of COAWST, the Community Sediment Transport Modeling System, was modified to include computationally efficient flocculation parameterizations for oil-mineral aggregates developed from laboratory experiments. These modeling components are linked together using a two-way Lagrangian-Eulerian mapping technique that enables interaction among the model components to track hydrocarbons from a source blowout to deposition in sediment and to account for microbial degradation and evaporation during transport through the ocean. The CSOMIO model can be run offline at increased computational speed to support spill response.

Dagestad et al. (2018) developed OpenDrift, a high-resolution open-source circulation ocean trajectory framework that contains the OpenOil oil drift module, which was improved, extended, and applied to modeling the DWH oil spill. Simple to set up, the independent and fast OpenDrift platform provides flexibility for scientific studies as well as robustness for operational services. The OpenDrift core includes everything common to ocean drift applications (e.g., search-and-rescue, plastics, and ichthyoplankton transport). The OpenOil module adds functionality specific for oil by including an interface with the NOAA OilLibrary (https://github.com/NOAA-ORR-ERD/OilLibrary with measurements for ~1,000 oil types) and offers parameterization of weathering processes such as evaporation, emulsification, biodegradation, and entrainment by breaking waves followed by vertical turbulent mixing with buoyancy and resurfacing.

Examples of research that utilized the OpenDrift trajectory modeling framework include DWH spill simulations by Hole et al. (2019), which showed that a large river outflow reduced the total amount of stranded oil by ~50% compared with no river input; these results compared well with satellite observations of the DWH surface oil patch. Using OpenDrift to simulate oil spills in the Cuban Exclusive Economic Zone, Androulidakis et al. (2020) showed the most likely scenario for oil stranding along the southern Florida coast would be from a release in the deep central Straits of Florida and, for oil stranding at Gulf of Mexico beaches, would be from a release near the Yucatán Strait and in the deep Gulf interior.

After adding functionality to the OpenOil module, Garcia-Pineda et al. (2020) employed it to initialize simulations of oil slicks near the Taylor Energy site for experiments aimed at understanding the residence time of oil slicks using a combination of remote-sensing platforms and GPS-tracked drifters. Although the projected oil residence times in low wind conditions were longer than observations, likely because the actual slick was very thin, this result demonstrates the importance of incorporating oil thicknesses into models.

ADVANCEMENTS IN STUDYING OIL, PARTICLE, AND MICROBIAL INTERACTIONS

In both off- and near-shore environments, oil droplets in the water column can encounter floating matter, microbial organisms, and sediment particles, all of which can influence the oil's fate. In response to oil in their environment, some marine organisms excrete a sticky substance that may cause floating matter, sediment, and oil droplets to aggregate and sink to the seafloor. During the DWH incident, these processes were discovered to have a significant influence on the deposition of oil and dispersant to the seafloor. Advancements in collecting and analyzing images of suspended matter and in simulating the formation and evolution of oil/particle aggregates (OPAs), marine oil snow (MOS), and oil/mineral aggregates (OMAs) are featured below. Farrington et al. (2021, in this issue) also discuss topics related to interactions among oil and floating particulate matter and marine organisms.

The ability to distinguish between oil and gas droplets in a mixed release and to quantify their distributions was achieved by Davies et al. (2017) with their new in situ particle imaging system, SilCam (Figure 5), designed to quantify high concentrations of suspended particles with diameters from 30 µm to several millimeters. The SilCam's backlighting and telecentric receiving optics configuration provides sharp, in-focus images of all particles, free from errors associated with standard lenses. The optical configuration is mounted within two underwater housings (rated to 3,000 m depth), and images are recorded on a solid-state disk to enable continuous operation at 15 Hz without the need for buffering. The system's optical properties can distinguish between similarly shaped particles for analysis of oil droplets and gas bubbles and for establishing an oil/gas ratio. The SilCam fills a gap in technology that now allows accounting for the concentration-size-shape space within in situ particle measurement that can also be applied to study other suspended particles in the ocean.

Brandvik et al. (2017, 2019) utilized the SilCam in experiments using facilities at SINTEF, SouthWest Research Institute, and Ohmsett to distinguish oil and gas bubbles and calculate particle size distributions during simulated deepwater releases of live oil and natural gas under high pressure, with and without subsurface dispersant injection.

Bi et al. (2015) customized a segmentation technique that locates objects within images and extracts them for classification to improve the processing of large volumes of data generated by plankton-imaging systems. Existing techniques worked for images acquired under laboratory conditions or within clear waters; however, the DWH incident underscored the need to process images from turbid coastal waters, where complex pathways transported oil toward shore. The two-step classifier procedure includes separating all non-target and target objects into different groups (arrow-like, copepod-like, and gelatinous zooplankton) and applying a support vector machine binary classifier (a supervised machine-learning method) to further identify non-target objects. Results using a test data set comprised of 89,419 images collected by the ZOOplankton VISualization (ZOOVIS) system in the Chesapeake Bay were consistent with visual counts, having >80% accuracy for all three object groups. This test demonstrated the technique's success in processing in situ imaging data collected in waters with large amounts of suspended matter.

This segmentation technique was utilized by Shahrestani et al. (2017) to analyze sonar footage of swimming fish and improve estimations of fish abundance at a fixed location. Cheng et al. (2019) drew upon the technique to develop and test an enhanced convolutional neural network for improved plankton image recognition that can be applied to images acquired from different systems.

Zhao et al. (2016) developed the A-DROP model to simulate the formation of OPAs and to predict how much oil from a marine spill an OPA might trap and transport. Application of a unique oil/particle coagulation efficiency formula to quantify the amount of oil that OPAs trap accounts for effects of particulate coating on an oil droplet's surface and effects of hydrophobicity and particle-to-droplet size ratio on OPA formation. After validating that the A-DROP model closely reproduced the oil-trapping efficiency reported in experimental studies, OPA formation was simulated in a coastal marine environment. Results suggested that although the increased particle concentration in the swash zone (the turbulent water layer that washes onto the beach) generated an increase in oil/particle interactions, it did not result in a corresponding increase in the amount

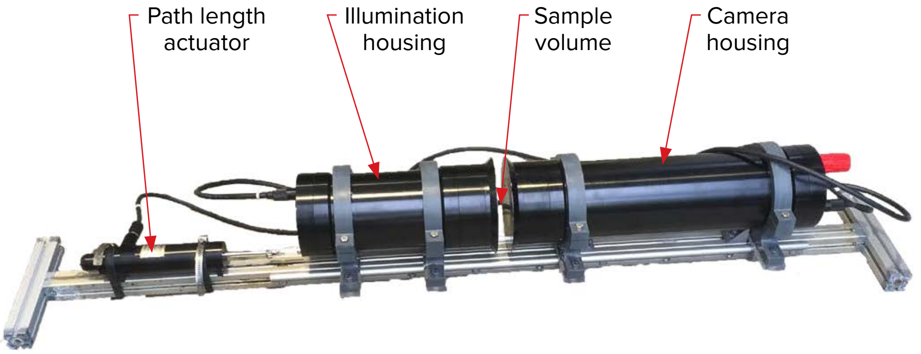


FIGURE 5. The SilCam in situ particle imaging system can distinguish between oil and gas droplets and quantify their distributions from a mixed release, as happened during the DWH incident (Davies et al., 2017). The SilCam (above) has an adjustable path length that ensures all suspended particles in the sample are in focus and utilizes signatures of transmitted light of different wavelengths through each particle to separate oil droplets, gas bubbles, and oil-coated gas bubbles of equal size and shape. The optical configuration is mounted inside of two underwater housings rated to 3,000 m depth. SINTEF senior engineer Frode Leirvik (left) prepares the SilCam for experiments at the Ohmsett National Oil Spill Response & Renewable Energy Test Facility in New Jersey. *Both images provided by and used with permission of Emlyn Davies, SINTEF Ocean*

of oil that OPAs trapped. The A-DROP's predictive capability for oil removal by OPAs, something that existing oil/particle models do not perform, advances this developing field of study.

The A-DROP model was utilized by Jones and Garcia (2018) in the development of a rapid response model for an oil spill in a riverine environment, and by Boglaienko and Tansel (2018) to characterize and classify different types of oil-particle aggregates as they developed oil spill response and mitigation methods.

Based on the success of earlier baffled recirculating tanks (BRTs; Knap et al., 1983), Wade et al. (2017) designed new versions of the tanks that reliably and efficiently produced large volumes of water-accommodated fractions (WAF) and chemically enhanced water-accommodated fractions (CEWAF) of oil for mesocosm studies to examine MOS formation. The BRTs produce ≥500 L of WAF and CEWAF within 24 h, which existing BRTs could not do, so that experiments can run in triplicate and provide sufficient exopolymeric substances for analyses. Each 43 × 88 × 44 cm glass tank contains four glass baffles (130 L total volume) and recycles water in ~6 h using a diaphragm pump and a magnetic stirrer. A high-speed camera with a 200 mm lens measures the size distributions of resulting oil droplets. MATLAB Imaging Processing Toolbox software was applied to reduce the impact of non-uniform background intensity. Oil concentrations in the WAF and CEWAF treatments were consistent with environmental concentrations (higher range) seen during spills (including DWH), providing data for models that estimate oil sedimentation and degradation.

The BRTs were used by Doyle et al. (2018) in mesocosm experiments designed to study the relationship among microbial community structure, oil and Corexit, and MOS in coastal surface waters; by Bacosa et al. (2020) to investigate the concentration and distribution of hydrocarbons in marine snow aggregates; and by Shi et al. (2020) to determine the half-lives of individual hydrocarbons in simulated oil spill scenarios with and without dispersant.

Ye et al. (2018) modified the high-resolution floc video instrument LabSFLOC by adding parameters to simulate the formation and settling of OMAs and study their effect on vertical oil transport. The modified LabSFLOC-2 system includes a 2 MP video camera and an LED-illuminated panel behind a settling column into which a suspension containing oil-mineral-microbial flocs is introduced. A digital video microscope and processing package enables detailed observations of individual floc size (5 µm to 8 mm), shape, settling velocity, density, mass, and more. Preliminary laboratory experiments demonstrated that LabSFLOC-2 can produce OMAs and characterize their mass settling dynamics, allowing for a systematic analysis of the role that each factor plays in this process. Knowledge of quantitative floc properties of OMAs can improve the parameterization and calibration of numerical models that include oil biodegradation when forecasting the fate of oil spills.

Research that utilized the LabSFLOC-2 includes work by Dukhovskoy et al. (2021) to provide flocculation parameterizations for their coupled modeling system that simulates the distribution and interaction of petroleum, lower trophic level organisms, biochemical constituents, and sediment in the marine environment. Also, Ye et al. (2020) employed LabSFLOC-2 to investigate the effect of mineral types (kaolinite and bentonite) on the structure of OMAs and settling velocities.

Dissanayake et al. (2018b) developed a numerical modeling technique to predict the formation of MOS aggregates and the amount of oil they transport to the seafloor. The technique is based on the Stochastic Lagrangian Aggregate Model for Sinking Particles that simulates marine particle coagulation and disaggregation. Modifications were made to characterize aggregates containing different amounts of oil, algae, and sediment particles and to incorporate seawater properties, stratification effects on aggregate settling velocities, disintegration, fractal dimensions, and stickiness. The model was validated with observational data collected during the DWH incident, and it was found to reproduce aggregate size spectra and oil deposition rates reasonably well. Oil spill transport and fate models do not typically account for oil sedimentation via MOS, as this phenomenon was not widely observed or studied prior to the DWH incident; therefore, this technique helps fill that gap by identifying and calculating aggregate parameters for MOS formation and sinking, which can inform calculations of oil fate in marine environments.

Passow et al. (2019) provide an example of research that further supports this MOS modeling technique. They conducted rolling table experiments that investigated the incorporation of two types of dispersed oil into diatom aggregates to provide specific input parameters for models that predict the transport of oil to depth via marine snow-sized aggregates. Another example can be found in Daly et al. (2020), who recommended coupling circulation and MOS models (that include coagulation as described above) to improve the predictions of MOS sedimentation events under varying environmental conditions.

DEVELOPMENTS IN COLLECTING AND ANALYZING BIOGEOCHEMICAL DATA

There is limited understanding of the biogeochemical properties and physical processes that can influence the transport and fate of oil in deep-ocean environments such as the Gulf of Mexico location of the DWH incident. Here, we feature techniques that link the ocean's biochemical structure to physical conditions that are influenced by atmospheric conditions, which have a combined effect on oil fate. We also discuss a technique used to analyze sediments near the DWH site that led to estimations of the amount of oil that settled to the seafloor. For developments in analytic chemistry techniques applied to study the chemical composition of spilled oil and its transformation products, see Rullkötter and Farrington (2021, in this issue).

Shay et al. (2019) deployed state-of-the-art Autonomous Profiling Explorer floats with biogeochemical and electromagnetic sensors (APEX-EM, developed by Teledyne Webb Research) near the DWH site to map physical processes and biogeochemical properties that could influence oil dispersion. This effort linked, for the first time, the ocean's biochemical structure to physical conditions including currents and shear as influenced by atmospheric conditions. The deployed floats operated in 2–2,000 m depth for four-to-seven-day intervals and utilized daily updated satellite remote-sensing products. The floats' payloads included sensors for temperature and salinity (Sea-Bird Electronics); dissolved oxygen (Aanderaa Optode 4330F); and chlorophyll, fluorescence, backscatter, and colored dissolved organic matter fluorescence with fluorophoric oil components (ECO Puck Flbb-CD). After the floats surfaced, data were transmitted via satellite (Iridium system), enabling real-time retrieval and reprogramming for adaptive sampling, which enabled an increase in the profiling rate during Hurricanes Irma and Nate. The floats also collected >1,600 continuous-mode samples of diurnal oxygen variations (Gordon et al., 2020). The easy-to-deploy end-to-end APEX-EM system measures evolving mesoscale structures, providing data needed for resolving submesoscale processes that are important to oil transport predictions.

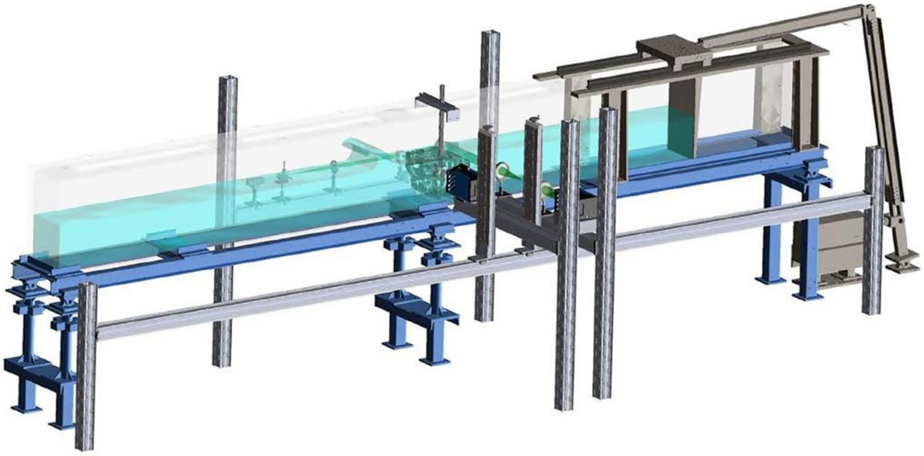
Chanton et al. (2015) employed an inverse isotopic approach to measure radiocarbon (^{14}C) in organic matter layered on the top of seafloor sediments and quantify sedimented oil following the DWH incident. The approach served as a proxy for oil spill-derived compounds, many of which had changed chemically from microbial and physicochemical processes and were no longer amenable to gas chromatographic analysis. This approach is "inverse" in that it looks for the absence of ^{14}C, which diminishes over time. Before the spill, there was a more recent ^{14}C signature of organic matter derived from land-plant, riverine, and marine sources than there was after the spill deposited carbon from crude oil that was millions of years old with no ^{14}C. Analysis of sediment collected shortly after the spill and around the site estimated that ~3%–4.9% of reported Macondo oil likely deposited on the seafloor, an estimate within the 1.8%–14.4% determined using a 17α-hopane biomarker tracer. Analysis of ^{14}C instead of a stable carbon isotope composition ($\delta^{13}C$) can distinguish crude oil from non-fossil-fuel carbon sources. Future environmental impact assessments of shorelines and ocean sediments can utilize the ^{14}C analysis method as demonstrated by Bostic et al. (2018), who traced oil-derived carbon in sand patties following the DWH incident, and by Bosman et al. (2020), who established the baseline isoscapes of surface sediments in the southern Gulf of Mexico.

ADVANCEMENTS IN STUDYING HEALTH RISKS FROM INHALED SPILL TOXINS

The DWH incident created health risks for response workers and others when the spilled oil was subjected to weathering from breaking waves, evaporation, atmospheric forcing, and other processes that contributed to the emission of fumes and the aerosolization of oil and dispersant constituents. Challenges remain in understanding those risks, especially in complex environments such as the turbulent marine-atmospheric boundary layer. In this section, we feature developments related to defining the interactions of waves, oil, and dispersed oil; processes that drive the formation of marine aerosols and their transport; and human exposure risks from aerosolized volatile organic compounds and particulate matter. Related topics are also discussed in Boufadel et al. (2021), Farrington et al. (2021), Quigg et al. (2021), Rullkötter and Farrington (2021), and Sandifer et al. (2021), all in this issue.

C. Li et al. (2017) built a wave tank to simulate the interactions of waves, oil, and dispersed oil and to investigate subsurface oil droplet evolution (Figure 6). The 6 × 0.3 × 0.6 m transparent acrylic tank is equipped with a piston-type wave plate that simulates waves from rolling ripples to plunging breakers. A dual-head laser illuminates the flow field and 12 halogen bulbs provide backlighting as three high-speed cameras visualize wave impingement on an oil slick and its breakup and dispersion. Particle image velocimetry characterizes turbulence, and digital inline holography quantifies droplet size distribution. Simulations showed that waves plunge down and splash up multiple times, leaving a series of droplet and bubble clouds behind. Wave structures and subsurface clouds presented similar features for both oil and dispersant-oil treatments, but droplet sizes were very different (1:25 dispersant:oil ratio formed <10 μm droplets compared to oil-only forming 22 μm to mm droplets). Quantifying interfacial tension, viscosity, density, and the effects of wave energy on droplet size distribution bridges small-scale physical processes for slick breakup and large-scale oceanic transport processes. This tank system was used by Afshar-Mohajer et al. (2018, 2019) to generate aerosolized volatile organic compounds and particulate matter that were then measured to provide data for a health risk assessment for oil spill response workers. Cui et al. (2020) used subsurface droplets generated by this tank system for corroboration of test results from a deepwater wave tank system designed to study oil dispersion.

M. Li et al. (2019) developed a hybrid large-eddy model to simulate the transport of aerosolized oil droplets (2.5, 40, 60, and 100 μm diameter) over progressive water waves. The model employs a hybrid spectral and finite-difference method for simulating wind turbulence, a bounded finite-volume method for modeling aerosolized oil transport, and a wave-following coordinate system and



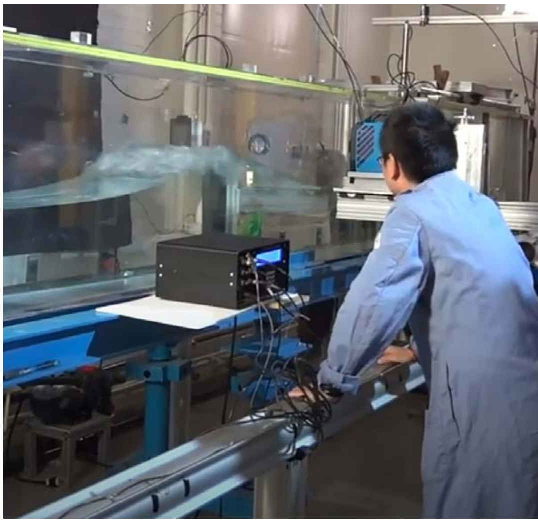


FIGURE 6. A custom wave tank was designed for experiments at the Johns Hopkins University Laboratory for Experimental Fluid Dynamics to study the interactions of waves, oil, and dispersed oil, and the evolution of subsurface oil droplets (C. Li et al., 2017). A piston-type wave plate produces a variety of waves, from rolling ripples to plunging breakers. After an oil slick is introduced, its dispersion is visualized and quantified by high-speed cameras, an illuminating laser, and holography. The tank has been used in various oil spill experiments, including one where aerosolized oil spill chemicals emitted by breaking waves were quantified in support of a health risk assessment for spill response workers (Afshar-Mohajer et al., 2019). *Illustration by and used with permission of Cheng Li, Johns Hopkins University. Photo extracted from the Dispatches from the Gulf video and used with permission of Marilyn Weiner, Screenscope Inc.*

computational grid to capture the flow fields adjacent to the waves. Simulations showed that wave-turbulence interaction enhanced the suspension of droplets and expanded the plumes, causing the oil concentration to dilute downstream. Larger droplets tended to resettle on the water, especially during downwelling events. Upwelling events helped to suspend the droplets and, when combined with fast waves, lifted even the 100 μm droplets to 40 m elevation. The 2.5 μm droplets transported like passive tracers, and a large fraction of the 40 μm and 60 μm droplets remained suspended for at least 600 m. The model enables estimations of the order of magnitude of oil droplet concentration near unsteady waves, which are challenging for existing models.

Chandrala et al. (2019) introduced a novel exposure chamber for use in the Real-Time Examination of Cell Exposure (RTECE) system that enables in situ imaging of lung cell cultures during and after exposure to airborne particles. The unique features of the enhanced system include three independently sealed chambers that are adaptable for housing different cell culture optimized, disposable nozzles that provide uniform aerosol deposition and prevent cross-contamination between experiments. The chamber can accommodate different optical components for live imaging of cell morphology and migration, ciliary beat frequency, and more. Validation tests of the enhanced system against existing commercial systems resulted in the same mass deposition and similar initial trends in cellular changes from cigarette smoke. The enhanced system further showed a complex, repeatable time evolution of response, capturing for the first time ciliary beat frequency fluctuations. Data generated with the RTECE system along with field measurements of aerosolized submicron droplets will support a transport model to determine the effects of aerosolized oil and dispersant particles on human lung epithelial cells.

DEVELOPMENTS IN INVESTIGATING OIL SPILL IMPACTS ON MARINE LIFE

As oil from the DWH incident moved from the seafloor through the water column, marine life in affected areas were exposed to hydrocarbons and dispersants. Benthic systems were also impacted by oil and dispersants that settled to the seafloor via sinking marine oil snow. Here, we feature novel applications of technology that led to the discovery and monitoring of damaged coral communities and their surrounding habitats. We also describe novel approaches for investigating oil-induced physiological and ecological impacts on commercially and environmentally important fish and marine mammal species that help to provide a more comprehensive understanding of acute and sublethal effects on long-term population dynamics. Topics related to oil spill impacts on marine life are also discussed in Farrington et al. (2021), Halanych et al. (2021), Quigg et al. (2021), Murawski et al. (2021), and Sandifer et al. (2021), all in this issue.

White et al. (2012) combined the use of technologies that can operate in the deep-sea environment with three-dimensional seismic data to find, image, identify, and collect samples of a damaged octocoral community 13 km southwest of the DWH site. Samples of corals, flocculate material, and sediments were collected using customized devices carried by ROV

Jason II and HOV *Alvin*. High-resolution chemical analyses were used to fingerprint oil found on or near the affected corals, and those present were associated with Macondo oil (GC×GC-FID identified and quantified biomarkers and GC×GC-MS confirmed biomarker structures). Fisher et al. (2014) discovered more coral communities in the region upon further review of seismic data together with additional data from the AUV *Sentry*'s multibeam echosounder surveys and new imagery collected by *Sentry* and a ship-tethered camera system. A Shilling ROV collected high-resolution images and samples of corals, sediments, and associated fauna, which confirmed that there were additional affected communities and expanded the known depth range and areas of spill impacts. Girard and Fisher (2018) developed a timeline of coral recovery or decline using seven years of digitized imagery to document longer-term effects, which may help future coral research.

Ziegwied et al. (2016) launched a new platform for collecting marine mammal acoustic data that integrates Seiche wireless communication and a passive acoustic monitoring (PAM) system with hydrophone arrays, all carried by two autonomous surface vehicles (ASVs). The approach provides a quiet platform (compared to vessel-towed systems), expands the range of frequencies and distances that can be monitored, continuously records acoustic data, and provides real-time monitoring and localizing of marine mammals. The PAM system has a processing electronics module, Wi-Fi connectivity, and 6 TB of storage capacity. The ASV *C-Worker* can operate for 30 days and has a modular payload bay and propulsion and communication systems. The ASV *C-Enduro* can operate for 90 days with its solar panels, wind turbine, and diesel generator. The PAM systems were mounted on the ASVs, launched near the DWH site, and monitored from a support vessel at 500–1,000 m distance. Data collected will be used to understand oil spill impacts on marine mammals and to advance detection and classification algorithms.

Frasier et al. (2017) used an automated network-based classification technique that employs unsupervised machine learning to develop an algorithm for processing large acoustic data sets of dolphin echolocation clicks. This method addresses the challenge of recognizing patterns in highly variable dolphin clicks by considering a set of clicks as a group of objects that are similar but not identical to one another based on click spectral shape and inter-click interval distributions. By reporting what it finds instead of being told what to look for, the algorithm can identify distinct types of dolphin clicks without prior knowledge of their distinguishing features, allowing for the identification of click types for known and potentially unknown species. Applied to a data set of 52 million dolphin clicks detected in the Gulf of Mexico, the technique identified seven distinct click types, one of which was known and six of which were not. This technique is a step forward in identifying marine mammal species under a big data paradigm that facilitates data analysis for population monitoring after environmental disturbances.

Data generated by the automated network-based classification technique were used by Solsona-Berga et al. (2020) in the development of the DetEdit graphical user interface that accelerates the editing and annotation of automated detections from marine mammal acoustic data sets.

K. Li et al. (2020) developed a three-stage automatic hybrid classifier algorithm that combines a traditional technique with unsupervised clustering to detect species-specific beaked whale calls in acoustic data. First, a spectral energy detector identifies signals in low, medium, and high frequency bands (with the user specifying the frequency for the species of interest), which allows for an initial discrimination of beaked whale calls from sperm whale calls and dolphin clicks. Next, an attribute-discriminator algorithm analyzes signals within the selected frequency band based on prior knowledge of species-specific acoustic properties. Finally, an unsupervised clustering algorithm assigns the remaining signals to species-specific groups based on a hierarchical dendrogram. The method was benchmarked against a manually annotated acoustic data set collected in the northern Gulf of Mexico and achieved a recall (relevancy) rate of 83% for Cuvier's and 78% for Gervais' species. This technique facilitates species-specific analysis, which helped identify differences in habitat preferences of two beaked whale species; it also improves our understanding of how marine mammals respond to environmental disturbances.

Main et al. (2018) extended the development of an aquaculture recirculating system (RAS) and designed an aquatic experimental system to simulate short- or long-term oil exposures of and investigate sublethal impacts on fish (Figure 7). The exposure system consists of nine 500 L fiberglass tanks coated with an isophthalic acid gelcoat that is resistant to chemical and atmospheric agents. The tanks can hold up to 30 fish for 28 days, with each tank system outfitted with a micro bubble diffuser and a flowmeter to maintain oxygen levels and a titanium heat/chill exchange system to control temperature. The tanks are linked to an RAS that includes solid filters, biofilters, oil filters, and UV sterilization filters to maintain water quality and chemistry with acceptable parameters and sumps to remove oil and dispersant. The system operated successfully during experimental trials with Florida pompano, red drum, and southern flounder to evaluate the effects of chronic versus episodic oil-dispersant exposure on fish health. Data from the experiments will be combined with field data to provide a more complete picture of oil spill impacts on fishery populations.

Sherwood et al. (2019) extended work on the aquatic experimental system (Main et al., 2018) and designed a system for sediment exposure trials with flounder to identify nonlethal biomarkers for oil exposure and oxidative stress and damage. The flow-through system consists of nine 552 L tanks (three control and six exposure tanks, each holding four flounder) linked to an RAS that ensures an uncontaminated seawater renewal of 5,000 L/tank/day to maintain water chemistry and quality. Oiled and control sediment are spread evenly to a depth of ~5 cm on the bottoms of the tanks, then clean seawater is gently added, and sediments are allowed to settle for 72 h. Flounder were sampled after 35-day exposure trials, and a subset were transferred to a clean tank for a 30-day recovery followed by blood and tissue assessments. This system allows for nonlethal biomonitoring of wild fish populations that can inform fishery management decisions following an oil spill. After trials of exposure to oiled sediment and recovery with flounder, Rodgers et al. (2021) observed varied responses in gill and liver tissues from the same individual fish, indicating that tissue type is a key driver of transcriptomic responses to oil.

Nelson et al. (2017) collected real-time measurements of fish cardiac function using blood flow probes inserted in oil-exposed cobia during swim trials in a respirometer chamber. The surgical procedure on anesthetized fish involved exposing the ventral aorta around which a silicone-cuff flow probe was placed with its leads anchored to the lateral body wall and the dorsal surface. After recovery, fish were placed in oil-exposure tanks for 24 h and then transferred to 90 L chamber respirometers for swim trials. The probe leads were connected to a directional pulsed-Doppler blood flow meter to simultaneously measure cardiac function, oxygen consumption, swim performance, and metabolic parameters. After the trial, the fish's blood was infused through the ventral aorta and flow signals were recorded, allowing for calculations of cardiac output, heart rate, and stroke volume. These techniques provided the first measurements of cobia cardiac function as it relates to oil exposure, and results suggest potential negative impacts on fish that could affect their ability to capture food and escape predation.

Heuer et al. (2019) isolated heart cells from adult mahi-mahi to clarify the mechanisms underlying cardiac function impairment and reduced swim performance following oil exposure, providing the first measurements of cellular contractility in oil-exposed cardiomyocytes from a marine pelagic fish. The hearts of euthanized fish were extracted, and the ventricle was isolated and triturated to free individual cardiomyocytes. An IonOptix Myocyte Contractility system (a perfusion chamber mounted to a microscope attached to a specialized fast-digitizing dimensioning camera) recorded kinetic properties of cardiomyocyte shortening in real time following exposure to various oil concentrations. During oil exposure, cardiomyocytes were stimulated at progressively increasing frequencies representative of heart rates reported in mahi-mahi (~100–180 bpm). In parallel experiments, a patch clamp amplifier (an electrophysiologic technique to study ionic currents in cells) recorded the cardiomyocyte action potential (a brief change in voltage or membrane potential across heart cell membrane). Results provided a link between electrophysiological parameters of oil-induced impairments with a functional consequence. This technique was used by Folkerts et al. (2020) to investigate the impact of flowback water generated by hydraulic fracturing on those same functions in mahi-mahi.

Tarnecki et al. (2016) developed a marine food web matrix of 474 Gulf of Mexico fish species based on diet information obtained from stomach sampling and online information. Diet information was sorted into 89 Atlantis functional groups, then fitted to a statistical model based on the Dirichlet distribution to quantify likely contributions of prey and determine error ranges that reflect diet variability and data quality. Hierarchical cluster analyses performed on the func-

FIGURE 7. Laboratory experiments were designed to investigate oil-induced effects on fish to better understand the impacts of oil spill contaminants on marine life. (left) A new aquatic experimental system with nine 500 L fiberglass tanks (blue tanks contain oil and dispersant mixtures) was used to study short- and long-term sublethal impacts of oil spills on Florida pompano, red drum, and southern flounder. To maintain appropriate water quality and chemistry parameters, the tanks are linked to an aquaculture system that provides recirculating filtered water, and sumps are used to remove oil and dispersant (Main et al., 2018). (right) Nonlethal biomarkers for oil exposure and oxidative stress and damage in southern flounder were investigated using a new experimental flow-through system composed of nine 552 L tanks containing oiled or control sediment (Sherwood et al., 2019). *Both photos by and used with permission from Kevan L. Main, Mote Marine Laboratory*

tional groups helped determine similarity between predator functional groups, and a food web diagram was constructed to visually represent the interconnectivity of predators and prey. A meta-analysis using principal coordinates analyses allowed comparison of this diet matrix to other food webs used in ecosystem modeling. A hindcast model (1980–2010) showed that these data offered an improved fit to observational data and reduced errors in biomass projections in the Ainsworth et al. (2015) food web matrix.

The marine food web matrix was incorporated into the Atlantis model, after which Ainsworth et al. (2018) simulated impacts from the DWH incident on fish guilds and their subsequent recovery, and Court et al. (2020) estimated the direct and total economic impacts associated with changes in commercial and recreational fishing activity following the DWH incident.

Ackleh et al. (2019) developed a non-evolutionary model to describe predator-prey dynamics and then extended it to an evolutionary model under the influence of an environmental toxicant. The discrete-time predator-prey model simulates how prolonged exposure to a toxicant or environmental disturbance, such as an oil spill, may impact predator-prey dynamics when only the prey evolves resistance to the toxicant. The evolutionary model combines population dynamics with an evolving phenotypic trait that measures the amount of toxicant resistance in the prey. Darwinian dynamics are applied so that the evolution of the prey's toxicant resistance occurs on a timescale commensurate with population dynamics (a few generations rather than a few hundred years). Simulations showed that rapid evolution in short-lived species can enable persistence at higher toxicant levels for that species and also for a species with which it interacts. This research was extended in Ackleh et al. (2020) to provide a more in-depth analysis of how the speed of evolution might impact population dynamics in a highly toxic environment.

EMERGENT DISPERSANT TECHNOLOGIES

Chemical dispersants were applied during the DWH incident to help reduce the harmful vapors emanating from crude oil surface slicks that response workers might be exposed to and to help reduce or prevent coastline oiling. Dispersants help break up an oil slick into small droplets and keep the droplets submerged in the water column to make them more available for biodegradation. However, there are concerns about the risks associated with chemical dispersants to both humans and the environment, prompting research efforts focused on modifications to or substitutes for existing dispersant systems. Emergent dispersant technologies as alternatives to Corexit that show promise as being effective and efficient in oil spill remediation and that are non-toxic to humans and the environment are considered below. Related topics are discussed in Quigg et al. (2021) and Halanych et al. (2021), both in this issue.

Saha et al. (2013) used surface-tunable carbon black (CB) particles as an alternative to Corexit for oil spill remediation. Tests that either added sodium chloride (salt) or reduced pH showed that the particles' hydrophilic-hydrophobic balance can be altered. Salt increased the hydrophilic content the most, indicating that seawater can help make CB particles efficient at spill containment. Comparison tests with Corexit 9500A showed that tuned CB created oil/water emulsions that remained stable in a vial for six months. However, Corexit emulsions destabilized in about an hour and also dispersed water drops into the oil layer, which can hinder oil spill remediation by reducing the energy content in the oil layer, reducing bioremediation efficiency, decreasing the ability to burn the oil, and increasing viscosity and volume that affect removal. Once at the oil/water interface, CB can adsorb polycyclic aromatic hydrocarbons (PAHs) and reduce their transfer to the water column. The availability of CB particles combined with their properties, biocompatibility, and a patent as a method for cleaning marine oil spills (https://patents.google.com/patent/US9233862B2/en) make this a viable alternative technology to Corexit for oil spill application.

Owoseni et al. (2018) formulated a gel-like surfactant with a structure that imparts buoyancy characteristics as a new class of alternative technologies for oil spill remediation. The formulation contains the surfactant components of Corexit (DOSS, Tween 80) and a widely available lecithin component, a phospholipid (L-α-phosphatidylcholine or PC). The combination of Tween 80, DOSS, and PC lowers the oil/water interfacial level. Increased amounts of Tween 80 lead to a transition from sheet-like lamellar structures to spherical, onion-like multilamellar structures. Optical microscopy showed that increasing the Tween 80 content results in smaller droplet sizes, with ~99% being in the 0–25 µm range when Tween 80 is at 27 wt%. The system's buoyancy characteristics provide potential for a floating dispersant that improves adherence to oil in a dynamic ocean environment. Delivery of the gel dispersant as pods, similar to laundry detergent pods, would avoid the use of propylene glycol and the generation of airborne volatile solvents, providing a safer environment for spill responders.

Yu et al. (2019) developed a method for controlling the relative hydrophilic and hydrophobic characteristics of clay halloysite particles by chemically modifying their surfaces using amphiphilic polypeptoids for improved stabilization of oil/water emulsions during spill remediation. Relative to unaltered particles, functionalization with appropriate hydrophobic content effectively lowers the interfacial tension, enhances the particles' thermodynamic propensity to partition at the oil/water interface, and increases the emulsion viscosity, resulting in more stable emulsions. Analysis of emulsions created by functionalized particles showed emulsions lasting 14 days with no change in oil droplet sizes after seven days; those created by pristine particles had unstable emulsions, and droplet size diameters increased to >300 µm. Functionalized particles are not toxic to the hydrocarbon-degrading bacterium *Alcanivorax borkumensis*; instead, they enhance bacterial proliferation compared to less hydrophobic or pristine particles, likely by serving as a nitrogen source, and provide a larger oil/water interfacial area onto which bacteria can better anchor. The use of polypeptoids may improve the viability of clay halloysite particles (https://patents.google.com/patent/US20180071225A1/en) for spill response application.

Ojo et al. (2019) designed a stoppering agent using an environmentally benign metal-phenolic network ($FeCl_3$) to slow the release of surfactant encased within clay halloysite nanotubes for oil spill applications. The stoppering agent addresses the drawback of an almost instantaneous surfactant release when introduced to the oil/water interface, requiring the nanotubes be delivered as a dry material instead of in a liquid solution, which is how dispersants are traditionally applied to an oil slick. The network forms a skin (stopper) around the nanotubes and sequesters the surfactant at a neutral pH value. Changing the pH to an acidic value dissembles the network for a gentle and targeted surfactant release. Tests showed that without the stopper, the surfactant releases in less than an hour, and with the stopper, it releases slowly over 12 h. Droplet size prior to network disassembly was 182.9 ± 14 µm, after disassembly it was <100 µm, and it then remained unchanged for two weeks. Farinmade et al. (2020) adjusted this system using a thin coating of paraffin wax so that the surfactant release is triggered by contact with oil instead of a pH change. These stoppering techniques may improve the viability of surfactant-loaded halloysite nanotubes (https://patents.google.com/patent/US20160114303A1/en) for spill response application.

Other advancements in alternative dispersant technologies include an optimal ratio for a lecithin/Tween 80 (L/T) surfactant-solvent system (Riehm et al., 2015), which confirmed earlier findings that L/T blends are effective dispersants (Athas et al., 2014; Nyankson et al., 2015), and a thermodynamic model to analyze two-dimensional graphene materials for their emulsification potential at the oil/water interface and the possible creation of graphene-based foams or microsacks to carry lipophilic cargos for spill response (Creighton et al., 2014).

CONCLUSION

The DHW oil spill was unprecedented in the amounts of oil and gas released and the quantities of dispersants applied near the blowout site at 1,500 m water depth and at the ocean surface. Although mitigation measures were planned for and ready at hand, the severity and unusual circumstances of the accident called for the development of new techniques and approaches, as well as the improvement of existing methods, for mitigation and for investigations of the fate and impacts of the released material and the physical, chemical, and biological processes involved. The 37 technological developments highlighted in this paper are examples of innovations that were introduced during the scientific response to the DWH incident. These innovations resulted from interdisciplinary research and collaborations among national and international entities that represent 49 universities, 10 government agencies, and 17 commercial businesses. The referenced publications for these 37 technological developments have a combined number of more than 2,000 citations (Google Scholar, January 29, 2021).

According to a National Science Board report on invention, knowledge transfer, and innovation, "the relationships among institutions underpin the environment in which ideas become innovations and diffuse through society" (NSF NSB, 2020). The report noted that coauthorship of innovative research in publications that result from collaborative efforts among universities, federal laboratories, and the business sector has increased over the last decade in both number and citations, which can serve as indicators of knowledge flow and communication that foster innovation. Collaborations that resulted in innovations applied to oil spill research described in this paper as well as in various scientific communications about them help set the stage for future innovations with a wide range of potential applications in the disciplines involved in their development.

Complementary and subsequent research drew on several existing techniques featured here that were applied in the early months following the DWH oil spill and provided fundamental data and information about the newly discovered oil plume and identified and assessed its impacts on sediment and deepwater corals. Those early efforts (Camilli et al., 2010; White et al., 2012; Chanton et al., 2015) reached a high level of awareness within the scientific community as evidenced by their combined number of nearly 1,300 citations (Google Scholar, January 29, 2021).

Several developments discussed here were applied to observations of ocean currents and properties and to observations of the subsurface dynamics of oil and gas droplets, and then contributed to new or improved data about the physical and biogeochemical processes affecting the transport and fate of the spilled oil. These observational data can be incorporated into circulation models to develop more accurate prediction capabilities.

A number of innovations featured in this paper involved laboratory experiments and models that helped to identify and quantify factors that drive the transport and fate of a deepwater oil spill, and their results can improve the simulation of scenarios in support of response decisions. For example, experiments that simulate the formation and evolution of aggregates and flocculant material in the water column provide data and insights that can improve predictions about the sedimentation of oil. Techniques for estimating droplet size distributions with and without dispersants can improve the simulations of broader oil spill scenarios. Technologies that simulate the generation of aerosolized droplets by breaking waves, the evolution of those droplets over the sea surface, and the effects of inhaled toxins provide data that can support the inclusion of health risk scenarios in response decisions. One of the challenges in oil spill research is to address the scaling of laboratory results to field conditions.

Three techniques featured in this paper improve the processing efficiency of large data sets. The acquisition of large data sets will likely continue with the advancement of efficient ocean acoustic monitoring platforms and the increasing affordability of the high-frequency, high-resolution cameras utilized in several techniques featured in this paper. Research related to the processing of large data sets is likely to be in demand as data scientists and mathematical science occupations are expected to grow 27% by 2029 (US Department of Labor, 2020).

Several innovations were used in oil exposure experiments on fish and used to simulate oil spill scenarios, revealing potential impacts on marine food webs and population dynamics. The developments utilized in these efforts are applicable to a wide range of environmental disturbances that can have cascading negative effects on commercial and recreational fishing and tourism industries that rely on a healthy marine environment. Research that provides information about the type, severity, significance, and duration of oil spill impacts on marine life can inform spill response decisions. Additionally, the development of less-toxic dispersants for spill response could, if utilized, lead to the reduction of oil spill impacts on the marine environment. The challenges for these alternative dispersant technologies include their acceptance, staging, and readying for use in a spill response, particularly on a large scale. As part of their efforts to generate viable dispersant options, academic researchers have cultivated relationships with response agencies and industries that have testing and production-scale capabilities. These collaborations show promise for improving responses to future oil spills.

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AUTHORS

Nilde Maggie Dannreuther (maggied@ngi.msstate.edu) is Coordinator, Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS, USA. **David Halpern** is Visiting Researcher, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA. **Jürgen Rullkötter** is Professor Emeritus, Carl von Ossietzky University Oldenburg, Oldenburg, Germany. **Dana Yoerger** is Senior Scientist, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.

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PREPAREDNESS, PLANNING, AND ADVANCES IN OPERATIONAL RESPONSE

By David G. Westerholm, Cameron H. Ainsworth, Christopher H. Barker, Peter G. Brewer, John W. Farrington, Dubravko Justić, Vassiliki H. Kourafalou, Steven A. Murawski, John G. Shepherd, and Helena M. Solo-Gabriele

A Phantom 4 Pro drone is released from R/V *Walton Smith* during the CARTHE Submesoscale Pathways and Lagrangian Analysis on the SHelf (SPLASH) experiment. High-resolution cameras on the drone collected aerial observations of floating bamboo drift plates and fast-evolving fronts at 1–200 m scales. *Photo credit: Tamay Özgökmen, University of Miami*

ABSTRACT. During the last 50 years, the numbers and sizes of oil spills have been significantly reduced through prevention. But spills still occur, and it is critical to prepare for these events through planning and exercises. Operational decisions are designed to expedite cleanup and minimize overall impacts, yet they often involve complex trade-offs between a multitude of competing interests. It is imperative to apply the best technology and science when events occur. However, while planning and response tactics have evolved over time, determining what may be most at risk is often confounded by sparse background data, modeling limitations, scalability, or research gaps. Since 2010, the Gulf of Mexico Research Initiative (GoMRI) and other oil spill research helped address many issues and propelled advances in spill modeling. As a result, there is an increased understanding of environmental impacts, how to assess damages, and the unintended consequences of spill countermeasures. The unprecedented amount of information resulting from this research has strengthened the bridge between the academic community and operational responders and brought improvements in preparedness, planning, and operations. This paper focuses primarily on GoMRI research and advances that relate to operational activities, as well as limitations and opportunities for gap-filling future research.

INTRODUCTION

During the last 50 years, the world has made considerable progress in reducing the numbers and sizes of oil spills through prevention. Despite these advances, oil spills still occur, and it is critical to prepare for these events through planning and exercises that can apply the best technology and science when actual events happen. Operational decisions during deployments of spill resources are designed to expedite cleanup and minimize the overall impacts of oil spills. It is a complex process, where response decisions must consider trade-offs between a multitude of competing interests such as maritime commerce, seafood safety, human health, tourism, recreational access, habitat loss, food web disruptions, endangered species protection, and critical energy and defense infrastructure. Political interests, prescribed uses of funding, and logistic constraints can also influence what response measures are used, when and where they are deployed, and how their effectiveness can be evaluated. While planning and response tactics have evolved over time, determining what may be most at risk is often confounded by sparse background data, modeling limitations, scalability, and research gaps.

As noted in other articles in this issue, petroleum fossil fuel oils are a very complex admixture of a thousand or more chemicals that interact with physical, chemical, and geological processes on spatial scales of centimeters to hundreds of kilometers and timescales of seconds to many months. The temporal and spatial progressions of spilled oil in various states of weathering also result in varying effects on organisms, from microbes to whales, marine ecosystems, and human society (Rullkötter and Farrington, 2021; Weiman et al., 2021; Murawski et al., 2021a; and Sandifer et al., 2021, all in this issue). Over the last 10 years, the Gulf of Mexico Research Initiative (GoMRI) as well as oil spill research funded by government and private sources has helped address these issues and propelled advances in our understanding of environmental impacts and the unintended consequences of spill countermeasures, and how this understanding can be applied to developing better response, damage assessment, and restoration. The academic community and operational managers have not always interacted within the topic of oil spills due to differing objectives, but with the unprecedented amount of information resulting from GoMRI-funded research, it is imperative to bring this information into the response community's preparedness, planning, and operational processes.

It should be noted again that this paper focuses primarily on GoMRI research and only generally refers to other oil spill research, including work that supported the US Natural Resource Damage Assessment (NRDA). The reader can find additional references and resources in academic journals related to oil spill research as well as composites of government, industry, and academic research found at the following websites:

- Interagency Committee on Oil Spill Research (which references federal government and other stakeholder oil spill research)
  https://www.dco.uscg.mil/ICCOPR/
- National Oceanic and Atmospheric Administration Damage Assessment and Restoration Program case files
  https://darrp.noaa.gov/case-documents-index
- National Academies of Science, Engineering and Medicine, Ocean Studies Board
  https://www.nationalacademies.org/osb/ocean-studies-board
- National Academies of Science, Engineering and Medicine, Gulf Research Program
  https://www.nationalacademies.org/gulf/gulf-research-program
- Industry technical reports and publications
  http://www.oilspillprevention.org/oil-spill-research-and-development-cente
- International Oil Spill Conference Proceedings
  https://meridian.allenpress.com/iosc/issue/browse-by-year

OPERATIONAL OIL SPILL MODELING

Deepwater Horizon (DWH) demonstrated the strengths but also exposed some of the limitations in the deep-sea blowout oil spill modeling capability of the United States, and more specifically of the National Oceanic and Atmospheric Administration (NOAA). Since DWH, incorporation into models of deep-sea and water-column fate and effects, three-dimensional capability, faster processing, improvements to algorithms, and more user-friendly displays has provided critical updates that render the models more useful for response plans, exercises, and actual oil spills. In addition, new parameterizations and methods have been developed that can be integrated into operational models in the near future. New transportation routes and lease sites associated with changes in energy production provide additional modeling opportunities, but certain limitations and variabilities still exist in spill prediction that will need to be addressed in future research. For a more detailed summary of operational modeling, see Barker et al. (2020). The response to a significant oil spill is a large and complex endeavor, requiring many decisions that balance trade-offs between a multitude of competing interests. Each of these many decisions must be made with some understanding of how the spill unfolds and might unfold in the future, and how response actions may improve or adversely impact the environment. Predictions developed from oil spill models can help guide these decisions and are used to support planning for spill response, environmental impact analyses, response decision-making, and determining public compensation for injuries from an event through the NRDA.

This section focuses on "operational" spill modeling, which must work on short timescales (hours/days) to support operational response decisions. How oil moves (transport) and how it is transformed (fate) is governed by ocean currents, surface winds, wave climate, and water temperature. Oil spill modeling relies on predictive numerical models related to these parameters. These models use simulations to solve complex equations that describe the phenomena of interest and have the advantage that they can be employed for past (hindcast), current (nowcast), and future (forecast) applications. Oil spill transport models guide the response through forecasting the potential locations of oil. Modeling the fate ("weathering") of oil can predict what harm the oil could cause, informing the efficacy and effects of potential response actions. Enhancing the capabilities and accuracies of spill models requires improvement of the corresponding inputs (Figure 1). It should be possible to display model results in a common operational picture (COP) along with other important environmental, safety, and response information in order to plan and prioritize the choice and deployment of response equipment and options.

Ocean circulation models provide an important basis for oil spill prediction, and several such applications were employed during DWH. Examples include the global HYbrid Coordinate Ocean Model (HYCOM; Chassignet et al., 2007), the Gulf of Mexico HYCOM (Mariano et al., 2011; Le Hénaff et al., 2012), the South Atlantic Bight-Gulf of Mexico model (Hyun and He, 2010), the Real-Time Ocean Forecast System for the North Atlantic Ocean (Mehra and Rivin, 2010), the intra-Americas-Sea Nowcast/Forecast System (Ko et al., 2008), and the University of South Florida West

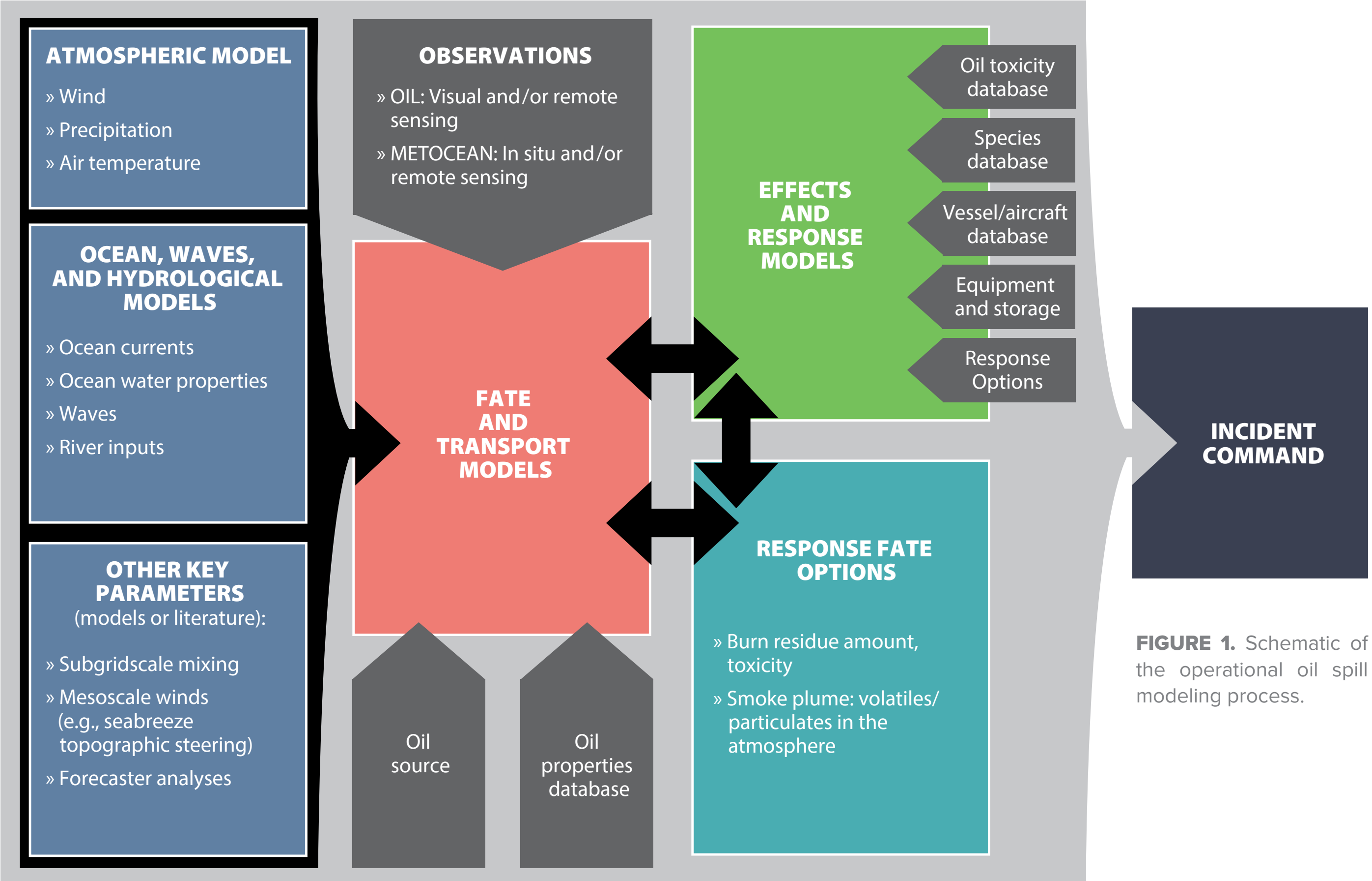

FIGURE 1. Schematic of the operational oil spill modeling process.

Florida Shelf model (Barth et al., 2008). Even though they were valuable tools for the immediate response, these models had limitations that influenced oil spill predictions. Many limitations of these models are still valid today, but recent advances have been made to overcome them, and progress continues (Fox-Kemper et al., 2019).

The sources of errors in ocean models may derive from both deterministic processes (such as tides, wind-driven events, and coastal freshwater flows) and instabilities (e.g., mesoscale eddies, submesoscale eddies, and associated fronts). For deterministic processes, the limitations in ocean model performance are controlled by model resolution, accuracy of model inputs, and ability to represent/parameterize the appropriate physical processes. Data-assimilative models improve accuracy, but are often subject to limited availability of observations, especially in subsurface/deep environments. Since DWH, most of the improvements in representations of the complex oceanic features that can drive oil movement are the direct outcome of more powerful computing platforms that allow for increased horizontal resolution. We can now perform basin-scale simulations (e.g., North Atlantic and the Gulf of Mexico) with grid spacing on the order of 1 km (submesoscale resolving; Le Hénaff and Kourafalou, 2016; Chassignet and Xu, 2017; Jacobs et al., 2019) and regional/coastal simulations with grid spacing on the order of 100 m (Capet et al., 2008). There remain deployment issues, and currently it is not practical to run such high-resolution models for every place there might be an oil spill. Rapidly addressing a future event requires having systems in place that can quickly set up a new high-resolution operational region nested in the existing larger-scale operational models. Freshwater flow presents additional challenges, as ocean models typically have represented it at only a few particular points and often at very course temporal resolution. The method employed and the parameterization of related processes can impact output on the circulation and transport in areas of river influence (Kourafalou et al., 1996; Schiller and Kourafalou, 2010; Tseng et al., 2016). Improved inputs on atmospheric and river forcings, in combination with high spatial resolution, will be necessary for accurate transport forecasts in ports and other areas that are influenced by freshwater and also likely to have spills.

Despite the new achievements in ocean models, computational capability limits models from explicitly representing processes at all the scales that control ocean circulation. As shown in detailed measurements around the DWH site by Poje et al. (2014), the influence of ocean processes on surface material dispersion increases enormously at small scales. One effect of this is enhanced dispersion over what would be predicted from larger-scale circulations. Submesoscale processes are typically much smaller in scale and have much weaker currents than mesoscale features; however, the effects on surface transport can be stronger than those coming from the mesoscale and can strongly influence oil fate by either spreading or concentrating the oil (Roth et al., 2017; Rascle et al., 2017; and Androulidakis et al. 2018).

Velocity structure in the upper meter of the water column has also been identified as particularly important in transport of spilled oil but has not been well represented in ocean models. While the ocean surface often garners the majority of attention, another critical component of accurate modeling and prediction of oil spills is deeper mixing and transport by ocean currents. Before DWH, a number of three-dimensional operational circulation models were available, but none of them could well capture the circulation at depth (MacFadyen et al., 2011). Even now, very few areas have real-time current measurements below 1,000 m, which will be critical for tracking subsurface plumes and forecasting oil movement from future deepwater releases. With higher model resolution and more powerful computing platforms, new classes of physics become resolved (Barkan et al., 2017), but high-resolution modeling requires high-resolution input data. Much of the GoMRI work showed the importance of submesoscale effects on transport and dispersion (D'Asaro et al., 2018). Targeted high-density observations allowed corrections at smaller scales so that greater forecast skill could be achieved (Carrier et al., 2016). Surface drifters can provide significant observational coverage over an area of high interest at a relatively low cost (Muscarella et al., 2015). Airborne observations could be used to provide better high-resolution data on currents for model initialization (Rodriguez et al., 2019), while satellites can provide high-resolution data with continuous global coverage (Rodriguez et al., 2018).

Prior to DWH, most operational oil spill modeling included wave transport only as part of a wind drift parameterization. This is an effective and practical approach, but as higher-resolution operational wave models come online, wave effects can be better captured (Weber, 1985). Spill models will also benefit from more closely coupled atmosphere-ocean-wave models such as the Coupled Ocean Atmosphere Prediction System (COAMPS; Allard et al., 2014). Blowout plume models were unable to answer some of the unanticipated questions that arose during DWH, including the effects of multiphase flow, dissolution of oil and gas within the plume, and droplet size distribution. Recent model development has focused on computational fluid dynamics (CFD) models of the three-dimensional multiphase plume flow field (Fabregat et al., 2015, 2016, 2017; Fraga and Stoesser, 2016; Fraga et al., 2016; and Yang et al., 2016). While these models are too computationally expensive to be deployed operationally, aspects of the physics investigated with these models can be leveraged for use in response models. Additionally, sophisticated integrated blowout plume models have been developed. NOAA has integrated the Texas A&M Oil spill Calculator (TAMOC; Dissanayake et al., 2018) with its General NOAA Operational Modeling

Environment (GNOME) suite that can be run on operational timescales to predict the behavior of the plume and the properties of the oil once it reaches the surface (Gros et al., 2018).

When oil is mixed with water in a turbulent environment, either in a blowout plume or at the surface in breaking waves, it is broken down into small individual droplets. The resulting droplet size distribution has a very large influence on the fate and transport of the oil (Thrift-Viveros et al., 2015; Gros et al., 2017; Socolofsky et al., 2019). Models for droplet formation at the surface had been developed and used in oil spill models for decades (Delvigne and Sweeney, 1988), but there were not many estimates for a deepwater well release. One model (F. Chen and Yapa, 2007) did estimate droplet size but did not account for the resulting droplet size distribution after application of dispersants, either at depth or at the surface. Recent work on mechanistic models such as VDROPJ (Zhao et al., 2014) and Oildroplets (Nissanka and Yapa, 2016) improved prediction of droplet size distributions under various conditions. These models may not be suitable for real-time operational predictions but have been invaluable in better understanding droplet formation and the effects of dispersant use, including reduction of volatile organic compounds at the surface (Gros et al., 2016). For operational use, a simpler class of droplet size distribution models, fitting distribution to laboratory data, has been developed and is being deployed in current operational oil spill models (Johansen et al., 2013; Li et al., 2017).

DWH provided an opportunity to study biodegradation on a large scale, and with new tools available (genomics), it has become clear that under certain conditions, biodegradation can be a significant process at fairly short timescales. As the application of dispersants at depth could influence biodegradation and, therefore, oxygen demand (Brakstad et al., 2020), biodegradation is an important factor to include in operational modeling, and advanced biodegradation models based on droplet size are now making their way into operational models (Brakstad et al., 2015, 2017; Thrift-Viveros et al., 2015). DWH also placed a focus on the marine oil snow sedimentation and flocculent accumulation (MOSSFA) event that continued for several months after DWH was capped (Passow et al., 2012; Brooks et al., 2015, Romero et al., 2017; Daly et al., 2016; Stout et al., 2017; Stout and German, 2018; Langenhoff et al., 2019; Passow and Stout, 2020). This process had not been included in operational response models, and GoMRI research devoted to the MOSSFA process illustrated that it is very complex and difficult to model.

Models have been developed using coagulation theory to study marine particle size distributions (Jackson, 1995; Jackson and Burd, 1998), but these are not suitable for operational models. Work is ongoing to develop simplified MOSSFA models that can be incorporated into operational models. As discussed above, when modeling spill transport, the greatest limitation is accuracy and precision of the models that provide the drivers (winds, currents, waves). Therefore, spill models must use parameterizations of processes not captured by those models, such as subgrid-scale diffusion. More work needs to be done to better capture spatially variable and non-isotropic diffusion.

The GoMRI-sponsored Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) field drifter experiments provide a rich data set that can inform the development of more sophisticated parameterizations of diffusion at the surface. For vertical mixing, improvements in near-surface diffusion will be incorporated into operational models (Nordam et al., 2019a,b). Near the surface, many transport and weathering algorithms require an estimate of the film thickness or surface area. The effect of wind on spreading has been quantified by the work of Zeinstra-Helfrich et al. (2017), and it may make its way into operational models. However, the patchiness of oil distributions is driven by submesoscale processes, such as Langmuir circulation, fronts, and small eddies. Much work has been done by GoMRI researchers on quantifying and better understanding these submesoscale circulations, but this work has not yet made it into parameterizations that can be included in operational models.

Knowledge of the fate of oil is critical for informing choices regarding response equipment and methods. New analytical techniques have greatly expanded understanding of photo-oxidation (Ward and Overton, 2020), which is thought to be important in the formation of emulsions, oil solubility, and toxicity. The implications for oil transformation on parameters important to response are not understood well enough to be included in response models, but current effort is being devoted to modeling of emulsion formation.

There will always be uncertainty in models. This uncertainty needs to be quantified and communicated to responders who rely on forecasting from those models to make decisions. One of the best ways to capture uncertainty is through ensemble modeling, which can quantify and reduce the uncertainly of forecasts (Brassington, 2017). Ensembles were used in an informal way during the DWH event (MacFadyen et al., 2011), but as more models come online, operational modeling centers are developing methods to better utilize ensembles during spill response. In the 10 years since the DWH event, the GoMRI program and other funders have supported advancing understanding of aspects of oil spill science and modeling, from individual droplets to oil slicks and biological effects of oil on wildlife and humans. This large collective focus over such an extensive set of scientific fields with multiple countries involved has set a new benchmark for knowledge in oil spill modeling and assessment. This legacy should be well used by future researchers and responders to improve oil spill modeling and response.

IMPROVEMENTS IN MODELING ENVIRONMENTAL IMPACT AND DAMAGE ASSESSMENT

As spill models improve, it is equally imperative to understand the expected impacts from the released oil in order to make informed decisions on appropriate response priorities and provide validity to the NRDA process. For example, given the extensive research on dispersants that has led to improved understanding of physical and chemical processes associated with them, the expected benefits and impacts of this countermeasure must be assessed against mechanical recovery of oil and other alternative actions such as in situ burning that also have limitations and potentially deleterious effects. The ability to predict and model ocean and coastal impacts through the nexus of laboratory research, mesocosm studies, and field measurements must be incorporated into models that will drive the environmental trade-off discussion.

As discussed, models have been refined to simulate oceanographic physical processes from the deep sea to the ocean surface where they are impacted by wind, waves, and surface ocean currents (e.g., Prasad and Hogan, 2007; Chassignet et al., 2009; Le Hénaff and Kourafalou, 2016; Weisberg et al., 2016; J. Chen et al., 2019). As study of the DWH spill progressed, it became apparent that the formation of a large undersea plume had also been important to representing oil dispersal and determining which organisms and biomes were exposed to oil (Camilli et al., 2010; Liu et al., 2011; Romero et al., 2018). However, representing undersea plume dynamics proved challenging for the physical models and required a sophisticated representation of the interplay of gas and oil, the preferential solubility of oil components, effects of dispersant on droplet size distribution, gas hydrate formation, behavior of oil and oil-degrading microbes under high pressure, oxygen consumption, and other factors.

Additional advancements were made in understanding and modeling biodegradation and chemical weathering processes, including volatilization, dissolution, and photodegradation. Processes associated with microbes also produced MOSSFA, which enhanced the sedimentation of oil. MOSSFA contributes toward the oil burden of the ocean in addition to the submerged and sunken oil that originates from the weathering process. A carefully coordinated program of field observations and laboratory experiments was critical in allowing models to accurately represent oil fate and associated injuries (Figure 2).

As mentioned above, in addition to GoMRI-funded research, other extensive studies supported as part of the DWH NRDA resulted in the publication of numerous technical reports and journal articles related to oil spill modeling. Many of these are listed on the US Department of the Interior website https://www.doi.gov/deepwaterhorizon/adminrecord and in the reference section of the National Academies dispersant report (NASEM, 2020). These studies of

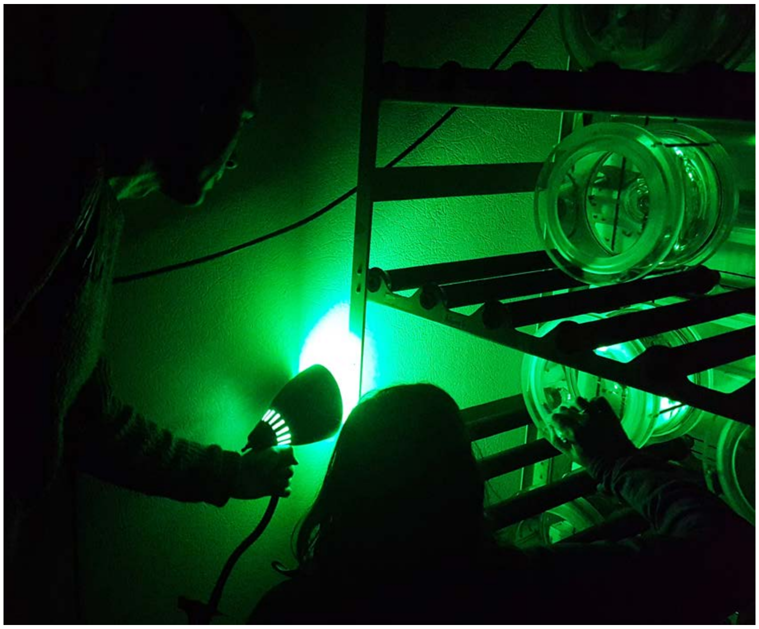

FIGURE 2. (above) Scientists conducted rolling table experiments to improve understanding of how marine oil snow forms and to provide input parameters for models that predict oil transport via sinking marine snow. *Photo credit: Julia Sweet* (left) CARTHE researchers launch the Ship Tethered Aerostat Remote Sensing System (STARSS) from M/V *Masco VIII* during the Lagrangian Submesoscale Experiment (LASER). STARSS was part of a large-scale oceanographic campaign designed to observe oceanic dispersion over a wide range of spatial and temporal scales and understand transport and dispersion of oil and other buoyant materials. *Photo credit: Maristella Berta, CNR-ISMAR, Venice, Italy*

DWH stand as examples of fruitful cooperation between empiricists and modelers. They represent considerable advancement in our ability to simulate transport and fate of oil (e.g., Reed et al., 2000; Beegle-Krause, 2001; Warner et al., 2010; Liu et al., 2011; Paris et al., 2013; Fabregat et al., 2017; French-McCay et al., 2019).

Nevertheless, of the many processes that influence the transport and fate of oil, some are yet to be integrated into larger-scale oil spill models (Spaulding, 2017). Despite impressive instances of the coupling of models by many different GoMRI authors, there remains a need to combine known processes across disciplines into a common predictive framework, for example, synthesizing ocean hydrodynamics, atmospheric dynamics, and physical, chemical, and biological process that influence oil weathering. There is also a need to further examine, for example, nearshore processes and the effects of freshwater fronts (Kourafalou and Androulidakis, 2013; Xia et al., 2020), which ultimately impact the beaching of oil in varying coastal environments. Oil beaching plays a role in a cascade of additional processes that further impact short-term mitigation and ultimately society as a whole.

In addition to the physical-biogeochemical processes that govern oil spill transport and fate, preparedness and planning for future oil spills should also consider the impacts of oil on additional knowledge domains. These additional domains include ecosystems (considers all living organisms and biotic and abiotic factors that influence their existence), socioeconomics (considers social, cultural, institutional, and economic factors that influence productivity within a community), and human health (considers both the physical and mental health effects associated with direct and perceived exposures to oil).

Some integration of physical-biogeochemical processes and biological systems has occurred through modeling efforts, for example, Atlantis, Connectivity Modeling System (CMS), Spill Impact Model Application Package (SIMAP), and Consortium for Simulation of Oil-Microbial Interactions in the Ocean (CSOMIO). These models simulate impacts in different environments, effects on organisms at different trophic levels, and the movement of organisms between different ocean regions (in some cases through passive transport by ocean currents and in others through the active movement of the organisms). For example, Atlantis (Fulton et al., 2005; Ainsworth et al., 2015, 2018) relies on coupling with hydrodynamic models for the purposes of representing the connectivity of populations and estimating oil exposure and impact. In some cases, modeling frameworks such as this allow injury assessment and also permit the exploration of different mitigation strategies. This is the case in Berenshtein et al. (2020a) and Suprenand et al. (2020), who explored possible impacts from hypothetical oil spills, and French McCay et al. (2017), who evaluated the net benefits of dispersant use. One of these models, CMS, ventures further from the physical-biogeochemical processes through biological systems and into the socioeconomics domain. This model simulates fishery capacity and evaluates the influence of fishery closures in addition to oil impacts on fishing stocks. In other examples, output from ecological models can be translated into socioeconomic impacts through coupling with input-output models (Court et al., 2019). Vulnerability indices are then defined for Gulf coastal counties, depending upon their socioeconomic conditions and the impacts of closures or changes in fishing stocks induced by the oil spill (Paris et al., 2012, 2013; Berenshtein et al., 2019, 2020a,b).

Although there has been considerable progress in integrating models across the domains of knowledge, no fully quantitative model yet exists that simulates oil spill impacts across physical, biological, socioeconomic, and human health knowledge domains. GoMRI synthesis and legacy efforts have focused on developing and exploring a framework for assessing a model that is useful for decision-making in the context of minimizing societal impacts from oil spills in the longer term. The framework is based upon a systems dynamics approach that begins by evaluating the interdependencies of the systems to be linked (Brennan et al., 2019). The causal loop diagram developed for this effort is intricate, with key processes that can be separated by domain or pairs of domains on the timescales of years, plus overall long-term (decadal) societal-level processes integrating all four domains into larger-scale loops (Figure 3; recent work of author Solo-Gabriele and colleagues).

For example, in the physical-biogeochemical process domain, the short-term operational models are utilized to simulate the hydrodynamics that influence the transport and fate of oil, and the processes that govern transport and fate are tightly integrated. Feedback between models relies on interlinked processes that impact oil transport and degradation inclusive of dispersant use and cleanup efforts aimed at mitigating shoreline impacts (represented by the large blue arrows in Figure 3). Similarly, processes influencing biological ecosystems are also tightly interlinked through interdependencies of species within various trophic levels and habitats (represented by the large green arrows in Figure 3). Ecosystems are influenced by toxins in the oil, which are impacted by physical-biogeochemical processes. Likewise, oil in the physical-biogeochemical environment is influenced by microbial degradation, which is part of the biological system processes. These two domains of knowledge, although each characterized by strong internal feedback mechanisms, thus have interdependencies that can serve to link the processes within each domain.

However, the human-focused domains of socioeconomics and human health are much more intertwined. Strong feedback loops cut across these human-focused domains, as human health is defined by both physical and mental health status, with each influencing the other (McEwen and Stellar, 1993; Seeman et al., 2001; Summers et al., 2018; Koliou et al., 2018; Ferguson et al., 2020; Sandifer et al., 2020). Societal factors influence mental health through general well-being that depends heavily upon income and employment, productivity, perceptions of harm, loss of housing stability, and loss of place and valued natural resources (Abramson et al., 2015; Sandifer, et al., 2017; Guo et al., 2018). Mental health impacts affect physical health, which in turn impacts productivity, with considerable socioeconomic consequences. Feedback is thus strong between human health and socioeconomics such that processes within the lower two domains of knowledge in Figure 3 are more completely intertwined. Additionally, these human-focused processes, although known in qualitative terms, are greatly lacking in terms of quantitation. Outside of traditional risk assessment approaches for evaluating physical health impacts (Black et al., 2016) and available economic models (Court et al., 2019; Sumaila et al., 2012), there is very limited quantification of processes needed to understand relationships between each of the processes that influence socioeconomics and human health. More work is needed to understand the links among physical health, mental health, community well-being, and societal factors. The feedback loops between human health and socioeconomics are considered strong. However, processes within these knowledge domains are also influenced during oil spills by physical-biogeochemical processes and biological systems and vice versa. For example, the human-focused domains influence the physical-biogeochemical and biological systems through decisions about mitigation efforts and pressures on seafood harvesting. During an active spill, the upper tier natural processes more strongly influence the lower tier human-focused processes, where oil spills influence the exposure of humans to toxins either through direct contact with oil or indirectly through consumption of seafood. This exposure then influences socioeconomics through restrictions on the use of natural resources via declines in seafood harvest and coastal resources and through beach closures.

Ultimately, there is a longer feedback loop that operates at decadal scales. This loop, based upon perceptions of oil spill effects on community welfare, influences the regulatory framework through which the short-term operational models are mandated (brown loop in Figure 3). Consequently, outputs from the short-term operational models not only influence how rapidly society responds to protect resources that are sensitive in the short term but also influence the longer-term socioeconomics and human health domains, which in turn feed back to the regulatory framework through

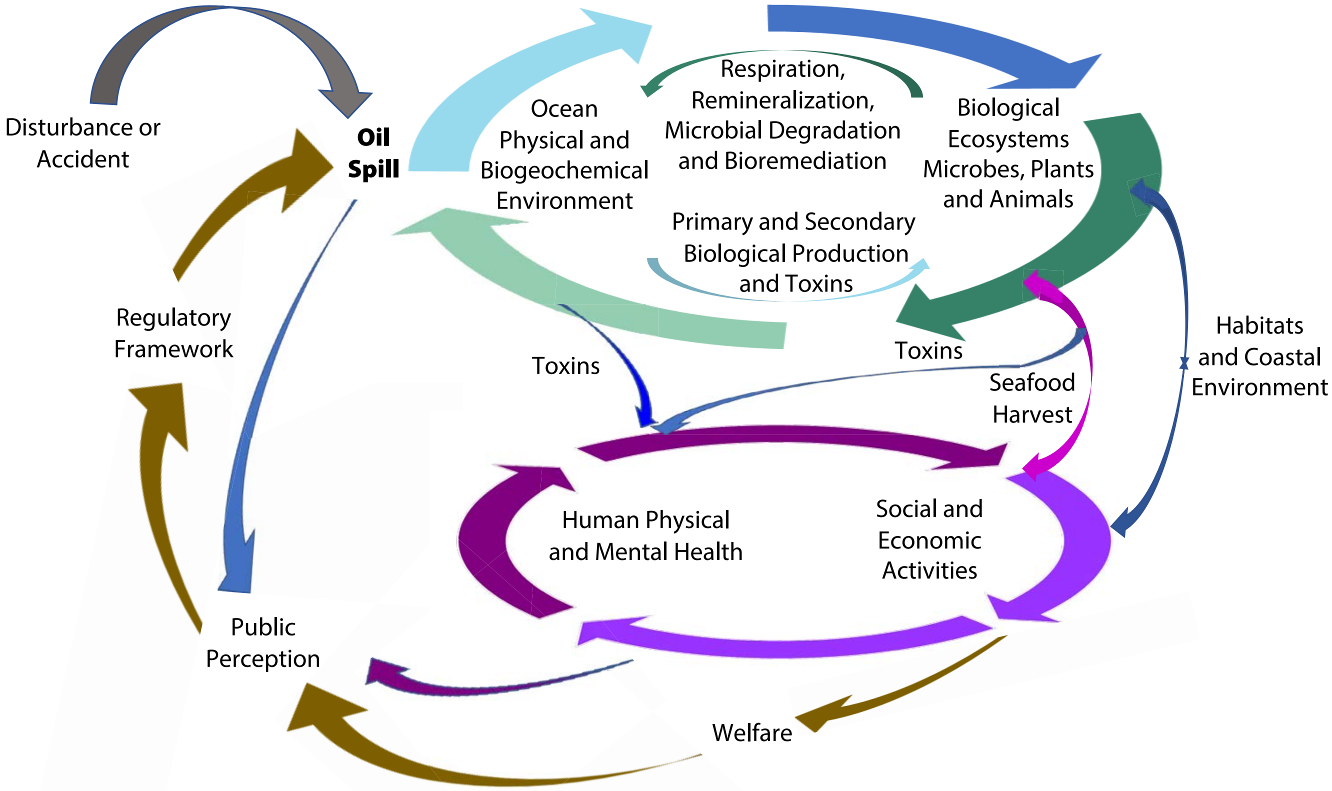

FIGURE 3. Framework for an integrated model for preparedness and planning of oil spill response. This framework is focused on facilitating decision-making that integrates long-term (decadal) impacts on physical-biogeochemical processes, biological systems, socioeconomics, and human health.

FIGURE 4. This image from a Gulf of Mexico research cruise in the spring/summer of 2010 captures in situ burning and mechanical recovery of oil at sunrise and illustrates the challenges of capturing and collecting all of the surface oil. *Photo credit: Samantha Joye, University of Georgia*

public perceptions of oil spill effects.

In order to consider the holistic impacts of decisions made at the short-term operational scale, models are needed that integrate physical-biogeochemical processes, biological systems, socioeconomics, and human health. Although work is needed to further understanding of all four knowledge domains, those most lacking sufficient information to create quantitative models are the human-focused domains of socioeconomics and human health (purple loops in Figure 3). The influence of these domains on the regulatory framework that influences whether or not an oil spill occurs (brown loop) also needs to be better understood in order to develop holistic decision-support models capable of assessing the effects of short-term decisions on longer-term societal impacts. Ideally, a fully developed systems dynamics model should be created to evaluate possible long-term outcomes from shorter-term decisions for immediate mitigation. Ultimately, it would be useful to link short-term operational models (as outlined above; Barker et al., 2020) to a systems dynamics model to create an integrated assessment model designed to evaluate long-term societal outcomes inclusive of socioeconomics and human health.

CHOOSING RESPONSE COUNTERMEASURES (MECHANICAL RECOVERY, BURNING, AND DISPERSANTS)

Future integration of models can better reflect impacts and help responders choose the optimum suite of countermeasures to expedite cleanup and minimize damage. However, decisions will still need to be made based on prevailing conditions at the time of an incident, including the use of chemical dispersants as countermeasures (Quigg et al., 2021, in this issue). While questions remain, if a spill were to happen, dispersant stockpiles and equipment are available, and the expected effectiveness, detrimental effects, and unknowns must be weighed against other alternatives, as well as the potential impacts of not using dispersants. Open-ocean spills may preclude recovery by mechanical equipment or in situ burning in certain wave and weather conditions where dispersants (surface and subsea) may still be effective (Figure 4). Even if mechanical equipment is utilized, the oil recovery rates may be insufficient, and decisions will have to be made on the use of alternatives. Chemical dispersant use is predicated on the decision that overall environmental and/or worker health impacts (associated with volatile organic compounds) are reduced by dispersing oil into the offshore water column, thus reducing the impact to the nearshore and coastal areas. Surface applied chemical dispersants, such as aerial sprays, may effectively cover much larger surface areas, but their use is time critical and therefore subject to prevailing conditions and oil weathering.

GoMRI and NRDA research provided new insights on water column and benthic area impacts of oil dispersed physically and chemically by subsea dispersant injection. Murawski et al. (2019) consider conflicting theories on the effectiveness of subsea injection. While there are still research gaps and political implications regarding the use of dispersants, to properly evaluate their use, response leaders will still need real-time predictive modeling of the fate and transport of oil that cannot be mechanically collected. In addition to GoMRI research, other efforts have also tried to address dispersant use (NASEM, 2020) but need to include the “what if dispersants aren’t used” or “what if burning isn’t used” impacts to and recovery times of nearshore and coastal environments.

Although modeling, as described above, along with a method for comparative risk assessment (French-McCay et al., 2018; Bock et al., 2018; and A.H. Walker et al., 2018), is beginning to address these questions, a fully developed and “agreed upon” systems dynamics model does not yet exist. It is challenging, if not impossible, to develop a value system where loss of deep-sea corals and closure of offshore fisheries could be weighed against the impacts to nearshore habitats and tourism, but during an event, those decisions must and will be made by the Incident Command. As we continue to improve our data collection and modeling, scientists need to work through the various scenarios and help lead the discussion of complex trade-offs that will continue to improve comparative models as they relate to response planning and operational decision-making.

FRESHWATER DIVERSIONS AND THE COMPLEXITY OF EVALUATING OPERATIONAL ALTERNATIVES

Future spills will inevitably present response leadership with novel spill conditions, requiring that alternative response approaches be quickly evaluated. Although an established protocol for this evaluation considers potential success, feasibility, and impacts, trying new methods or untested equipment can have adverse impacts and increased liability. During DWH, numerous alternatives were offered for evaluation, and some were undertaken, including freshwater diversion and construction of sand berms. The freshwater diversion of Mississippi River waters, which was designed to minimize damage to coastal wetlands by keeping oil offshore, demonstrated a trade-off decision that put tremendous stress on other parts of the ecosystem. Equally important is applying the same rigorous trade-off decision to any restoration project that might be funded through damage assessment or other restoration efforts. This could incorporate even more complex processes associated over time with nutrient overloads, land use management, climate change impacts, natural erosion, and future energy development.

During DWH, several ad hoc countermeasures were employed to forestall oil coming ashore or entering sensitive wetlands where there would be significant damage and difficult remediation. Coastal defense measures such as the construction of sand berms around islands (e.g., Suir et al., 2016) and increasing flow rates of Mississippi River water diversions were implemented in an effort “to try and push the oil away from our coastal wetlands” (State of Louisiana, 2010). The concept of using existing river diversions to create elevated coastal flows and thereby divert surface oil was simulated in late April 2010 by the US Army Corps of Engineers Engineering Research Development Center using their Adaptive Modeling System. These simulations evaluated the hydrology resulting from increasing flows through the Davis Pond Diversion (upstream from New Orleans) and the Caernarvon Diversion (Downstream of New Orleans) to flood marshes of Barataria Bay and Black Bay/Breton Sound, respectively (Figure 5; USACE, 2010). Results

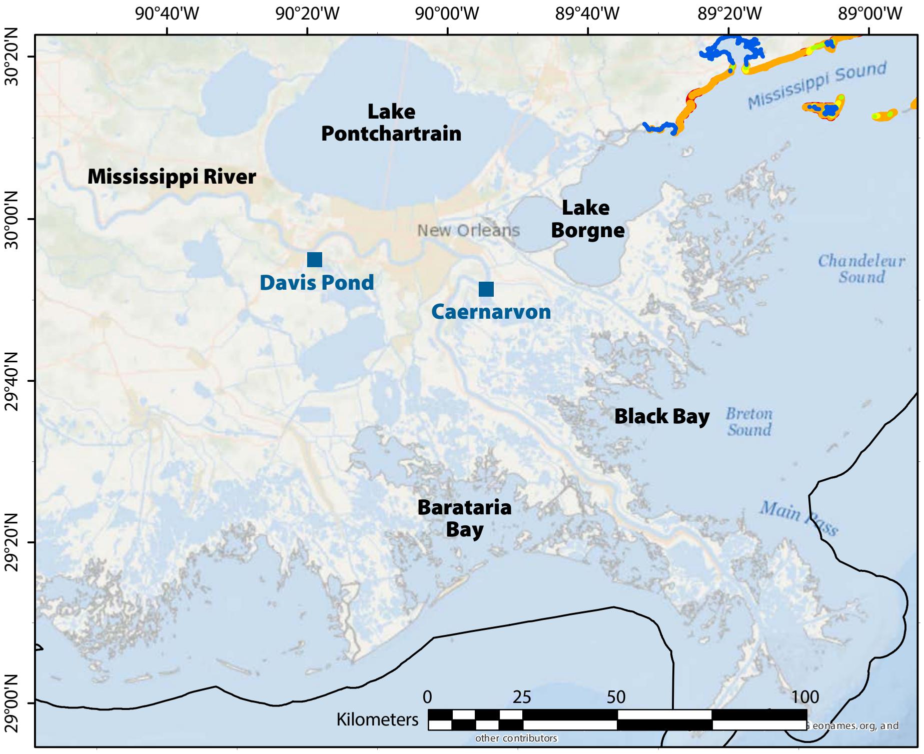

FIGURE 5. Locations of the Davis Pond and Caernarvon water diversion structures along the Mississippi River. The black line is the three-mile state territorial boundary.

of these simulations were promising, and during the first week of May 2010, flow rate discharges were increased dramatically through these two structures and a number of other smaller diversions (Figure 6; State of Louisiana, 2010; O'Connor et al., 2016).

In the case of the Davis Pond Diversion, flow rates were increased to about three times the pre-2010 average, and for Caernarvon, about eight times normal flow (Figure 6; O'Connor et al. 2016). While the degree to which these elevated freshwater discharges affected oil transport into these bays is conjectural, they were not completely effective, as oil concentrations within the bays reached over three orders of magnitude greater than background contamination in some locations (Turner et al., 2019a) and remained several orders of magnitude higher than baselines for at least five years thereafter (Duan et al., 2018). Model simulations have shown that elevated diversion discharges have no influence on hydrodynamics >30 km from the diversion sites and are not effective in preventing offshore oil slicks from drifting into Barataria Bay and Breton Sound estuaries (e.g., Huang et al., 2011).

The effects of diversions are closely linked to the dynamics of river plumes and the overall coastal and shelf processes that influence the transport and fate of materials (e.g., sediments, nutrients, oil) that are either river-borne or entrained on the shelf areas from offshore sources. Large rivers such as the Mississippi create their own offshore circulation, driven by the buoyancy of the fresher waters and mediated by winds and topographic controls (Androulidakis et al., 2015). In the Northern Gulf of Mexico, a unique effect is that the river-induced circulation can be heavily influenced by offshore currents, specifically the Loop Current and its associated eddies (N.D. Walker et al., 2005; Schiller and Kourafalou, 2014), causing a possible advection of river-borne materials far away from the freshwater discharge sites (N.D. Walker et al., 1994; Schiller et al., 2011; Androulidakis et al., 2019). Therefore, the amounts of riverine waters and materials that might remain on the shelf do not solely depend on the amount of river discharge that can be controlled through diversions (e.g., Androulidakis and Kourafalou, 2013; Le Hénaff and Kourafalou, 2016).

Initial simulations conducted by the US Army Corps of Engineers evaluated the hydrologic effects of diversions on marsh flows but did not assess the degree of change in the salinity gradients across marsh landscapes nor the effects of such alterations on ecosystems. Considerable research conducted contemporaneously with the diversions documented sustained reductions in salinity and concomitant impacts on sessile euryhaline species including the eastern oyster (Grabowski et al., 2017; Powers 2017a,b) and other species. While resident marsh species such as oyster are extremely tolerant of normal variations in salinity and other physical attributes, sustained periods of very low salinities will result in mortalities. Powers et al. (2017b) estimated that billions of excess mortalities of oysters occurred because of sustained (>50 days) low salinity (<5 ppt) conditions that resulted from the water diversions associated with DWH. They succeeded in disentangling the impacts on oyster mortality due to low salinity from those due to oiling and concluded that there was no discernible relationship between oiling and elevated oyster mortality, but rather mortalities were due to sustained freshwater conditions.

In contrast to oysters, salt marsh fish assemblages (e.g., killifishes and associated species) were relatively unaffected by the spill and changes in the salinity regimes (Able et al., 2014), primarily because these species are adapted to locations (salt pans and upstream marshes) that naturally exhibit extremes in temperature, salinity, and water levels. However, for the community of fishes and invertebrates occupying the open estuary in Barataria Bay, the region most affected by wetlands oiling (Nixon et al., 2016) and subject to significant freshwater diversions, there was a regime shift in the abundance and species composition of trawl catches that has persisted post-spill and is likely associated with decreased salinity and increased water clarity since the spill (Murawski et al., 2021b).

The impacts of the 2010 diversions could have been predicted based on the wealth of pre- and post-construction ecological studies conducted for the

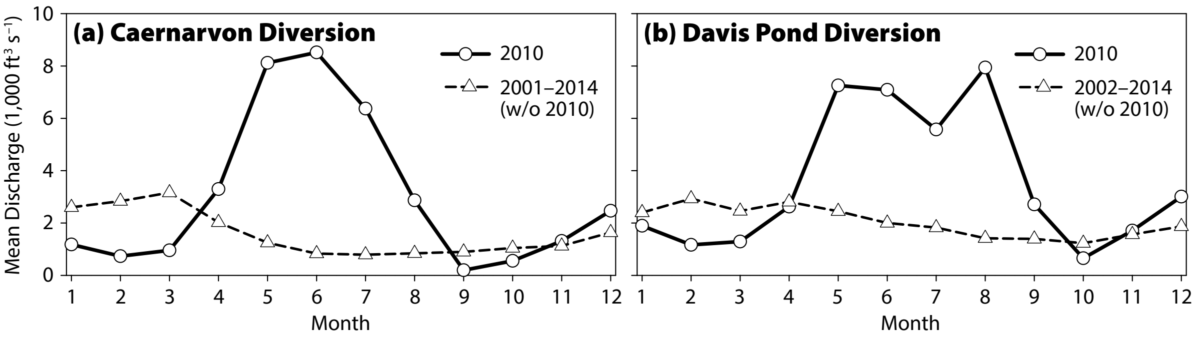

FIGURE 6. Mean discharge rates (1,000 ft^3 s^{-1} or 28 m^3 s^{-1}) from Mississippi River diversions at (a) Caernarvon and (b) Davis Pond for 2010 and mean 2001–2014 without 2010 for Caernarvon, and 2002–2014 without 2010 for Davis Pond. Data are found at: https://nwis.waterdata.usgs.gov/usa/nwis/.

Caernarvon diversion (see Chesney et al., 2000, for a summary). Numerous studies conducted prior to the 1991 opening of Caernarvon and the 2002 opening of Davis Pond, and undertaken since DWH, point to shifting of the salinity gradients, potential increases in freshwater species such as bass and catfish, downstream movement of key estuarine fish species, and reduced oyster survival in prime habitats (Das et al., 2012; de Mutsert and Cowan, 2012; Rose et al., 2014; Powers et al., 2017a). During and after the DWH episode, oiling of bottlenose dolphin populations resulted in severe negative health effects and elevated mortalities (Schwacke et al., 2014, 2017). As dolphins are intolerant of extended periods in fresh waters, there is an open question regarding the role that lower salinities may have played in concentrating dolphins near passes and inlets where the DWH oil entered marshes (White et al., 2018).

Given the tremendous investment in additional permanent, large-scale diversions of Mississippi River water and sediments into Barataria Bay and Breton Sound (Coastal Protection and Restoration Authority of Louisiana, 2017), we can anticipate that many of the ecological changes resulting from the experimental use of elevated discharges during DWH will be played out in the long term. The intentions of these planned diversions are to create additional sediment substrate supporting fresh and brackish marshes and to reclaim wetlands habitats from open waters. Documenting such effects from these diversions and other parallel engineering projects will be critical in justifying their enormous expense—estimated to be over $50 billion (Coastal Protection and Restoration Authority of Louisiana, 2017). With respect to the use of water diversions as a countermeasure for future oil spills, we can conclude that in the case of DWH they were ineffective in achieving their primary objective, to "try and push the oil away from our coastal wetlands," and that doing so resulted in unanticipated, severe negative ecological effects.

Research Priorities

The use of freshwater diversions during the DWH event and their ecological impacts highlight important research gaps that should be closed, not only if diversions are once again considered as oil spill countermeasures, but primarily to better understand the consequences of additional large-scale diversions planned as restoration activities, supported in part by DWH settlement money. While it is clear that these efforts are directed toward ecosystem improvement, the effectiveness of the diversions and other measures in creating habitat substrate has been questioned (Teal et al., 2012; Turner et al., 2019b). Likewise, by developing a firmer understanding of how ecological processes and individual species will react to both the acute effects of the diversions and the long-term consequences of habitat alterations, it may be possible to optimize the operation of the diversions to better achieve multiple natural resource goals. It will be critical to:

- Monitor the long-term impacts of DWH on marine and estuarine habitats affected by freshwater diversions and those planned as part of large-scale restoration activities. Monitoring should be used in an adaptive management approach to minimize negative ecological effects and maximize potential to meet the prime objective (substrate creation).
- Understand the movement ecology of freshwater, estuarine, and marine species likely to be affected by the operation of current and planned diversions to parameterize predictive models of ecosystem response. These studies could include an intensive network of tag sensors to track the movements of individuals and allow determination of the connectivity/modularity of key living resources and their roles in ecosystem resilience and recovery.
- Develop new classes of predictive numerical models to explore the effects of planned large-scale freshwater diversions. Such models would integrate estuarine, coastal, and shelf hydrodynamics and incorporate ecological processes and outcomes, thus allowing for better predictions of the outcomes of long-term habitat restoration activities over decadal to century scales and also of their short-term effectiveness in oil spill countermeasures.

THE FUTURE

Oil spill research after DWH resulted in improvements in the tools needed to guide operational response, but continuing this effort will be dependent on dedicated effort and funding. Questions still remain, and new questions and opportunities need analysis. New technologies may be useful in future spill responses, but they too could produce unintended impacts. A few of these include remote deployment of surface sensors that feed immediately into models and of untethered sensors to obtain droplet size distribution and other data at depth, introduction of genetically modified microbes to enhance biodegradation, use of oil herders and enhanced burn technologies, new formulations of dispersants, increasing use of genomics in damage assessment, and deployment of unmanned boats and aircraft that could manage mechanical equipment and alternative countermeasures. DWH and associated funding provided a rare opportunity for researchers across disciplines in industry, government, and academia to work with and improve plans, preparedness, and response. Because oil spills will continue to occur, research funding and academia's connection to operational decision-makers must continue to be fostered in order to close gaps, evaluate new opportunities, and bring forward the best science for application to spill response plans and operations.

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AUTHORS

David G. Westerholm (dwesterholm1@msn.com) (retired) was Director, Office of Response and Restoration, National Oceanic and Atmospheric Administration, Silver Spring, MD, USA. **Cameron H. Ainsworth** is Associate Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Christopher H. Barker** is Oceanographer, National Oceanic and Atmospheric Administration, Seattle, WA, USA. **Peter G. Brewer** is Senior Adjunct/Ocean Scientist, Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA. **John W. Farrington** is Dean Emeritus, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Dubravko Justić** is Professor, Department of Oceanography and Coastal Sciences, College of the Coast & Environment, Louisiana State University, Baton Rouge, LA, USA. **Vassiliki H. Kourafalou** is Research Professor, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. **Steven A. Murawski** is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **John G. Shepherd** is GoMRI Research Board member and Professorial Research Fellow, School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton, UK. **Helena M. Solo-Gabriele** is Professor, Department of Civil, Architectural, and Environmental Engineering, University of Miami, Miami, FL, USA.

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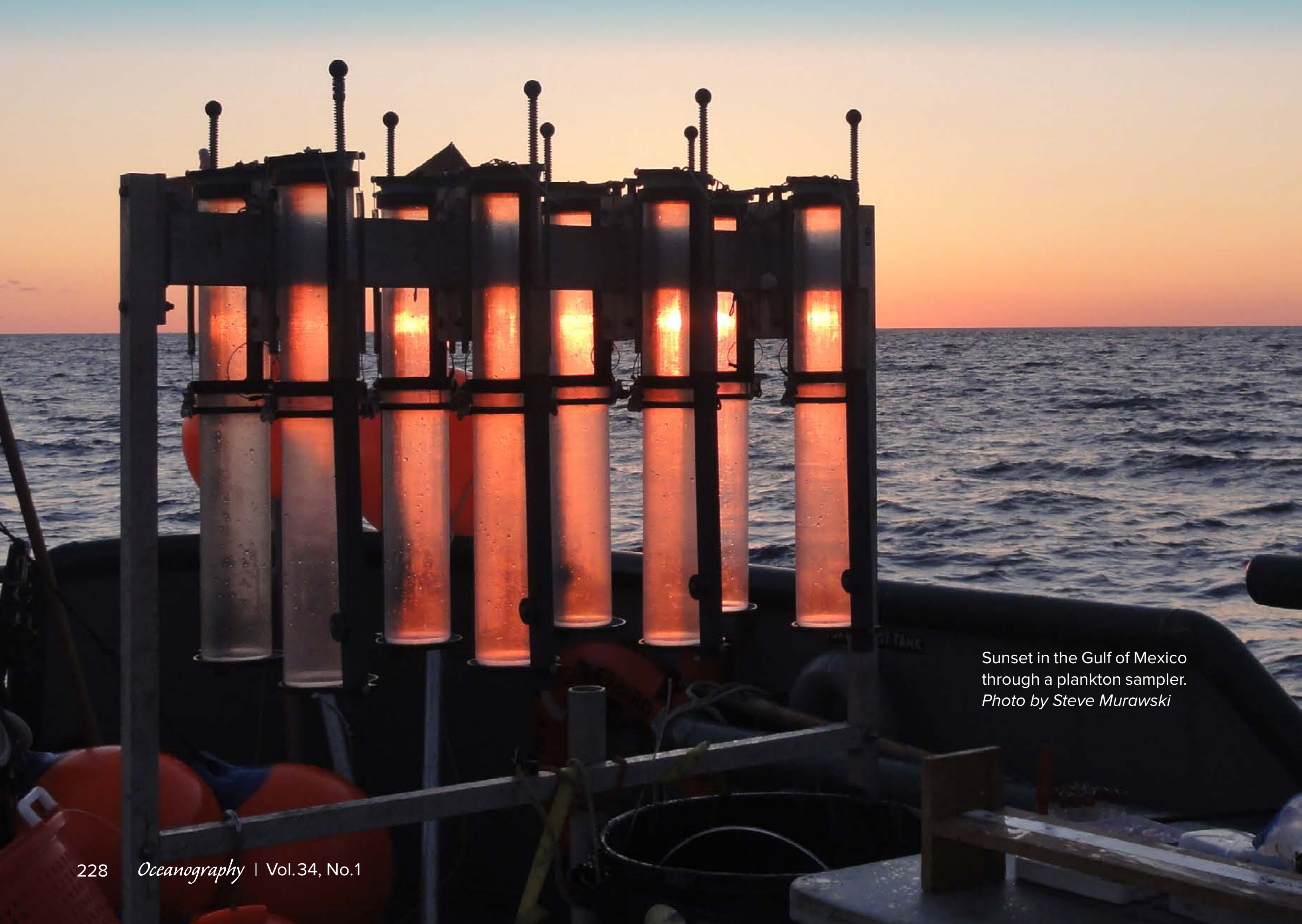
Summary of Findings and Research Recommendations from the Gulf of Mexico Research Initiative

By Charles A. Wilson, Michael G. Feldman, Michael J. Carron, Nilde Maggie Dannreuther, John W. Farrington, Kenneth M. Halanych, Jennifer L. Petitt, Jürgen Rullkötter, Paul A. Sandifer, J. Kevin Shaw, John G. Shepherd, David G. Westerholm, Callan J. Yanoff, and Leigh A. Zimmermann

ABSTRACT. Following the Deepwater Horizon explosion and oil spill in 2010, the Gulf of Mexico Research Initiative (GoMRI) was established to improve society's ability to understand, respond to, and mitigate the impacts of petroleum pollution and related stressors of the marine and coastal ecosystems. This article provides a high-level overview of the major outcomes of the scientific work undertaken by GoMRI. This i scientifically independent initiative, consisting of over 4,500 experts in academia, government, and industry, contributed to significant knowledge advances across the physical, chemical, geological, and biological oceanographic research fields, as well as in related technology, socioeconomics, human health, and oil spill response measures. For each of these fields, this paper outlines key advances and discoveries made by GoMRI-funded scientists (along with a few surprises), synthesizing their efforts in order to highlight lessons learned, future research needs, remaining gaps, and suggestions for the next generation of scientists.



Sunset in the Gulf of Mexico through a plankton sampler. *Photo by Steve Murawski*

INTRODUCTION

The articles in this special issue of *Oceanography* provide an extensive overview of the Gulf of Mexico science community's accomplishments. Much of the work discussed in this article was funded by the Gulf of Mexico Research Initiative (GoMRI), created in response to the Deepwater Horizon (DWH) disaster that began on April 20, 2010. Zimmermann et al. (2021, in this issue) summarize the genesis and operation of GoMRI, and McKinney et al. (2021, in this issue) describe the complexity of the Gulf of Mexico ecosystem. Here, we provide a high-level overview of the major outcomes of the studies conducted by GoMRI researchers whose work advanced existing paradigms in oil spill science and extended aspects of findings from previous studies. These outcomes, in combination with the other GoMRI synthesis products (https://research.gulfresearchinitiative.org/research-awards/gomri-synthesis-projects/) represent an important and simultaneous accomplishment in advancing the overall breadth of general scientific knowledge across the physical, chemical, geological, and biological oceanographic research fields, as well as in related technology, socioeconomics, human health, and oil spill response measures.

With over 4,500 scientists and experts involved with GoMRI, the program funded nearly 300 projects that resulted in more than 1,700 peer-reviewed articles. These projects helped educate and train some 1,400 MS and PhD students and 1,050 undergraduates. While the majority of researchers were located in the Gulf of Mexico region, the program included participation from researchers in 43 states and 17 countries. This colossal effort not only fostered collaboration among researchers located at institutions within the Gulf of Mexico region but also established national and international research connections that will facilitate future research endeavors.

GOMRI-funded research was interactive, especially in the first few years, with research and related activities funded by BP, along with the National Science Foundation's Rapid Response Research (RAPID) grants program, the Natural Resources Damage Assessment, National Oceanic and Atmospheric Administration (NOAA) Sea Grant college programs, and several other federal, state, and nongovernmental organizations that contributed to advances in oil spill science.

PHYSICAL PROCESSES

Physical transport processes such as the circulation and mixing of waters largely determine the spatial distribution of materials in the ocean. These processes establish the physical environment within which biogeochemical and other processes transform materials that include naturally occurring nutrients and human-mobilized contaminants. An understanding of these physical driving forces and their influence on biological, geological, and chemical processes was significantly advanced through improvements made by GoMRI researchers to models representing the transport of materials.

Boufadel et al. (2021, in this issue) review the physical processes that are responsible for distributing oil, dispersant, and related decomposition products. These processes operate on a very wide range of scales, from the *microscale* of droplets and bubbles; to *small-scale* turbulence in buoyant plumes and the near-surface "mixed" layer; to the *submesoscale* of fronts, convergent and divergent flows, and small non-geostrophic eddies; to the *mesoscale* of larger quasi-geostrophic eddies; to the *large-scale* circulation of the Gulf of Mexico and its interaction with the Atlantic Ocean and the Caribbean Sea. The circulation and mixing processes near the Gulf's coasts are strongly affected by wind- and river-induced currents, and further modified by its complex seafloor topography. Gulf of Mexico physical processes are further characterized by strong linkages between coastal/shelf and deeper offshore waters that dictate connectivity to the basin's interior. This physical connectivity influences the transport of materials among different coastal areas within the Gulf and also to adjacent waters. GoMRI scientists have made major advances in observing, understanding, and modeling all aspects of the physical environment. These advances include development of new tools and methodologies for collecting, analyzing, and synthesizing data, and techniques for capturing coastal to offshore deep-sea linkages and transport.

Advances, Discoveries, and Surprises

Among many other advances, GoMRI contributed to the understanding of how pressure-induced processes affect gas-saturated oil. Refinements of transport modeling tools have materially improved abilities to predict Gulf of Mexico circulation and oil transport, ecosystem connectivity, and ecological impacts. The application of detailed computational fluid dynamics (CFD) modeling has resulted in a transformational shift in the ability to model complex multi-phase (oil, gas, and water) plumes using numerous methods over a wide variety of environmental conditions. CFD models demonstrated the unexpected importance of Earth's rotation on the near-field plume dynamics, affecting both entrainment rates and detrainment levels.

GoMRI-funded scientists developed new biodegradable drifters and used them to measure and constrain models of small and submesoscale ocean surface currents in unprecedented detail. This advancement allowed researchers to explore implications for oil transport at a level of complexity that was novel to physical oceanography. Field observations and models of near-surface, submesoscale processes, such as Langmuir circulation, have shown the previously under-appreciated importance of vertical rise velocity in controlling dispersion and surface distribution of buoyant materials such as oil.

A new-found appreciation was developed for the important role that river-induced fronts play in longshore and cross-shore transport, acting both as barriers to material transport and as convergence zones that guide transport along frontal lines. Researchers now have explicit data on advection of pollutants along frontal pathways that link coastal areas, and on how both mesoscale and submesoscale circulation features influence the open ocean. These new data greatly improved scientists' understanding of transport because they were directly examined over a long period on a variety of scales.

For the larger (mesoscale and beyond) spatial scales, predictive improvements have been made through use of high-resolution regional modeling (improving from 4 km to 1 km resolution). This advance incorporated river-estuarine coupling, the ability to resolve both the surface and the bottom Ekman layers, explicit consideration of Stokes drift, and the widespread use and assimilation of operational meteorological and reanalysis products.

Lessons for the Future

The use of river diversions was ineffective in achieving the objective of pushing DWH oil away from coastal wetlands and resulted in unanticipated deleterious ecological impacts. The potential consequences of diversions need to be more carefully considered before they are implemented.

We also learned that accurate prediction of oil transport at the surface can only be achieved by using the best available high-resolution models combined with real-time assimilation of comparable-resolution data and paying careful attention to the effects of winds, waves, Stokes Drift, and submesoscale motions in the near-surface layers. The deployment of large numbers of floats in real time was shown to be feasible and efficient, and thus can provide an excellent source of additional information on near-surface circulation.

Scientists quickly learned that significant quantities of contaminants from a deep spill can be carried laterally over large distances in subsurface plumes as both dissolved and particulate material. These contaminants can then be deposited on the continental slope within a restricted depth range and consequently impact organisms living there.

Future Research Needs/Gaps

While numerous advances have been made, predicting the distribution of spill products remains challenging. We consider the following areas of further research particularly important:

- Improving methods for both observing and modeling velocity profiles in the uppermost meter of water, where changes may be both large and transient
- Improving the time-varying estimation of initial droplet size distribution as live oil rises from the buoyant plume into the far-field water column
- Quantifying the impact of turbulent thermal wind effects on frontal turbulent intensities and the evolution of submesoscale fronts
- Improving algorithms to achieve a multiscale modeling approach for simulating wetlands, estuaries, river-estuary coupling, riverine forcing, and shelf exchanges, and their linkages with open ocean transport
- Improving understanding of the role of bottom-boundary dynamics, where model parameterizations remain underdeveloped and data scarce
- Collecting additional field data from shelf breaks at critical locations to constrain exchanges between estuarine, coastal, and open ocean regions
- Integrating all model improvements into an operational Earth system modeling framework (ocean-atmosphere-waves-biogeochemistry)

To sustain future growth and amplify benefits, we recommend developing and sustaining regional forecast systems that are based on a suite of appropriately scaled and nested ocean circulation, atmospheric, and wave models. This system should be capable of strategically focusing on the key components of the land-ocean continuum and supported by well-designed observing arrays targeting process understanding, data assimilation, and model validation.

CHEMICAL AND BIOGEOCHEMICAL PROCESSES

Petroleum is an extremely complex mixture of many thousands or more of gaseous, liquid, and some solid constituents. The chemicals in oil are modified while being transported to and through different environments. These changes occur due to natural processes (e.g., photo-oxidation and other forms of weathering), biological transformations (e.g., microbial degradation and decomposition), and via response measures (e.g., in situ burning). The oil constituents and their reaction products are transported by processes described above (see section on Physical Processes). Adding to the significance of the DWH oil spill is the sheer quantity of petroleum released from the Macondo petroleum reservoir in an uncontrolled way, making it the largest incident of this kind in history (Rullkötter and Farrington, 2021, in this issue.) The scale of the DWH disaster, the time over which it occurred, the geographical extent of the spread of oil, the weathering and biodegradation, and the variety of ecosystems affected presented challenges to a comprehensive understanding of the fates of the materials released to the environment.

Resuspension, horizontal transport, and redeposition moved sediment and seawater contaminated with weathered and biodegraded Macondo oil away from continental shelf areas to continental slope and abyssal areas, as well as onshore. Continental slope sediments were also contaminated with deposition from overlying waters or by impingement of the subsurface plume in some areas.

Understanding these processes was further complicated by the unprecedented volumes of dispersant (Corexit 9500, 9527) that were sprayed from planes and boats onto surface slicks as well as applied directly at the wellhead through subsea dispersant injection (SSDI) at about 1,500 m water depth.

The interrelationship between gas bubbles, oil droplets of various sizes, and early dissolution of petroleum components in the water column immediately adjacent to the damaged wellhead, with and without dispersants, was a major barrier for trying to understand the spill. Although both vertical and horizontal plumes were anticipated, their scales and extents were not. The processes determining these interrelationships were the subject of modeling and laboratory simulations. The expected dissolution of chemicals in subsurface waters was confirmed by field sampling and analyses at varying distances and depths away from the well site (Farrington et al., 2021, and Quigg et al., 2021, both in this issue).

Advances, Discoveries, and Surprises

Significant progress in assessing the fate of spilled petroleum components was made, and several important lessons were learned and discoveries made that could pertain to future spills of various sizes. Over this past decade, scientists have followed the distribution and fate of Macondo oil in the water column and sediment. Scientific studies have described the role of photo-oxidation of petroleum compounds at the sea-air interface and the roles particulates and microbes play in the fates of hydrocarbons. These studies included various documented processes, such as marine oil snow (MOS) formation and marine oil snow sedimentation and flocculent accumulation (MOSSFA), that expanded our understanding of hydrocarbon deposition and accumulation in sediments, fates on beaches and in marshes, and bioaccumulation.

Depending on sunlight irradiance and weather conditions, photo-oxidation was a significant process at the sea surface in the breakdown and fate of spilled oil. Despite earlier research in the 1970s and 1980s noting the sensitivity of petroleum to photo-oxidation, the related effects were downplayed and grossly underestimated in terms of mass balance significance over more than a decade (Transportation Research Board and National Research Council, 2003). As a result of recent advancements in chemical analysis, especially Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR-MS), this underestimation has been corrected so that we now have a better understanding of the large numbers and types of breakdown products (Rullkötter and Farrington, 2021, and Farrington et al., 2021, both in this issue). Photo-oxidation products were found to be significant components in weathered oil on contaminated beaches and in marshes affected by the oil spill. Resultant contamination of the surface sediments was very patchy, but measurable, in several places and lasted in some areas for three years or more. Contamination of the subsurface sediments persists and is expected to be long lasting.

The microbial community was also a significant contributor to the fate of Macondo oil. Hydrocarbon-degrading microbes efficiently remove hydrocarbons from the water column, with some degradation products being directly incorporated into marine food webs. Surprisingly, microbially mediated MOS was documented as an important factor in the biogeochemistry and fate of oil spilled to the marine environment in continental margin and deep ocean ecosystems. Similarly, the biogeochemical processes of MOSSFA and its role in transport was better elucidated and exceeded marine snow-associated oil transport estimates of the past (Farrington et al., 2021, in this issue). It was concluded that MOS and MOSSFA processes and associated biodegradation were also affected by interactions of Macondo oil with dispersants.

The vulnerability of coastal ecosystems to oiling has been the subject of decades of research. The oiling of beaches is problematic from human health, commercial tourism, recreation, and aesthetic perspectives (Sandifer et al., 2021, in this issue). Oiled beaches in the Gulf coast region were subjected to extensive cleaning activities during the DWH spill response. Despite these efforts, small residual oil particles in sand known as sand-oil aggregates and small tar patties remained for years and can still be found. In part, this was due to the action of storms uncovering buried oiled sand and moving oil-sand accumulations from shallow-water nearshore regions onshore. The degree of resuspension following storms and hurricanes needs to be accounted for in future planning for response, mitigation, and remediation activities.

Despite the intense response efforts to protect marshes, one of the most challenging ecosystems for removal of oil, significantly oiled areas persisted (Rabalais and Turner, 2016; Halanych et al., 2021, in this issue). One GoMRI project focused on Barataria Bay, Louisiana, and documented that initial oiling of marsh edges was soon spread to greater areas within the marsh by tides and storms and then tidal flows. Oil residue concentrations decreased markedly during the first few years but were still approximately a factor of 10 higher than background concentrations when last sampled eight years post spill. Weathered oil also remains buried in the marsh sediments along the shoreline (Halanych et al., 2021, in this issue).

Corexit 9500 dioctyl sodium sulfosuccinate surfactant, or DOSS, components were found at a considerable distance from the DWH well in the deepwater plume, with oil residues in sediments and also on some deep-sea coral communities. Future research should consider that reaction products resulting from photo-oxidation of surface slicks and films may interfere with efficacy of dispersant applications. Soluble chemicals from in situ burning were found beneath the slick and as residue within experimental simulations (Rullkötter and Farrington, 2021, in this issue).

Lessons for the Future

Several important lessons were learned regarding the conduct of and advances in oil spill chemistry research. Newer analytical methods, for example, GC×GC-MS and FT-ICR-MS as discussed in Rullkötter and Farrington (2021, in this issue), present significant opportunities to advance knowledge of the composition of crude and fuel oils and their weathering and biodegradation products. Concerning chemical techniques, scientists should be mindful of the lack of spatial uniformity in the molecular weight range and individual compounds analyzed in field samples and in mesocosm/microcosm and laboratory experiments. Need for this awareness also applies to the variability in chemical techniques, which hampers cross-comparison of results among different studies (i.e., variability between FT-ICR-MS and gas chromatography-mass spectrometry [GC-MS] used to detect and quantify hydrocarbon compounds; Rullkötter and Farrington, 2021, in this issue). The key new findings noted above, especially regarding photo-oxidation, MOS formation, and MOSSFA, need to be incorporated in a practicable manner into oil spill response, mitigation measures, and assessment models, with appropriate attention to the various types of ecosystems and climates where spills may occur.

The development of extensive data archives has proven helpful for follow-on research by the scientific community at large in unraveling details of the biogeochemical cycles of Macondo oil chemicals. GoMRI data will be broadly used by others for years to come (Zimmermann et al., 2021, in this issue). Given the advances noted above, it is important to employ this information for future spills in order to develop useful and accurate ways to detect, quantify, and budget the fate of spilled oil over time. Bulk oil budget estimates not based on compound-specific analysis are thus problematic. Moreover, any one compound may have successively different fates—a simple example is initial photo-oxidation at the sea surface followed by partial microbial degradation, incorporation into marine snow, and deposition on the seafloor (Farrington et al., 2021, in this issue).

Proper measurements are needed in the field to document the chemical composition and environmental distribution of in situ burning products. It is equally critical to follow the transport pathways of residues from burning as they enter the water column and are eventually deposited as sediment, even in deeper waters (Rullkötter and Farrington, 2021, in this issue).

Concerning the application of surface and subsea injection of dispersants, patent laws and confidentiality regulations initially made it difficult to obtain precise data quickly and reliably on the actual chemical formulation of dispersants used. This lack of information hampered research on the detection, decomposition, fate, and effects of oil and dispersants in parallel laboratory and mesocosm studies.

Future Research Needs/Gaps

Future efforts should seek out new ways to further interpret and use the complex data from FT-ICR-MS analyses of high-molecular-weight constituents of crude oils, fuel oils, and their photo-oxidation products. Beyond the large number of very useful elemental composition data provided by FT-ICR-MS, there is the need for more exact chemical structures, for example, by combining FT-ICR-MS with other analytical techniques. This knowledge gap hampers the understanding of reaction pathways, reaction rates, and the potential for effects of reaction products on organisms and for human health concerns. Additional areas of research include the following list.

- Field measurements accompanying in situ burning of spilled oil are scarce but are urgently needed to document the chemical composition and environmental distributions of products of this mitigation process (including soluble organic compounds) and pathways of transport of oil and combustion product chemicals into the water column and eventual deposition into sediments, even in deeper waters.
- Products of in situ burning need to be further assessed for both atmospheric emissions and chemicals in the water column under slicks subjected to in situ burning. Of particular concern are chlorinated aromatics (e.g., polychlorinated dibenzodioxins) formed in chloride-bearing seawater or in air at the air-sea interface.
- The high-molecular-weight chemicals produced by photo-oxidation and microbial degradation processes (and perhaps subsequent chemical reactions of initial reaction products) need further elucidation as does the role of such materials in sorption-desorption reactions and bioavailability for lower-molecular-weight constituents of partially weathered and partially biodegraded oil.
- Advanced analytical chemistry techniques and advanced genomic/proteomics analyses should be applied to both field samples and samples from laboratory and mesocosm experiments. Scientists reviewing the literature suggest that results would be more useful/meaningful if both techniques were used for analysis of the same samples. This will maximize collection of rich data sets leading to new discoveries in studies of the biogeochemical cycles/fates of spilled oil.
- Improvements are needed in our understanding of SSDI and its effects on physical processes that influence oil and gas droplet sizes and how these droplets interact with subsequent near-field mixing processes. Future studies should focus on the interactions of gas and oil bubbles/droplets; how large oil droplets evolve to small droplets in both horizontal and vertical plumes; interactions among oil, organisms, and exopolymer substances released by microorganisms (MOS and MOSSFA); and determining whether SSDI reduces exposure of response workers to volatiles at the air-sea interface.
- The experimental designs of laboratory and mesocosm experiments need to be optimized to gain new knowledge of fates and effects (including various sublethal effects) of oil and oil dispersant mixtures beyond the standard acute toxicity testing. Also needed are experiments to disentangle the effects of different chemical substances in oil or dispersants.
- A better understanding is needed of how photo-oxidation products may

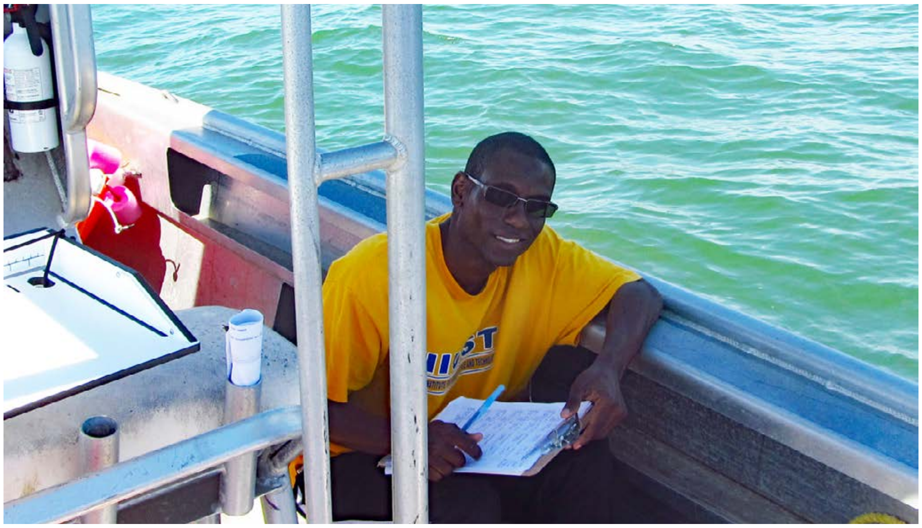
interfere with the efficacy of dispersants in time and space, of the underlying fundamental physical chemistry governing the efficacy of various dispersant formulations, and of how dispersants impact microbial accessibility to oil at the water/oil interface.

- The utility of existing and newly developed dispersant formulations needs to be improved for various crude oil and fuel oil types and for various climatic regimes and ecosystem types.

BIOLOGICAL AND ECOLOGICAL PROCESSES

The DWH oil spill negatively impacted a wide variety of Gulf of Mexico organisms and ecosystems. The primary drivers of those impacts were oil and degraded oil, oil mixed with dispersants, and management responses related to the oil spill. Toxicological impacts upon organisms, generally characterized as lethal and sublethal, were heavily studied over the last 10 years in laboratory and mesocosm settings, as well as in the field, and included field-measured levels of exposure dosages. Impacts identified include immediate and gradual mortality, reproductive failure, and influence on behavioral, olfaction, vision, cardiac function, and gene response. Sublethal effects can be short term, long term, permanent, or even multi-generational (Murawski et al., 2021, and Weiman et al., 2021, both in this issue) and can impact feeding, survival, reproduction, and future generations. Examples of the various documented impacts illustrate common patterns and trends across organisms and/or their environments and show that such impacts might translate to population levels (Murawski et al., 2021, and Halanych et al., 2021, both in this issue).

The development and application of advanced genomic and bioinformatics tools enabled scientists to examine and describe complex microbial communities, identify new species, redefine previously described species and genera, and quantify cellular responses across taxa. These new omics-based technologies and strategies provided an in-depth and comprehensive study of Gulf communities in unprecedented detail and set the stage for integrating genomic data and organismal biology with analytical chemistry and oceanographic modeling. Research communities are now better prepared for new data-driven approaches to monitor and restore ecosystem health.



Stephan O'Brien, a PhD student at the University of Southern Mississippi and a GoMRI Scholar, collects water samples at Main Pass, Alabama, for suspended sediment laboratory analyses. *Photo credit: Brian Dzwonkowski*

Advances, Discoveries, and Surprises

Although many instances of organism and ecosystem recovery have been observed since the DWH oil spill (e.g., beaches), in some cases, spill impacts are ongoing and may have caused shifts in the baselines of ecosystem interactions (e.g., deep-sea coral communities). Exposure to polycyclic aromatic hydrocarbons alone may not sufficiently characterize longer-term impacts of oil spills on organisms because environmental impacts were spatially heterogeneous in nature. Rapid recovery tended to occur (to some extent) in high-energy environments, such as marshes and shallow-water regions, whereas low-energy environments, such as the deep-sea benthos, will sustain documented impacts that may last for generations.

Transport of oil spill toxicants throughout the northern Gulf of Mexico was facilitated by organismal activities (e.g., feeding, migration, etc.). Fortunately, microbial communities in the Gulf of Mexico (beaches, marshes, water column, and sediments) were and are uniquely primed for rapid response to oil spills. Some oil-degrading microbes are capable of nitrogen fixation, enabling them to utilize hydrocarbon energy sources without nutrient restriction and providing a strong selective advantage over other species. Moreover, some of these microbial taxa are found to be ubiquitous in oil spills around the globe (e.g., *Macondimonas diazotrophica*). Bacteria are a primary food source for many organisms and introduce oil-derived carbon into the food web through metabolic pathways. Due to oil droplet sizes that resemble forage bacteria, zooplankton were documented ingesting oil droplets and excreting the oil in their feces, thus depositing oil directly into food webs.

Research has revealed that deeper water communities continue to exhibit impacts. Species abundances in the midwater mesopelagic zone showed major sustained and persistent declines that continued through 2019 (Murawski et al., 2021, in this issue). Reduction in mesopelagic community numbers may have impacted cetacean migration. As described above in the section on

Chemical and Biogeochemical Processes, MOSSFA was part of the natural microbial systems' responses to oil; some deep-sea benthic habitats were smothered by the accumulation of MOSSFA and will take decades to recover. Deep-sea corals showed considerable long-term impacts from spilled oil, but also showed signs of recovery (Halanych et al., 2021, in this issue).

Oiled marshes and associated communities showed unexpected resilience and recovery over time since the spill. However, dolphins in Barataria Bay—where oil entered the marsh—suffered adverse effects, including reduced reproductive success (20% vs. 70%), chronic lung damage, and modified endocrine responses. In addition to the impacts documented for dolphins, novel sublethal impacts of hydrocarbons and dispersants were observed and connected to fish olfaction, metabolic fatigue, immune response, and neural system issues, among others. An associated short-term decrease in abundance of coastal fishes may have accelerated invasion by non-native lionfish.

While many species suffered, several targeted commercial species (including shrimp, crab, and some fish) showed remarkable resilience in the wake of the spill. The closure of commercial fisheries at the time of the spill did not appear to have long-term ecological effects.

Lessons for the Future

Biological systems are highly complex and interconnected. These linkages can aid microbial decomposition of oil or result in damaged ecosystems resetting to a different stable state. In the event of an oil spill, oil-degrading microbes can act as essential and natural first responders, providing critical ecosystem cleanup, transport, and stabilization functions.

Traditional measures of damage to a biological system may not be the best indicators of toxicant impact. Sublethal organismal impacts can turn up in any system or function of an organism's body. The degree to which toxicological impacts can be placed in meaningful biological or environmental contexts is dependent upon the deployment of analytical chemistry tools.

The DWH spill caused major alterations in microbial community structure and function. Researchers found that novel gene expression, species composition and metabolic capabilities involved in hydrocarbon degradation and nitrogen fixation emerged to dominate ecosystems ranging from the deep sea to salt marshes.

Specific mechanisms behind many organismal and ecological impacts can now be elucidated through the use of genomic tools, which may yield insight into yet unknown long-term implications.

Future Research Needs/Gaps

To complement the many advancements made over the last 10 years, we recommend the following further studies of biological and ecological processes and actions to insure long-term monitoring.

- Conduct long-term monitoring and assessment to provide baseline data for understanding and mitigating the impacts of oil spill toxicants. Biological systems of note are:
    - The Barataria Bay, Louisiana, dolphin population, including its reproductive success and endocrine response recovery.
    - Mesopelagic communities from plankton to nekton to apex predators, notably the effects of community change and recovery on associated cetaceans and pelagic predators.
    - Barataria Bay wetlands, with emphasis on reoiling events.
    - Deep-sea benthos and coral habitats that are subject to slow rates of growth and low fecundity.
- Investigate the impact(s) of various components of dispersants on biological systems.
- Conduct longer-term studies on seafood contamination and associated sensory and chemical testing techniques through collaborations between NOAA and the US Food and Drug Administration. Studies should include the investigation of previously unanalyzed oil degradation compounds on marine organisms and associated seafood safety for humans.
- Develop methods to define microbial biomarkers of ecosystem health that will lead to the ability to detect ecosystem disruption, predict risk, guide mitigation strategies, and assess restoration efforts in the face of diverse threats.
- Make progress on translating omics data from observations of novel genes and species into metabolic activity, currently the greatest hurdle to accurately predicting biochemical outcomes.
- Develop more detailed and complete predictive models for biological systems that should integrate biological data and response with chemical, geological, and physical parameters.
- Conduct extensive and regular sampling in diverse ecosystems around the globe to document the normal, or baseline, state of microbial and other communities prior to a crisis in order to plan intelligent mitigation strategies aimed at restoring native communities and their ecosystem functions.

TECHNOLOGICAL DEVELOPMENTS

The severity and unusual circumstances of the DWH incident called for innovative technological developments to mitigate and investigate the fate and impacts of the released material and the physical, chemical, and biological processes involved. The technological developments highlighted in Dannreuther et al. (2021, in this issue) represent only a small sampling of such developments. However, this small representation demonstrates the collaborative and interdisciplinary nature of innovation with application to a wide range of scientific endeavors.

Advances, Discoveries, and Surprises

Technological advancements were applied to obtain measurements of the subsurface dynamics of oil and gas droplets that could then inform estimations of droplet size distribution, a critical component in predicting the transport and fate of a subsurface oil spill. Some measurements were made in laboratory experiments that combined existing imaging techniques with new or enhanced technologies that simulated oil and wave interactions. Other measurements were made in experiments that combined initial blowout conditions with high pressure, mixing forces, and jet stream dynamics. Measurements were also conducted in the field using new deep-sea imaging techniques transported by a remotely operated vehicle to the ocean floor that recorded oil and gas droplets and bubbles rising from natural hydrocarbon seeps. Additionally, the inclusion of oil biodegradation processes in spill simulation scenarios to predict the amount of oil that may reach the ocean surface provided insights that can inform response decisions, especially those related to dispersant use.

Advancements were made in tracking and visualizing the dynamic nature of currents at or near the ocean's surface, including the potentially different velocities of multiple currents that run just beneath the surface. These discoveries were made possible by new biodegradable GPS-enabled drifters along with drogues, drones and aerostats equipped with cameras, and the novel combination of sensing instruments that mitigated each other's blind spots. These innovations improved our understanding about the significant transport role that submesoscale processes play and provided data that informs near-real-time transport forecasts during an oil spill.

Several technological modeling developments enabled advancements in quantifying the fate of oil from a marine spill. Such models simulated oil transport via aggregation with floating particulate matter, such as MOS processes, and via oil/particle/mineral interactions that allowed for the inclusion of transport processes not previously accounted for in oil spills. In situ imaging techniques can now distinguish oil and gas droplets in a mixed release that can inform estimations of oil/gas ratios. Additionally, a novel approach that can distinguishing crude oil from non-fossil-fuel carbon sources was applied to estimate the amount of Macondo oil deposited on seafloor sediments.

New techniques were applied to improve the understanding of sublethal impacts from an oil spill on fish. This yielded new insights on the degree to which transcriptomic response to oil is dependent on tissue type. For example, oil-induced impairments to heart cells are linked to a fish's ability to capture food and escape predation.

Advancements in new dispersant technologies offer the potential for safer and more effective alternatives to existing chemical dispersants used in oil spill response. Scientists revealed that oil/water emulsions created by carbon black particles are more stable and last longer than emulsions created by Corexit. Another discovery showed that clay particles loaded with nontoxic surfactants can be rendered more effective by the use of a stoppering agent that allows for the slow release of the surfactant.

Lessons for the Future

Cross-disciplinary and multi-institutional collaborations can enhance technological developments and increase awareness of, and communications about, the resulting innovations. Such collaborations may include the involvement of spill-response operational scientists directly with academic research projects, which could improve the chance that technological developments and resultant data can immediately inform response decisions during an oil spill. Technological developments designed for use during a marine oil spill can benefit from collaborations with institutes that have facilities for oil-in-water tests, such as the European research organization SINTEF, the SouthWest Research Institute, and the US National Oil Spill Response & Renewable Energy Test Facility Ohmsett. Including academic researchers in spill response preparedness training exercises may improve the academic community's understanding of the needs and challenges that the response community faces and, thus, can shape academic research and encourage developments to be application focused.

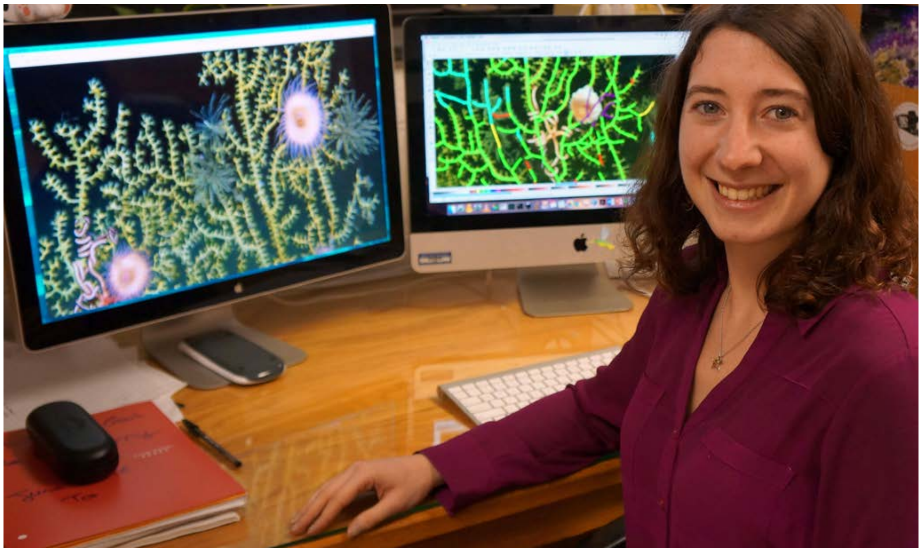
Future Research Needs/Gaps

Innovative technological developments will continue to be driven largely by need and circumstance. Specific suggestions for future development include:

- Continue to advance the processing efficiency of large data sets as the technologies used to acquire those data become increasingly efficient and affordable.
- Continue collaborations with legal authorities, response agencies, and industries that have testing and production-scale capabilities to enable the use of alternative dispersant technologies in large-scale oil spill response.
- Incorporate the latest technological/chemical measurement techniques into safety devices worn by response workers to assess levels of exposure to chemicals of human health concern.
- Increase the use of remotely operated technologies to improve the safety and cost efficiency of conducting in situ biological experiments in the environment, such as using drones to gain access to, and sample, contaminated areas.
- Focus on development of nanoscale assessment technologies for genomics.
- Improve visualization techniques for multiple types of data to help understand and convey the complexity and scale of disasters like DWH.

SOCIOECONOMIC AND PUBLIC AND HUMAN HEALTH ISSUES

The DWH oil spill, according to the National Oil and Hazardous Substances Pollution Contingency Plan, is the only declared spill of national significance in US history. DWH caused significant and lasting adverse impacts on the health and well-being of people and their communities in the Gulf of Mexico region. These impacts compounded and exacerbated



Graduate student Fanny Girard of Penn State, a GoMRI Scholar, digitizes a high-definition image of a coral colony to quantify impacts, growth, and recovery. *Photo credit Cherisse DuPreez*

the negative effects of Hurricane Katrina and previous disasters in the Gulf, and, in turn, may add to effects of subsequent disasters as well as ongoing threats from chemical pollution, oil seeps, and harmful algal blooms. Studies to date, and those still underway, have shown various adverse mental, physical, and community health effects in some individuals who responded to the spill and/or participated in clean-up efforts, as well as some coastal residents in all five Gulf states (Sandifer et al., 2021, in this issue).

Additionally, the spill had socioeconomic impacts, especially to the tourism and recreational sectors, and those dependent on living resources, such as fishing. These effects also harmed the health and well-being of individuals and communities that were primarily dependent upon natural resources for employment and as a way of life. Residents who were already disadvantaged, low-income, and of minority ethnicity or otherwise vulnerable were most affected. Negative perceptions about the safety of Gulf seafood and its marketability persisted long after data demonstrated its safety according to regulatory protocols in place at that time. These perceptions caused consumers to question the potential for exposure to toxic oil-related chemicals during the spill and clean-up, as well as from seafood consumption. Parents were concerned about children as they played on beaches that may have been contaminated with oil. Some residents reported more stress from navigating the legal and claims processes following the spill than from the spill itself. The breadth and severity of mental, physical, and community health effects, perceived effects, and anxiety about potential effects were significant and, in some cases, were long lasting.

Advances, Discoveries, and Surprises

During initial post-DWH public health data collection, except for information available about US Coast Guard personnel (Rusiecki et al., 2018), researchers were faced with the reality that baseline health and socioeconomic data against which to compare spill effects were woefully inadequate. As a result, this scarcity of systematically collected and curated health and socioeconomic data made it difficult to characterize individual, community, and societal impacts and to connect outcomes with their causes. The need for ongoing data collection of these sorts was further emphasized when studies revealed that secondary events occur in the periods between major disasters.

This information made it evident that health services are especially important for community members who are not directly involved in spill operations but are vulnerable to indirect spill effects such as social and economic impacts. Unfortunately, well-structured and funded human health services and data collection associated with large oil spills were lacking compared to those for environmental effects. US oil spill response protocols focus on mitigating the environmental pollutant but generally lack formal mechanisms, developed with public input and support, for assessment of impacts on humans and communities and recovery of damages. Furthermore, insufficient involvement of the public in communicating health and safety information resulted in increased anxiety and distrust of authorities.

Lessons Learned

In the event of another disaster, the lessons learned from the DWH oil spill need to be applied to future human health assessment and recovery. Researchers should be aware that large oil spills are associated with a broad range of mental and physical health impacts and may amplify the adverse effects of both prior and future traumas. Such impacts are most pronounced among vulnerable people and those individuals and communities dependent upon natural resource-related industries.

These health impacts occur through both direct contact with spilled oil and indirect exposures to it, such as a spill's social and economic effects. Also, health studies on oil spill response workers tend to be slow to start and inadequate in duration and depth; health studies for those not involved in spill response are even less adequate. While there is an increasing awareness of the need to deal with indirect health impacts associated with oil spills, structured programs and secure funding to do so are lacking.

Future Research Needs/Gaps

Recommendations for future research and study regarding socioeconomic and public and human health issues are outlined in Sandifer et al. (2021, in this issue). Some of the most critical actions recommended are:

- Implement the health observing system framework (Sandifer et al., 2021, in this issue). This will require participation of a diverse group of health professionals and government, institutional, and private sector entities.
- Collect and analyze health, environmental, and socioeconomic data to identify cause-and-effect links between spills and health outcomes to improve preparation, response, recovery, and damage assessment.
- Develop robust mechanisms for dialogue among oil spill and other disaster preparedness authorities and researchers prior to disaster events.
- Improve toxicological profiles for oil spill chemicals, including dispersants, in humans, prioritizing vulnerable human populations.
- Improve human exposure and effects models and human health risk assessments.
- Substantially increase research on models of human health and socioeconomic effects and integrate them with oceanographic and ecosystem models.
- Increase transdisciplinary research on the human dimensions of oils spills and other disasters.
- Improve personal protective equipment supply and its utilization for responders.

PREPAREDNESS, PLANNING, AND ADVANCES IN OPERATIONAL RESPONSE ISSUES

Planning and preparing for oil spills are key to expediting clean-up and minimizing environmental harm during an actual event, but response leaders are often faced with time-critical and complex options that inevitably create trade-offs (Westerholm et al., 2021, in this issue). Determination of oil fate and transport and associated environmental impacts accurately and promptly is imperative. Over the last 10 years, research helped propel advances in spill response, damage assessment, and quantifying resources at risk, but research gaps remain. The nexus between operational response and research involves many entities, including state and federal agencies, industry, academia, and nongovernmental organizations (Halanych and Westerholm, 2021, in this issue). In future efforts, industry and government should continue to collaborate with academia to improve operational response.

State-of-the-art fate and transport models were developed and utilized during the DWH event to predict landfall and assist strategic deployment of response resources, but these models had limitations. Because the DWH incident was an undersea blowout, the few available three-dimensional operational models were inadequate for capturing droplet formation and circulation at depth, which limited the federal government's deep-sea blowout oil spill modeling capability. Since the DWH incident, improvements in spill modeling have included the addition of weathering parameters, enhanced three-dimensional capability, faster processing, new algorithms, and more user-friendly displays on a variety of platforms (Westerholm et al., 2021, in this issue). Other modeling needs remain, as there are no fully quantitative models that can simulate oil spill impacts across all the physical, chemical, biological, socioeconomic, and human health knowledge domains.

As a result of the DWH Natural Resource Damage Assessment and GoMRI research, improvements in sample collection, use of genomics, and extensive toxicity testing have all led to a better understanding of the Gulf of Mexico ecosystem (Murawski et al., 2021, and Halanych et al., 2021, both in this issue). Multidisciplinary researchers continue to discuss the nexus between laboratory research and mesocosm studies on toxicity, dispersion, microbial degradation, and other spill impacts and how these should be incorporated into the planning process and environmental trade-off discussions (Halanych and Westerholm, 2021, in this issue). Response decision-makers are typically faced with new and alternative technologies, in addition to dispersants, that require quick evaluation. While there is a process for evaluation, deploying new methods or untested equipment during an emergency can have adverse impacts and increase liability. During the DWH spill response, numerous alternatives were proposed and some, such as freshwater diversion, were utilized. The diversion, which was designed to minimize damage to coastal wetlands by keeping oil offshore, instead demonstrated a trade-off decision that had unintended and severe ecological consequences.

Lessons for the Future

The operational response command structure must continually strive to develop and evaluate new scenarios that can be incorporated into spill planning and exercises. Often, plans and models are based on past assumptions of expected spill impacts (e.g., specific amount and type of oil, specific location, what additional injury might result from response actions). However, more work needs to be done on the few models that currently allow comparative predictive modeling of alternative mitigation scenarios and the expected impacts of using, not using, or combining specific technologies. For example, "what if dispersants or in situ burns are not utilized?" In those cases, the plans and models need to evaluate the expected impacts and recovery times for the oil (and its products) that might now reach nearshore and coastal environments. By updating plans and models, future response leaders can better predict real-time impacts that optimize the deployment of response resources and that allow them to make difficult trade-off decisions on these alternatives.

As research brings new capabilities to bear, the command structure will also need to evaluate these alternatives and incorporate them into their existing spill response plans. This might include introducing microbes to enhance biodegradation (natural and engineered), new dispersant or chemical herding formulations, more efficient in situ burning, uncrewed equipment for sample collection and dispersant applications, and detection and imaging technologies that could safely increase operational windows to a continuous 24/7 response. Communicating these options and engaging the public as early as possible will promote understanding and may have profound benefits for addressing societal concerns and mental health issues.

Prior to a spill, federal agencies must work with stakeholder groups and seek expert opinions that allow for a clear value system relative to oil impacts. These agencies and the command structure during the spill will need to communicate this process more effectively to explain how and why certain decisions were made.

Future Research Needs/Gaps

The ultimate goal of GoMRI was to improve society's ability to understand, respond to, and mitigate the impacts of petroleum pollution and related stressors of the marine and coastal ecosystems, with an emphasis on conditions found in the Gulf of Mexico. As highlighted in this issue, GoMRI has significantly increased the ability for the response community to react, respond, and mitigate future spills; however, there are several areas that require additional research, focus, and funding:

- High-resolution oceanographic models do not yet exist for all areas where spills might occur. A system is needed that can quickly employ a high-resolution operational regional model, nested within the existing larger-scale operational models. Future models must also capture spatially variable and non-isotropic diffusion as well as vertical transport associated with MOSSFA. While simplified MOSSFA models can currently be incorporated into operational models, improved parameterizations of processes such as subgrid-scale diffusion are still lacking.
- Fate models can be improved by incorporating biodegradation and photo-oxidation and their effects on emulsions, oil solubility, and toxicity, including sublethal impacts. This also includes modeling the expected interaction of response alternatives, such as dispersants, for these processes and any changes that would occur over time in microbial degradation or photo-oxidation.
- Quantifying and reducing the uncertainly of forecasts, as well as including other domains of knowledge such as biological ecosystems, socioeconomics, and human health, are critical for development of accurate models. GoMRI has explored a framework for assessing a quantitative model that simulates oil spill impacts across these domains, but the model itself does not yet exist.
- Future models will need to be scalable and incorporate combinations of all response options over time, evaluating and comparing the expected benefits and impacts while accounting for the predicted and often changing environmental factors associated with specific spill locations.
- As seen in DWH, when restoration alternatives are implemented, long-term impacts on marine and estuarine habitats must be considered and monitored.
- Modeling restoration alternatives should include even more complex processes associated with nutrient overloads and land use management, climate change impacts, natural erosion, and future energy development. Based on the DWH incident, it is imperative to develop new classes of predictive numerical models to explore the effects of planned large-scale projects, such as freshwater diversions. Such models would integrate estuarine, coastal, and shelf hydrodynamics, such as riverine forcing, and incorporate ecological processes and outcomes, thus allowing for better predictions of both the short-term effectiveness as a spill countermeasure and the expected outcome of long-term habitat restoration projects.

CONCLUSIONS

The human tragedy and ecological impacts of DWH will persist for years/decades to come and will never be forgotten. Yet, this tragedy has taught those involved to be safer, smarter, and better prepared for managing offshore resources. The subsequent funding by BP, which led to the establishment of GoMRI, demonstrated that an independent, science-based research program can successfully bring diverse groups of scientists together to achieve common goals. This cross-pollination of different disciplines yielded advances and real-world impacts that benefit understanding of the Gulf of Mexico as well as other locations where marine oil exploration and extraction occurs. The past 10 years of effort and attention have reinforced how important and understudied coasts and the open ocean remain. It was imperative to use the best science available to fully understand environmental impacts and determine the appropriate means to ameliorate those impacts through restoration. Filling critical data gaps, some of which are highlighted above, will be necessary to support better future restoration and response decisions while also establishing new baselines that require long-term studies (Wiesenburg et al., 2021, in this issue).

GoMRI research has built a foundation of knowledge and tools that will enable scientists to play key roles in guiding future oil spill response and Gulf of Mexico science with data-driven strategies. The creation and preservation of a permanent data archival system (Zimmermann et al., 2021, in this issue) will prove invaluable in the future and support the new mindset of open-source data in science. Government and private supporters of science should be encouraged to require that future research grants, awards, and contracts submit collected data to open-source data portals.

GoMRI presented a rare opportunity to successfully assess and follow spill impacts and synthesize findings across academia, industry, and government. The post-DWH cooperation and information sharing between empiricists, modelers, and decision-makers should be a guiding example for future large-scale events. The relationship between research funding and academia's connection to operational decision-makers should continue beyond GoMRI in order to close gaps, evaluate new opportunities, and bring the best available science to spill response plans and operations.

After 10 years and a $500 million investment, GoMRI scientific research yielded findings that will benefit the Gulf of Mexico ecosystem for decades. New species were discovered and understanding of ocean currents and microbial degradation of oil was significantly advanced. This new knowledge helps us better understand the environmental impacts of released oil in the environment and how spilled oil moves through the Gulf of Mexico, with many complex effects on both the environment and citizens of the region.

As a closing statement, the authors wish to express their gratitude to all established and early career researchers who undertook such excellent work. The support and partnerships within industry, academia, the Gulf of Mexico state governments, and federal agencies greatly aided the research. Lastly, we acknowledge the sacrifices, as well as the contributions, of those who lived through the DWH spill, as well as those we have lost.

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AUTHORS

Charles A. Wilson (chuck.wilson@gomri.org) is Chief Scientific Officer, Gulf of Mexico Research Initiative (GoMRI), Fairhope, AL, USA. **Michael G. Feldman** is Program Manager, GoMRI, Consortium for Ocean Leadership, Washington, DC, USA. **Michael J. Carron** is Program Director, GoMRI, Williamsburg, VA, USA. **Nilde Maggie Dannreuther** is Coordinator, Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS, USA. **John W. Farrington** is Dean Emeritus, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Kenneth M. Halanych** is Professor, Department of Biological Sciences, Molette Biology Laboratory for Environmental & Climate Change Studies, Auburn University, Auburn, AL, USA. **Jennifer L. Petitt** is Program Manager, American Institute of Biological Sciences, Herndon, VA, USA. **Jürgen Rullkötter** is Professor (retired), Institute of Chemistry and Biology of the Marine Environment, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany. **Paul A. Sandifer** is Director, Center for Coastal Environmental and Human Health, College of Charleston, Charleston, SC, USA. **J. Kevin Shaw** is Program Manager, GoMRI, Fairhope, AL, USA. **John G. Shepherd** is Professorial Research Fellow, School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton, UK. **David G. Westerholm** (retired) was Director, Office of Response and Restoration, National Oceanic and Atmospheric Administration, Silver Spring, MD, USA. **Callan J. Yanoff** is Program Associate, GoMRI, Consortium for Ocean Leadership, Washington, DC, USA. **Leigh A. Zimmermann** is Senior Program Manager, GoMRI, Consortium for Ocean Leadership, Washington, DC, USA.

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REGULAR ISSUE FEATURE

MOORED OBSERVATIONS OF CURRENT AND TEMPERATURE IN THE ALAS STRAIT

COLLECTED FOR SUBMARINE TAILING PLACEMENT, USED FOR CALCULATING THE INDONESIAN THROUGHFLOW

By R. Dwi Susanto, Jorina M. Waworuntu, Windy Prayogo, and Agus Setianto

ABOVE. Survey vessel *Tenggara Ranger*, with Kenawa Island and the Alas Strait in the background. LEFT. Batu Hijau mine pit. BELOW. Mooring deployment. *Photo credits: PT Amman Mineral Nusa Tenggara*

> “The results of our research in the Alas Strait serve as an example of how collecting and analyzing oceanographic data are essential to the management of environmental issues facing mining companies located near coasts.”

ABSTRACT. Newly released current velocity and temperature measurements in the Alas Strait collected from November 2005 to February 2007 permit calculation of the mean and variable transport of the Indonesian Throughflow (ITF) in this region. These data were collected by the Environmental Division of the Amman Mineral Nusa Tenggara mining company to serve as a guide for the deep submarine placement of tailings produced by the Batu Hijau open pit copper-gold mine. Ocean currents, temperatures, and winds in the Alas Strait region exhibit intraseasonal and seasonal variability, with modulation at interannual timescales that may be associated with intraseasonal Kelvin waves, the regional southeast monsoon, the El Niño Southern Oscillation, and the Indian Ocean Dipole (IOD). Currents in the Alas Strait were found to flow steadily southward not only during the boreal summer from mid-April to October but also when a prolonged anomalously easterly wind associated with positive IOD extended this flow direction through the end of December 2006. A steady shear between the northward-flowing upper layer and the southward-flowing layer beneath was recorded from November 2005 to early April 2006 and from January to February 2007. The 2006 annual transport was –0.25 Sv toward the Indian Ocean and varied from 0.4 Sv in early April 2006 to –0.75 Sv in August 2006. Hence, Alas Strait transport plays a dual role in the total ITF, increasing it during boreal summer and reducing it during boreal winter. Northward flows tend to carry warmer water from the Indian Ocean to the Flores Sea, while the southward ITF flow carries cooler water to the Indian Ocean. Although the Alas Strait is located next to the Lombok Strait—one of the major ITF exit passages—they have different current and temperature characteristics. For a more complete evaluation of the ITF, the Alas Strait must be included in any future monitoring.

INTRODUCTION

The complex coastlines and narrow passages of the Indonesian seas provide the only pathways for inter-ocean exchange of Pacific and Indian Ocean tropical waters, known as the Indonesian Throughflow (ITF; Figure 1; Gordon and Fine, 1996, and references therein). The ITF varies at intraseasonal to interannual timescales, driven by regional and remote forcings from the Pacific and Indian Oceans, which set up a pressure gradient and sea level differences between the two (Wyrtki, 1987; Susanto and Song, 2015; Sprintall et al., 2019). Water, heat, and salt fluxes measured within the ITF have been found to be a significant factor in the global ocean thermohaline circulation. Hence, the ITF may impact climate variability of both the Pacific and Indian Oceans and beyond. Temperature and salinity changes in the Pacific and Indian Oceans may influence dynamics of the Asia-Australia monsoon, the El Niño Southern Oscillation (ENSO), and the Indian Ocean Dipole (IOD) (Bryden and Imawaki 2001; Lee et al., 2002; Sprintall et al., 2019).

Although the ITF has been measured over the last three decades, these data have only been collected in the passages of major inflow, the Makassar Strait and the Lifamatola passage, and outflow, the Lombok, Ombai, and Savu Straits and the Timor passage (Arief and Murray, 1996; Murray and Arief, 1988; Murray et al., 1990; Gordon et al., 1999, 2010, 2019; Molcard et al., 2001; Susanto and Gordon, 2005; Sprintall et al., 2009, 2019; van Aken et al., 2009; Susanto et al., 2012; Wang et al., 2020). Only recently have minor inflow (Karimata Strait) and outflow (Sunda Strait) passage measurements been collected (Fang et al., 2010; Susanto et al., 2010, 2013, 2016; Wang et al., 2019; Wei et al., 2016; 2019; Li et al., 2018). However, none of these measurements include the ITF in the straits along the Nusa Tenggara (Lesser Sunda) island chain from Bali to Timor (i.e., Bali, Alas, and Sape Straits). Hence, their contributions to inter-ocean exchange between the Pacific and the Indian Oceans have not been recorded.

This paper presents newly released current velocity and temperature measurements collected in the Alas Strait. These measurements were made from November 2005 to February 2007 using bottom-mounted acoustic Doppler current profiler (ADCP) and thermistor arrays. The Alas Strait, located between the islands of Lombok and Sumbawa, is one of a series of straits within the Nusa Tenggara island chain that connects the internal Indonesian seas (the Banda and Flores) to the Indian Ocean. The water depth at the northern entrance of the Alas Strait is approximately 400 m, and there

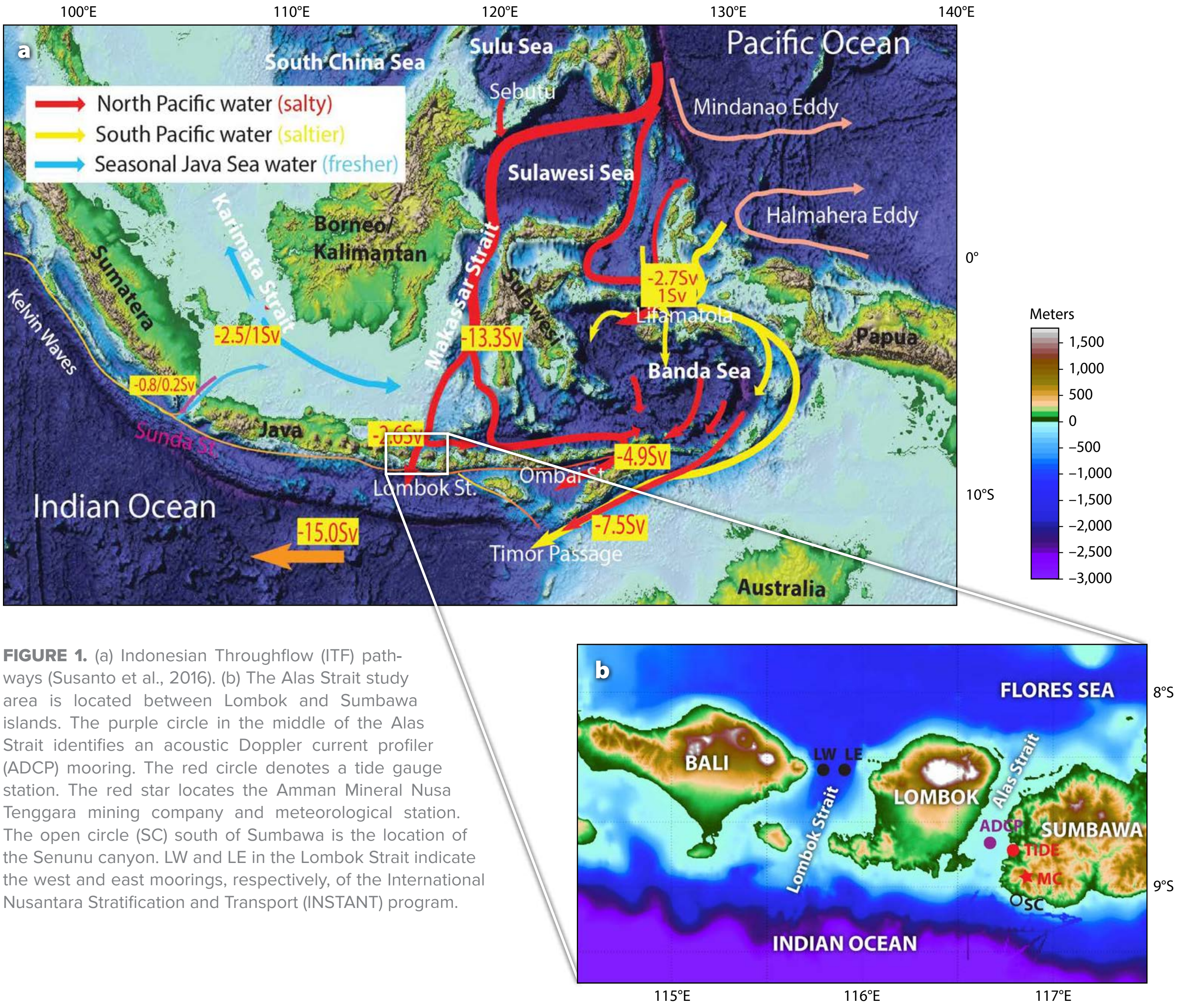

FIGURE 1. (a) Indonesian Throughflow (ITF) pathways (Susanto et al., 2016). (b) The Alas Strait study area is located between Lombok and Sumbawa islands. The purple circle in the middle of the Alas Strait identifies an acoustic Doppler current profiler (ADCP) mooring. The red circle denotes a tide gauge station. The red star locates the Amman Mineral Nusa Tenggara mining company and meteorological station. The open circle (SC) south of Sumbawa is the location of the Senunu canyon. LW and LE in the Lombok Strait indicate the west and east moorings, respectively, of the International Nusantara Stratification and Transport (INSTANT) program.

are some small islands on either side off of Lombok and Sumbawa. Along the north-south strait, the water depth decreases slightly from 180 m to 125 m, with a sill at 95 m depth, where the mooring is located. The strait's average width is ~15 km. The mooring location (width 16.8 km) is slightly north of the narrow constriction, placed to avoid a ferry route that connects Lombok and Sumbawa (Figure 1).

The main objective of the field measurements made by the Environmental Division of the Amman Mineral Nusa Tenggara (PT AMNT; previously PT Newmont Nusa Tenggara) mining company was to understand and assess oceanographic conditions in the Alas Strait in order to ensure the effectiveness of their submarine disposal of mine tailings. As required by the Indonesian government, detailed oceanographic assessments must be made before permission is granted to dispose of mine tailings in Indonesian waters. We use these newly released data to attempt to fill the gap in oceanographic measurements from previous studies of the ITF. We present our findings on the dynamics of current and temperature variability in the Alas Strait, its contribution to ITF transport, and heat-flux variability from the Pacific into the Indian Ocean. We also describe an interesting application of oceanographic measurements.

FIELD MEASUREMENTS AND ANALYSIS

As part of the PT AMNT mining company's environmental monitoring program, oceanographic measurements were collected in the Alas Strait using a subsurface mooring, CTDs, and underway ADCPs. Current measurements in and near Senunu Canyon, where the tailings were to be disposed, were collected using a bottom-mounted ADCP mooring, a ship-mounted ADCP, an ADCP/current meter lowered from the ship, and an ocean glider (Waworuntu and Febriana, 2002; Bachtiar et al., 2011). In general, the measurements show that the South Java Current, the South Equatorial

Current, the Monsoon Current, and the ITF consistently contribute to the current system southwest of Sumbawa. The ITF plays a crucial role in carrying a fine particulate tailings plume offshore through the Alas Strait, as detailed in a five-year mapping of tailings distribution and footprint conducted by the Oceanographic Division of the Indonesian Institute of Sciences (LIPI).

A subsurface mooring was deployed in the middle of the Alas Strait from November 2005 to February 2007, with recovery and redeployment every three months. The mooring consisted of an RDI workhorse (300 kHz) ADCP, five to nine Star-Oddi Starmon Mini thermistors, and two InterOcean Systems acoustic releases. To adequately resolve velocity to the surface and to reduce mooring drawdown, the mooring was deployed at 95 m water depth, with the ADCP placed 5 m above the bottom where the velocity is close to zero; the uppermost instrument on the mooring was situated below the maximum current. Current velocity and temperature were recorded every 10 minutes. Vertical bins for current profiles were set for every 4 m. Thermistors were placed 10 m apart between 32.5 m and 82.5 m depth.

Other environmental monitoring data collected by the mining company and used for our analysis were drawn from a tide gauge installed at Benete Port (Tide in Figure 1b), where the water level was recorded every 10 minutes, and a weather station located on a peak near the mine pit (MC in Figure 1b), where an automatic wind sensor collected data every 10 minutes. Data from the automatic tide gauge and the weather station were telemetered to the company's base.

Here, we analyze all of these newly released data sets. Following quality control of the individual ADCP bins, the time series data were filtered and interpolated onto a time base, typically of one hour. The velocity data were then vertically linearly interpolated onto a 4 m-depth grid for each hourly time step, as described in Sprintall et al. (2009) and Susanto et al. (2012). To avoid surface reflection contamination, the first two bins near the surface were removed and replaced with a mean of constant velocity as observed in the third bin from the surface along with continuous shear to the surface. The vertically gridded ADCP velocity time series were then four-day low-pass filtered with a Lanczos filter (Duchon, 1979) to suppress inertial and tidal variability (Sprintall et al., 2009).

WIND, CURRENTS, AND TEMPERATURE IN THE ALAS STRAIT

Indonesia is located along the equatorial line that runs between Asia and Australia. Thus, its climate is strongly influenced by the six-month reversal of the Asia-Australia monsoon system (Aldrian and Susanto, 2003). Figure 2a shows the wind speed and direction measured at the mine location (MC in Figure 1b). Figure 2b shows the current velocity at 25 m depth in the Alas Strait. Winds strongly affected the strait's upper layer flow, especially during the boreal summer (southeast monsoon) from April to October, and even to December, in 2006. Strong, easterly, wind-induced upwelling generated lower sea levels along the southern coasts of the Nusa Tenggara island chain during the southeast monsoon (Wyrtki, 1987; Susanto et al., 2001), creating a stronger north-south pressure gradient and increasing the southward ITF flow (Susanto and Marra, 2005; Iskandar et al., 2009; Ningsih et al., 2013; Siswanto et al., 2020; Wirasatriya et al., 2020). The prolonged anomalous easterly winds extended until December because 2006 was an El Niño year (Niño3.4 positive) and the Indian Ocean Dipole Mode Index was also positive, (Horii et al., 2008; Iskandar et al., 2009), thus inducing more vigorous upwelling along the southern coasts of the island chain and driving a more substantial southward flow (ITF).

Local winds and large-scale remote forcing affect current velocity and temperature in the Alas Strait. To the first order, regional monsoon forcing dominates the velocity profile. Figure 3 shows that north-south velocity measured by ADCP at 0–95 m water depth from November 2005 to February 2007 varies from −1.2 m s^{-1} (southward) to 0.5 m s^{-1} (northward). Figure 3a shows the annual and seasonal means in velocity. During the boreal winter (northwest monsoon) of December 2005 to mid-April 2006, northward flow was observed in the upper layer above a southward flow induced by locally wind-driven Ekman currents. This persistent southward flow in the lower layer plays a crucial role in

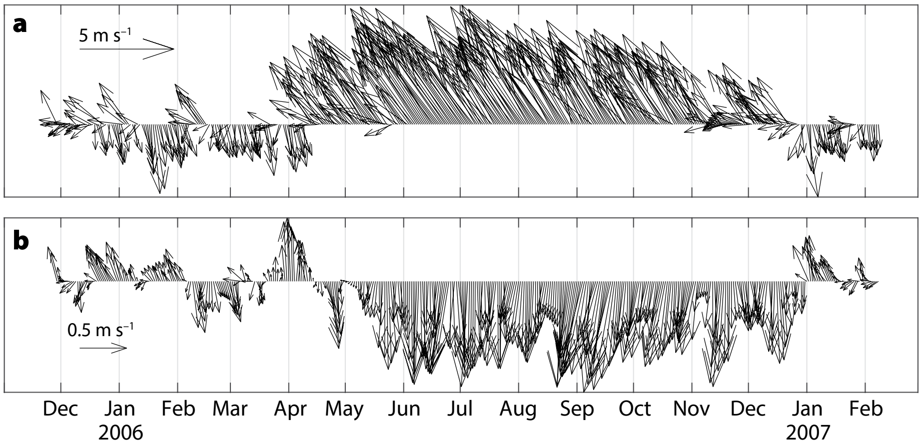

FIGURE 2. (a) Winds observed southwest of Sumbawa island. (b) Current velocity (m s^{-1}) at 25 m depth in the Alas Strait. A negative sign denotes southward flow toward the Indian Ocean. The upper layer flow in the Alas Strait is strongly affected by wind during the boreal summer (southeast monsoon) from April to October 2006 and even extended until December 2006 due to the El Niño condition (positive NINO3.4 and Indian Ocean Dipole indices).

placing the submarine tailing system.

During the boreal summer (southeast monsoon) from mid-April to October 2006, a vigorous southward flow in the upper layer was observed in the Alas Strait. During this monsoon, the combination of lower sea level off the coast of Nusa Tenggara (Wyrtki, 1987, Susanto et al., 2007) and divergence in the Banda Sea (Wyrtki, 1987; Waworuntu et al., 2000; Gordon and Susanto, 2001) drew waters into the Indian Ocean and maximized this upper-layer southward flow. The maximum velocity occurred at 20 m to 30 m depth (Figure 3b). We observe modulation of an interannual signal on top of the intraseasonal and seasonal variability. Starting in the boreal summer of 2006, a positive Dipole Mode Index increased significantly (third largest in the last 30 years after 1997 and 1994), then subsided in January 2007 (Horii et al., 2008). When the easterly wind terminated in early 2007, the regular northwest monsoon reversal flow is observed in the Alas Strait. The presence of the reversal currents is likely due to remote forcing from the equatorial Indian Ocean associated with coastally trapped Kelvin waves as observed in the Sunda Strait (Susanto et al., 2016; Li et al., 2018; Xu et al., 2018), the Lombok and Ombai Straits (Iskandar et al., 2014; Sprintall et al., 2009), and the Sumba Strait (Bayhaqi et al., 2019).

Similar to the velocity profiles, temperature variability in the Alas Strait is due to regional monsoon forcing, with interannual modulation associated with ENSO and IOD events. Figure 4 displays temperature measurements acquired with five to nine thermistors attached to the mooring rope between 30 m and 85 m depth. The temperature profile appears to follow the velocity profile. During the 2006 boreal summer and half of the boreal winter (to December 2006), cooler temperatures were associated with the southward flow, while warmer water during the 2005 boreal winter to mid-April 2006 and January–February 2007 was related to northward flow from the Indian Ocean (Figures 3 and 4).

One of the results of the Alas Strait measurements is observation of the dominant intraseasonal variability on top of the seasonal variability in both ocean currents and temperature. The intraseasonal variability exhibits periods of 13–17 days, 25–30 days, and 70–90 days, and includes reversal flows (northward toward the internal Indonesian seas) during the boreal winter and spring. The 25–30 day and 70–90 day intraseasonal variability are likely associated with coastally trapped Kelvin waves that are generated in the equatorial Indian Ocean and propagate along the southern coasts of Sumatra and the Nusa Tenggara island chain (e.g., Iskandar et al., 2005, 2014). The higher frequency signals (13–17 day period) observed in the Alas Strait during boreal summer were also observed in the Lombok and Ombai Straits (Iskandar et al., 2014). However, there is little energy in the currents at these periods in the equatorial Indian Ocean; thus, these higher-frequency signals, whose maximum velocity occurs at 20–30 m depth

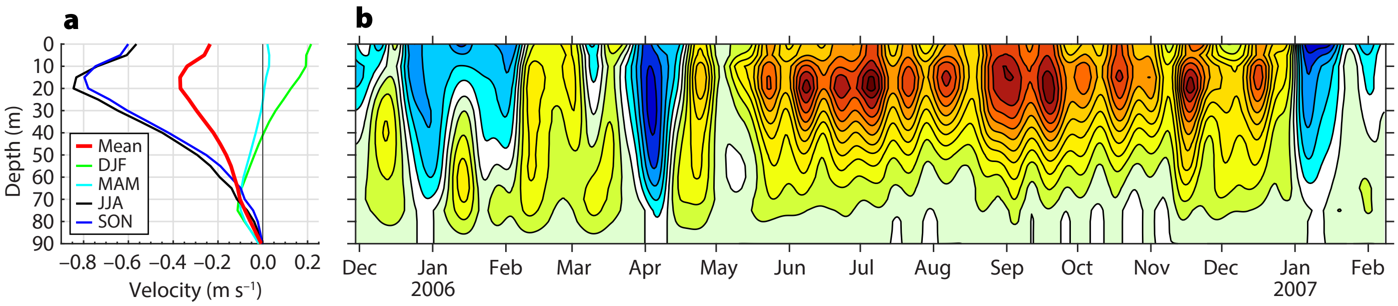

FIGURE 3. Current profiles observed in the Alas Strait. (a) Seasonal mean and variability of the velocity profile. (b) Velocity profile from November 29, 2005, to February 8, 2007. The negative value denotes southward velocity toward the Indian Ocean.

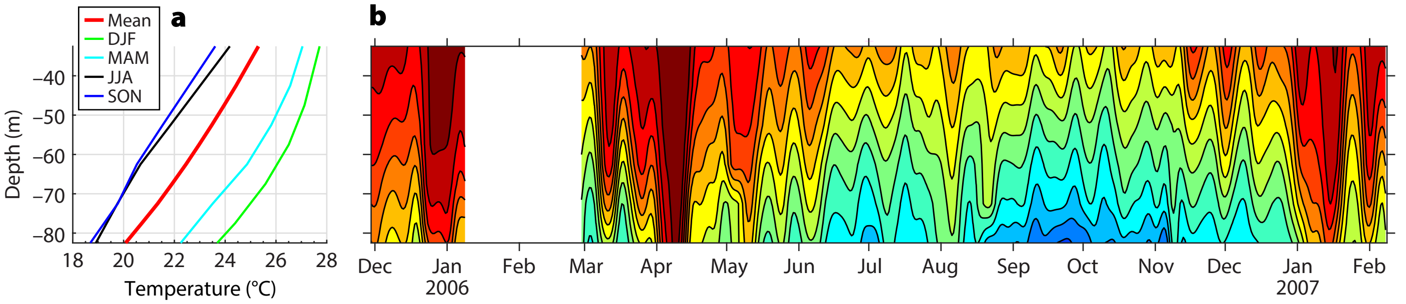

FIGURE 4. (a) Seasonal mean and variability of temperature profiles observed in the Alas Strait. (b) Temperature profile (°C) from November 29, 2005, to February 8, 2007.

(**Figure 3b**), are likely locally generated and possibly associated with nonlinear interactions between semidiurnal lunar and solar tidal constituents (S_2 and M_2) and (S_2 and N_2), which generate fortnightly (period of 14.7 days) and monthly tidal signals (period of 27.5 days; Ray and Susanto, 2016, 2019). Indeed, harmonic analysis of Benete tide gauge data (figure not shown) shows strong lunar and solar semidiurnal components, near fortnightly and fortnightly signals. In situ tidal mixing measurements using a microstructure profiler are needed to validate this finding.

THROUGHFLOW IN THE ALAS STRAIT

The Alas Strait throughflow was calculated with the procedures described in Sprintall et al. (2009) for the Lombok Strait, Gordon et al. (2019) and Susanto et al. (2005, 2012) for the Makassar Strait, and Susanto et al. (2016) for the Sunda Strait. In principle, to estimate the transport within any strait, the mooring point observations need to be extrapolated across the strait with a no-slip condition at the sidewalls. At each bin depth, along-strait velocity is assumed to be uniform across the strait, with zero flow in the last 1 km bin nearest to the sidewalls (i.e., Sprintall et al., 2009; Susanto et al., 2012). The choice of extrapolation schemes (i.e., linear or cubic spline) may generate uncertainty in estimating total integrated transport. Ideally, we should have repeat cross-sectional measurements of ocean currents to reduce uncertainty; however, for various reasons (high fishing activity, ferry traffic, and ship-time constraint), this ideal approach is not always possible.

Given that the Alas Strait is narrow and its along-strait velocity is much larger than its across-strait velocity, we used the only cross-strait velocity data available as a guide for extrapolating data from the mooring site to the sidewalls. Total volume transport is calculated by multiplying the along-strait velocity by the strait's cross-sectional area at each bin depth and then integrating to the full depth. **Figure 5** shows the variability of Alas Strait (red line) and Lombok Strait transport (blue line; the transport is based on the mean of the Lombok west and east moorings from Sprintall et al., 2009) and mean sea level observed at the Benete tide gauge station. The 2006 annual transport was −0.25 ± 0.24 Sv toward the Indian Ocean, varying from 0.4 Sv in early April 2006 to −0.75 Sv in August 2006. Stronger southward throughflow during the boreal summer compared to the boreal winter was evident and was manifested in the mean sea level recorded by the tide gauge. Higher sea level and clearer intraseasonal variability were observed during the northwest monsoon, and low sea level and less apparent intraseasonal variability during the southeast monsoon. Although the annual mean transport through the Alas Strait is low, the seasonal variations are large: ~30% of the Lombok Strait even in reversed direction. This means that the Alas Strait transport serves a double role in the total ITF transport into the Indian Ocean: it enhances the total ITF during the boreal summer and reduces the total ITF during the boreal winter.

Alas and Lombok transport also exhibit intraseasonal variability. At times they are in sync, as they were during the boreal winter from December 2005 to April 2006 (**Figure 5**). However, during the boreal summer, intraseasonal events evident in the August and October 2006 Lombok transport do not appear in the Alas data. Instead, the Alas transport displayed higher frequency signals (fortnightly and monthly) during that period, which may be associated with nonlinear interactions between lunar and solar semidiurnal signals (Ray and Susanto, 2016). On top of intraseasonal and seasonal variabilities in transport, there is also interannual modulation. The prolonged anomalously early winds in 2006 associated with El Niño and a positive Dipole Mode Index extend the southward flow until December 2006 (Horii et al., 2008). These interannual events may suppress the intraseasonal signals originating from the equatorial Indian Ocean.

In general, there is good in-phase correlation (r = +0.6 with confidence interval 99%) between the throughflow in both the Lombok and Alas Straits, especially from December 2005 to April 2006. The northward flow in April 2006 is likely related to a Kelvin wave event (Sprintall et al., 2009). However, during the boreal summer, when strong seasonal upwelling occurred along the southern coast of the Nusa Tenggara island chain, no northward transport was observed in the Alas Strait (August and October 2006) as it was in the Lombok Strait. These reversal flows are also likely related to Kelvin wave events. Occasionally, Kelvin waves occur at depth and have no significant surface signature (Sprintall et al., 2009).

Similar to the Lombok Strait, Alas

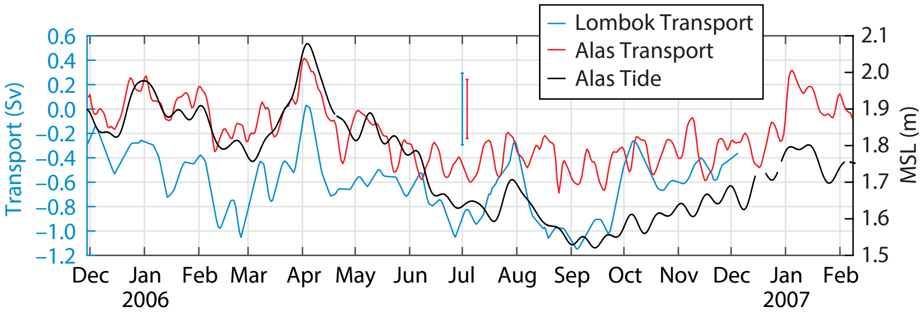

FIGURE 5. Throughflow transport in the Alas Strait (red line) from November 2005 to February 2007 compared to that of the Lombok Strait (blue line; average transport derived from west and east INSTANT moorings, Sprintall et al., 2009). Vertical lines (blue and red) are the standard deviations of Lombok and Alas total integrated transports, respectively. The correlation value between Alas and Lombok transport is 0.6, with a 99% confidence interval. The solid black line is sea level observed at the Benete station tide gauge.

Strait transport is surface intensified, with the maximum velocity occurring at ~25 m depth. Due to frequent fishing and shipping activities in the Alas Strait, placement of our temperature sensors is limited to 30 m below the surface. To estimate the heat transport of the Alas flows, we used CTD data routinely collected by PT AMNT (nearly every month from November 1999 to November 2007) from the eastern side of the Lombok Strait (near Benete Bay) to fill the top 30 m of the temperature profile. Based on the temperature profile's monthly climatology mean, a difference between the CTD and the mooring temperatures ranging from 0.5°C to 1.8°C causes error and uncertainty in calculating the heat flux. The heat flux is estimated based on the transport-weighted temperature or the throughflow's effective temperature. Thus, the vertical distribution of transport and temperature controls the heat flux carried by the ITF flow in the Alas Strait. The mean transport-weighted temperature of the Lombok Strait from 2004 to 2006 is 21.5°C (Sprintall et al., 2009). Because of its shallower sill compared to that of the Lombok Strait, the Alas Strait carries the warmer ITF (25.7 ± 1.8°C). While allowing for vertical stratification in each layer across the strait, the errors and uncertainty of transport-weighted temperature may increase due to the assumption that there is no horizontal gradient in temperature and current across the strait.

> “…the Alas Strait transport serves a double role in the total ITF transport into the Indian Ocean: it enhances the total ITF during the boreal summer and reduces the total ITF during the boreal winter.”

DISCUSSION AND CONCLUSIONS

Fluxes of heat and mass in the Indonesian Throughflow measured over the last three decades demonstrate that it plays a significant role in the global ocean thermohaline circulation. While the measurements have been concentrated in the main inflow passages (the Makassar Strait and the Lifamatola passage) and the outflow passages (the Lombok and Ombai Straits and the Timor passage), the outflow straits along the Nusa Tenggara island chain (i.e., the Alas and Sape Straits) have been neglected. Now, for the first time, we have direct measurements of velocity and temperature collected at the Alas Strait. Our measurements partially overlap those from the International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al., 2004, 2009), allowing us to compare velocity and temperature profiles, total volume integrated transport, and transport-weighted temperature. Our measurements reveal the complex ocean dynamics of this fascinating region, which depend on local and remote forcing and encompass many timescales.

There is a strong correlation between current velocity and throughflow in the Alas and Lombok Straits. Both are strongly affected by the regional Asia-Australia monsoon, and modulated by intraseasonal and interannual variability associated with Kelvin waves, ENSO, and IOD. Southward transport toward the Indian Ocean is more robust during the boreal summer (southeast monsoon from April to October) than during the boreal winter (northwest monsoon from October to April). The direct measurements coincided with the 2006 El Niño and a positive IOD, which prolonged the anomalously easterly winds until December 2006 and induced strong upwelling, cooler temperatures, and lower sea level at the southern coasts of the Nusa Tenggara island chain. Consequently, these two events generated stronger throughflow during the extended southeast monsoon.

There is interannual variability in the phase delay between the throughflow observed in the Makassar Strait and the Lombok and Alas Straits. During the 2006 El Niño and the positive IOD, the annual mean ITF transport in the Makassar Strait was lower than in a normal or La Niña year (Gordon et al., 1999, 2010, 2019; Ffield et al., 2000; Susanto et al., 2012; Sprintall et al., 2014). In contrast, the Alas and Lombok Straits (as well as the Ombai Strait and the Timor passage; Sprintall et al., 2009) exhibited higher transport during the El Niño year and the positive IOD. One plausible explanation for these observations relies on the strength of remote forcing associated with ENSO and the IOD and the divergence/convergence of the Banda Sea (Gordon and Susanto, 2001). More extended time series are needed to resolve the competing remote influences of ENSO and the IOD on the ITF transport variability during 2006. Longer time-series measurements should be collected within the straits along the Nusa Tenggara island chain, in addition to the Lombok and Ombai Straits and the Timor passage, to create a complete picture of the ITF and associated heat and freshwater fluxes into the Indian Ocean.

The intraseasonal to semiannual signals that are associated with coastally trapped Kelvin waves generated in the equatorial Indian Ocean and that propagate along the southern coasts of Sumatra-Java-Nusa Tenggara require further investigation. Direct mooring observations indicate the existence of Kelvin waves in the Sunda Strait (Susanto et al., 2013; Li et al., 2018; Xu et al., 2018), the Lombok and Makassar Straits (Sprintall et al., 2000; Susanto and Gordon, 2005; Drushka et al., 2010; Susanto et al., 2012), and the Ombai Strait and the Timor passage (Sprintall et al., 2009). The northward reversal of flow/transport in the Lombok and Alas Straits in April 2006 is likely related to the Kelvin wave event. Similarly, the current reversal from southward to northward in August and October 2006 in the Lombok Strait may be associated with Kelvin wave events. However, these events were not observed in the Alas Strait. Therefore, in addition to a strait's geometry (width and depth), the dynamics and characteristics of the Kelvin waves control whether they can enter shallow straits such as Sunda and Alas. Northward reversal flows during the intrusion of Kelvin waves reduce the ITF into the Indian Ocean and at the same time carry Indian Ocean water into the internal Indonesian seas. Further studies are needed to understand the dynamics of these Kelvin waves and are essential to more accurately estimating the ITF.

In addition, given that the Alas Strait is located next to the Lombok Strait and that they show some amplitude and phase variabilities in velocity, future simultaneous field measurements of the ITF should include all exit passages into the Indian Ocean (the Sunda, Bali, Lombok, Alas, Sape, and Ombai Straits, and the Timor passage) to avoid redundancy in estimating ITF and associated heat and freshwater fluxes into the Indian Ocean. For example, waters from the Indian Ocean entering the internal Indonesian seas during boreal winter (i.e., via the Sunda, Lombok, and Alas Straits) and re-exiting into the Ombai Strait and the Timor passage have been counted as ITF. Detailed numerical modeling studies are needed to resolve the total ITF. The inflow transport from the Indian Ocean to internal Indonesian seas likely contributes to the imbalance between the inflow and the outflow of the ITF (Gordon et al., 2010).

Knowledge of the dynamics and circulation in the Alas Strait not only contributes to understanding the total ITF and associated heat flux into the Indian Ocean, which is important for global ocean circulation and climate and input for general circulation models, it is also of interest to Batu Hijau mining company management in placing the submarine tailing system. The current patterns south of Lombok and Sumbawa islands are of interest to the mining company because they influence the distribution of the water column tailing plume. Although the bulk of the tailings flow down the submarine canyon as a gravity flow before they finally settle at the base of the Lombok Basin, a small fraction of fine suspended material associated with the tailings will be transported with currents before settling on the seafloor. The persistent southward flows of lower layer ocean currents in the Alas Strait support the company's decision to dispose of tailings in the ocean via a 3.2 km submarine pipeline whose exit is located at a depth of 125 m at the head of the very steep Senunu Canyon. From here, the tailings are expected to flow down the canyon's axis to their final deposition location in the Lombok Basin at depths greater than 3,000 m. The results of our research in the Alas Strait serve as an example of how collecting and analyzing oceanographic data are essential to the management of environmental issues facing mining companies located near coasts.

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AUTHORS

R. Dwi Susanto (dwisusa@umd.edu) is Senior Research Scientist, Department Atmospheric and Oceanic Science, University of Maryland, College Park, MD, USA. **Jorina M. Waworuntu** is Environmental Manager, **Windy Prayogo** is General Supervisor of Environmental Monitoring, and **Agus Setianto** is Senior Specialist Environmental Monitoring, all at PT Amman Mineral Nusa Tenggara, Mataram, Indonesia.

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THE RISE OF DYNAMICAL OCEANOGRAPHY

A Fragmentary Historical Note: The Stommel-Munk Correspondence, 1947–1953

By Carl Wunsch

Two of the dominating figures of twentieth century physical oceanography/geophysics were Henry (Hank) Stommel and Walter Munk, whose early correspondence is discussed here. Stommel worked on the East Coast at the Woods Hole Oceanographic Institution (WHOI), the Massachusetts Institute of Technology, and Harvard University from 1944 to 1992, when he died at age 71. Munk's career was based on the West Coast at Scripps Institution of Oceanography (SIO), University of California San Diego, from 1941 until his death at age 101 in 2019. Both were well recognized during their lifetimes, and a number of descriptions of their lives and works are listed in a bibliography at the end of this note. An intended centenary observation for Stommel was planned for September 2020 but was postponed because of the pandemic. Anyone fortunate enough to have known these two oceanographers would have recognized the remarkable differences in their personalities and lives.

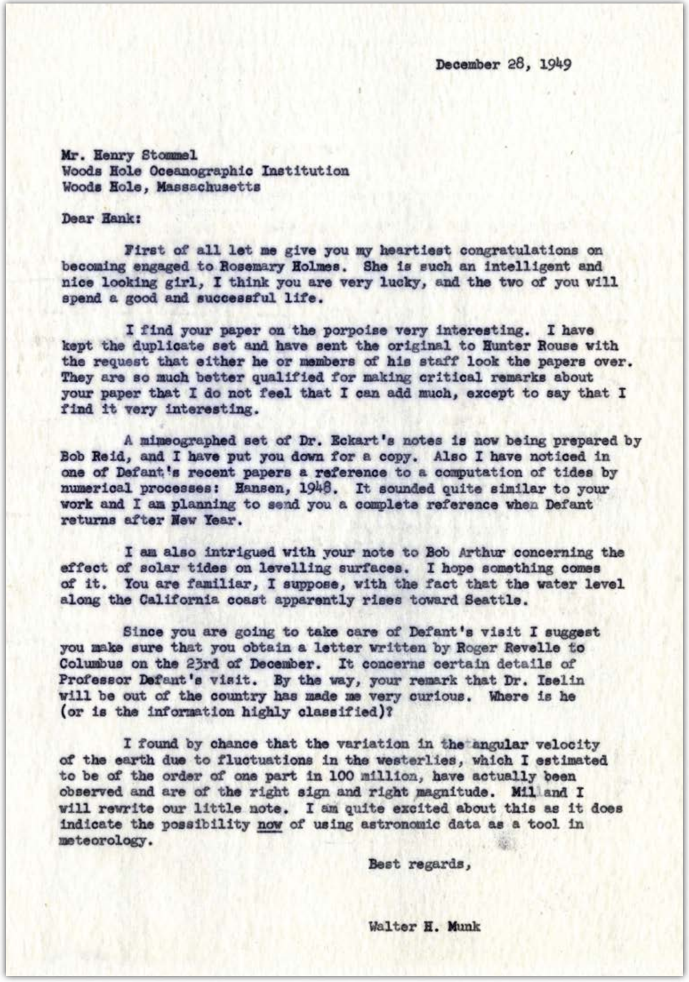
In the process of attempting to document the scientific achievements of these men, an exchange of letters between them in the period onward from 1947 came to light in the UC San Diego (UCSD) Library's Special Collections & Archives (see Acknowledgments). Reading through the available correspondence (with inevitable evidence of gaps), one is struck by the great cordiality, collegiality, and clear evidence of their enjoyment of each other's company; their mutual interests in dynamical oceanography and its biological implications; and the great diversity of scientific problems in which they had a joint interest.

THE PHYSICAL CORRESPONDENCE

The correspondence material available to me consists only of that produced through the good auspices of Laurel McPhee of the UCSD library, as well as the online published material of Walter Munk and Henry Stommel. That correspondence consists of scanned copies of their letters that were available in the Munk Archive. As such, the Munk end of the correspondence is carbon copies of what were clearly secretary-typed letters (Figure 1). The Stommel end is largely, but not completely, handwritten letters for which the existence of a copy anywhere is doubtful. Later in the correspondence, some of Stommel's letters are a mixture of his own typing and those of a professional. A few letters to and from Roger Revelle, Scripps Director from 1950 to 1964, presumably copied to Munk, are included as well.

At the beginning of the period, Walter Munk was 29 years old, and Henry Stommel was 26—two young scientists starting out. Their letters are a glimpse into ways of doing science that are now almost as remote from the modern form as are those of the 1870s HMS *Challenger* Expedition. Readers will note some interesting quirks, often related to the mores of the time. Harald Sverdrup is always "Dr. Sverdrup" in Munk's letters. Stommel, as was his wont, sometimes used home-printed letterheads and addresses that ranged from the fanciful Central Bureau, The Hydrosphere, and The Observatory, Bermuda Biological Station.

As this note was written during the coronavirus apocalypse shutdown by a non-historian, professional science historians will



December 28, 1949

Mr. Henry Stommel
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Dear Hank:

First of all let me give you my heartiest congratulations on becoming engaged to Rosemary Holmes. She is such an intelligent and nice looking girl, I think you are very lucky, and the two of you will spend a good and successful life.

I find your paper on the porpoise very interesting. I have kept the duplicate set and have sent the original to Hunter Rouse with the request that either he or members of his staff look the papers over. They are so much better qualified for making critical remarks about your paper that I do not feel that I can add much, except to say that I find it very interesting.

A mimeographed set of Dr. Eckart's notes is now being prepared by Bob Reid, and I have put you down for a copy. Also I have noticed in one of Defant's recent papers a reference to a computation of tides by numerical processes: Hansen, 1948. It sounded quite similar to your work and I am planning to send you a complete reference when Defant returns after New Year.

I am also intrigued with your note to Bob Arthur concerning the effect of solar tides on levelling surfaces. I hope something comes of it. You are familiar, I suppose, with the fact that the water level along the California coast apparently rises toward Seattle.

Since you are going to take care of Defant's visit I suggest you make sure that you obtain a letter written by Roger Revelle to Columbus on the 23rd of December. It concerns certain details of Professor Defant's visit. By the way, your remark that Dr. Iselin will be out of the country has made me very curious. Where is he (or is the information highly classified)?

I found by chance that the variation in the angular velocity of the earth due to fluctuations in the westerlies, which I estimated to be of the order of one part in 100 million, have actually been observed and are of the right sign and right magnitude. Mil and I will rewrite our little note. I am quite excited about this as it does indicate the possibility now of using astronomic data as a tool in meteorology.

Best regards,

Walter H. Munk

FIGURE 1. A not untypical letter from Walter Munk to Henry Stommel covering a great variety of topics.

recognize its incompleteness. Allusions exist to missing letters and manuscripts. Munk in particular had a well-known habit of intermittently clearing his office by simply throwing everything away. Production of a full discussion of this period would involve personal visits to archives of SIO and WHOI, and to surviving family members, which I have not been able to undertake.

At a time when much of the science was in a more primitive state, individuals could readily range over a wide variety of problems—without mastering an overwhelming literature. What seems clear is that Munk and Stommel found in each other kindred scientific interests at a time (with the hindsight of 70 years) when few people would have shared their interests in ocean observations as describable by mathematical means. One Stommel note (December 17, 1952) states "There are few people here at Woods Hole at the moment with whom I can discuss this…".[1] The range of scientific subjects they shared is remarkable, particularly given that they later came to be identified with somewhat distinct interests.

The numerous subjects on which they exchanged sometimes detailed manuscripts and long letters included tides and tidal dissipation, surface gravity waves, the problem of inferring sea surface temperatures from infrared radiation, the construction and use of surface drifting buoys, the swimming physics of porpoises/dolphins, electromagnetism and the GEK (geomagnetic electromagnetic kinetograph—a velocity measuring device for use on a ship), wavelengths of instabilities in the Gulf Stream, and, notably, ocean dissipation and mixing. In one letter (December 7, 1951), Munk refers in a single sentence to both ongoing studies of Earth wobble from winds and to nutrient absorption in diatoms. I have heard colleagues speculate that Munk and Stommel were rivals. The correspondence in this interval shows the opposite—it includes a wish to see more of each other, arrangements for Stommel to spend extended periods at SIO and for Munk to visit WHOI, and detailed comments on each other's papers and calculations.

Mixed in with the scientific exchanges are personal allusions, comments from both about the dire state of post-WW II English food availability, questions about whether the US Office of Naval Research would support a trip for Munk to Scandinavia, a discussion of whether a potential graduate student would be better off at SIO or working with Raymond Montgomery at Brown University, and bits of fiancée/marital problems and the arrival of children.

THE SCIENCE OF THE CORRESPONDENCE: SSM PAPERS

The period from about 1947 to 1950 was marked by the publication of three notable papers: Sverdrup (1947), Stommel (1948), and Munk (1950); I will call these the SSM papers. It is not an exaggeration to claim that these three papers marked the beginnings of modern dynamical oceanography and of the wider field of geophysical fluid dynamics. Many of us who have taught courses in physical oceanography will have treated them as a series of intellectually connected, but independent, contributions.

The SSM papers surely instigated the field of geophysical fluid dynamics (GFD)—the GFD summer program was initiated at WHOI in 1959 and continues there today. To an applied mathematician, or sophisticated dynamical meteorologist, the ocean appeared to be a far simpler, more accessible, interesting system than did the atmosphere. We now know that the ocean appeared much simpler than the atmosphere mainly as a consequence of the lack of observations! A theory of large-scale, wind-driven gyres made sense because the only real data were the temporally stable, large-scale temperature and salinity measurements collected from ships, and they could be interpreted quantitatively using some appealingly simple, albeit undemonstrated, theoretical ideas. Had the extremely time-dependent, turbulent velocity field that varies substantially hour to hour been measured in the earliest exploration days of the nineteenth century, theory likely would have taken a completely different course. The complexity of the modern ideas about the circulation probably would have inhibited many of the theoreticians—who were often retreating from the complexities of known meteorology—from attempting what became beautiful theories of a steady-flowing ocean.

Looking back with full hindsight, it is notable that between Ekman's (1905) theory of the surface boundary layer and the appearance of the SSM papers, ocean dynamics was a sporadic endeavor not leading to any sort of synthesis. Stommel (1948), remarkably, contains no references at all and so does not mention Sverdrup's paper. The Sverdrup and Munk papers provide references to the work of Ekman, Fjeldstad, Goldsbrough, and Hidaka. Munk's paper attributes his study to three earlier efforts: (1) Rossby's (1936) discussion of the importance of lateral dissipation, (2) Sverdrup (1947), and (3) Stommel (1948). Stommel's paper is an outstanding example of the importance of asking the right question (a Munk maxim) relative to getting the right answer. Mathematically, any of the people already mentioned could have solved Stommel's equation had they formulated it.[2]

In his 1983 Crafoord Prize lecture (reprinted in Hogg and Huang, 1995), Stommel says that because Sverdrup's paper had been published in the "somewhat obscure" *Proceedings of the National Academy of Sciences*, he was unaware of it when he wrote his own paper. The submission date of his 1948 paper in the American Geophysical Union (AGU) *Transactions* is September 25, 1947—for a paper presented at a September 18, 1947, meeting of the AGU in Woods Hole. A note from Walter to Hank dated September 9, 1947, describing Sverdrup's work apparently came too late for Stommel. In the days before photo-

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[1] Willem Malkus, a recent arrival in Woods Hole, was the first of a number of people who were comfortable with the mathematics of fluid dynamics, and who remained there through the 1950s.

[2] Mills (2009) is a general account of dynamics to this period.

copiers, sharing of scientific publications depended upon mailed carbon copies or offprints.[3] Munk did later write Stommel telling him that he was a reviewer of the paper, and that he was recommending it most highly. Whether Stommel considered a note added-in-proof is not known. It fell to Munk (1950) to publish the connections.[4]

What follows in the letters are complimentary comments in both directions—Munk emphasizing the originality of what Stommel had done and admiring the character of the way he describes the science, and with Stommel embracing Munk's emphasis on the importance of understanding the eddy viscosity coefficients that the latter had made the center of his own theory. As an example of the "character" of Stommel's (1948) discussion, he was provoked to repeat an alleged remark from Carl Eckart that it was "science done in the manner of Rossby" (Hogg and Huang, 1995), which he despised. Stommel, on a number of occasions (e.g., 1984) claimed that Eckart's own work had come to almost nothing because he confused "rigor with vigor."

A COLLABORATIVE BOOK?

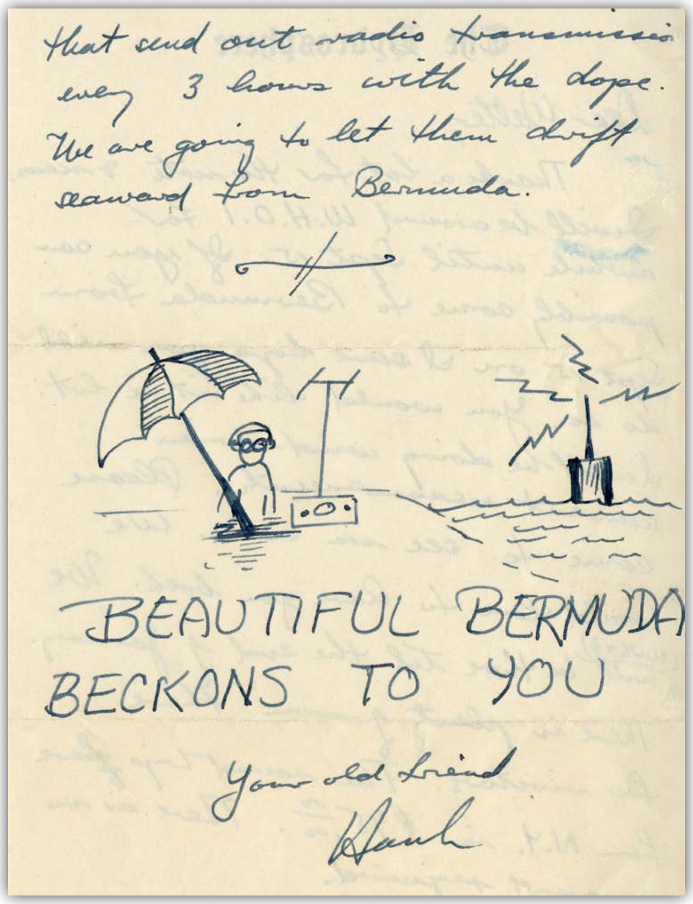
As part of the discussion of oceanic turbulence and eddy viscosities and thermal and salinity circulations (problems continuing in full force today!), at least three letters (November 18, 1949; November 23, 1949; February 9, 1950) refer to a book to be jointly written and published by the "University Press," presumably California. Mysteriously, reference to such a book vanishes after that. By 1955, Stommel had completed the first edition of *The Gulf Stream: A Physical and Dynamical Description*, which was published in 1958 by the University of California Press. Exactly what led to the failure to produce a joint book is not clear from the available material. Munk did have a strong, specific, growing interest in Earth rotation that led to his own book with Gordon MacDonald (Munk and MacDonald, 1960) and which may have played a role. (In their letters, Munk and Stommel had discussed some of the Earth rotation problems that interested them both.)

OTHER SCIENCE

A large number of diverse topics is touched upon in the correspondence. One notable letter from Stommel to Munk (November 8, 1950) is a description of the efforts of William von Arx of WHOI to make a rotating-table laboratory model of the ocean circulation. Stommel describes the basic idea and then asks for advice from Munk as to how to make it more realistic. The use of the bottom slope as a prototypical beta effect[5] is delineated. He then goes on to ask about how to minimize the bottom friction so that the lateral friction would dominate the gyre circulation. If there was a reply from Munk, I have not seen it.

Another subject that did lead to some back and forth was the problem of the physics of swimming in dolphins/porpoises. Stommel (December 15, 1949) lists the published competing and contradictory hypotheses and sends his own analysis. The correspondence ends with a letter from the director of the Stevens Institute Laboratory in New Jersey analyzing the various ideas. The well-known fluid-dynamicist Hunter Rouse (University of Iowa Institute of Hydraulic Research) was brought into the debate by Munk, but Stommel concludes that he had missed the point.

Stommel became interested in using Bermuda as an observatory for obtaining proper time series. In the correspondence, he describes his expectations for tracked surface buoy measurements along with repeated hopes that Munk will visit (see Figure 2). Whether Walter ever did visit is not known to me, but the single existing joint Munk/Stommel paper is Haurwitz, Stommel, Munk (1959), which relies heavily on Munk's practical knowledge of time-series analysis. (Hank once explained to me that Bernhard Haurwitz was the lead author because he and



that send out radio transmissio
every 3 hours with the dope.
We are going to let them drift
seaward from Bermuda.

BEAUTIFUL BERMUDA
BECKONS TO YOU

Your old friend
Hank

FIGURE 2. Part of a letter (not dated, but sometime in 1953) from Stommel to Munk inviting him to visit the Bermuda Observatory. A typical Stommel sketch.

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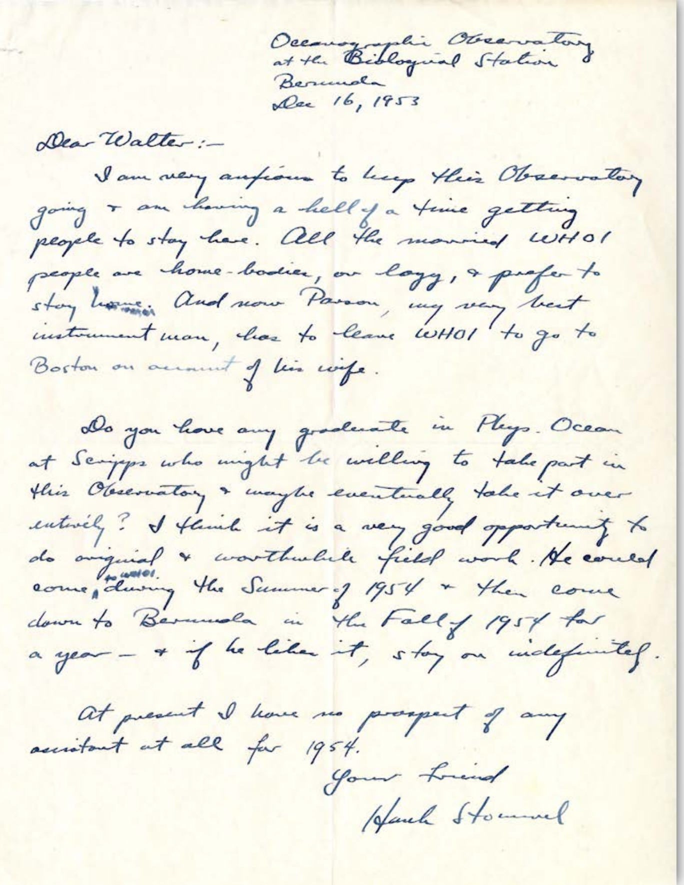
[3] Some of the correspondence suggests that in this era it was taking only two days for letters to get to or from SIO and WHOI.

[4] Munk's struggles with non-meridional boundaries led him into contact with the mathematician George Carrier (then at Brown University), and their collaboration instigated the, for a while, enthusiastic application of singular perturbation methods to almost everything in physical oceanography.

[5] The beta effect is a phenomenon arising from the variation with latitude of the influence on the ocean of Earth's rotation.



Oceanographic Observatory
at the Biological Station
Bermuda
Dec 16, 1953

Dear Walter:–

I am very anxious to keep this Observatory going & am having a hell of a time getting people to stay here. All the married WHOI people are home-bodies, or lazy, & prefer to stay home. And now Parson, my very best instrument man, has to leave WHOI to go to Boston on account of his wife.

Do you have any graduate in Phys. Ocean at Scripps who might be willing to take part in this Observatory & maybe eventually take it over entirely? I think it is a very good opportunity to do original & worthwhile field work. He could come to WHOI during the Summer of 1954 & then come down to Bermuda in the Fall of 1954 for a year – & if he likes it, stay on indefinitely.

At present I have no prospect of any assistant at all for 1954.

Your friend
Hank Stommel

FIGURE 3. Letter from Stommel asking for help in finding an assistant to remain in Bermuda. Some negative comments are made about his married colleagues in Woods Hole.

Walter were under the mistaken impression that Haurwitz was terminally ill [Stommel, *pers. comm.*, circa 1970].) The paper is an analysis from the bottom cable temperature measurements at Bermuda, an addition to the observatory made by Stommel after he recognized the uninterpretable behavior of his tracked surface buoys. A later letter (Figure 3) is a slightly acerbic request from Stommel to Munk for help in finding someone to man the station in Bermuda. Later (after 1953), Stommel, who never did find a proper assistant, became disillusioned with the intellectual isolation he felt on the island.

PERSONAL LIFE

Munk and Stommel exchanged a number of comments about their personal lives, marriages, etc.—much of which will be of primary interest to their families. One correspondence is perhaps of wider interest. Stommel did not have a PhD, and that sometimes made him uncomfortable with his Harvard (particularly) and MIT colleagues.[6] He told people that he had applied to graduate school at Scripps, but that Harald Sverdrup had refused him because he had published the popular book *Science of the Seven Seas* (Stommel, 1945; see Figure 4). I subsequently asked Walter if he knew anything about that and his reply was, "Of course not. Sverdrup said that this man did not need a PhD!" But the correspondence shows that neither account is true.

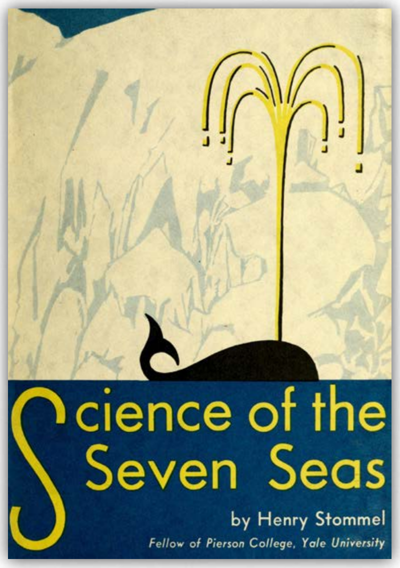


FIGURE 4. Cover jacket of Stommel's popular book, published in 1945, that he claimed led Sverdrup to reject him as a Scripps Institution of Oceanography graduate student. The back cover features an interesting autobiography of the young Stommel, written while he was still at Yale University, that can be found in the special *Oceanus* (1992) issue.

Hank had visited SIO sometime in 1949. He then writes Roger Revelle (November 28, 1949) asking if he can come back as a (visiting) assistant professor. Revelle's reply is ambiguous—saying that he doesn't have a budget that would cover such a position, and that if it can be worked out, the university would probably require that he would have to stay four to five months. Stommel responds that he could manage that duration. But the next available letter is quite different: he writes Munk announcing that he is applying to graduate school at SIO and could Walter help him find housing? Walter's reply is positive, but says, "I agree with Roger that it would be appropriate to give you a degree sight unseen." But then later, Hank writes that he is withdrawing his application because his then fiancée had "dumped" him and that it was only her urging that had led him to apply in the first place.

SOME FINAL COMMENTS

Communication goes on until Stommel's death in 1992, and much more can be said about their science and their interactions. They both published interesting professional papers to the very ends of their lives. The 1953 cutoff in this present note is an arbitrary one dictated by mere practicality. I will not attempt any synthesis except to say that as both became well-established figures with groups of colleagues and students, had families, and the Munks lost a child, their lives became far more complicated in various ways—and they were separated by a continent. Visits to each other did continue at long intervals, evidently made somewhat tense by spousal cultural disparities. Their highly divergent personalities might have ultimately led to a diminution of the earlier cordiality; however, Stommel (1984) provided an illuminating tribute on the occasion of Walter Munk's 65th birthday,

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[6] MIT had many faculty members, principally engineers, who did not have doctoral degrees.

Munk wrote a ringing endorsement letter supporting the offer of a Harvard professorship for Stommel in 1960, and Munk contributed to the special issue of *Oceanus* devoted to Stommel (Munk, 1992), saying "…I do not consider myself as one of his closest friends. But I admire him tremendously. There was something magical about his person…" Exploration of the Stommel Archives in Woods Hole and those at Harvard and MIT for the later period of correspondence would likely be rewarding.

For More Insights

Readers are cautioned that memories are fluky, including mine, and as seen in some instances here, they are sometimes contradictory and highly divergent from the contemporaneous documentation. Walter's wife, Judith, enjoyed telling listeners that "Walter never let the facts get in the way of a good story!" Stommel's autobiographical memoir (Hogg and Huang, 1995) is notable both for what it omits altogether and for some of the acidic comments about individuals and institutions that he almost never made publicly during his lifetime.

The public link to the online correspondence is https://library.ucsd.edu/dc/search?f%5Bcollection_sim%5D%5B%5D=Walter+Munk+Papers%3A+Selections&q=stommel&sort=object_create_dtsi+asc%2C+title_ssi+asc. Note that it extends far beyond the present discussion, which ends with 1953.

A more conventional outline of Stommel's scientific life can be found in Wunsch (1997). Similarly, Wunsch (2019) and Garrett and Wunsch (2020) describe Munk. The autobiographical parts of the *Collected Works of Henry M. Stommel* (Hogg and Huang, 1995), the Munk (1984) autobiography, and the Munk interview in von Storch and Hasselmann (2010) are helpful. A popular account of Stommel's life and times appears in Chapter 6 of Dry (2019). The collected commentaries of colleagues in *Oceanus* (1992) for Stommel and in Garrett and Wunsch (1984) for Munk give some feeling for the wider lives of both men. A video interview with Munk at age 101 conducted by Joe Pedlosky in anticipation of the Stommel centenary is an informal recollection and can be accessed online at https://stommel100.whoi.edu/background/.

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AUTHOR

Carl Wunsch (carl.wunsch@gmail.com) is Professor Emeritus of Physical Oceanography, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, and Visiting Professor of Physical Oceanography and Climate, Harvard University, Cambridge, MA, USA.

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Whirlpool in Western Passage at the entrance to Passamaquoddy Bay, with Deer Island in the background.

Interdisciplinary Research Collaborative Trains Students to See Through Turbulent Systems

By Kristina Cammen, Gabriella Marafino, Sarah Burton, Jillian Dow, Emma Dullaert, Madalyn Jorge, Kate Macolini, Louise McGarry, Christopher Tremblay, Jessica Jansujwicz, Tora Johnson, Lauren Ross, and Gayle Zydlewski

ABSTRACT. Despite the availability of interdisciplinary academic training programs, the practice of environmental science is often hampered by a lack of convergence across diverse disciplines. This gap is particularly salient in settings characterized by complex environmental issues, such as multiple-use coastal ecosystems. In response, we developed and implemented a training, research, and communication framework to provide undergraduates with an authentic operative experience working at the interface of interdisciplinary science and public decision-making within a case study of marine renewable energy. In our program, students gained hands-on experience with the scientific process and learned how to make information relevant, useful, and accessible to diverse stakeholder groups. Application of this framework demonstrates that the process of integrating data from biological (visual and acoustic monitoring of fish and marine mammals), physical (hydrodynamics), and social (local ecological knowledge) sciences can provide a more complete understanding of complex and turbulent ecosystems for better informed decision-making. We offer several recommendations to facilitate the adaptation and implementation of our interdisciplinary framework to diverse research contexts, with a focus on interdisciplinary training for the next generation of marine scientists.

INTRODUCTION

Environmental science is inherently an interdisciplinary field, with academic training programs that include coursework in the physical, biological, and social sciences. Yet, the practice of environmental science is often hampered by a lack of convergence among these diverse disciplines. This gap exists despite significant efforts to design training programs in environmental and sustainability sciences that aim to prepare students to "craft usable knowledge" through interdisciplinary collaborations and stakeholder partnerships (S.G. Roy et al., 2019). Improvements to curriculum-based training programs alone may not be sufficient to produce environmental practitioners that are fluent in interdisciplinary research and communication. These limitations are particularly salient in settings that are characterized by complex and dynamic environmental and societal issues, such as coastal oceans.

Here, we describe the development and implementation of a training, research, and communication framework to provide undergraduates with an authentic experience working at the interface of interdisciplinary science and public decision-making within the context of marine renewable energy. Students are increasingly interested in professional paths that offer active engagement in solving sustainability problems. Recognition of the benefits of using a sustainability science problem, such as marine renewable energy, as a focal point for student training is emerging (Hart et al., 2016). By bringing together faculty and students from different disciplines to actively engage in solving a complex sustainability science problem, we aim to "re-envision the role of students" and build future capacity (Hart et al., 2016).

We established the Western Passage Student Research Collaborative (WPSRC) in the spring of 2019 to engage undergraduates in a one-year training program focused on research relevant to an area of growing interest and contention: the development of marine renewable energy in coastal areas and the associated need for environmental impact monitoring. Traditional environmental monitoring programs often fall short in settings where environmental impacts are likely to be highly complex and distributed across diverse components of an ecosystem (Thomas, 1993; Maurer et al., 1999). Effects of renewable energy development in coastal systems can include, for example, changes to the physical structure of an environment, altered biology, and cascading effects on associated natural resource-dependent human communities (Dadswell et al., 1986; Cullen-Unsworth et al., 2013; McDowell and Ford, 2014). Policy development and decision-making in these systems are further complicated by multiple, competing marine resource uses and uncertainty surrounding cumulative impacts (Lester et al., 2010; Fox et al., 2017).

Although several frameworks for holistic monitoring and management of coastal ecosystems have been proposed (Levin et al., 2009; Christie, 2011; Alexander et al., 2019), their implementation is stymied by barriers to integration across different disciplines and different types of knowledge (Cash, 2006). In particular, synthesizing knowledge into a form that is practical for managers to use in making day-to-day decisions continues to be a significant challenge (Clark et al., 2016). Efforts to strengthen research collaborations that transcend disciplinary approaches and include input from various communities of knowledge, including all relevant disciplines and stakeholder groups, has gained considerable momentum (e.g., Lang et al., 2012). However, while these previous experiences offer guidance on what should be considered when designing and conducting integrative collaborative research (e.g., Jansujwicz and Johnson, 2015), student training opportunities are not explicitly considered. A lack of such opportunities to provide upcoming marine scientists with practice in interdisciplinary thinking outside of the more traditionally disciplinary-distinct classroom setting hampers efforts to translate knowledge into action.

In this paper, we first outline our training, research, and communication framework and describe the case study that motivated the development of the WPSRC. We then share how undergraduates were engaged in an integrated approach to data collection, analysis, and communication, and discuss the challenges we faced along the way. We conclude by offering several recommendations to facilitate the adaptation and implementation of our interdisciplinary, student-focused framework to diverse research contexts.

AN INTERDISCIPLINARY TRAINING, RESEARCH, AND COMMUNICATION FRAMEWORK

The University of Maine is one of many institutions nationwide that promote interdisciplinary research to train undergraduates in innovative and integrative ways of thinking (Davis et al., 2015; S.G. Roy et al., 2019). Multidisciplinary and team-based approaches to undergraduate research have been shown to promote students' academic engagement (Koch et al., 2017) and their acquisition of skills important for employability following graduation (Juhl et al., 1997; Doerschuk et al., 2016). We approached these goals through a training, research, and communication framework that engaged students, alongside research mentors and diverse stakeholders (e.g., industry and community members, policy- and decision-makers), with the integration of physical, biological, and social science data relevant to a current environmental and societal issue (Figure 1). The key tenets of our framework include (1) a training program that emphasizes experiential, bidirectional learning across diverse epistemologies, (2) an interdisciplinary research program that is intentionally open to iteratively reconsidering objectives and methodologies to ensure their continued relevance, and (3) a communication plan that emphasizes reflexive communication among researchers and stakeholders.

TRAINING. The research collaborative intentionally included people from different disciplines (e.g., physical, biological, and social sciences), different career stages (e.g., undergraduate to early career and tenured faculty), and different career tracks (e.g., academic and non-academic), who each brought their own way of knowing or seeing the world (i.e., unique epistemologies). The WPSRC included five undergraduates who were co-mentored by individuals from different disciplines, including one graduate student, five faculty, two research associates, and one marine extension associate. WPSRC members represented the diverse fields of marine biology, coastal engineering, human dimensions of natural resources, and geospatial sciences. Explicitly acknowledging the value of this diversity encouraged bidirectional learning, with students learning from faculty and vice versa. As part of our one-year interdisciplinary research collaborative, students gained hands-on experience that puts the training they receive in the classroom into practice. Students engaged with the scientific process from start to finish, including planning and executing fieldwork and data analyses as well as presenting research findings in written and oral formats. Through turning data into stories and stories into data, students gained insight into how to make information relevant, useful, and accessible.

RESEARCH. Drawing upon discrete disciplinary areas of expertise, our initial approaches to the research were based within the methods and practices of singular disciplines. However, the process of troubleshooting challenges in data collection and interpretation required that we remain open to revisiting objectives and methodological approaches, and to bringing in new disciplinary experts as questions arose that required additional insights. In fact, the WPSRC was itself an outcome of such an iterative process, being identified as a need when traditional monitoring approaches fell short, as described further below.

COMMUNICATION. Our stakeholder-engaged approach to data collection and sharing emphasizes the need for proactive and transparent communication throughout the interdisciplinary research process. We committed to frequent meetings in person or via remote conferencing to provide space and time for formal and informal discussions and learning. Interdisciplinary discussions at full research collaborative meetings were fodder for "aha" moments that are harder to come by in isolation. Communication with stakeholders was key to ensuring research questions were informed by stakeholder needs and research products were presented in a usable and useful form that encouraged the uptake of information.

As a result of the persistent and engaged commitment of all team members to the tenets of our training, research, and communication framework, the WPSRC successfully integrated diverse data sources to contribute to a more complete under-

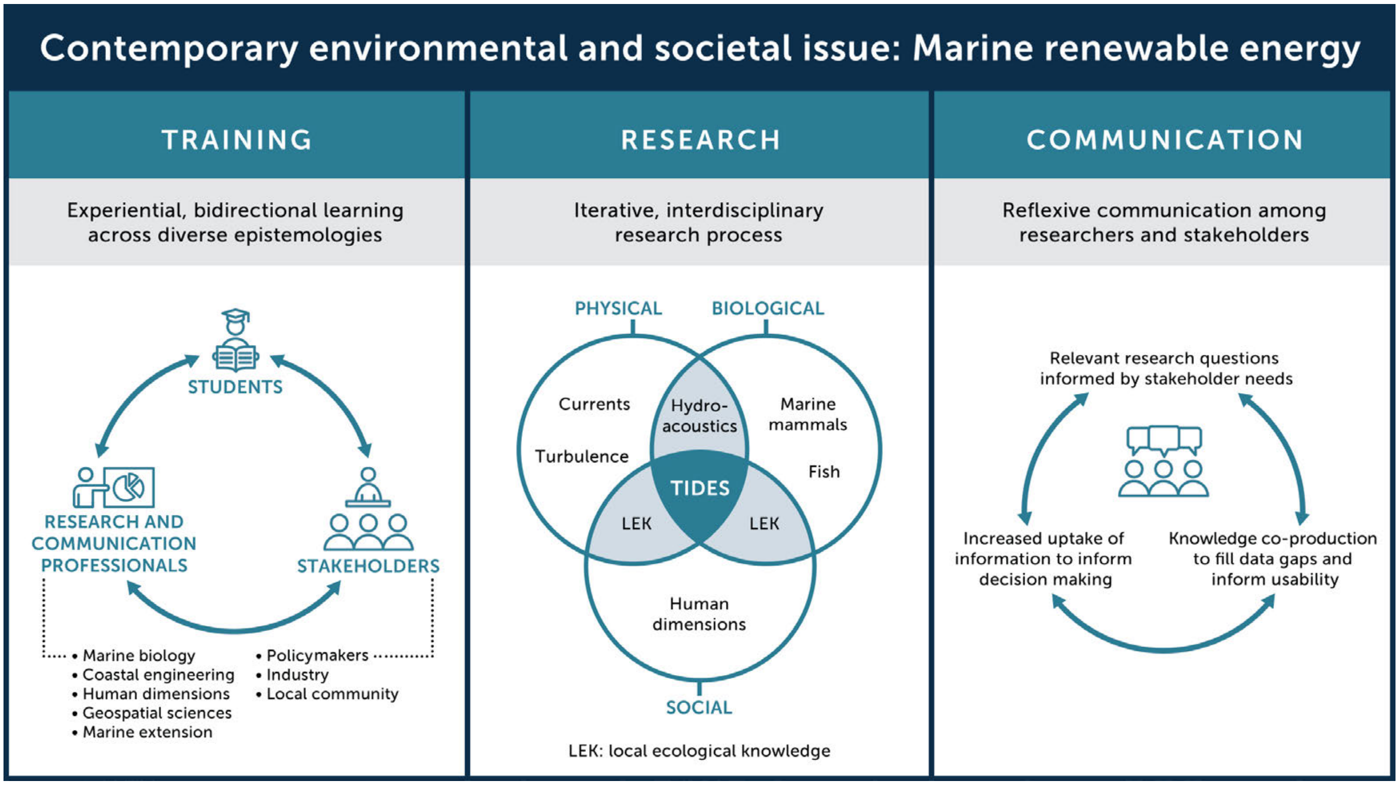


FIGURE 1. This training, research, and communication framework is designed to provide undergraduates with an authentic experience working at the interface of interdisciplinary science and public decision-making within the context of marine renewable energy.

standing of a complex, turbulent coastal ecosystem. By adopting a stakeholder-engaged approach, we ensured that our research questions and outputs are relevant, useful, and accessible to better support informed decision-making around coastal development, using marine renewable development as an exemplary case. Students participating in this interdisciplinary work built a transferable skill set that will be broadly applicable and desirable as they progress along their chosen career paths.

A CASE STUDY OF MARINE RENEWABLE ENERGY

Western Passage is located between Maine and New Brunswick, Canada, near the gateway to one of North America's preeminent tidal energy (hydrokinetic) resources in the Bay of Fundy (Figure 2). This region has been the focus of proposed renewable energy since the 1940s, with renewed interest over the past decade. Western Passage ranks as one of the top five most promising hydrokinetic energy sites in the United States (Kilcher et al., 2016), but it is also a unique and valuable natural environment. It includes iconic physical (largest tidal whirlpool in the Western Hemisphere), biological (habitat for endangered marine mammals), and social (traditional and commercial fishing grounds, ecotourism attractions) features that require careful consideration in coastal development. The combination of these factors creates a broadly defined "turbulent system," with both physical and social contributions to turbulence.

The confluence of tides combined with complicated seafloor topography creates a complex hydrodynamic environment dominated by strong current velocities and physical turbulence, as well as iconic eddies and whirlpools (Figure 2). Water moving through Western Passage, which ranges from 1.3 km to 2.8 km wide and approximately 30 m to 120 m deep at mid-channel (https://maps.ngdc.noaa.gov/viewers/bathymetry/), can reach velocities of approximately 3 m s^{-1} at peak tidal current flow (Rao et al., 2016).

Social turbulence in this system results from past and ongoing changes to the socio-ecological system of Western Passage and its surrounding communities. For centuries, fish and other marine resources in this region have held significant spiritual, cultural, and subsistence value for indigenous Passamaquoddy communities (Bassett, 2015). The herring fishery was also central to the economic vitality of this region until its decline, and the loss of associated fish processing plants (canning, drying, and smoking) during the mid to late 1900s resulted in increased unemployment, poverty, and outmigration (Johnson et al., 2014). More recently, this area has witnessed additional natural resource declines and subsequent regulations that have limited access to key fisheries, such as groundfish, urchin, and scallops (Hall-Arber et al., 2001). To address social turbulence and remain viable and resilient, these communities rely on alternative economic opportunities outside of fishing, such as

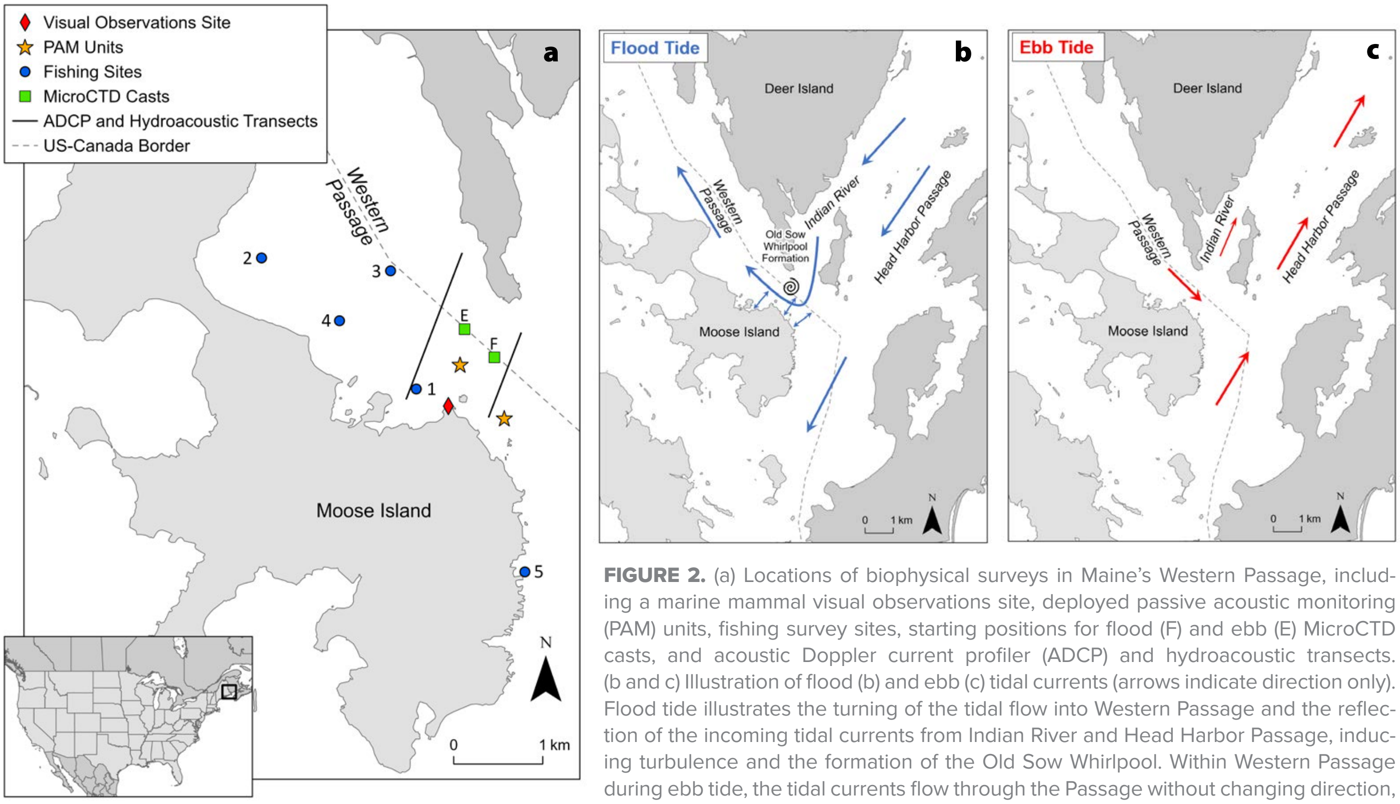


FIGURE 2. (a) Locations of biophysical surveys in Maine's Western Passage, including a marine mammal visual observations site, deployed passive acoustic monitoring (PAM) units, fishing survey sites, starting positions for flood (F) and ebb (E) MicroCTD casts, and acoustic Doppler current profiler (ADCP) and hydroacoustic transects. (b and c) Illustration of flood (b) and ebb (c) tidal currents (arrows indicate direction only). Flood tide illustrates the turning of the tidal flow into Western Passage and the reflection of the incoming tidal currents from Indian River and Head Harbor Passage, inducing turbulence and the formation of the Old Sow Whirlpool. Within Western Passage during ebb tide, the tidal currents flow through the Passage without changing direction, and elevated turbulence and whirlpools do not result. This figure was adapted from Figure 4 presented in International Passamaquoddy Fisheries Board (1960).

marine tourism and renewable energy development (Johnson et al., 2014).

Environmental monitoring and decision-making around tidal energy development is complicated by the physical and social turbulence that typifies coastal ecosystems like Western Passage. Yet, with the growing interest in developing marine energy technologies and other coastal infrastructure, managers are increasingly called upon to make timely decisions regarding the siting and permitting of new marine uses despite significant data gaps. Over the past 10–15 years, tidal energy development and commercialization have been significantly hampered by lack of data or data that are insufficient or not well integrated into a form that can be readily used (Leeney et al., 2014; Copping, 2018).

Key challenges that contribute to these critical data gaps were identified by the Maine Tidal Power Initiative (MTPI) during an earlier effort to bring together stakeholders and researchers from different disciplines to address questions related to tidal power development. Securing funding for large interdisciplinary initiatives (~$1.5M annually, in this case) and the high level of commitment required to sustain and manage them were two of the challenges identified. The MTPI also found that student involvement can foster linkages between disciplinary teams and is critical to training the next generation of scientists and decision-makers (Jansujwicz and Johnson 2015). In addition, a focus on student training can attract new sources of funding for such efforts. The WPSRC emerged as a strategy for overcoming barriers to interdisciplinary science and problem solving by placing student training at the forefront of developing, implementing, and evaluating an ecosystem-level monitoring program. Our research collaborative was funded through an internal institutional grant for interdisciplinary student training programs.

INTEGRATING DIVERSE DATA SOURCES ILLUMINATES THE IMPORTANCE OF TIDES

Demonstration and testing of new marine renewable energy technologies have thus far resulted in mostly singular disciplinary knowledge of the potential effects of tidal power on marine animals and hydrodynamics. For example, in our previous research, we discovered that fish were commonly present in the wake of a test turbine, that schools of fish had a lower probability of entering a turbine than individual fish (Viehman and Zydlewski, 2015), and that fish counts were not linked to current speed (Viehman and Zydlewski, 2017). Studies of how tidal turbine farms impact hydrodynamics elsewhere have found that tidal turbines may locally reduce current velocities in estuaries and tidal channels, which can ultimately lead to a decrease in sediment fluxes (Defne et al., 2011; Fallon et al., 2014; Thiébot et al., 2015). Importantly, these studies have infrequently considered ecosystems as a whole and have often excluded the human component (Bonar et al., 2015).

Ironically, the impressive currents that are favorable to tidal energy development, such as those in Western Passage, pose one of the challenges to conducting ecosystem-level studies (i.e., studies that integrate across these traditionally siloed disciplines) (Melvin and Cochrane, 2015). Many research approaches that are typically used to monitor marine species (e.g., hydroacoustics, trawling, passive acoustic monitoring) have limited capability for collecting viable data throughout such dramatic tidal cycles. To overcome this challenge, the WPSRC drew upon the expertise, tools, and theories of diverse natural and social science disciplines to study the fish, marine mammals, humans, and hydrodynamics of Western Passage (**Figure 3**). Our aim was to engage students and stakeholders in the design and implementation of an interdisciplinary research program that would lead to a better understanding of baselines across multiple components of this complex ecosystem.

Overall, our integrated approach to data collection and analysis revealed a common theme across all data types. Tidal dynamics were found to be a significant factor affecting biological, physical, and social data, highlighting their importance to the Western Passage ecosystem and future monitoring programs

> “The professional relationships that developed between students, research mentors, and diverse stakeholder groups during this year of study and the experiential learning gains achieved across all levels provide critical building blocks for further exploration of this system and others.”

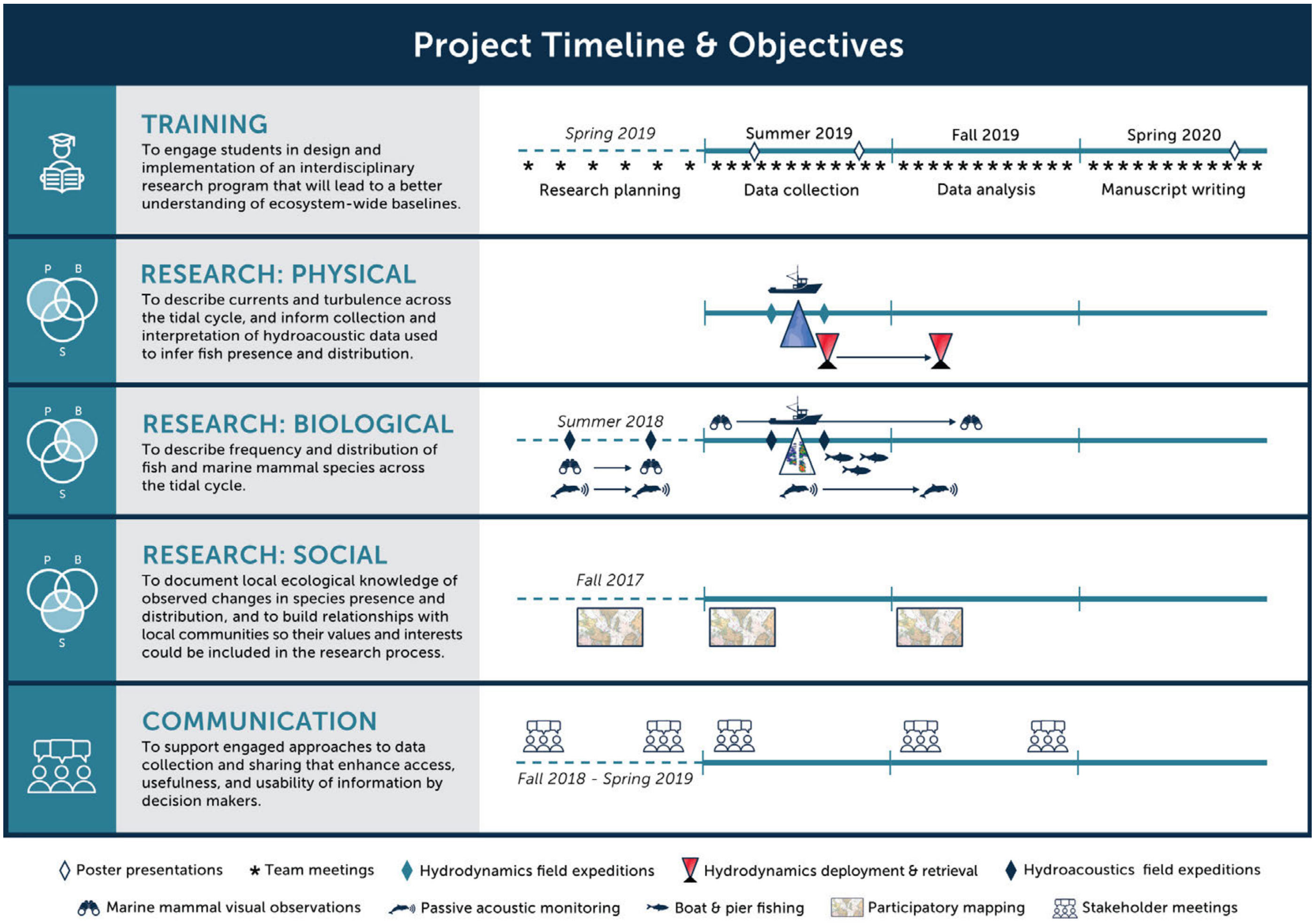


FIGURE 3. Timeline and objectives for training, research, and communication elements that undergraduates participated in as part of the Western Passage Student Research Collaborative (WPSRC) from May 2019 to May 2020. Research included disciplinary and interdisciplinary physical (P), biological (B), and social (S) science components. Preceding activities (dashed lines in the timelines) that informed WPSRC activities were conducted by research mentors and a graduate student research assistant.

for coastal development in this region. Recognizing this link enabled synergies between data streams that would not have been possible if each were considered alone. Here, we provide an overview of the research methods employed by our student research collaborative and the preliminary findings that were an outcome of our focus on integrating disciplines to better understand a tidally dynamic ecosystem. Further details on individual methods are provided in the online supplementary materials.

Hydrodynamics Inform Biological Data Collection

A primary goal of our research collaborative was to describe the currents and turbulence of Western Passage across the tidal cycle in ways that would inform biological data collection. This goal was intentionally envisioned to integrate physical and biological components of our research team. Hydroacoustic methods, using sonar, are employed to increase understanding of many components of aquatic ecosystems, including bathymetry and the presence and distribution of fish (Shen et al., 2016; Viehman et al., 2018; Staines et al., 2019). However, it is difficult to collect data using hydroacoustic methods in highly turbulent environments because the presence of velocity shears and air entrained in the water can obfuscate the backscatter from biological sources (Ross and Lueck, 2005; Lavery et al., 2007; Warren and Wiebe, 2008). To quantify the influence of physical forces on biological data collection, biologists and coastal engineers collaborated to concurrently collect hydroacoustic and hydrodynamic data (turbulence and current velocities). Throughout a spring and a neap tidal cycle in Western Passage, WPSRC students gained hands-on technical training while working alongside their research mentors during fieldwork and subsequent analysis of data collected in Western Passage.

Integration of the concurrently collected hydrodynamic and hydroacoustic data was critical to documenting the source (physical or biological) of the dominant backscatter signal observed in Western Passage throughout each tidal cycle. The concurrently collected hydroacoustic, turbulence, and current velocity data sets together showed that elevated backscatter observed during the flood tide co-occurred with the period of strongest mixing rates (Figure 4). Together, these data suggest that the high level of backscatter measured during the dynamic flood-tide flow in Western Passage was not solely from a biological source (i.e., fish) and precluded our ability to use hydroacoustics to observe the distribution and abundance of fish. These findings confirm that traditional hydroacoustic approaches have limited capacity in this physically turbulent system, necessitating alternative monitoring approaches to observe biological activity during the flood tide.

Observing Across Trophic Levels Indicates the Importance of the Flood Tide

With guidance from biological oceanographers who provided knowledge of tidal influence on species biology, marine ecologists who considered the trophic relationships among species, and social scientists who focused on the human dimensions and value of local ecological knowledge, the WPSRC developed alternative monitoring approaches to describe the frequency and distribution of fish and marine mammal species in Western Passage. This component of our research was in part motivated and guided by decision-makers, including federal and state regulators who incorporate baseline information on marine species when considering permitting of marine renewable energy projects. To fulfill these needs, the WPSRC sought to describe the frequency and distribution of species across trophic levels, including fish and the marine mammals that feed on fish.

Given that the fast-flowing and highly turbulent conditions preclude safe and effective net tows to ground truth hydroacoustic data, regulators who were engaged in decision-making around marine permitting in this region recom-

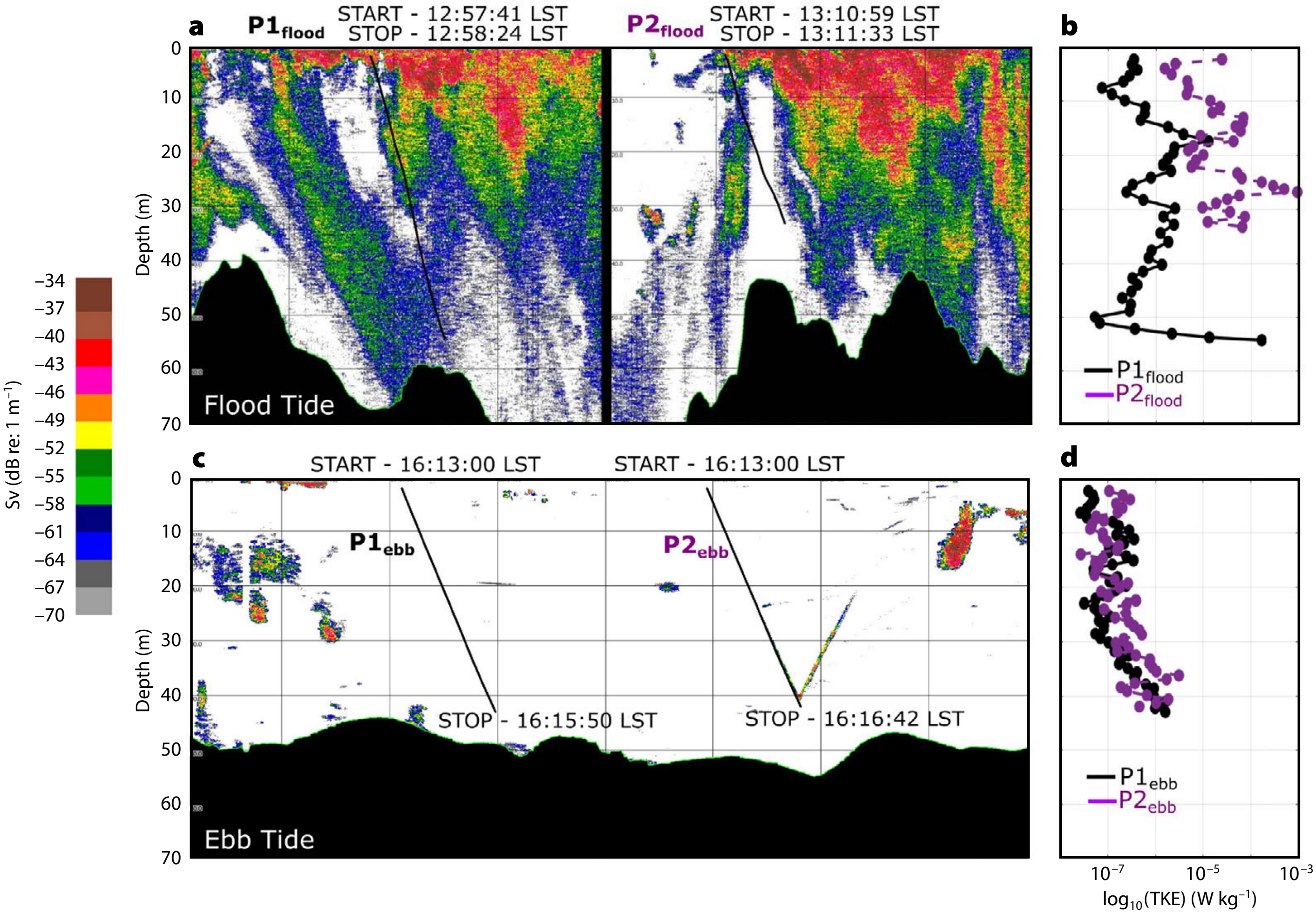


FIGURE 4. Depth traces for MicroCTD profiles (black lines) overlaid on hydroacoustic echograms collected during the flood (a) and ebb (c) phases of the spring tide to provide a visual representation of the backscatter observed concurrent with the MicroCTD data collection. These time intervals were chosen to characterize the most extreme instance of hydroacoustic backscatter (during spring flood tide) and the most limited instance (during the subsequent ebb tide). MicroCTD turbulence profiles are provided for comparison with hydroacoustic backscatter (b,d). Measurements of turbulent kinetic energy (TKE), a proxy for mixing, were three orders of magnitude greater during the flood than the ebb tide. Warmer colors (red) represent stronger observed backscatter (S_v) while cooler colors (blue) represent weaker backscatter. The color bar is provided in increments of 3 dB. An increase/decrease of 3 dB indicates a doubling/halving of the observed backscatter. Every 10 dB is an increase/decrease by an order of magnitude. Bathymetry is indicated by the black region at the bottom of the echograms.

mended testing recreational fishing gear as an alternative approach. WPSRC students worked with a marine extension associate to test fishing with sabiki rigs, which are equipped with several small hooks, as a method to characterize species presence and size. In July and August 2019, four boat-based sites and one land-based site were surveyed. Our diverse catch of both pelagic and ground fish suggests that fishing with recreational gear can provide insights into fish biodiversity in the region.

From May to October 2019, WPSRC students, research associates, and faculty with marine mammal expertise also used a combination of visual surveys and passive acoustic monitoring to study marine mammals in Western Passage. Through the iterative process of collaboratively creating and testing survey protocols, students learned firsthand about the logistics and challenges associated with both land- and boat-based marine mammal research in a tidally dynamic system. The marine mammal species we most commonly sighted in Western Passage was the harbor porpoise (*Phocoena phocoena*). The students observed these small odontocetes during almost every one of their twice weekly visual surveys, detecting them during all hours of acoustic recordings from July through October. The harbor porpoise were most frequently seen and heard during the flood tide, with detections increasing as water levels increased in Western Passage and declining as water levels ebbed (Figure 5).

Students integrated data from fishing and marine mammal surveys to test hypotheses that may explain trends in biological activity in Western Passage; for example, does the increase in harbor porpoise detections during the flood tide correlate with increased prey/fish abundance in the Passage? Atlantic mackerel (*Scomber scombrus*), the fish most frequently caught in Western Passage with recreational fishing gear, is a common prey species for harbor porpoise (Smith and Gaskin, 1974). Our preliminary analyses suggest a significant positive relationship between water level and harbor porpoise detections but not mackerel catch during the flood tide (Figure 5), yet importantly, our fishing efforts did not cover the full tidal range or target all prey species. We therefore present these preliminary results primarily as an example of the ecological hypotheses that students explored using a data integration approach.

Expanding Understanding in Time and Space Through Local Ecological Knowledge

The WPSRC's final research objective was to document local ecological knowledge in the Western Passage region in order to expand the temporal and spatial resolution of the knowledge gained through biophysical surveys. Although participatory methods and alternative sources

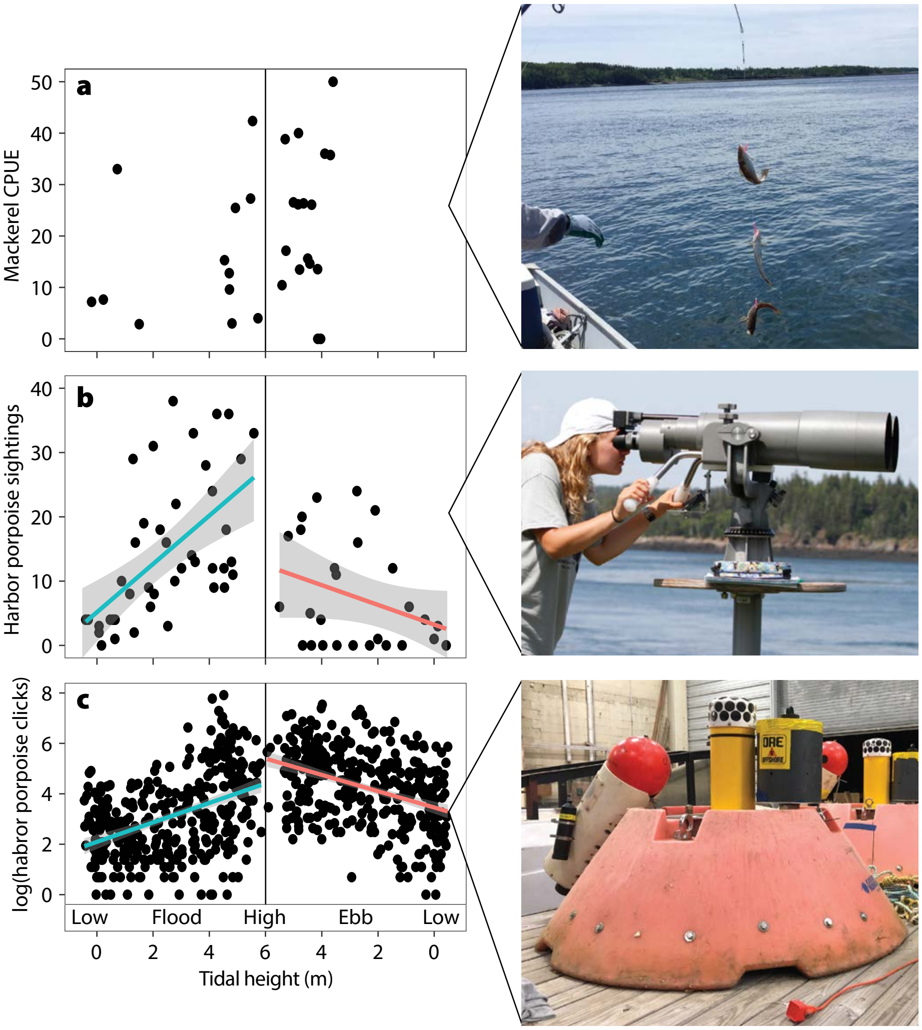


FIGURE 5. Integration of discrete data sets from fishing, marine mammal visual surveys, and passive acoustic monitoring to assess relationships between detections of prey and predators across the tidal cycle during a one-month period (September 9, 2019–August 8, 2019) in Western Passage. Fish and porpoise detections are compared to verified tidal heights extracted from NOAA Tide & Currents database (https://tidesandcurrents.noaa.gov/) for the Eastport, Maine, station. (a) Catch per unit effort (CPUE by hour) of mackerel caught using recreational fishing gear at four boat-based sites in Western Passage (blue circles, Figure 2). (b) Number of harbor porpoise sighted per half-hour of visual land-based survey from Eastport (red diamond, Figure 2). (c) Harbor porpoise clicks detected per half-hour from a passive acoustic recorder deployed in Western Passage (western yellow star, Figure 2). Significant linear models predicting detections from water level, with shaded 95% confidence interval, are shown for harbor porpoise sightings on flood ($F_{1,40} = 19.61$, $p < 0.0001$, $r^2 = 0.329$) and ebb tides ($F_{1,28} = 4.705$, $p < 0.05$, $r^2 = 0.144$), and for harbor porpoise clicks on flood ($F_{1,357} = 30.83$, $p < 1 \times 10^{-7}$, $r^2 = 0.079$) and ebb tides ($F_{1,378} = 34.91$, $p < 1 \times 10^{8}$, $r^2 = 0.085$). Relationships between mackerel CPUE and tidal height were not significant during either tide.

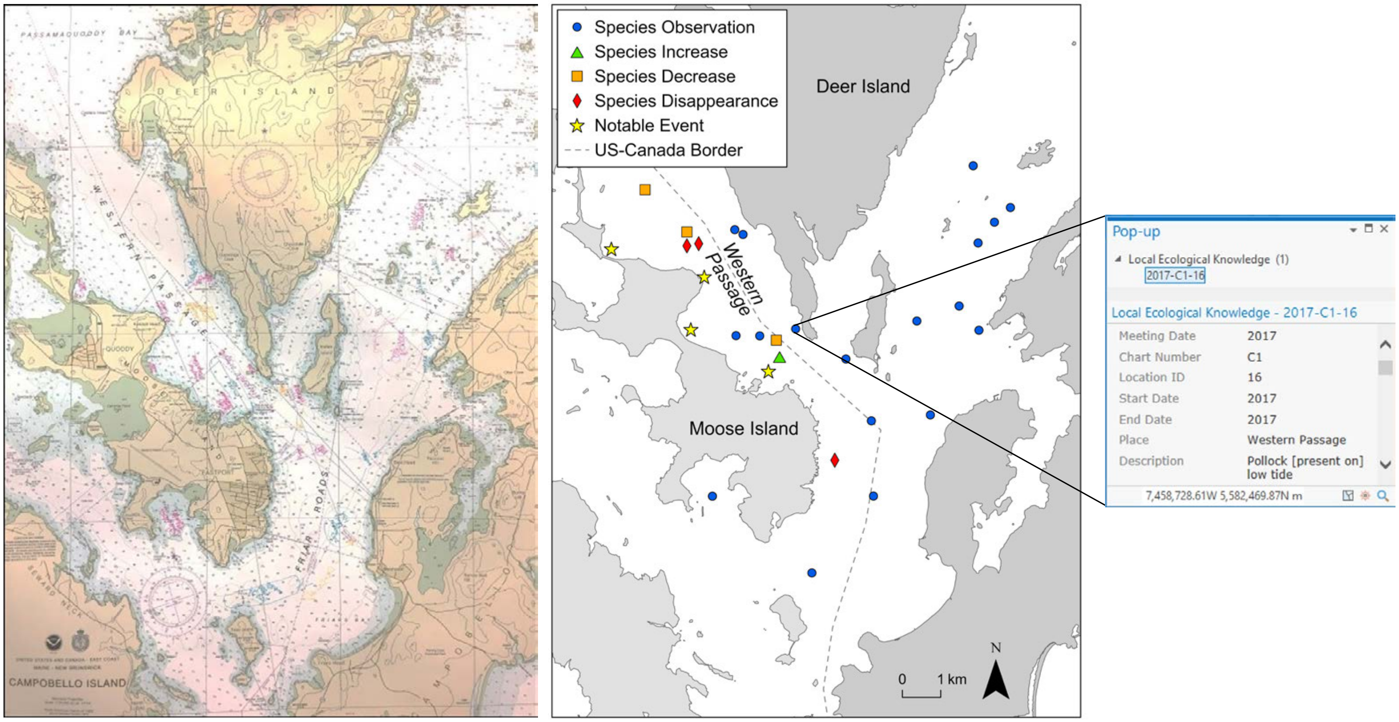
of knowledge are increasingly appreciated for their contributions to designing more effective monitoring protocols (Chambers, 2006), acknowledgment of local communities as an important source of place-based knowledge is often missing when researchers attempt to understand an ecosystem (Mackinson and Nottestad, 1998; Ames, 2003; Teixeira et al., 2013). The WPSRC therefore used an engaged and participatory approach, as described below and in the online supplementary materials, to gather and share data with local communities. A strong baseline of trust that emerged from earlier MTPI interactions between the research team and individual community members contributed significantly to critical long-term working relationships (Jansujwicz and Johnson, 2015).

Beyond its value for biological data collection, a secondary objective for fishing with recreational gear from one land-based site (a local pier) was for students to engage with local fishermen, note their observations of fish in the area, and gain an understanding of how fish and fishing are valued within the community. In addition to informal conversations at the pier, the WPSRC also convened a public meeting to engage community members, including local commercial and recreational fishermen, in participatory mapping exercises. This meeting built off an earlier public meeting in the local community where community members shared personal connections to the adjacent Western Passage and recorded their knowledge of fish and other marine species directly on hard-copy nautical charts (Figure 6). This recorded knowledge included memories of observed changes in the ecosystem over time, as well as how species presence fluctuates daily with the tidal cycle.

Integration of local ecological knowledge regarding fish and marine mammal presence significantly expanded the temporal and geographic scope of our understanding of the ecological community beyond our hydroacoustic transect lines and the limited scope of our fishing and marine mammal observation sites. Furthermore, engaging with the local community also led to other collaborative efforts, including working with fishermen to collect fishing and phenology data that will further expand our understanding of the Western Passage ecosystem. We aim for these additional data to ultimately be incorporated into decision support tools, such as those described in the following section, alongside the data collected by the WPSRC students.

Data Visualization Strengthens Decision-Support Tools

Data visualization in space became a key WPSRC tool for integrating, interpreting, and communicating different kinds of knowledge. Maps constructed through participatory mapping activities formed the foundation for a geospatially referenced collection of local ecological knowledge. Adding our contemporary fish capture and marine mammal sighting data to these maps of recent and historical observations contributed to our understanding



Pop-up

Local Ecological Knowledge (1)
2017-C1-16

Local Ecological Knowledge - 2017-C1-16

Meeting Date	2017
Chart Number	C1
Location ID	16
Start Date	2017
End Date	2017
Place	Western Passage
Description	Pollock [present on] low tide

7,458,728.61W 5,582,469.87N m

FIGURE 6. Nautical chart used in the participatory mapping activity (left panel) with handwritten local ecological knowledge collected during a 2017 community meeting in Eastport. We intentionally did not zoom in to these handwritten notes for confidentiality purposes. These data were digitized using ArcGIS Pro to produce an interactive map (middle panel). A "notable event" on these maps is defined as an unusual or noteworthy occurrence, such as legislation, development, or other human impact. Clicking on a selected point opens a pop-up window with the attribute table (right panel).

of baselines and potential for change in species presence and distribution. Finally, a WPSRC student mentored by a geospatial scientist also worked to create a three-dimensional base map of bathymetry in Western Passage that provided critical context for interpreting how physical features affect biological and social dynamics in this turbulent environment.

Overlaying the student-collected data on this three-dimensional bathymetric model will ultimately form the basis of a web-based, interactive map that will be accessible to local community stakeholders and managers to inform future decision-making. We are continuing to add information from multiple sources to this map with feedback from stakeholders about its utility and their data needs. We view tools and maps like this one as components critical to an engaged, interdisciplinary, ecosystem-based monitoring approach. It represents a clear shift from the unidirectional information exchange that typifies traditional reporting of environmental monitoring data to a two-way exchange that determines how compiling all sources of information can be useful to communities (Cvitanovic et al., 2015).

CHALLENGES AND RECOMMENDATIONS FOR EFFECTIVE INTERDISCIPLINARY TRAINING, RESEARCH, AND COMMUNICATION

The experience of the WPSRC provides a striking example of what can be gained through the integration of diverse disciplines. However, this approach is not without challenges. Similar to other studies of interdisciplinary science, the primary challenges encountered by the WPSRC included the time commitment needed to coordinate with large and diverse research teams (E.D. Roy et al., 2013; Pischke et al., 2017) and the cognitive load required to engage meaningfully in conversations about unfamiliar disciplines and different ways of knowing (MacLeod, 2018). To address these challenges, members of our research collaborative shared coordination roles, with different individuals responsible for coordinating research team meetings and the overall student training experience, fieldwork, and communication with stakeholders. Faculty and students alike acknowledged and reflected upon the challenge and value of conducting interdisciplinary work regularly throughout the process. As evident in this article, maps often served as boundary objects for the WPSRC to foster dialogue and learning among this interdisciplinary and diverse group of collaborators (Cutts et al., 2011; Luna-Reyes et al., 2018).

To conclude, we reflect on the value of our training, research, and communication framework (Figure 1) and offer three general recommendations for facilitating the broader implementation or adaptation of the framework to other contexts in oceanography, marine ecology, coastal development, as well as non-aquatic environments.

RECOMMENDATION 1: TRAINING

Build a team that acknowledges the value of diverse epistemologies and bidirectional learning in student training. Our interdisciplinary framework was based on the equal involvement of people from different disciplines and different career stages who each brought their own way of knowing or seeing the world. As a training model, it was valuable for students to share the learning experience with their mentors, who were also learning from new disciplines. When forming our team, we considered the existing knowledge gaps in our study system and identified individuals with discrete areas of expertise who would approach data collection to fill these gaps in multiple, complementary ways. Students were co-mentored by practitioners from different disciplines. The inclusion of individuals with training and prior experience in collaborative research methods and undergraduate research mentoring, as well as the relatively small size of our collaborative, also contributed to our success. We acknowledge here the tradeoffs inherent in offering an in-depth training opportunity to a small number of students but suggest that some elements of our program provide a scalable structure. These elements include co-mentoring, clear roles and responsibilities, frequent meetings, and an emphasis on boundary objects as well as dedicated time and space to learn from different disciplinary perspectives.

RECOMMENDATION 2: RESEARCH

Be open to an iterative research process. A process with multiple aims and multiple disciplines is inherently complex, and this complexity often precludes defining a straight path to success at the beginning of the process. Rather, remaining open to an iterative process of revisiting objectives and methodological approaches was integral to our framework and allowed our research collaborative to be flexible and responsive to shifting needs. After recruiting students to our team, our first several meetings were focused on revisiting and refining research objectives and methodologies. Students presented their research proposal to an external audience of regional stakeholders at a local scientific meeting early in the project period. Following subsequent field trials, methods were further refined and new synergies among disciplines were discovered through this process.

RECOMMENDATION 3: COMMUNICATION

Adopt a reflexive approach to communication within the research team and with external stakeholders. In all of our interactions, we remained open to adapting our approaches to how we conduct research to ensure that the questions we investigated fit the needs, values, and interests of diverse groups. Key to our ability to remain reflexive was a commitment to frequent meetings and both electronic and in-person communication. Students met weekly, or more frequently as needed, with their mentors. Our team held biweekly meetings of the full research collaborative (all students and their mentors) and approximately quarterly meetings with diverse stakeholders (community members, managers, and industry). Students also had multiple opportunities to practice scientific communication through their participation in the writing and revising of this manuscript, as well as presentations at regional meetings with scientific, stakeholder, and general public audiences.

As a result of the persistent and engaged commitment of all team members to the principles listed above, the WPSRC successfully achieved outcomes in student training, research, and communication. We acknowledge that data from a single year of research limits our ability to accurately infer ecological interactions (Rehme et al., 2011) or estimate cumulative impacts of multiple anthropogenic activities (Lester et al., 2010; Fox et al., 2017) because neither was directly measured. Yet, through the collection and integration of diverse data sources, the WPSRC contributed to the creation of baseline knowledge of a complex, turbulent coastal ecosystem. The professional relationships that developed between students, research mentors, and diverse stakeholder groups during this year of study and the experiential learning gains achieved across all levels provide critical building blocks for further exploration of this system and others. Students gained transferable skills in disciplinary methods, interdisciplinary research approaches, and stakeholder engagement. These skills will set them up for success in a future sustainability science seascape that necessitates a convergence research approach. Finally, by embracing the commitment to sharing these data in highly visible forms that are available and accessible to stakeholders, the WPSRC contributed to future decision-making around coastal development in a physically, biologically, and socially valuable natural environment. Renewable energy development is still being considered in Western Passage, and a subset of team members remain engaged in research to support the decision-making process.

SUPPLEMENTARY MATERIALS

The supplementary materials are available online at https://doi.org/10.5670/oceanog.2021.102.

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AUTHORS

Kristina Cammen (kristina.cammen@maine.edu) is Assistant Professor, **Gabriella Marafino** is a master's student, and **Sarah Burton** is an undergraduate, all at the School of Marine Sciences, University of Maine, Orono, ME, USA. **Jillian Dow** is an undergraduate in the Division of Environmental and Biological Sciences, University of Maine at Machias, Machias, ME, USA. **Emma Dullaert** and **Madalyn Jorge** are undergraduates at the School of Marine Sciences, and **Kate Macolini** is an undergraduate in the Department of Civil and Environmental Engineering, all three at University of Maine, Orono, ME, USA. **Louise McGarry** and **Christopher Tremblay** are Research Associates at the School of Marine Sciences, University of Maine, Orono, ME, USA. **Jessica Jansujwicz** is Research Assistant Professor, Department of Wildlife, Fisheries, and Conservation Biology, and Senator George J. Mitchell Center for Sustainability Solutions, University of Maine, Orono, ME, USA. **Tora Johnson** is Associate Professor, Division of Environmental and Biological Sciences, University of Maine at Machias, Machias, ME, USA. **Lauren Ross** is Assistant Professor, Department of Civil and Environmental Engineering, and **Gayle Zydlewski** is Professor, School of Marine Sciences, both at University of Maine, Orono, ME, USA.

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OCEAN EDUCATION

VIRTUAL AND REMOTE

Hands-On Undergraduate Research in Plankton Ecology During the 2020 Pandemic: COVID-19 Can't Stop This!

REU student Andria Miller deploys her homemade plankton net (left) and Secchi disk (right), and measures chemical water properties (middle) using test strips. *Note: The photos were staged without a life vest, although one was worn during actual sampling.*

By Pierre Marrec,
Andria Miller,
Lucie Maranda, and
Susanne Menden-Deuer

ABSTRACT. The pandemic has had innumerable impacts on the oceanographic community, including on summer research internship programs that expose undergraduates to diverse career paths in oceanography while immersed in an active laboratory. For many students, these internships are formative in their career choices. The Summer Undergraduate Research Fellowship in Oceanography (SURFO) at the University of Rhode Island's Graduate School of Oceanography is one of the Research Experiences for Undergraduates (REU) programs that proceeded remotely during the summer of 2020. Here, we highlight one project that, although remote, maintained a hands-on research experience focused on quantitative skill building. The pandemic forced the REU advisors to identify key learning goals and ensure their safe delivery, given the circumstances. Although all participants agreed that in-person instruction would have been preferable, we were pleased that we did not let a virus halt essential oceanographic research training.

INTRODUCTION

Summer internships, such as the Research Experience for Undergraduates (REU) programs sponsored by the US National Science Foundation (NSF), offer an excellent opportunity for students to gain hands-on research experience, along with a number of career-building opportunities. These intensive internships often occur in locations that are new to the students and cover cutting-edge research topics that are not typically addressed in undergraduate curricula. When REU students become members of active laboratories, they are exposed to professionals across career stages (graduate students, postdoctoral fellows, laboratory technicians, research scientists, and professors) and learn what it might be like to be a scientist. Frequently, students receive their first intensive research training and chances for peer collaboration as REU fellows. For many, an REU internship can be foundational to a career path and may be a life-altering event.

The summer of 2020 was remarkable and unorthodox for many REU fellows across the United States, especially for students in oceanography and other sciences that incorporate strong elements of observation and fieldwork or experimentation. However, the willingness, enthusiasm, imagination, and involvement of many researchers ensured opportunities for students to participate in summer internships despite the restrictions imposed by the pandemic. Here, we wish to share details of one such project at the University of Rhode Island's Graduate School of Oceanography (URI-GSO). The pivot to socially distant and remote learning required the REU advisors to reflect on which aspects were essential and would be most useful to pursue. Revamping the REU experience on short notice with entirely new approaches (e.g., no in-person contact, no access to facilities or equipment for the student) was the foundation for an intense collaboration among us and provided the student researcher and coauthor of this article, Andria Miller, with far more responsibility and agency to lead her research project. Constant adaptation and communication were keys for making the REU experience a success. The pandemic required re-prioritizing the multi-layered goals of the REU program. The main challenge was to identify strategies that would ensure the project would support immersive, student-led research, and development of analysis skills, agency, and autonomy.

BACKGROUND

The REU at URI-GSO, known as SURFO (Summer Undergraduate Research Fellowship in Oceanography), emphasizes math, engineering, and data science (https://web.uri.edu/gso/academics/surfo/). It has been held every summer since 1985. Because participating faculty recognize that oceanographers traditionally do not reflect the diverse spectrum of humanity and that oceanography needs to be strengthened by contributions from a broad range of perspectives, SURFO particularly welcomes applicants from groups historically underrepresented in our field, and the program has successfully recruited diverse students.

The NSF-funded SURFO aims to provide a pathway for students into research and graduate school. The pivot to online instruction was directed at maintaining the strengths of the program, not only to support the individual student's research project but also to include the many auxiliary opportunities the program provides, including networking and exposure to the diverse career paths open to oceanographers. While it was going to be difficult to replace living shoreside in beautiful Rhode Island and enjoying the in-person interactions on our splendid Bay Campus, much could be offered remotely: roundtable discussions with representatives from industry, nongovernmental organizations, government scientists, and graduate students; networking with peers; and professional development workshops.

The decision to move the program online was not an easy one. Uncertainties on the trajectory and spread of SARS-CoV-2 abounded in spring 2020. Like many REU sites across the United States, SURFO directors considered a variety of options from business-as-usual following student quarantines after arrival, to a hybrid online/in-person program, to an entirely virtual program, to outright cancellation. Subsequent to consultations with state and university authorities, and with the dozen Bay Campus laboratories that had offered summer research projects, URI-GSO decided in late April on a remote and thus virtual SURFO program as the only practical option to ensure the health and safety of all involved. With just a little over one month to the official start of the program, SURFO advisors adjusted or fully changed their research projects to give selected REU students a meaningful experience. Thanks to NSF's flexibility, SURFO directors were able to modify the grant budget to ensure that students would have the resources needed to be successful. With REU students spanning 11 time zones from Puerto Rico to Guam, scheduling online events became a challenge, but everyone involved, from REU students to advisors to guest speakers, came through with goodwill and compromises. Below is a description of the research project that gave one student, Miller from Mississippi, hands-on research experience, while collaborating with a team of mentors based in Rhode Island.

RESEARCH QUESTION

Our plankton ecology laboratory has worked with eight REU students since 2010. To ensure a meaningful research experience, we have always placed the highest priority on helping students develop quantitative research and analysis skills, as well as autonomy. For summer 2020, this necessitated some flexibility with respect to details of the research project, especially if we were to include fieldwork. Most importantly, we wanted the REU fellow to follow his/her scientific interests, while discovering how to be creative in science. Typically, students admitted to the SURFO program rank different projects and labs with which they may want to engage, and this information is used to match potential mentees with mentors. In the past, the projects our laboratory offered always included exposure to a broad range of questions and methods and emphasized skill building. This was achieved through supporting students with collection of several different types of data (e.g., climate, water column properties and chemistry, species identity and characteristics, continuous vs. discrete data). The main learning objectives were to record and manage large volumes of data, analyze them through different statistical techniques, visualize the findings, and present a synthesis of the results both in writing and orally. The main goal for summer 2020 was to maintain this emphasis. Therefore, for the research component, we prioritized experimental design, data collection and analysis (including statistics), and communication.

The scientific question posed for this year's project was whether differences in freshwater plankton communities in three different bodies of water in Mississippi, both over time and location, are due to differences in environmental conditions. The main questions included:

1. What is the abundance and distribution of plankton types in dissimilar bodies of water (e.g., a recreational lake and a reservoir)?
2. What are co-occurring environmental conditions and water column properties (e.g., nutrient loading)?
3. Are there discernible patterns in both community composition and environment that reflect the sites' uses for recreation or as a municipal water source?

The project was constrained by safety and equipment availability. Because of the pandemic, there could be little reliance on local research facilities, which URI-GSO typically makes available (e.g., cruise opportunities on a coastal vessel or on R/V *Endeavor* along with state-of-the-art equipment in Bay Campus centers and principal investigators' laboratories). Thus, one major learning objective included fundamental oceanographic (i.e., life) skills, such as making do and winging it. The pivot to online learning made it clear just how important these REU opportunities are for allowing students to demonstrate the many soft skills internships require, including teamwork, reliability, flexibility, and effective communication.

ACTIVITY

The chronological steps for Miller's research activity were:

- Identify suitable sampling locations, within 30 minutes driving distance that could be visited safely (e.g., a sparsely populated recreational lake; Figure 1).
- Develop a sampling plan with documentation in appropriate sampling records (Supplementary Table S1).
- Purchase and construct needed equipment (e.g., Secchi disk, plankton net; Supplementary Table S2).

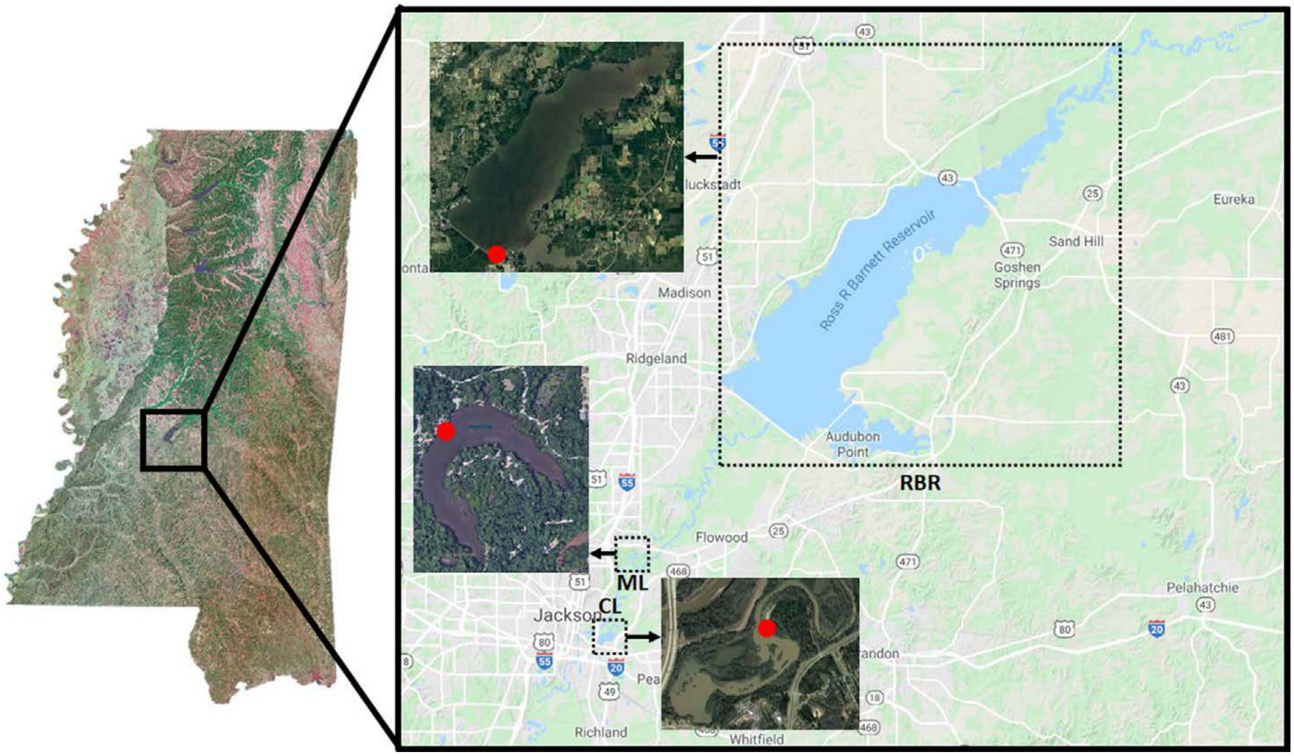


FIGURE 1. Satellite images of the sampling sites located in central Mississippi: Ross Barnett reservoir (RBR, 32°23'20.50"N, 90°2'53.71"W), Mayes Lakes (ML, 32°19'48.19"N, 90°9'34.49"W), and Crystal Lake (CL, 32°17'26.02"N, 90°9'34.49"W). Red dots on the satellite images indicate sampling locations.

- Test equipment and procedures to determine the suitability of instrumentation and methodology.
- Execute the sampling plan at identified locations.
- Build an image database of plankton and a data record of environmental observations.
- Apply the latest advances in image analysis and automated computation to the image database in order to categorize and size thousands of plankton cells.
- Categorize plankton types based on criteria of shape, size, and color.
- Examine data for associations among plankton community structure, environmental parameters, locations, and times.

Ultimately, the work allowed for repeated environmental assessments of several primary water sources that serve Mississippi's state capital, along with identification of the most relevant drivers of plankton community dynamics in these water bodies for a better understanding of the roles of these drivers and their consequences in a wider socio-economical context.

One-hour mentee/mentor meetings were scheduled twice a week via an online communication platform. The use of a dedicated Slack channel to communicate and keep constant contact between the mentee and the mentor was particularly useful for daily, rapid exchanges when needed. In addition, regular weekly lab meetings provided exposure to other researchers and their projects and fostered integration of the SURFO student into the lab community. Miller also had scheduled meetings with members of the lab to learn about other research projects and the experiences of graduate students and postdoctoral fellows. In addition, along with her SURFO peers, Miller attended online seminars on oceanographic topics and participated in training workshops on ethics in research, scientific writing, oral presentations, and blogging, among others. The project ended with Miller giving a public (remote) presentation to the whole URI-GSO community and writing up the project.

Materials

The required materials had to be accessible and affordable (**Supplementary Table S2**) and relied heavily on a do-it-yourself approach. It is well established that simple materials can be turned into a meaningful research project or outreach activity in aquatic sciences. A Secchi disk was built based on instructions provided by the Secchi Disk Foundation for its seafarer, citizen Secchi Disk Study (Lavender al., 2017). We added a temperature and light data logger controlled via Bluetooth for mounting on the Secchi disk to record temperature and light profiles during deployment. The recorded light intensity (in Lux) is in the visible light spectrum (400–700 nm), in a range similar to that of photosynthetically active radiation (PAR). A second temperature and light data logger was used for continuous measurements at a fixed outside location (the roof of Miller's garage) during the entirety of the study (the month of July 2020). In this manner, we collected one continuous data record, purposefully different from the discrete data collected at the sampling sites. We followed Matthew Rossi's instructions on the Microcosmos Foldscope Community website to build a plankton net (https://microcosmos.foldscope.com/?p=17431). All the items necessary for building the net (e.g., metal ring from an old lampshade, small metal keyrings, nylon stocking, ropes) were found at home by Miller. We provided 200 µm mesh netting, disposable pipettes, and petri dishes. Miller also got a bucket, a rope, and coffee filters from home to complete the material list. Macronutrient concentrations were measured using test strips, including nitrate, nitrite, ammonium and phosphate concentrations, and pH. We agreed that a life vest would always be worn during all sampling and an acquaintance should accompany Miller so that she would not be in the field alone. The plankton community was observed using a secondhand basic microscope (LW Scientific Revelation III) obtained from an acquaintance of Miller after an inexpensive, digital microscope failed to provide the appropriate resolution. Plankton images were taken directly with a smartphone mounted to the eyepiece of the microscope. Purchase of a headset to improve the quality of our communications rounded out the equipment acquisition. Overall, the costs were <$400. The cost of the project outlined here could have been cut in half with omission of the data loggers, but collection of continuous data supported a key analysis learning goal.

Additional environmental parameters were retrieved from US federal agency monitoring programs during the project. Gauge height and total discharge of the water bodies were obtained from the US Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis). Meteorological data (wind speed, precipitation, and temperature) were retrieved from the NOAA National Weather Service (https://www.weather.gov/).

Sampling Sites and Procedures

We identified three sampling sites (**Figure 1**) that provided easy and safe access to the water from piers. The main sampling site was the Ross Barnett Reservoir north of Jackson, Mississippi (32°23'20.50"N, 90°2'53.71"W), a major drinking water reservoir that also provides outdoor recreation for central Mississippi. It was identified as a prime sampling location because of previous work carried out on its plankton community (Sthapit et al., 2008; Sobolev et al., 2009). The other two sampling sites, Crystal Lake (32°17'26.02"N, 90°9'34.49"W) and Mayes Lake (32°19'48.19"N, 90°9'34.49"W), two small recreational lakes in Jackson and Flowood, Mississippi, were subsequently selected in order to include different characteristics from the reservoir. Sampling was performed twice a week, depending on weather conditions. The

Ross Barnett Reservoir was always sampled, whereas Mayes Lake and Crystal Lake were sampled alternately. Miller obtained data covering the full range of environmental parameters on five occasions between July 9 and July 22, 2020 (Figure 2). She sampled the Ross Barnett Reservoir five times and Crystal and Mayes Lakes twice each.

Before departing for a sampling trip, Miller would alert members of her family and her remote mentors about the sampling duration and location and would contact everyone again upon completion. Each sampling trip was conducted with one additional person, a family member or a friend of Miller, for safety. Air temperature and light intensity were recorded upon arrival at each sampling site. Other environmental indicators such as wind conditions, wind direction, water surface and waves, water scent, and water color were also recorded. Total depth, Secchi disk depth, and temperature and light profiles were measured simultaneously using the homemade Secchi disk equipped with a mounted temperature and light data logger. Profiles were taken by deploying the Secchi disk at 0.1 m intervals for 10 seconds from the surface down to 1 m depth and at 0.5 m intervals after the first meter down to the bottom. The light attenuation coefficient (K_d, m^{-1}) was determined from the linear relationship of the natural logarithm of light intensity against depth according to the Beer-Lambert-Bouguer law (Equation 1):

$$I_z = I_0 \times e^{(-K_d \times z)}, \tag{1}$$

where I_z is the light intensity (lux) at depth z (m) and I_0 the light intensity just below the surface (lux).

Miller collected water samples using a bucket from the surface. She measured nitrate, nitrite, ammonium, phosphate, and pH using the test strips. Sampled water was transferred into a one-gallon (3.785 L) plastic bottle through a 200 µm mesh net fixed at the end of a funnel to remove large zooplankton. The plastic bottles containing samples were kept on ice in a dark cooler until transported to Miller's home. Plankton samples were not preserved to avoid safety complications in handling hazardous materials. To increase plankton concentration and facilitate sufficient sample acquisition, one-gallon samples were concentrated using a coffee filter, ensuring a sufficient volume of water to keep specimens afloat above the filter. Ten milliliters of the concentrated sample were pipetted into a petri dish, and a maximum of four drops of vinegar were added to observe plankton cells under the microscope by limiting their movement. The volume concentration was done precisely to maintain quantitative accuracy of the counts.

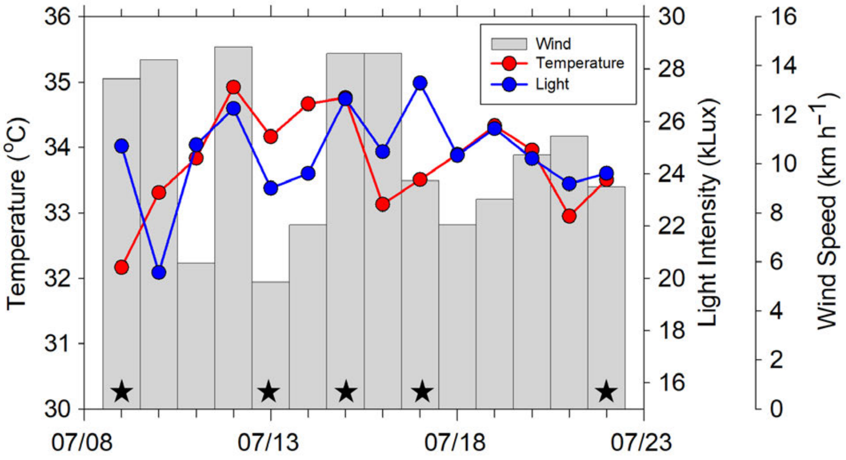


FIGURE 2. Mean daily outdoor temperatures (red dots and line), light intensity (blue dots and line), and wind speed (gray bars) in central Mississippi during the month of July 2020, with sampling dates indicated (black stars).

Plankton Image Analysis

With remote guidance and support from a mentor (author Marrec), Miller analyzed plankton images using a MATLAB routine developed for automated analysis. A micrometer ruler was used to convert pixels to size. Over 1,300 raw photographs were taken during the study. The raw images were first adjusted to enhance the contrast of the pictures and to reveal the color of the plankton cells. Then images of plankton cells were automatically cropped and their associated size properties (height, width, and area) were retrieved. After manual selection of all raw cropped photographs, we obtained a total of 100–200 individual plankton photographs, with associated size properties for each sampling site and day. While we used the URI-supplied MATLAB license, it is worth noting this basic image analysis can easily be performed using open access programing languages such as R or Python or using the dedicated image processing library provided by MorphoCut (https://morphocut.readthedocs.io/en/stable/).

Data Analysis and Interpretation

After each sampling day, Miller retrieved data from the data logger, maintained the database, and stored all images taken on a shared drive. Data management was an essential part of the project. The SURFO student had the opportunity to work with NES-LTER (North East Shelf Long Term Ecological Research) information manager Stace Beaulieu of Woods Hole Oceanographic Institution to better understand the challenges associated with data management.

The light profiles obtained during Secchi disk deployment represented a good introduction to aquatic optics. We were impressed by the quality of the light profiles obtained by the concocted Secchi disk light and temperature "profiler." The simple system permitted excellent characterization of the water column physical (temperature) and optical (light attenuation as a proxy of chlorophyll *a* concentration) properties, and it represented an inexpensive and efficient alternative to a CTD profiler. In situ light data were well approximated by Equation 1 (**Figure 3**) and enabled robust estimates of the light attenuation coefficient K_d. As light availability is a key driver of phytoplankton dynamics, profiles of light availability (%) were computed from the K_d values for each sampling site and date to compare water column optical properties. Finally, we observed a significant linear correlation between Secchi disk depths and K_d values ($n = 9$, $R^2 = 0.80$), which highlighted the strength of using this simple device. Secchi disk depth has been used by many aquatic biologists as a useful and informal visual index of the trophic activity, or trophic status index (TSI), of a lake or oceanic region (Carlson, 1977; Preisendorfer, 1986; Lavender et al., 2017; Pitarch, 2020). Following established relationships, we were able to estimate chlorophyll *a* and phosphorus concentration from Secchi disk depth (Carlson, 1977). Measurements of phosphorus concentrations observed using test strips were in the same range as phosphorus concentrations estimated from the Secchi disk depths.

Observed plankton cells were sorted into 15 categories by color, shape, and size (**Figure 4, Table 1**). While building taxonomic expertise was not an explicit goal of the project, we did aim to have a high-quality data set and leveraged similarities among species categories to combine them into four groups. Group A represented small green cells; Group B was composed of red, brown, and purple cells; Group C comprised cells with special shapes and larger sizes; and Group D represented the other small (OtherS) cells observed during our study. The categorization was sufficient to document that the plankton community structure, based on the four groups, varied among sampling sites both in terms of abundance and composition. Moreover, monitoring of the Ross Barnett Reservoir on five occasions provided clear indications of the temporal variability of the plankton community structure.

The scientific goal of this research was to investigate linkages between plank-

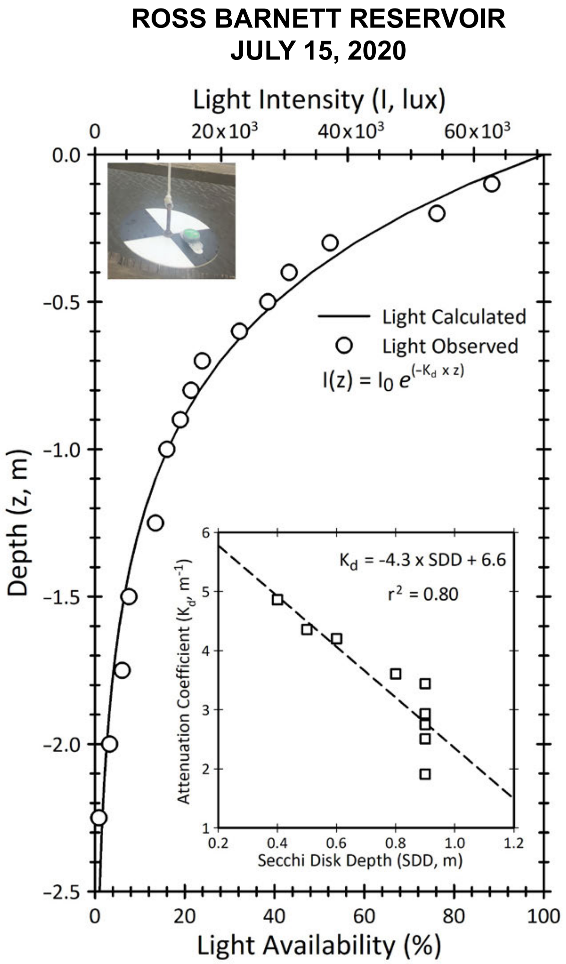


FIGURE 3. Light attenuation in the Ross Barnett Reservoir on July 15, 2020, as measured with a lux-meter (HOBO) attached to a homemade Secchi disk (top left inset). The data inset represents the linear regression obtained between Secchi disk depth (m) and light attenuation coefficient K_d (m^{-1}) computed from the light profiles using Equation 1.

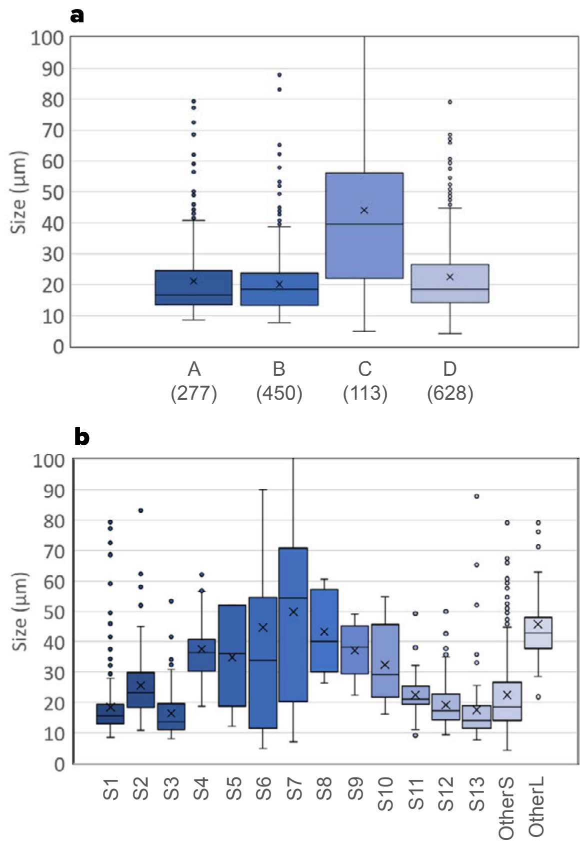
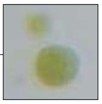
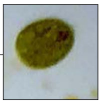
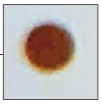
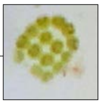


FIGURE 4. (a) Box plot of A, B, C, and D group sizes (µm) corresponding to the height/length of the cell. The number for each category indicates sample size. (b) Box plot of category sizes (µm). Refer to Table 1 for group and category identification. The boundary closest to zero indicates 1st quartile, the black line within the box marks the median, the x indicates the mean, and the boundary furthest from zero is the 3rd quartile. Error bars represent the lowest and largest data points, excluding any outliers, and outlying points are represented.

TABLE 1. Classification of organisms based on shape, color, and size. Taxonomic identification was deliberately avoided due to limited observation capacity.

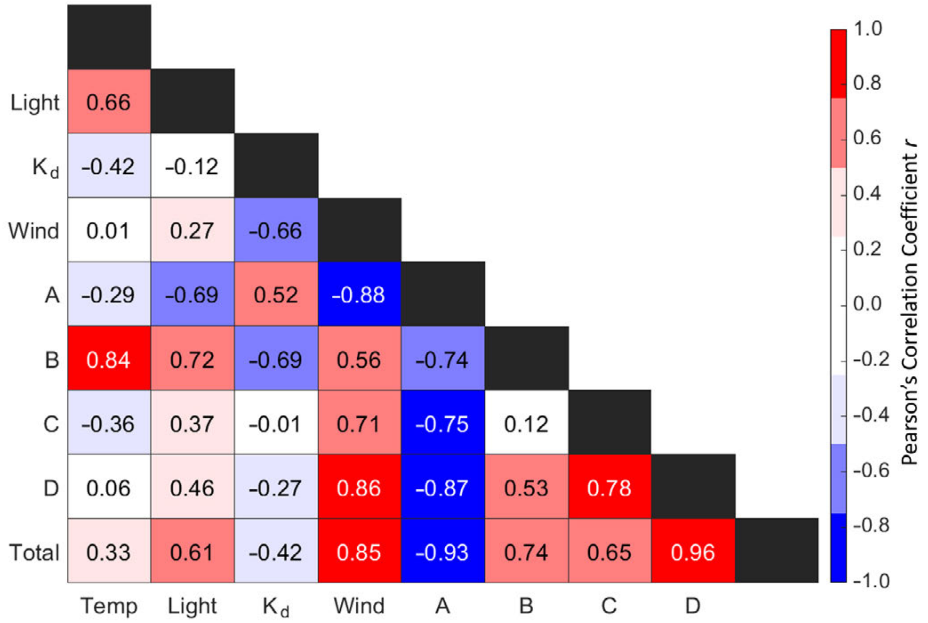
GROUP	SPECIES CATEGORY	DESCRIPTION	EXAMPLE
A	S1	Round/circular green dots/balls	
	S4	Oval/circular green dots/balls with a rough texture	
	S9	Green burrito-shaped	
B	S2	Round/circular red dots/balls	
	S3	Round/circular purple dots/balls	
	S11	Round/circular orange dots/balls	
	S12	Round/circular brown dots/balls	
	S13	Round/circular grayish dots/balls	
C	S5	Rotini-shaped dark/grayish	
	S6	Green/yellowish chains	
	S7	Circular grayish chain	
	S8	Snail-shaped/spade-shape greenish/reddish	
	S10	Clear gel-like round	
	OtherL	Large cells	
D	OtherS	Small cells	

ton community structure and environmental conditions using multivariate statistical techniques. For pedagogical purposes, we stepped through this process by first establishing paired relationships. This allowed Miller to discover that the highest plankton abundances were observed during peak wind conditions, and led her to ask the question: what were the relationships among the studied parameters? Further analysis resulted in a correlation matrix representing the Pearson's correlation coefficients between each variable (Figure 5). During the study, wind was observed to be the main environmental driver of the plankton community, with the highest abundances occurring during high wind events. The water column at the Ross Barnett reservoir was stratified, with warm surface waters having low nutrient concentrations. Presumably, during high wind events, the water column became mixed, bringing nutrients to the surface from bottom waters. This new nutrient supply likely favored the growth of phytoplankton, which in the absence of predation would increase in concentration. The research effort was not necessarily aiming to reveal the underlying mechanisms of plankton dynamics but rather to reveal testable hypotheses. Even by adopting a simplistic approach for plankton identification, Miller was able to assess essential aspects of plankton ecology, such as identifying how different environmental variables can affect plankton abundance and community composition.

CONCLUDING REMARKS

Based on the unique achievements of this project, Miller has been selected to participate in the virtual ASLO Aquatic Sciences meeting in Palma de Mallorca, Spain, in June 2021 to show that hands-on research training can be performed safely during a pandemic with limited and affordable materials. Most importantly, we were forced to identify key learning objectives and had the opportunity to turn challenges into achievements.

The 2020 SURFO students were grateful for the opportunity to participate in the REU experience, although all would have preferred an in-person program. They missed cohort interactions and integration into the Bay Campus community. However, the experience showed that some opportunities can be easily changed to a remote instruction model and provided ideas for outreach, for example, to high school or college groups that do not typically gain exposure to oceanography. The project outlined here could easily be part of a semester course in



	Temp	Light	K_d	Wind	A	B	C	D
Light	0.66							
K_d	-0.42	-0.12						
Wind	0.01	0.27	-0.66					
A	-0.29	-0.69	0.52	-0.88				
B	0.84	0.72	-0.69	0.56	-0.74			
C	-0.36	0.37	-0.01	0.71	-0.75	0.12		
D	0.06	0.46	-0.27	0.86	-0.87	0.53	0.78	
Total	0.33	0.61	-0.42	0.85	-0.93	0.74	0.65	0.96

FIGURE 5. Pearson's coefficients quantifying associations between environmental conditions (temperature, light intensity, K_d, and wind) and plankton community structure (abundances of Groups A/B/C/D and total abundance).

aquatic ecology. Additionally, the virtual approach could benefit future REU students under circumstances that prohibit in-person participation.

Refocusing a project as we did under pandemic circumstances demonstrates that compromising some aspects of a research question (e.g., replacing marine with freshwater) can still expose the student to the process of formulating a scientific question and nurture the development of fundamental research skills. The virtual approach was beneficial for the student, as she was able to develop an independent project with remote guidance. The DIY approach provided Miller with the confidence to claim ownership of the work accomplished and involved the development of many soft skills, such as budget and time management, creativity, adaptability, and communication. It was a unique opportunity for empowerment. In this manner, this virus has helped us focus on the essentials, which will promote continued delivery of a high caliber REU program at URI-GSO.

SUPPLEMENTARY MATERIALS

Supplementary Tables S1 and S2 are available online at https://doi.org/10.5670/oceanog.2021.104.

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AUTHORS

Pierre Marrec (pmarrec@uri.edu) is Postdoctoral Fellow, Graduate School of Oceanography, University of Rhode Island (URI-GSO), Narragansett, RI, USA. **Andria Miller** was a Summer Undergraduate Research Fellowship in Oceanography (SURFO) student at URI-GSO and is a senior undergraduate at Jackson State University, Jackson, MS, USA. **Lucie Maranda** is Emeritus Marine Research Scientist, and **Susanne Menden-Deuer** is Professor, both at URI-GSO, Narragansett, RI, USA.

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A NEW WAY OF LEARNING

By Simon Boxall

SIX MONTHS AGO in this column, I reviewed how COVID-19 had impacted learning and teaching of oceanography and marine biology at the university level. At that stage, things were looking hopeful for a return to normality—I was even going out on the boat teaching small cohorts in a safe and socially distanced way. Six months on, little has changed. The UK government encouraged universities to return to face-to-face teaching on May 17, 2021, the same week that most universities finish formal lectures and practical sessions to go into the assessment period—brilliant timing. Even postgraduate teaching ends as master's students go into dissertation mode. So, we now have a full year's cycle of experience to review how the teaching environment has changed and also to review some of the changes in the marine environment itself.

The pandemic has had some positive environmental impacts. There are reports from around the globe that water quality (or at least clarity) has been improving. With a dramatic cut in cruise liner voyages, leisure boat use, and ferry travel, we have seen low levels of suspended particulate matter in most coastal regions. Four weeks ago, our students measured a Secchi disk depth of 3.2 m in Southampton Water. In my many years sampling the region, the most I have ever observed prior to the pandemic was 1.7 m. This increase in the photic zone along with lower levels of sediment resettling has also led to a measurably improved and more diverse seabed environment. The fact that we were all flying less (if at all), and many are working from home, has also decreased carbon emissions, by up to 17% at the peak of the crisis, according to the World Meteorological Organization. However, the long-term trend is sadly still on the increase, albeit two-thirds of what would have been expected had this been a normal year.

I have done significant amounts of teaching online from home, with interludes of taking small groups of students out on the boat. In the past, teaching schedules were limited by timetabling issues—with clashes for either the professor or the student, but also issues around availability of lecture theaters of the correct capacity. In my study at home, I can accommodate a tutorial for four or a lecture for two hundred—online of course. The only other demand on my study space is from my dog, and she just sits at my feet, making occasional guest appearances mid lecture. I asked one group of students what they would like more of in their lectures, and they said, "the dog!"

As with many lecturers in marine science, I love to perform on stage and see the live audience as part of the fun—perhaps we are all extroverts at heart. In the new regime, I have avoided the prerecorded lecture and still deliver live online using a variety of platforms. No one platform seems ideal, and I vary them depending on what I am doing and how they seem to develop week to week. I still get the buzz of the live lecture and have noted one big advantage—students ask far more (sensible) questions. In the lecture theater, there is always a small selection of students who will have their hands up on a regular basis, but the majority are nervous to do so. With the many platforms we use, students can put their hands up and ask questions via their microphones, but many will do so in the typed chat. Anyone who is really nervous can do so in a private message that only I see. In the early days I felt this was an intrusion in the flow of my delivery, but actually it turns a lecture into far more of an interactive experience for both teacher and student alike, even if it does test my multitasking capabilities. Students can see and hear the presentation clearly rather than as some distant blur from the back of the lecture theater. They can have their coffee and sandwich while listening, frowned upon in many university lecture theaters, and—a "win" for the average student—they can arrive at a 0900 lecture without having to have showered, breakfasted, and caught the bus.

The counter to all of this remote learning is the lack of face-to-face contact. There are still things that work best that way. Although the lecture experience does not have to be face-to-face, it is a must for boat and laboratory sessions. The move to small groups of seven or eight compared with pre-COVID groups of over 20 on the boat, and 20 in a lab rather than 60, provides a far better face-to-face experience than we have ever delivered before. It is intensive for us at the teaching end, running a session maybe 15 times rather than five. You do find yourself forgetting what you have and haven't said by the time you get to session number 10, but I have found I have gotten to know our students better in this new regime, and they are more involved in the practical work. There are, after all, only so many things each individual can do on a boat in a group of 24 over a four-hour period.

With the potential for a return to normal in the fall of 2021 (note the caution there, after past over-optimism), there is a "demand" that we return to traditional lectures, traditional exams, and traditional practical sessions (whatever they may be). This demand is coming in part from governments, but mainly from the media, driven by a few student groups. Whether these groups are mainly in the humanities and have had no direct contact with their academic staffs for nearly 18 months now, or are looking for reduced fees in the future, is hard to tell. As formal teaching for this academic year came to a close last week., I (virtually) sat down with my course groups covering three years of oceanography along with marine biology students to see what their thoughts were. Most actually like what we have come to call blended delivery. They really appreciate the face-to-face teaching on the boat and in labs, and many like a component of online delivery, particularly for the more traditional lectures. What they do miss from lectures is the social contact with their peer group, and as much can be said when it comes to the academic staff—I do miss those corridor chats. Nonetheless, in the future, many of my colleagues are looking to work from home more than they have in the past. We get more done, if only because we save a couple of hours of commuting each day, and online meetings tend to be more focused. You can also catch up on those emails in meetings where you are expected to attend but have limited input…or so I have heard.

One problem with this positive view of how well things are going is that we are not only missing those corridor chats with our colleagues but also those chats with colleagues from other institutions around the globe. The benefit of conferences being run online is that you no longer need to find the budget for the travel and hotels from those ever-stretched faculty finances. It also reduces our carbon footprint, which as environmental scientists we should be doing. However, the new science ideas and collaborations, so often born out of informal chats in the evening over a meal or a drink, are not coming along so often. This lack of opportunities to meet across institutions also means we're not sharing our educational experiences and developments either.

At the end of 2020, a COVID-19 Working Group led by Kate Hendry of the University of Bristol and supported by Jackie Pearson of the National Oceanography Centre Association of Marine Science National Capability Beneficiaries conducted a survey to assess the impact of COVID-19 on the wider UK marine science community. Of 193 respondents, just half of were university based. The full report, which can be found at https://naqbase.noc.ac.uk, identified those most strongly impacted by the pandemic as being (1) early career researchers, (2) women (who have often ended up juggling a career with home schooling of children), and (3) staff on fixed-term contracts. That covers many of my academic and research colleagues. In the early stages of the pandemic in the UK, 35% of marine fieldwork teaching was canceled or postponed along with over half of the face-to-face teaching. A large number of staff have found it hard to work from home, and many feel isolated without those corridor chats and interactions. Many (40%) have seen their administrative workloads increase. Over half have had less time or opportunity to write new grant proposals, which is not surprising, given that much of the past year has been about major restructuring of courses as the main priority for delivering high-quality learning experiences for our students.

It would appear from the report that the current modi operandi, mid-COVID, are not sustainable in the long term for most institutions. However, there are some aspects that I think should be kept. I have sat in countless curriculum meetings in past years exploring how we might dramatically improve learning experiences for both undergraduate and postgraduate students, as well as making the learning more efficient. To start from a ground zero approach and rebuild better, and with experience, is a perfect solution that would never be implemented due to the time and effort it would take. Rather than the faculty forcing our approach, it has taken a pandemic. Many of my colleagues, who I do still meet online, on the boat, and in the lab, see a blended approach as the future. More materials will be placed online (both live and recorded) for the dissemination of information—the role the traditional in-class lecture has played. There will be smaller and more involved practical and boat sessions for the face-to-face component of a student's learning pathway. Fewer assessments will be carried out, often moving away from the traditional exam approach of decades past into more innovative activities, which may be more time-consuming to grade, but will provide better indications of students' abilities. Such suggestions would have been untenable two years ago, but we have found ourselves in a very different learning environment in 2021. Let's hope that 2022 brings us the opportunity for a new approach to learning, rather than continued firefighting in a pandemic.

AUTHOR

Simon Boxall (srb2@noc.soton.ac.uk) is Associate Professor, Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton, UK.

CAREER PROFILES Options and Insights


Photo credit: John Woods

John W. Farrell, Executive Director, United States Arctic Research Commission – jfarrell@arctic.gov

Degree: When, where, what, and what in?

Having completed a bachelor's degree in geology at Franklin & Marshall College in 1983, I proceeded straight to graduate school at Brown University, where I finished a master's degree in 1986 and a PhD in 1991, both in geological sciences, with an emphasis on marine geology (paleoceanography, paleoclimatology, isotope geochemistry). Given his patience, understanding, and generosity, I couldn't have been more fortunate than to have Warren Prell as my thesis advisor.

Did you stay in academia at all, and if so, for how long?

While a graduate student, I participated in two scientific ocean drilling expeditions (Legs 121 and 138) of the Ocean Drilling Program. Those experiences connected me to an incredible cross section of international scientists, many of whom became colleagues and friends after 60-day stints at sea. I also learned how to write proposals, initially to the Joint Oceanographic Institutions – US Science Support Program, funded by the US National Science Foundation (NSF), and how to manage the resulting grants. I parlayed that experience into writing proposals directly to NSF and was fortunate to receive grants as a graduate student (although technically submitted by more senior departmental personnel). While these grants extended my tenure as a student, they also set the stage for a self-funded postdoc at Brown in a different subdiscipline (strontium isotope geochemistry). I loved the research, learning new subdisciplines, generating data with sophisticated equipment, writing papers, giving talks, meeting new colleagues, and doing laboratory and field work.

I applied for a number of faculty positions and accepted a position as a Senior Research Associate at the University of British Columbia, in Vancouver, to work on the Joint Global Ocean Flux Study (JGOFS). This was a transition for me, from a department of geological sciences to oceanography. Again, jumping into new research areas was exciting, and I loved it. There was so much to learn and do, and my Canadian sponsors, Tom Pedersen and Steve Calvert, were wonderful. The perspective of working as a scientist, outside the United States, was also enlightening as I came to appreciate the global perspective of US scientific research.

How did you go about searching for a job outside of the university setting?

While in Canada, I continued to apply for faculty positions, but, because I had interests in addition to research, I also looked at a wide range of job opportunities outside of academia, such as at the National Academy of Sciences, as a Congressional Fellow, at philanthropic foundations, in the federal government, and at nonprofit science organizations. In early 1995, I had a tenure-track offer at a state university and another offer to work as an Assistant Program Director at Joint Oceanographic Institutions Inc. (JOI). It was a difficult choice. I loved research (more than teaching), had some early successes with it, and most of my colleagues were from the "Ivory Tower" and expected me to remain in it. Nevertheless, I was concerned about what appeared to be a glut of Earth science PhDs on the job market, the lower success rates of proposals, the less-than-transparent process by which proposals were selected for funding, the endless appetite of university administrators for more tuition-paying students, and the high start-up costs for the kind of research I was most interested in pursuing as a faculty member. At the same time, while I never envisioned working as a geologist in Washington, DC, at a desk, let alone wearing a suit. I was attracted to the Assistant Program Director job because I really liked the Ocean Drilling Program and hoped that I could somehow help contribute to its success. I was also most fortunate to be selected by Ellen Kappel, who taught me how to be a program manager and who has remained a valued colleague and friend for over 25 years.

Is this the only job (post-academia) that you've had? If not, what else did you do?

Ironically, after nine years at JOI, I accepted a job back in academia, as Associate Dean of Research and Administration at the University of Rhode Island's Graduate School of Oceanography. I bypassed the tenure track route and went straight to university administration. Given my experience as a program manager, it was easy to return to academia in such a position, and I enjoyed it immensely. But another great opportunity arose in Washington, DC, in the federal government, and for family and professional reasons, I applied.

What is your current job? What path did you take to get there?

Since 2006, I have held a US Federal Government Senior Executive Service position as Executive Director of the US Arctic Research Commission, a small, independent federal agency (www.arctic.gov). The immediate path to this position was an announcement about the job opportunity from Garry Brass, the previous director, whom I knew through association with the Ocean Drilling Program (again, emphasizing the value of an extensive network of colleagues). But I would be the first to admit that the true "path" to this position was more like a "drunken sailor's random walk." My only prior experience with Arctic research had been a challenging effort to plan and execute the first high-Arctic scientific drilling expedition in 2004 with the Integrated Ocean Drilling Program (ACEX, Expedition 302: Arctic Coring Expedition). So, despite limited Arctic knowledge and experience, and no prior federal service, I applied, hoping that I'd get a shot, because the job looked interesting. Fortunately, I got the nod.

What did your oceanographic education (or academic career) give you that is useful in your current job?

An extended period of formal training in any natural science is excellent preparation for life in general. I credit that education with nurturing my inherent curiosity and developing an ability to apply the scientific method to all sorts of challenges: observing keenly and reasoning rigorously, seeking empirical evidence, verifying and proving thinking critically, maintaining impartiality, and developing theories while regarding them with caution. I find this quote from Brian Deer to be apt: "Courage in science isn't proving yourself right. It's in your efforts to prove yourself wrong."

For two reasons I think that, compared to other disciplines, being a geological oceanographer is interesting. First, we tend to develop a knack for coming up with explanations and hypotheses despite having sparse data sets. So, either we're comfortable with uncertainty, or we love arm waving. Second, we often tend to be generalists, drawing on a number of subdisciplines (such as geochemistry, geology, geophysics, physical oceanography, biology, ecology, statistics) to address questions. I have found this approach to be rewarding, given my broad range of interests. I'm not an expert in any one of them, yet there's strength and value in being minimally facile in all. This has taught me to not fear diving headfirst into new and often completely unfamiliar issues. I've found it an advantage to be a generalist in a world where others are encouraged to specialize, often to extremes, which, admittedly, is also necessary to advance science.

Is there any course or other training you would have liked to have had as part of your graduate education to meet the demands of the job market?

If there is a course or training on how to effectively and legally circumvent mindless bureaucracy, sign me up. I've had to learn that on the job, and it's "life-long learning." It's always helpful to understand how money flows, is budgeted and accounted for, but I'd have dreaded sitting through a formal course on that. Similarly, deeply understanding people, including yourself, and how to communicate, motivate, and work with others is key, but I imagine the only way to learn that is on the fly, in your day-to-day life. The best thing you can do is continue to expose yourself to new and sometimes uncomfortable situations. Take risks. You'll learn from them.

Is the job satisfying? What aspects of the job do you like best/least?

After early employment doing yardwork, newspaper delivery, busboy gigs, and construction (day laborer), I've had the great fortune and privilege of having wonderful jobs. They have enabled me to live in beautiful and exciting places and to travel a good portion of the world, many times over; to work at sea in the Arctic, Indian, Atlantic, and Pacific Oceans; and to meet an amazing array of professionals, not just scientists, but also diplomats, military personnel, technologists, doctors and veterinarians, engineers, analysts, agents, politicians, journalists, pilots, artists, and yes, even attorneys (along with a few charlatans). Currently, I like being the head of a small organization. It provides great freedom and opportunity. You can fly below the radar when necessary, but if lucky and plucky, punch above your weight class because of your flexibility and autonomy.

Do you have any recommendations for new grads looking for jobs?

Feed and foster your curiosity. Read broadly. Be open, even if it feels unnatural. When given the option, meet and work together in person (as opposed to virtually) in challenging situations and environments to forge strong and lasting relationships. Don't be reluctant to apply for jobs for which you are not fully qualified. Prepare well for job interviews, read up, know your stuff, listen carefully, and ask questions. Learn how to negotiate an offer. Don't give up.

CAREER PROFILES Options and Insights

Francis K. Wiese, Senior Principal, Marine Science Lead, Stantec – francis.wiese@stantec.com

Degree: When, where, what, and what in?

I earned a BSc from the University of Victoria, Canada, in 1993, taking advantage of all the marine science courses I could get my hands on. Many years later, I went back to graduate school at Memorial University of Newfoundland, Canada, and completed a PhD in conservation biology in 2002. My dissertation focused on the impacts of chronic marine oil pollution on seabird populations in the eastern Canadian Arctic. Hundreds of oiled seabirds had been washing ashore on beaches in Newfoundland for decades, and no one was quite sure how big a problem this was or how to mitigate it. Through a combination of statistics, beached bird surveys, studying carcass beach persistence, drift block experiments, and a whole bunch of spatial and population modeling, I found the answer: up to 300,000 birds were being killed a year due to illegal dumping of bilge oil from ships transiting the great circle route from Europe to North America. By engaging with several Canadian federal agencies and nongovernmental organizations (NGOs), we finally managed to change Canadian environmental legislation to address this issue. The number of dead oiled birds in this area has been declining since.

Did you stay in academia at all, and if so, for how long?

I did stay in academia for almost three years. I went from Newfoundland to do a postdoc at the University of Washington in Seattle, working with Julia Parrish. We focused on the strange nexus of internationally protected seabirds being shot at hydroelectric power dams along the Columbia River as part of a predator control program designed to safeguard federally protected salmon that were being raised in hatcheries.

How did you go about searching for a job outside of the university setting?

My PhD and my postdoc exposed me to a breadth of professionals in many fields outside academia, and the topics I focused on nurtured my interest in studying large-scale marine ecosystem dynamics. I did not want to focus on just one issue. About two years into my postdoc, I started considering my next steps, always thinking I would go back to the tropics where I had spent a significant amount of time after my undergraduate degree. Open to anything fun and interesting anywhere on the globe—but that would pay the bills because I was married and had three kids by then—my search pattern was pretty wide. Then one day, I believe through the electronic university job postings, I came across an ad for the North Pacific Research Board (NPRB). They were looking for someone to help build out a marine science funding program in Alaska focused on marine ecosystem understanding and sustainable fisheries management. I jumped at it.

Is this the only job (post-academia) that you've had? If not, what else did you do?

Having always had many different interests and loving to travel, I took some time after my undergraduate degree to figure out if I wanted to go to grad school at all. So, I worked in a variety of marine programs: studies of humpbacks off Cape Cod for a summer, seabirds in the North Sea for a few months, and sharks in the Bahamas for six months, and then as a dive instructor in the Galápagos Islands for a year. In between, I needed to make a more substantial living and worked as a cab driver and a bar keeper on night trains throughout Europe. Then, during grad school, having started a family a few years prior and not being able to live on a grad student stipend, I did a lot of consulting work on the side, mostly for the Canadian government on issues related to my PhD studies. I also did some conservation work for NGOs and translations from different languages into English for various institutions. While working for NPRB, I began to take time off to work as a lecturer and naturalist on ships in the Antarctic. After eight years at NPRB, I was considering going back to academia or doing something on my own when I was approached by Stantec, a global environmental and engineering consulting firm. Eventually, they convinced me to join them, and that is still where I am now.

What is your current job? What path did you take to get there?

I currently lead the marine sciences for Stantec in the United States and help spearhead marine and coastal projects around the world. In this capacity, I contribute to the technical quality of the marine-related work we do; design marine research, monitoring, and assessment studies; work on climate change drivers and impacts; and support our internal innovation office in designing new tools and implementing new ideas and technologies to help solve problems related to coastal and marine ecosystems and climate change around the world. Everything is a team effort, and I love working with people across the globe from a plethora of disciplines in science, engineering, and architecture. Stantec is originally a Canadian firm, and I got hired because they wanted someone who could think broadly but also knew the players across North America, initially in Canada in particular, and I was adept at writing proposals. How I ended up here was not a straight line by any means, but reflecting back, the varied interests and opportunities I pursued, the focus on applied science, reviewing hundreds of proposals every year, and the curiosity to experience all the different sectors of society studying the ocean prepared me perfectly for what I do now.

What did your oceanographic education (or academic career) give you that is useful in your current job?

To think creatively, critically, and in multiple dimensions. The ability to take a lot of information and distill it down to the pertinent issues, then design a robust scientific program to address the question at hand. Throughout my academic career, and in between, I also had the opportunity to work with a lot of different people from communities, industry, and government. All those skills and that exposure is critical in what I do today, where I work on half a dozen projects at any one time, creating solutions with people from all walks all life, all the while maintaining scientific quality and integrity.

Is there any course or other training you would have liked to have had as part of your graduate education to meet the demands of the job market?

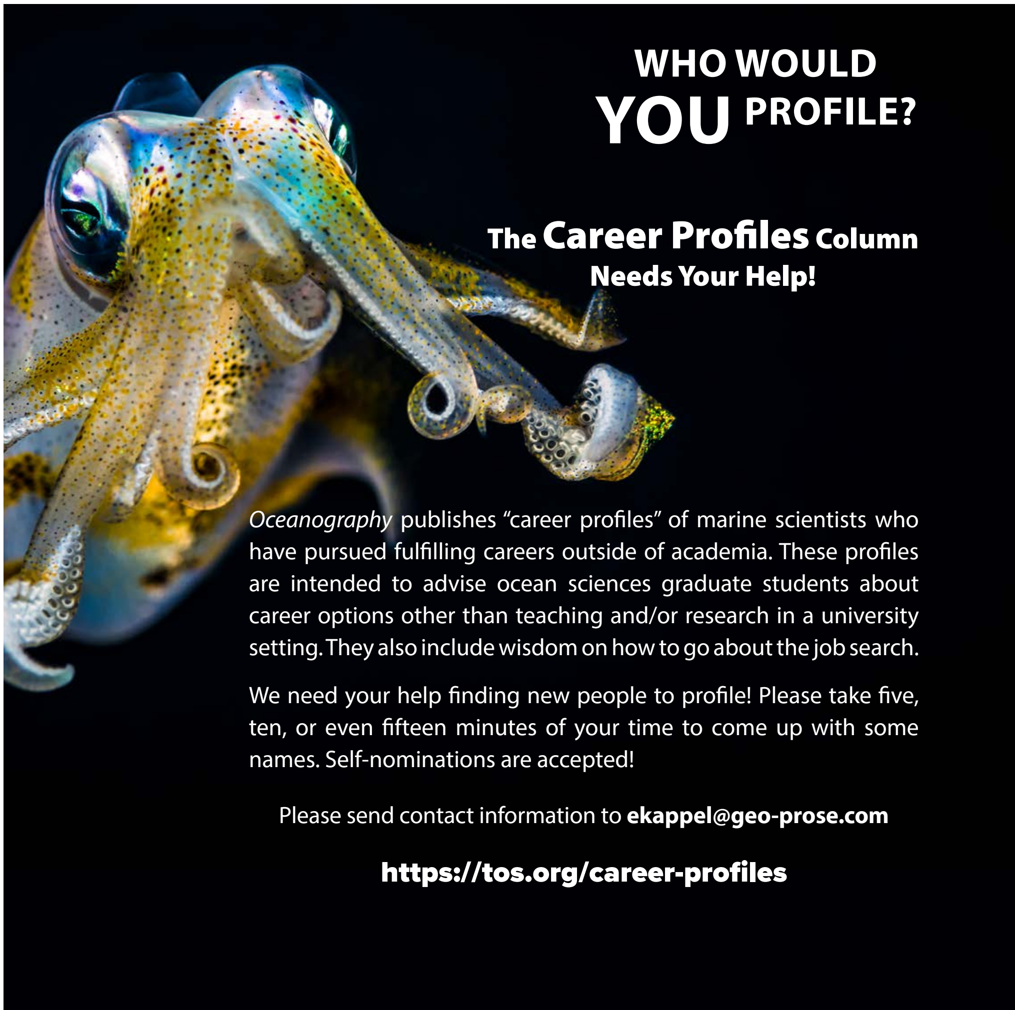
Proposal writing would have been good, although eventually I got the hang of it. More GIS skills and learning how to do more sophisticated spatial analyses would have been helpful. I learned to program in SAS and MATLAB, but R would have been more useful. Business management would have come in handy when I first started at this large consulting firm to better understand how this world works, and a degree in communication—you figure it out eventually, but nothing is more important than being able to communicate clearly and succinctly to a wide variety of audiences. Oh, and fluvial geomorphology, just because it's amazing how it makes landscapes come to life.

Is the job satisfying? What aspects of the job do you like best/least?

I love what I do because of the global scope of my job and because the opportunity to be involved in many different projects with many different people speaks to my many interests and the system thinking my mind likes to go to. Even within this large structure, I get to pursue my passions in marine research and climate change, and participate in national panels and committees on a variety of issues. I don't enjoy the administrative part, but fortunately I have many colleagues who do, so it is kept at a reasonable minimum.

Do you have any recommendations for new grads looking for jobs?

Follow your passion and keep an open mind to different opportunities that come your way, even if they are not what you expected to be doing next. Few careers develop on a straight path, but when you get there, it all falls into place. If it seems interesting and fun, go for it. I interview many people for work, and their passion for what they do is half the ticket; you can't fake that. Talk to everyone, and don't be afraid to use those connections to get in the door. Sometimes getting noticed for that first look at your CV is all you need, and then you can take it from there. You might be nervous in an interview, but it's best to just be yourself, and don't hide your passion. You never know when one opportunity or conversation will lead to the next one that will help land your dream job.



WHO WOULD YOU PROFILE?

The Career Profiles Column Needs Your Help!

Oceanography publishes "career profiles" of marine scientists who have pursued fulfilling careers outside of academia. These profiles are intended to advise ocean sciences graduate students about career options other than teaching and/or research in a university setting. They also include wisdom on how to go about the job search.

We need your help finding new people to profile! Please take five, ten, or even fifteen minutes of your time to come up with some names. Self-nominations are accepted!

Please send contact information to **ekappel@geo-prose.com**

https://tos.org/career-profiles

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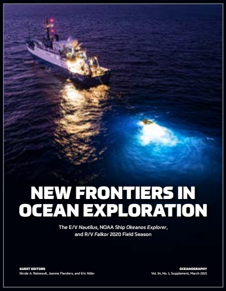

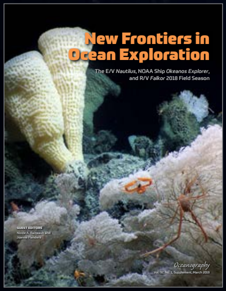

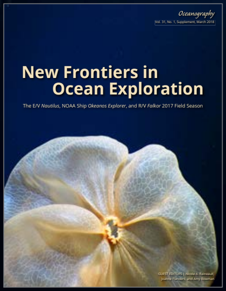

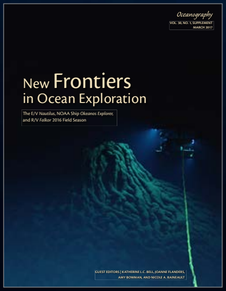

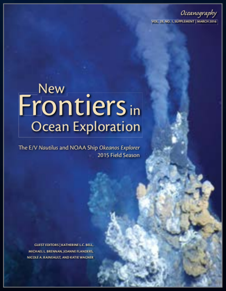

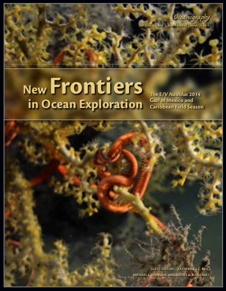

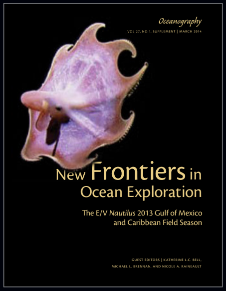

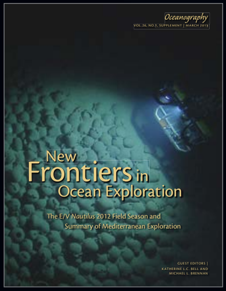

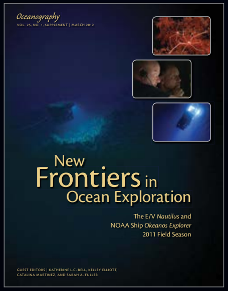

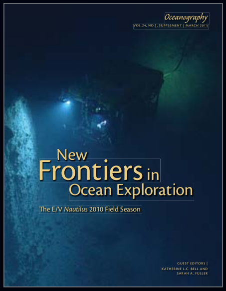

First published in 2011, these annual supplements to *Oceanography* provide details about the innovative technologies deployed to investigate the seafloor and water column and explain how telepresence can both convey the excitement of ocean exploration to global audiences and allow scientists as well as the public on shore to participate in expeditions in real time. The supplements also describe the variety of educational programs the Ocean Exploration Trust, the NOAA Office of Ocean Exploration and Research, and the Schmidt Ocean Institute support in conjunction with schools, museums, visitors centers, and aquariums, as well as internships that bring high school students, undergraduates, graduate students, teachers, and artists on board ships. Through these supplements, we have explored the geology, chemistry, biology, and archaeology of parts of the global ocean and seas. We hope you enjoy these booklets and share them widely.

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