Science in support of the *Deepwater Horizon* response

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This introduction to the Special Feature presents the context for science during the *Deepwater Horizon* oil spill response, summarizes how scientific knowledge was integrated across disciplines and statutory responsibilities, identifies areas where scientific information was accurate and where it was not, and considers lessons learned and recommendations for future research and response. Scientific information was integrated within and across federal and state agencies, with input from nongovernmental scientists, across a diverse portfolio of needs—stopping the flow of oil, estimating the amount of oil, capturing and recovering the oil, tracking and forecasting surface oil, protecting coastal and oceanic wildlife and habitat, managing fisheries, and protecting the safety of seafood. Disciplines involved included atmospheric, oceanographic, biogeochemical, ecological, health, biological, and chemical sciences, physics, geology, and mechanical and chemical engineering. Platforms ranged from satellites and planes to ships, buoys, gliders, and remotely operated vehicles to laboratories and computer simulations. The unprecedented response effort depended directly on intense and extensive scientific and engineering data, information, and advice. Many valuable lessons were learned that should be applied to future events.

science-based decision making | Gulf of Mexico | Spill of National Significance | Macondo | Oil Pollution Act

> "We are fighting an omnidirectional, almost indeterminate threat here. 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

The *Deepwater Horizon* (DWH) disaster, which began on April 20, 2010 with a blowout of BP Exploration and Production, Inc.'s Macondo well located in lease block MC252 in water ~1,500 m deep and 84 km from Venice, Louisiana, resulted in the largest mobilization of resources to address an environmental emergency in the history of the United States. From day 1 to well shut in on day 87 and the present (timeline in Fig. S1), we oversaw or assisted the tactical and strategic responses of our agencies and supported the overall US Government's effort. The papers in this Special Feature focus on how scientific information was used to inform the response.

Although the US Coast Guard (USCG), the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA) were well-versed in oil response and remediation and the National Response Team responded quickly, the level and scope of DWH taxed our organizations in unprecedented ways, requiring substantial mobilization of resources and people inside and outside of the government and extraordinary interagency coordination.

As Admiral Allen's quote emphasizes, the situation of the Macondo blowout was unprecedented, with oil spewing forth into an extreme ocean environment—deep, cold, dark, and high pressure—but rapidly spreading to midwaters, the surface, and the atmosphere. These circumstances resulted in a constantly changing set of logistical and policy challenges (1) (Fig. 1). Although predicted as likely (2, 3), the presence of deep suspended microscopic oil droplets was not part of BP's federally approved spill response plan and had never before been confronted as an operational response priority. Assessing the quantity of subsurface oil and its likely environmental consequences (e.g., threats to biota and potential for inducing hypoxia) required considerable human and material resources.

Experience and response methods applicable for other oil spills in many cases proved either impossible to apply or ineffective. New science needed to be developed and delivered rapidly to allow appropriate decisions and actions to be taken—day in and day out for months. We applied lessons from the *Exxon Valdez* Oil Spill (EVOS), such as using caution in choice of shore cleanup techniques to avoid doing more harm than good and paying attention to the vulnerability of juvenile stages of living organisms. From EVOS, we know that oil exposure has both acute toxicity and chronic effects (4), especially for juvenile stages. However, DWH was different from EVOS; the latter occurred in a cold environment near the surface and the shore, and it entailed a different type and known quantity of oil.

This introduction to the Special Feature integrates much of the key science mobilized or conducted during DWH. We highlight ways in which science was used in real time to inform the response and the public. We draw on our experiences, papers in this Special Feature, and other published literature. We highlight areas where scientific information used was later determined to be accurate and areas where it was not. We identify lessons learned about use and communication of scientific information and priority areas for research.

This Special Feature focuses on the physical and environmental science and engineering that guided the response. We do not address environmental health, human health, social impacts, or economic impacts; as of November of 2012, they are still being documented and evaluated as part of the Natural Resource Damage Assessment (NRDA) and the Gulf Long Term Follow-up Study of the National Institute of Environmental Health Sciences, for example.

To understand how science informed the response, knowledge of the response structure and process is essential. The basic legal authorities and responsibilities in place to deal with a major oil spill stem from the Oil Pollution Act, which was amended in 1990 (OPA90) and implemented through the National Contingency Plan (NCP). Oil spill provisions of the NCP specify a role in response for Responsible Parties (RPs; here, BP): specifically, the responsibility for costs associated with

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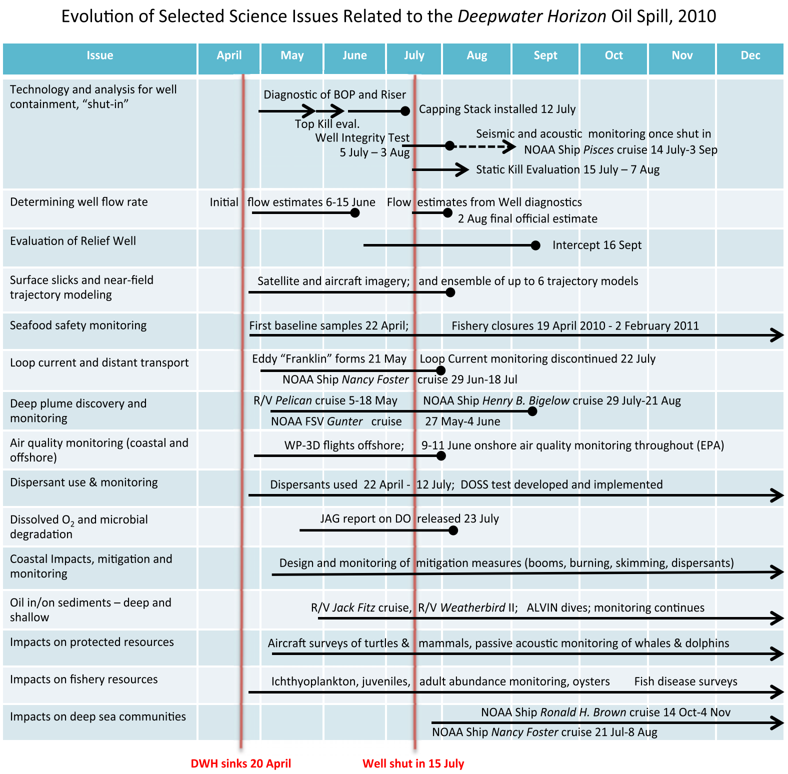

Fig. 1. Timeline of various science-related issues during the DWH oil pollution event. Some additional science-related issues continue beyond 2010.

removal, cleanup, and claims resulting from discharge or threat of discharge and costs of much of the response under the direction of the federal government. The USCG, as the On-Scene Coordinator (OSC) for maritime spills, is charged with ensuring that the RP takes appropriate action. NOAA is designated by Congress to be the scientific advisor to the OSC and act as the Scientific Support Coordinator for scientific issues that include "expertise in environmental chemistry, oil slick tracking, pollutant transport modeling, natural resources at risk, environmental tradeoffs of countermeasures and cleanup, and information management." (5)

The NCP provides for an extraordinary determination that the spill is one of national significance on the basis of several factors, including a substantial threat to public health or welfare. In this case, the USCG established a National Incident Command that assumes specified duties of the OSC in directing the response. Under the NCP, on day 10, DWH was declared a Spill of National Significance, giving the RP significant responsibilities under the direction of the OSC and the newly named National Incident Commander (NIC), USCG Commandant Admiral Thad Allen.

The NCP has been used to respond to a number of oil spills but never one of this magnitude and complexity. Moreover, DWH was unlike conditions envisioned in the tanker-centric OPA90 (passed in the wake of EVOS). Drilling technology had evolved significantly since OPA90 was passed, but comparable advances in response capacity had not been achieved.

A key role of the NIC was to coordinate the whole of government response. The response included multiple interagency command centers in Washington, DC and three states (National Incident Command, Unified Area Command Center, and Incident Command Centers in Houma, LA, Mobile, AL, and Miami, FL—moved to St. Petersburg, FL). In addition, the NIC, a Senior Advisor to President Obama, and the US Government Principals (Secretaries of the Departments of Interior, Homeland Security, and Energy and the Administrators of EPA and NOAA) met at least daily throughout most of the event.

Scientific Responsibilities and Timeline of Scientific Support

Some scientific responsibilities are prescribed in legislation or regulations (described above). However, the unique nature of DWH posed unanticipated needs for scientific information. In response to these novel challenges, new scientific working groups were formed. These groups were established during the first several weeks as the scope and scale of the accident and the resulting oil spill began to emerge (Fig. 1 and Fig. S1). Most teams were constituted by the NIC under the auspices of the Federal Interagency Solutions Group and drew on expertise within and outside the federal government. They reviewed and evaluated scientific and technical information, devised solutions to specific problems, and advised the NIC, the Principals, and the President. Not well-integrated initially, these teams became better coordinated in time through the NIC and the Principals' group (6). New scientific teams created for DWH included the following:

i) The Flow Rate Technical Group (FRTG), chaired by US Geological Survey (USGS) Director Marcia McNutt, was composed of more than six research groups and independent experts that developed assessments of the rate of escaping oil from the Macondo blowout.

ii) The Oil Budget Calculator Science and Engineering Team (Oil Budget Team), co-led by Bill Lehr of NOAA, Sky Bristol of USGS, and Antonio Possolo of the National Institute of Standards and Technology and composed of government, academic, and industry experts, estimated the amount of oil in different categories to enable effective oil recovery efforts.

iii) The Government-Led Science Team (GLST), led by the Secretary of Energy Steven Chu and Tom Hunter (Sandia National Laboratories, retired) and consisting of Department of Energy National Laboratories and USGS, and outside scientists developed technical analysis and paths forward for flow control in close collaboration with BP and provided an independent determination of leak rate.

iv) The Operational Science Advisory Team, chaired initially by Carl Childs (NOAA) and later by Lieutenant Commander Kenneth Boda (USCG), directed and then synthesized information on the amount of residual oil in the subsurface, on the bottom, and in the water column to devise response and potential recovery strategies.

v) The Joint Analysis Group (JAG), chaired by NOAA Fisheries Chief Scientist Steven Murawski, analyzed the plethora of data produced by government, academic, and industry-sponsored monitoring activities to determine the concentration, distribution, and impacts of subsurface oil, particularly the evidence for dissolved oxygen depletion in subsurface waters as a result of the DWH spill.

This paper provides an overview of the overall response and emphasizes information from the last two teams, other agency's scientific efforts, and papers in this Special Feature. Results from efforts of the first three groups are presented in the work by McNutt et al. (7).

The interagency scientific coordinating mechanisms relied heavily on new intra-agency coordination bodies. For example, NOAA stood up coordinating bodies to integrate scientific efforts across its satellite, weather, oceanographic, atmospheric chemistry, fisheries, seafood safety, protected species, habitat, oil spill cleanup expertise, research, mapping, impacts, and restoration units. With partners at the University of New Hampshire, NOAA adapted its spatially explicit management tool, the Emergency Response Management Application (ERMA) (*SI Text*), for broad interagency use, populating it with relevant data and information to enable efficient evaluation of assets and needs as well as rapid decision-making. Consistent with policies on openness and transparency, the Obama Administration decided to make large portions of ERMA available to the public on day 56. On the first day of going public, ERMA (http://gomex.erma.noaa.gov) received 3.5 million hits—a powerful indicator of the intensity of public interest in DWH.

Nongovernmental scientists played a vital role during the response. Traditionally, academic and private institutions provide scientific input primarily through contracting mechanisms on various aspects of spills, which are determined by needs of science agencies (e.g., documenting damage to natural resources through the NRDA process as outlined in OPA90). DWH triggered an unprecedented response by the academic community. Not only were numerous academics under contract by federal and state agencies and BP, but the National Science Foundation also awarded 88 grants totaling over $11 million in its Rapid Response program to study various aspects of the spill. Additionally, on day 35 (May 24, 2010), BP committed $500 million over 10 y to fund a broad independent research program, the Gulf of Mexico Research Initiative, although the first funds were not available for months. Additionally, numerous academic and private institutions launched independent investigations. As described above, numerous academic scientists also participated in the ad hoc scientific working groups that advised the NIC.

Given the enormous interest by the academic community, there was difficulty in mobilizing unified approaches and communication systems. The White House Office of Science and Technology Policy, federal agencies, universities, and partners, such as the Consortium for Ocean Leadership, convened a series of meetings with government, academic, and independent research scientists (*SI Text*). Each meeting was productive, but collectively, they were insufficient to satisfy the need for near real-time transmittal of new findings and discussions of priorities moving forward. Many independent and university scientists were frustrated, and misunderstandings resulted from scientists obtaining most of their information from the news media rather than scientific reports.

From the outset, scientific support was necessary to address a diverse and continually evolving suite of issues and potential threats to worker safety, human health, and ecosystems (Fig. 1). The response and mitigation of the spill grew to encompass over a dozen major sets of scientific investigations, all requiring multiple agencies, review mechanisms, and collaboration with academic and in some cases, international partners. Balancing the portfolio of resources (both human and logistic) among these many diverse issues was a management challenge. Even collectively, we did not possess all of the ships, aircraft, laboratory access, or personnel necessary to evaluate every issue to the satisfaction of all.

The following sections address major questions that drove the scientific support effort. Where is the oil going? Should dispersants be used and if so, at the surface, at depth, or both? How should oil be removed, captured, and cleaned up? Is seafood safe? How should wildlife and habitats be protected? The work by McNutt et al. (7) summarizes the parallel efforts to estimate the flow rate, control the source, test for well integrity, and determine the oil budget. We conclude by reflecting on improving the use of science for future events with the hope that it will never be needed.

Where Is the Oil? Where Will It Go? Where Did It Go?

Tracking and predicting surface oil was a clear priority, even before the extent of the Macondo blowout was known. Within hours of the explosion, NOAA's oil trajectory models and spot weather forecasts began providing at least daily guidance to first responders and then later, those individuals involved in all aspects of the response. The location and amount of oil on the surface of the water varied considerably from day to day (Movie S1). Early modeling of surface trajectories involved three separate models—by NOAA, Texas A&M University, and the Navy; these models evolved into an ensemble of six models providing short- and longer-term forecasts of surface trajectories for oil. These models used ever more sophisticated ground truthing to document distribution of surface oil and inform the models with oceanographic data (oceanographic modeling for DWH is archived at http://www.aoml.noaa.gov/phod/dhos/index.php, and detailed oceanographic cruise data are archived at http://www.nodc.noaa.gov/General/DeepwaterHorizon/ships.html). Satellite imagery (coordinated by the National Aeronautics and Space Administration and NOAA) and images and reports from fixed-wing and helicopter aircraft provided model starting conditions daily. Comparison of results from the ensemble of surface trajectory models allowed evaluation of forecast uncertainty. *SI Text* and Fig. S2 have information about longer-term modeling and the Loop Current.

An oil budget was developed and maintained by the NIC (8) specifically to target efforts to recover oil (7). The oil budget depended on estimates of flow rate, finally determined to be 62,000 ± 10% barrels per day (bpd) at the beginning of the event and 53,000 ± 10% bpd on day 87 at well shut in (7, 9). Despite aggressive recovery and removal efforts, only around one-quarter of the oil was removed by the federally directed response. Most of the oil on the surface was too distributed for efficient skimming and burning. The final tallies for recovered oil indicate that around 5% was burned, 3% was skimmed, and 17% was recovered directly through the riser pipe (8).

Airborne, surface, and subsurface chemical measurements (10) were used to independently calculate a total hydrocarbon flow rate. Those analyses showed that ~5% by mass of the discharged hydrocarbons evaporated to the atmosphere and 10% contributed to the surface slick; the balance dissolved or dispersed within the water column, with about one-third directly detected in the deep persistent plumes.

Unexpected new methodologies to estimate flow rate emerged (e.g., estimating flow rate from air chemistry measurements). NOAA and academic scientists flew a special mission to evaluate air quality for workers on vessels in the Gulf near the spill. They discovered that not all constituents in the hydrocarbon fluids emanating from the well reached the surface or evaporated. However, with a sample of the original well fluid (11), the study by Ryerson et al. (12) was able to determine those components that passed through the ocean filter to the atmosphere unabated and use the detection of those components to estimate the total flow rate from the well. In addition, by observing the depletion of the other constituents, the study by Ryerson et al. (12) estimated the fraction of hydrocarbons dissolved in the ocean. Because this methodology is not dependent on access to the well or well shut in, it shows considerable promise for future spills.

Combined with the total flow rate and hydrocarbons remaining on the ocean surface (13), a consistent picture emerged about where the oil went. Only about one-half of the oil and none of the methane gas ever reached the ocean surface (10). A third remote-sensing estimate of flow rate, consistent with other values, was provided by imaging oil droplets in the water column using a narrow-beam echo sounder deployed from a surface ship sonar (14). This methodology is also independent of direct access to the well, but it is inherently less accurate than a direct measurement. Nonetheless, both indirect methods should be pursued as useful tools during any future catastrophic spill.

What Remains of DWH Oil in the Environment?

Repeated sampling of offshore waters revealed that, by August 3, 2010 (106 d after oil began flowing and 19 d after shut in of the well), oil had dissipated to background levels in offshore water samples (15). Sediment sampling in deep (15) and shallow (16) waters revealed grounded oil in deep areas around the wellhead, deep-water sites to the northeast and southwest of the well, and many shallow coastal areas around oiled marshes and near some beaches (*SI Text*).

The assessment of oil in deep-water benthic animals (15) concluded that there were areas that experienced significant accumulation of oil on sediments. Some deep coral communities around the well have been impacted, mostly less than 20 km from the wellhead (17). In the beach and near-shore environment, weathered oil samples showed 86–98% depletion of total polycyclic aromatic hydrocarbons (PAHs) (16). Models predict that PAH concentrations in supratidal buried oil will decrease to 20% of current levels within 5 y, except under isolated conditions (16). Two particular routes of exposure pose potentially elevated risks to aquatic and wildlife resources in the beach environment: ingestion of tar balls by adult subsurface-probing shore birds and contact between buried oil and sea turtle eggs and hatchlings (16). A comprehensive assessment of DWH-associated injuries to natural resources is underway as part of NRDA.

Should Oil Be Dispersed Chemically? How?

The decision to apply chemical dispersants in response to the DWH oil spill was driven by two initial goals: accelerate natural degradation of hydrocarbons by changing the surface-to-volume ratio, thus exposing more oil to naturally occurring bacteria, and keep oil from sensitive coastal ecosystems, fisheries, and estuaries. The scientific literature and lessons learned from previous spills provided some insights into the conditions and circumstances under which dispersants would be more or less effective (sea-state conditions, geographic location of the spill, and physical properties of spilled material) (3) as well as the environmental tradeoffs associated with surface dispersant application (18).

Novel subsea application of dispersants was raised early in the event as a potential response strategy. Arguments in favor included (*i*) direct injection of dispersant into the leaking wellhead 1,500 m below the water surface could maximize the exposure of oil to dispersant before it significantly weathered and emulsified with water, (*ii*) compared with surface applications to slicks, significantly less dispersant would be required to achieve the same goal, and (*iii*) potential exposure of spill response workers to both airborne dispersants from surface application and volatile organic compounds associated with the spill could be minimized (19). This latter concern was not trivial considering the hundreds of workers on the rigs drilling the relief wells and the dozens of support vessels on scene directly above the leaking well (*SI Text*). Arguments opposing subsea application of dispersants included (*i*) lack of understanding of potential consequences, (*ii*) potential to trigger severe hypoxia as microbial action rapidly degraded oil droplets and methane gas in the water column, and (*iii*) potential for dispersed oil and dispersants to cause damage to subsea flora and fauna. Balancing these tradeoffs was not easy, but the potential for more rapid degradation of hydrocarbons was compelling.

Because of the unprecedented nature of this technique, the EPA administrator responsible for making the final decision, in consultation with the NIC, decided that implementation should be contingent on (*i*) strict monitoring of dissolved oxygen, particle size, rotifer toxicity, and water and sediments, (*ii*) additional toxicity screening of dispersants, and (*iii*) rapid communication of data to responders and the public (20, 21). Results from daily toxicity testing on rotifers using commercially available Rototox testing kits indicated no significant biological impacts on test organisms (22).

Repeated sampling in the waters surrounding the spill detected an oxygen "sag," but this reduction never approached levels considered hypoxic (Fig. 2) (23–25). Dissolved oxygen (DO) measurements collected along vertical profiles and in discrete water samples remained above the 2 mL/L hypoxia threshold set by the EPA, the USCG, and the NIC that would trigger possible suspension of subsea dispersant injection (25).

An important technical issue also arose during this monitoring. DO is customarily measured using electronic meters with a semipermeable membrane. Researchers and one instrument manufacturer raised concerns that the membrane might be fouled in oiled waters and provide unreliable measurements. Accordingly, the JAG advised that the DO measurements be confirmed by traditional Winkler titrations to supplement the meter-derived observations (Fig. 2). In some instances, contemporaneous observations with both methods confirmed the advisability of dual sampling methodologies (25, 26).

Aerial surveys and shallow fluorometric monitoring are typically used to measure particle size of near-surface oil as an indicator of dispersant efficacy. Particle size monitoring in the deep sea required modified approaches, such as vertical profiling and sampling at the ocean floor (27, 28). Cumulative particle size data suggest that the range of observed droplet diameters was consistent with chemically dispersed oil (25).

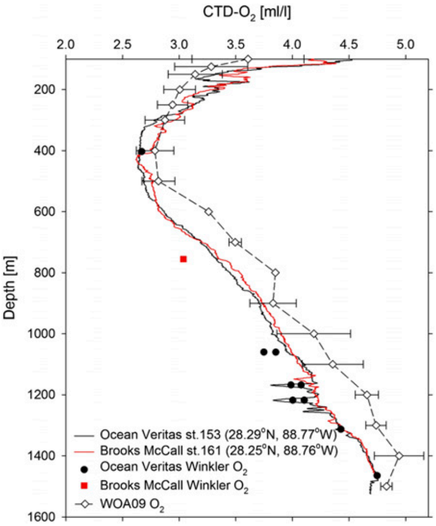

Fig. 2. Comparison of DO profiles in the vicinity of the DWH site: conductivity–temperature–density (CTD)/O$_2$ (SBE43) and Winkler O$_2$ values for Research Vessel *Ocean Veritas* station 153 (occupied on August 2, 2010), Research Vessel *Brooks McCall* station 161 (occupied on August 5, 2010), and World Ocean Atlas 2009 (WOA09) (56) annual mean and SD from a 1° grid box centered at 28.5°N and 88.5°W. The figure and other analyses (57) suggest that the CTD/O$_2$ sensors on both ships were comparable and within ~0.1 mL/L of the Winkler O$_2$ analyses. The O$_2$ depressions at ~1,200 m shown by the SBE43 sensor are also reflected in the Winkler values, and these profiles are representative of measurements taken earlier in the summer in the vicinity of the wellhead (24). They also illustrate the importance of both measurement techniques in accurately assessing DO levels in the presence of oil.

These measurements and others led to revisions of the relative amount of chemically vs. naturally dispersed oil in the Final Oil Budget (8). The amount of chemically dispersed oil doubled from the initial estimates (from 8% to 16% of the total).

In response to concerns about potential persistence of dispersants in the environment, thousands of water and sediment samples from near-shore and offshore were collected and tested for major dispersant constituents, such as butoxyethanol, dipropylene glycol *N*-butyl ether, propylene glycol, and dioctyl sodium sulfosuccinate (DOSS). Few water and sediment samples showed detectable levels. None of the water samples showing detectable concentrations exceeded EPA's aquatic life benchmarks (22). Although the NCP requires manufacturers to submit toxicity information for approved products (29), additional data on oil-dispersant mixtures, endocrine effects, and other parameters were and are needed.

The EPA conducted in vitro and whole-animal toxicity tests on eight dispersants listed on the NCP product schedule, including the product predominantly used in DWH (Corexit 9500A) as well as mixtures of dispersants with Sweet Louisiana Crude (SLC) oil and SLC oil alone. Whole-animal tests were conducted on two test species commonly found in the Gulf: mysid shrimp (*Americanmysis bahia*) and silverside fish (*Menidia beryllina*). Results indicate that none of the dispersants tested displayed biologically significant endocrine-disrupting activity (30); dispersants alone were less toxic than dispersant–oil mixtures. SLC oil alone was generally similarly toxic to both test species as dispersant–oil mixtures, and the toxicity of Corexit9500A was generally similar to the toxicities of other available dispersants (31).

Additional studies are required before a more complete understanding of tradeoffs with use of dispersants is known (*SI Text*), including potential impacts of dispersants, dispersed oil, and oil alone on the plethora of other species in the Gulf, especially plankton and juvenile stages.

Is Seafood Contaminated with Hydrocarbons?

Before DWH, around one-fifth of the seafood caught commercially in US waters came from the Gulf of Mexico (32). Keeping Gulf seafood safe was a crucial part of the response (33). NOAA has authority to close federal waters to fishing during an oil spill; states regulate fisheries in their waters. The first step was to close oiled or potentially oiled waters based on the observed presence of oil or model projections of where oil was expected to be in the next 24, 48, and 72 h. The first fishery closure in federal waters occurred on day 13 (May 2, 2010); at its peak in early June of 2010, ~88,500 square miles (~37%) of federal waters in the Gulf were closed to fishing.

New scientific protocols were developed by NOAA, the US Food and Drug Administration (FDA), and the Gulf Coast states to determine when waters were safe to be reopened to fishing or harvest of oysters. Knowledge of differential uptake, metabolism, and disposition of PAHs in fish, crustaceans, and bivalves informed the tests (34): fish were known to metabolize PAHs relatively rapidly, crustaceans metabolized PAHs less rapidly, and bivalves metabolized PAHs almost not at all. The bivalves of greatest concern in the Gulf were oysters. Once contaminated, they should not be eaten. (Oyster fisheries occur in state, not federal, waters.) For an area to be reopened to fishing, it had to meet three criteria: be free of oil for at least 30 d, be free of expected oil for the next 72 h based on model trajectories, and pass repeated tests on different types of seafood (fish and crustaceans) sampled over multiple days for PAHs and DOSS (the dispersant component of greatest potential concern). Of oil contaminants, the high molecular weight PAHs are of greatest health concern because of their environmental persistence and potential for toxic or carcinogenic effects in humans (35).

Lessons learned from previous oil spills guided efforts to ensure that consumers would not be exposed to contaminated seafood (33, 36, 37). Risk management analyses informed reopening protocols (37); specifically, a human health risk assessment was conducted to determine maximum PAH exposure levels believed to be safe and associated with negligible risk for consumers. Because uncertainty is inherent in any risk assessment process, various assumptions are made to estimate human population risks, with some subpopulations being at higher risk because of higher seafood consumption per unit body weight or more susceptible to PAH effects because of compromised health. The inputs used in the health risk assessment were derived to be overly protective to account for uncertainty and variability. Subsequent testing of Gulf seafood revealed very low levels of PAHs or levels below quantification. Thus, even when higher consumption values were applied to the risk model and at-risk subpopulations (e.g., pregnant mothers), seafood tested did not seem to pose a health risk (33).

Extensive sampling across a large geographic area and a wide range of species was required. Testing for PAH and DOSS was needed to respond to public concerns. In total, more than 8,000 seafood specimens were tested for PAHs and DOSS.

Before DWH, tests for PAH were time consuming, and no validated routine tests existed for dispersants. During the response to DWH, a rapid method to measure PAHs in seafood was developed and validated by the FDA (38); NOAA and the FDA developed and validated a sensitive method to measure DOSS (39, 40). The rapid PAH method allowed larger numbers of samples to be analyzed faster. In developing a more rapid PAH method, there were tradeoffs in both sensitivity and specificity; however, these tradeoffs were offset by also using a well-validated comprehensive GC/MS method (41) as the standard for measuring PAHs in seafood and confirming PAH screening results.

Of the compounds in the dispersant mixture, DOSS was the greatest potential concern because of its bioactivity, extremely low volatility, and potential to persist in the environment longer than other dispersant components. Although previous research suggested that DOSS posed a low risk to seafood consumers (42), the new methods allowed quantification of presence in Gulf seafood. Development and application of analytical methods during DWH were key scientific achievements. Beginning on day 130, federal waters that met all criteria (absence of oil on the water, and if oil had been present, seafood passing repeated laboratory tests for PAHs and DOSS) were successively opened to fishing, progressing from least to most oiled areas. By day 210 (November 15, 2010), all but 0.4% of federal waters had been opened. The final closed area, in the immediate vicinity of the well, was opened on day 365 (April 19, 2011) (Fig. S1).

This extraordinary effort to protect the integrity of seafood seems to have been successful: no tainted seafood was reported to have reached the market. An independent assessment arrived at the same conclusion (43). Nevertheless, public perceptions about seafood safety continued throughout the event and beyond. This area is ripe for social science research. After seeing images of oil and gas flowing from the riser pipe and images of oil-covered shores and birds day after day and week after week, many people had difficulty believing that oil was disappearing rapidly from open waters, fish could metabolize PAHs, and seafood testing was reliable.

What Is the Process for Assessing the Environmental Impact of the Spill? What Is the Best Path to Restoration? What Is the Role of Science in Damage Assessment?

Science was as important to assessment of damage and design and monitoring of restoration as it was to the response. Among the numerous potential economic, social, human health, and environmental impacts of DWH, injury to natural resources and the public's access to them is regulated under OPA90 (specifically, the NRDA regulations) (44). [NRDA statute is 15 CFR § 990 *et seq*. Trustees (or natural resource trustees) means those officials of the federal and state governments, Indian tribes, and foreign governments designated under 33 USC 2706(b) of OPA 15 CFR § 990.30. There are seven primary trustees involved in the DWH NRDA, the five affected states (Texas, Louisiana, Mississippi, Alabama, and Florida), and two federal agencies (the Department of Interior and the Department of Commerce through NOAA). Baseline means the condition of the natural resources and services that would have existed had the incident not occurred. Baseline may be estimated using historical data, reference data, control data, or data on incremental changes (e.g., number of dead animals) alone or combined as appropriate.] These regulations designate federal, state, and tribal natural resource trustees to conduct NRDAs on behalf of the public. To meet this mandate, the trustees seek to restore to baseline (the condition that they would have been in had the spill not occurred) injured resources and services and compensate the public for interim losses (i.e., the losses that occur during the time that it takes the resources to recover to baseline).

In view of the size, duration, and four-dimensional and complex nature of the spill in the Gulf, the DWH NRDA (including restoration; see below) may continue for years. Federal and state trustees are working together to determine how the oil spill affected the Gulf of Mexico's natural resources and the human use of those resources. With potential natural resource injury spanning five states and their waters as well as federal waters, this damage assessment is the largest ever undertaken.

Under OPA90, NRDA has three phases: the preassessment phase, in which the trustees determine whether impacts to natural resources have occurred; the injury assessment/restoration planning phase, in which the trustees quantify injuries and identify possible restoration projects; and the restoration implementation phase, in which the trustees implement restoration to baseline and monitor its effectiveness. Typically, the information in all three phases is initially retained outside the public domain. During DWH, in support of a commitment to openness and transparency and after determining that doing so would not jeopardize their case, the trustees decided to allow public access to most of the data collected during phase one before assessment of injury (*SI Text*).

Conclusion, Lessons Learned, and Research Priorities

The DWH event required real-time science to inform responders on varied aspects of the spill—from directly collaborating with BP to mitigate risks associated with stopping the release and determining the flow rate to measuring and modeling the fate of the oil to assessing effects on the air, seafood, species, and habitats (Fig. 1). Scientists from government, industry, and the broader research community responded with novel applications of existing methods—e.g., reservoir modeling (45), echo sounder flow detection (14), enhanced-resolution γ-ray imaging of the blow out preventer (BOP) (46), and use of technologies originally adapted for researching deep-sea geological processes (47). New methods were also developed such as testing for dispersant in seafood (33, 42) and estimating flow rate from atmospheric measurements (12). The science of deep spill containment, mitigation, and impacts has rapidly accelerated because of the necessity of responding to this event. Response to future deep spills globally will benefit from the many scientific breakthroughs applied to DWH and emerging after the response as well as the lessons learned. The scale of this spill and the scientific efforts directed to assessing its magnitude and containing it deserve attention, both for what was revealed about subsurface processes and the ability of public institutions and industry to respond to such a disaster and for what new approaches and tools that we now have at our disposal.

Scientific revelations from the DWH spill are many, and we continue to be surprised by numerous aspects, such as the discovery of novel microbial communities (48) and the conditions that led to rapid decomposition of hydrocarbons during this event (49). Full conclusions about the impact of the oil on species, ecosystems, and people will necessarily await ongoing analyses for detecting long-term impacts. Some results are beginning to emerge, such as effects on marsh fish (killifish) (50), but sweeping conclusions about impacts are premature. Similar to the EVOS spill, some effects may be unknown or unappreciated for years, if ever (4).

Based on the DWH experiences, we compiled a list of scientific priorities for future oil spill response preparedness (51).

- Gather adequate environmental baselines for all regions at risk.
- Develop new technologies for rapid precise reconnaissance and sampling to support a timely and robust response effort.
- Support the development of models and decision support tools, such as scenario planning (52), to enhance response and damage assessment.
- Fill large information gaps regarding biological effects of oil, changing climate, and other simultaneous drivers of variability in coastal and aquatic ecosystems.
- Build coupled ecosystem-scale routine monitoring/research/communications for every large marine ecosystem (LME) in US waters, including the coastal zone, to provide integrated interdisciplinary understanding of how the ecosystem works and is changing, ideally as a partnership with academic institutions in the region.
- Put greater emphasis on social science data collection, including adequate baselines, to understand costs to the region and the nation of oil spill disasters.
- Conduct research on impacts of dispersants and dispersants plus oil on a broad array of species and life stages.
- Develop more efficient methodologies for capturing oil at the surface.
- Conduct social science studies to understand public perceptions about seafood safety.

Additional lessons and suggestions for improvements related to preparedness and coordination with the scientific community are below.

Although there was much criticism of the pace of response efforts, we witnessed a tremendous effort on the part of our scientific institutions, various ad hoc and standing committees, and individuals to be nimble, think outside the box, and work in collaborative ways unanticipated under the provisions of OPA90. Throughout the crisis, we provided integrated and comprehensive information to guide the response—to stop, contain, track, measure, and remove the oil, protect the integrity of the seafood supply from the Gulf, and safeguard wildlife. Coordination of these efforts required a monumental effort and careful attention to scientific information.

Throughout the crisis, we also shared new information publicly as soon as we had good reason to believe that it was accurate given the information at hand. Notably, we did not speculate. We were criticized both for sharing information and not speculating about consequences or significance when pertinent facts were not available. Some thought that we were minimizing the extent and severity of the spill. Therefore, it is relevant to ask: "how accurate was the information released during the event?" With the benefit of postcrisis information, much, although not all, of the information that we released during the crisis is now known to have been accurate. Here is a short summary of both based on information provided in this paper and the work by McNutt et al. (7).

i) The basic conclusions of the preliminary oil budget released on August 4 were correct (7, 8): approximately one-half the oil was, indeed, gone (recovered, burned, skimmed, evaporated, or dissolved).

ii) However, the science team underestimated the amount of oil that had been dispersed chemically (8% of the total in the preliminary oil budget vs. 16% in the final budget) and slightly overestimated the amount of naturally dispersed oil (16%; later determined to be 13%). (The total amount of dispersed oil was originally estimated at 24% and later revised to 29%.)

iii) As we reported in early August, to the disbelief of many people, much of the oil that had been dispersed (either naturally or chemically) was rapidly being consumed by bacteria (23, 26, 48, 49).

iv) Fishery closures plus newly developed and rigorously implemented protocols for testing of seafood for the components of hydrocarbons and dispersant that were of potential concern seem to have been successful, because no tainted seafood was reported to have entered the seafood supply.

v) The lack of DOSS in tested seafood (fishes and crustaceans) seems to support our expectation that either dispersant degraded rapidly or it was metabolized quickly by exposed animals. (This finding does not mean that dispersants had no environmental impact but only that the information in hand is consistent with the expectation that this component of dispersant degraded or was metabolized rapidly with respect to contamination in these taxa.)

vi) Luckily, the Loop Current (*SI Text*) did not behave in an average fashion. Based solely on climatology, there was concern early in the disaster (by numerous scientists, including government scientists) that the Loop Current might transport oil to the Florida Keys and possibly beyond. Fortunately, 2010 was an atypical year.

vii) Although there was much speculation in the scientific community (government and academic) and some modeling results predicted hypoxia caused by oxidation of deep dispersed oil and methane, such an event never occurred. The evidence suggests that this result is because of two factors: rapid biodegradation of hydrocarbons by bacteria (23, 26, 48, 49) and use of dispersants where hydrocarbons were spewing forth. The use of deep injection of dispersants was carefully monitored on a daily basis along with the levels of dissolved oxygen in the 1,000- to 1,200-m depths, where dispersed oil was known to be accumulating. The full extent of environmental damage caused by the use of such dispersants is not yet fully known, but if we are faced with such a choice in the future, information available to us now would lead to a similar recommendation to proceed with caution and an abundance of monitoring.

viii) Although the flow rate announced as 5,000 bpd on day 9 was suspected by government scientists as well as others of being a significant underestimate (7), the absence of a single credible methodology available to derive an accurate flow rate quickly led the NIC to establish the FRTG and charge it with devising the best possible estimate using a combination of methodologies. Successive estimates were announced on days 37 (12,000–19,000 bpd), 53 (20,000–40,000 bpd), and 57 (35,000–60,000 bpd) as new information came to light, with a final estimate derived from pressure measurements of 62,000 bpd at the outset and 53,000 bpd at well shut in for a total of 4.9 ± 10% million barrels (7) (Fig. S1). Note that it is misleading to compare the FRTG flow rates directly with higher flow rates from nongovernment researchers, because the FRTG rates are oil flow rates only, whereas the early nongovernment flow rates are total discharge: oil plus liquid natural gas. The total discharge (oil + liquid gas) numbers should be multiplied by 0.29 before being compared with days 37 and 53 FRTG estimates and 0.41 to compare with day 57 FRTG flow rate to account for only the oil fraction.

The lack of reasonable estimates of flow rate early on was problematic from the perspectives of both communications and response, but the lack was caused by real uncertainty rather than any attempt to hide information or underestimate numbers. It is true that much of the response did not depend on knowing the exact rate, but some of it did, particularly the capacity to capture oil directly from the well. It is reasonable to suggest that future permits be conditional on having mechanisms to rapidly assess flow rate to ameliorate the problem in the future.

Still unresolved are issues having to do with environmental impacts (impact of oil, dispersants, and dispersed oil on coastal, midwater, and benthic taxa and communities, marine mammals, turtles, and birds), human health, and economic and social impacts.

Based on these conclusions and our broader experiences, some of the lessons that we learned include the following:

i) The importance of preparedness cannot be overstated. The consequences of lack of investment over the last few decades in scientific understanding and technological development were obvious during DWH. Despite significant advances in technology that allowed drilling in deep waters, comparable progress had not been made in devising methods that would have enabled us to stop the flow from deep wells or deal with a spill of the magnitude seen in DWH. Both could and should have been anticipated. Scientific and technological expertise had to be mobilized de novo to create solutions. Cleanup technologies had advanced little since EVOS. The Herculean efforts expended during the event were admirable, but planning for events like those that began on April 20, 2010 and investing in developing the capacity to deal with them would likely have made a significant difference. In view of how important it is to know flow rate to mobilize part of the response effort, preparedness should include devices installed on extraction equipment to provide flow rate information if needed as well as redundant mechanisms in case of failure.

ii) Preparedness also extends to acquiring a basic understanding of the places likely to be affected by a spill at the LME scale (e.g., the Gulf of Mexico). Accidents during exploration, extraction, transport, or offloading take place within coupled human and natural systems. Basic understanding of the dynamics of the ecosystem and consequences of changes to people requires a comprehensive, integrated monitoring/research/communication effort focused on an LME, ideally through the development of regional scientific collaboration networks. This understanding must be more than spatially explicit descriptions of the species present. It should include an integrated understanding of the physical and ecosystem dynamics sufficient to know where oil is likely to flow (along the shallow and deep inner shelf and not just open surface waters), which species and life stages would be affected at different times of the year, and how impacts to those species would affect other species, the functioning of the ecosystem, the provision of ecosystem services, and other impacts on people. This knowledge is needed for every LME in the US Exclusive Economic Zone (and adjacent waters, where relevant), and it would vastly enhance effective response and understanding of impacts. Moreover, it has the added benefit of significantly enhancing a variety of other management efforts—water quality, invasive species, fisheries, shipping, recreation, and conservation. Achieving this integrated knowledge and sharing it publicly require stable funding and mechanisms to integrate monitoring, research, and communication activities across a region and the nation.

iii) The DWH spill highlighted the need for enhanced capacity to respond to spills and conduct training and other preparedness activities before spills occur. Capacity includes trained people, technical knowledge, equipment for oil removal, and protocols and networks that can be activated quickly. The spill pushed our agencies to the limit. Had another significant spill or natural disaster (such as a major hurricane) occurred at that time, our ability to respond would have been severely limited. The government and industry have taken some steps to increase response capacity, such as with the establishment of two containment consortia, but more progress is needed on an adequate funding mechanism for research and development focused on improving oil spill response, especially in frontier areas such as the Arctic (53). The DWH incident also saw the willingness of the academic community to act in disaster-response mode. New arrangements for training and funding need to be developed to enable greater participation from academic and other sectors.

iv) Mechanisms are needed for rapid mobilization of more funding for research during a spill, especially early in an event. Although some funds were available through mission agencies and the National Science Foundation early in the response, they were insufficient to enable the broader array of knowledge acquisition that researchers were ready to tackle and that could assist in providing a more complete understanding of DWH impacts as well as better response to future events (54). Mission agencies rapidly mobilized numerous preexisting relationships (e.g., with university or independent scientists) through ongoing research relationships financed through competitive grants and preexisting contracts to provide services in the event of a spill. For example, all of the seven NOAA vessels deployed for DWH response in the Gulf had academic researchers on board doing research at one time or another. In parallel, the National Science Foundation quickly provided funds to many other researchers. However, taken together, these mechanisms were insufficient to provide adequate funds with the rapidity required. Moreover, legal constraints stipulated in OPA90 on funding provided by the RP during the event meant that only response activities, not research, could be supported with those funds.

v) Effective mechanisms are needed to enable rapid two-way communication with the broader scientific community. No single mechanism existed for us to communicate easily with the large, undefined, and interdisciplinary community of scientists. The US Government set up daily calls with governors, members of Congress from Gulf Coast states, parish presidents, and journalists. Unlike those easily identified groups, "scientists interested in the spill" were a challenging group to identify quickly and communicate with frequently and in the depth required for meaningful exchanges. New vehicles for that communication needed to be created. Universities in the Gulf region and the Consortium for Ocean Leadership were helpful but did not begin to represent the universe of interested scientists. Meetings and workshops were valuable but did not begin to meet the ongoing desire for credible scientific information. For the most part, many scientists could get and share updates only through information in the public press, which led to considerable misunderstandings and great frustration. Solutions include the development of regional scientific collaboration networks (discussed in lesson *ii*) that could serve as a starting point and better use of web-based communication tools.

vi) A new dialogue within the scientific community and possible new mechanisms are needed to resolve the tensions around the appropriate time to share preliminary findings with the public. The public demand for information created a challenging dynamic. A clash of three cultures emerged: the media/public appetite for instantaneous information regardless of accuracy, the need for rapid but accurate information to inform the response, and the scientific convention of waiting for journal peer review and publication before sharing results. Some academics waited for results of the journal peer review before talking about any of their results. Agencies and some academic scientists held themselves accountable for ensuring quality assurance and quality control (QA/QC) of results (but not peer review) before releasing data or interpreting findings; then, there was peer review for final results. Other academics talked about new findings with the media well before any QA/QC, much less any peer review. Our rationale for sharing new data and preliminary results after they had gone through the QA/QC process reflected a commitment to rapid but accurate results and openness and transparency in the midst of a crisis and a recognition of the additional, sometimes significant time required for peer review. One option is to explore ways for very rapid peer review.

A parallel problem concerns intellectual property. The community currently lacks effective processes to provide rapid but accurate information for decision-making while still respecting many journals' interests in reporting new knowledge not previously shared. During DWH, some nongovernmental researchers did not want their findings widely disseminated in the press, because they thought it would prevent subsequent publication. Some prestigious journals, like *Science*, sent clear signals that, in light of the need for all credible information to inform the response, the journal would make an exception (55). Responders need to make decisions in a timely way that takes advantage of diverse science and views. Protecting intellectual capital is also important. However, some scientists communicated misleading or wrong information and conclusions in the press before results had been substantiated, leading to massive and avoidable confusion, waste of resources, and loss of public confidence. There is a need for a vigorous debate among scientists, editors, and agencies to find common ground to act on best science in a crisis while still protecting scientific discovery.

vii) During a crisis, scientists must respect that the priority needs of the response must come before acquisition of new knowledge when the two are in direct conflict. In parallel, responders must support gathering new data, unless those activities interfere with the response. Another culture clash ensued in the immediate vicinity of the wellhead. Academic and independent researchers wanted access to the well site at depth, but their presence had strong potential to interfere with operations to stop the flow of oil. Remotely operated vehicles (ROVs) controlled from the surface with acoustic commands were attempting delicate maneuvers at depth in the dark. Scientific ROVs had strong potential to interfere physically or acoustically with response ROVs. After one response ROV accidentally bumped into and dislodged the riser insertion tube tool (an early device for collecting oil inside the riser), the NIC declared a "no go" zone in the critical area around the well. Permission to enter that zone was then allowed by the NIC only if activities would not interfere with response operations. Although some researchers understood and respected the "no go" zone, others complained that a heavy-handed government was preventing science from proceeding.

viii) Although a new standard for transparency and rapidity of data sharing was set with DWH, it was not enough to satisfy everyone. The federal agencies made an unprecedented effort—in the midst of the response—to provide data about the spill in raw and synthesized form using the web and other vehicles. (*i*) A spatially explicit management tool previously available only to responders, the innovative ERMA, was rapidly transformed into a publicly accessible platform that could serve the millions of hits per day expected (and received). This tool made very large datasets available as soon as they could be go through the QC process. In some cases, private businesses, such as ESRI, Inc. and Google, assisted in developing data visualization capabilities specifically for oil spill communication. (*ii*) New web vehicles were developed to communicate both spill and restoration efforts (*SI Text*). (*iii*) In light of the keen interest in the question of "where did the oil go?," the Administration chose to share a preliminary version of the oil budget, consistent with its commitment to transparency. (*iv*) The NRDA Trustees, at the urging of NOAA, took the unprecedented step of releasing much of the preassessment data collected for the NRDA. Notwithstanding this significant and ongoing effort at transparency, public and media interest in the event created a demand for almost instantaneous collection and synthesis of information far beyond the capabilities of existing science and institutions to collect, process, and verify as accurate.

ix) The scientific teams (FRTG, Oil Budget, GLST, Operational Science Advisory Team, and JAG) created during DWH were highly successful in trouble-shooting, designing solutions, analyzing and synthesizing data, and evaluating options. Similar mechanisms should be used for future Spills of National Significance or other major crises, where interagency, interdisciplinary, broad-based scientific input is needed. Equally important is the commitment of leadership during the response to use information from science teams. These teams ensured that strong scientific expertise was available to inform the response. An important element of these teams was the inclusion of outside experts. Equally important were scientists at the helms of agencies who articulated the need for these scientific teams, supported the inclusion of expertise within and outside government, and ensured the groups' reports and recommendations were understood and incorporated into the response. These teams provided an excellent complement to the Scientific Support Coordinators advising the OSC in the region. The newly created science teams during DWH provided broader interdisciplinary expertise to deal with the many new challenges faced in the DWH disaster. Strong support by the NIC for the science teams and a firm commitment to use their input in responding was fortuitous and essential. Planning for future event should include similar mechanisms and specific roles for scientific information and scientists in the process at multiple levels of decision-making.

x) Intimate engagement with industry is essential. The government did not have the equipment needed to perform the mechanical operations required near the sea floor, but it played an unprecedented role in helping BP gain control of the well. Although formal guidance was issued to BP through directives from the NIC, intimate engagement with BP in Houston allowed independent assessments of events to support timely decisions in support of the government's role in the crisis (7). In the process of understanding the issues of the well and well control, the GLST found that deep-water drilling technologies would have benefited from an improved systems perspective. Instrumentation built into the BOP capable of providing accurate and redundant data that would allow cross-verification of the situation was missing. For example, a system of ROV-accessible electronic and visual measurements of the position and lock status of the BOP's rams would have been greatly helpful. There was no pressure instrumentation installed on the Top Hat, and several pressure gauges on the BOP and capping stack failed during the DWH incident. Other examples of needed deep-water technologies include autonomous underwater vehicles capable of station-keeping in the deep sea with methods for delivering data for satellite transmission at the ocean surface to remotely monitor the well during storms. Another important contribution of the GLST was its insistence that relevant data be taken whenever possible. These data proved to be critical to the most significant evaluation of the crisis—the determination that the capped well was not leaking (7). The GLST required enhanced ROV monitoring, more seismic monitoring and analysis, and the addition of unique acoustic monitoring provided by the NOAA vessels. This information ultimately proved to be invaluable in reaching agreement with BP to install the capping stack, conduct the well integrity test, and proceed with the Top Kill.
To engage wider participation from the scientific community, it would be advisable to consider establishing legal protocols and agreement with industry that would allow those individuals involved in any future response access to necessary proprietary data. The oil/gas industry had information that was key to response—video, access to ROV feeds of imagery and data, oil samples, formulations of dispersants, detailed geological maps of the region, and other information. Although the GLST had access to the information that it needed, it was often difficult—especially early on—for other science teams to obtain information from BP in a timely manner. For academic scientists, it was even more difficult (e.g., access to Macondo samples).

Despite these challenges, the response effort was effective, because in large part, high-quality scientific and engineering information was available and used. It is our hope that lessons learned from this disaster will be implemented before and used during any future events.

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1. Anastas PT, Sonich-Mullin C, Fried B (2010) Designing science in a crisis: the *Deepwater Horizon* oil spill. *Environ Sci Technol* 44(24):9250–9251.
2. National Research Council (1999) *Spills of Nonfloating Oils: Risk and Response Committee on Marine Transportation of Heavy Oils* (National Academy Press, Washington, DC).
3. National Research Council (2005) *Oil Spill Dispersants: Efficacy and Effects* (National Academy Press, Washington, DC).
4. Peterson CH, et al. (2003) Long-term ecosystem response to the Exxon Valdez oil spill. *Science* 302(5653):2082–2086.
5. National Oil and Hazardous Substances Pollution Contingency Plan, 40 *Federal Register* 300 (1994).
6. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) *DEEPWATER: A Report to the President, January 2011* (US Government Printing Office, Washington, DC), p 149.
7. McNutt MK, et al. (2012) Applications of science and engineering to quantify and control the *Deepwater Horizon* oil spill. *Proc Natl Acad Sci USA* 109:20222–20228.
8. Lehr B, Bristol S, Possolo A (2010) Oil Budget Calculator *Deepwater Horizon, Technical Documentation, A Report to the National Incident Command, November 2010*. Available at http://www.restorethegulf.gov/sites/default/files/documents/pdf/OilBudgetCalc_Full_HQ-Print_111110.pdf. Accessed January 21, 2012.
9. McNutt MK, et al. (2012) Review of flow rate estimates of the Deepwater Horizon oil spill. *Proc Natl Acad Sci USA* 109:20260–20267.
10. Ryerson TB, et al. (2012) Chemical data quantify *Deepwater Horizon* hydrocarbon flow rate and environmental distribution. *Proc Natl Acad Sci USA* 109:20246–20253.
11. Reddy CM, et al. (2012) Composition and fate of gas and oil released to the water column during the Deepwater Horizon oil spill. *Proc Natl Acad Sci USA* 109:20229–20234.
12. Ryerson TB, et al. (2011) Atmospheric emissions from the Deepwater Horizon spill constrain air-water partitioning, hydrocarbon fate, and leak rate. *Geophys Res Lett*, 10.1029/2011GL046726.
13. Clark RN, et al. (2010) *A Method for Quantitative Mapping of Thick Oil Spills Using Imaging Spectroscopy*, US Geological Survey Open-File Report, Vol 2010–1167. Available at http://pubs.usgs.gov/of/2010/1167/downloads/pdf/OF10-1167.pdf. Accessed February 25, 2012.
14. Weber TC, et al. (2012) Estimating oil concentration and flow rate with calibrated vessel-mounted acoustic echo sounders. *Proc Natl Acad Sci USA* 109:20240–20245.

15. Operational Science Advisory Team (OSAT) (2010) *Summary Report for Sub-Sea and Sub-Surface Oil and Dispersant Detection, Sampling and Monitoring*. Available at http://www.restorethegulf.gov/sites/default/files/documents/pdf/OSAT_Report_FINAL_17DEC.pdf. Accessed January 21, 2012.
16. Operational Science Advisory Team (OSAT) (2011) *Summary Report for Fate and Effects of Remnant Oil in the Beach Environment*. Available at http://www.restorethegulf.gov/sites/default/files/u316/OSAT-2%20Report%20no%20ltr.pdf. Accessed January 21, 2012.
17. White HK, et al. (2012) Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. *Proc Natl Acad Sci USA* 109:20303–20308.
18. Etkin DS (1998) Factors in dispersant use decision-making process: Historical overview and look to the future. *Proceedings of the 21st Arctic and Marine Oil Spill Program Technical Seminar* (Environment Canada, Ottawa), pp 281–304.
19. Coastal Response Research Center (2010) Deepwater Horizon *Dispersant Use Meeting Report, 26–27 May 2010*. Available at http://docs.lib.noaa.gov/noaa_documents/NOAA_related_docs/oil_spills/dwh_dispersants_use_meeting_report-2010.pdf. Accessed January 21, 2012.
20. Dispersant Monitoring Directive EPA (2010) *Dispersant Monitoring and Assessment Directive for Subsurface Dispersant Application*. Available at http://www.epa.gov/bpspill/dispersants/subsurface-dispersant-directive-final.pdf. Accessed February 25, 2012.
21. Quality Assurance Sampling Plan EPA (QASP) (2010) *BP Spill Quality Assurance Sampling Plan to Evaluate the Effects to Water and Sediment from Oil and Dispersant to Shoreline, Nearshore, and Far Off-Shore Areas*. Available at http://www.epa.gov/bpspill/samplingplanjune1/BP_Spill_QASP_May_30_v2.pdf. Accessed February 25, 2012.
22. BP (2010) *BP Rotifer Toxicity Test Results as of September 3*. Available at http://www.epa.gov/bpspill/dispersants-bp.html. Accessed February 25, 2012.
23. Hazen TC, et al. (2010) Deep-sea oil plume enriches indigenous oil-degrading bacteria. *Science* 330(6001): 204–208.
24. Joint Analysis Group (JAG) (2010) *Review of R/V Brooks McCall Data to Examine Subsurface Oil*. Available at http://www.noaa.gov/sciencemissions/PDFs/JAG_Report_1_BrooksMcCall_Final_June20.pdf. Accessed January 21, 2012.
25. Joint Analysis Group (JAG) (2010) *Review of Preliminary Data to Examine Oxygen Levels in the Vicinity of MC252#1, May 8 to August 9, 2010*. Available at http://www.noaa.gov/sciencemissions/PDFs/JAG_Oxygen_Report%20(FINAL%20090410).pdf. Accessed January 21, 2012.
26. Camilli R, et al. (2010) Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. *Science* 330(6001):201–204.
27. SMART (2006) *Special Monitoring of Applied Response Technologies (SMART), v.8/.2006*. Available at http://response.restoration.noaa.gov/sites/default/files/SMART_protocol.pdf. Accessed February 25, 2012.
28. Fingas M-F (2003) *Review of Monitoring Protocols for Dispersant Effectiveness in Report for Prince William Sound Regional Citizens' Advisory Council* (Environment Canada, Ottawa).
29. National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (1994) *National Oil and Hazardous Substances Pollution Contingency Plan (NCP) in Code of Federal Regulations Ch. I (7–1–03 Edition) 59 FR 47453, Sept. 15, 1994, § 300.915, Subpart J*. Available at http://www.epa.gov/oem/docs/oil/cfr/900_920.pdf. Accessed February 25, 2012.
30. Judson R-S, et al. (2010) Analysis of eight oil spill dispersants using rapid, in vitro tests for endocrine and other biological activity. *Environ Sci Technol* 44: 5971–5978.
31. Hemmer MJ, Barron M-G, Greene RM (2011) Comparative toxicity of eight oil dispersants, Louisiana sweet crude oil (LSC), and chemically dispersed LSC to two aquatic test species. *Environ Toxicol Chem* 30(10): 2244–2252.
32. Fisheries of the United States (FUS) (2011) *NOAA, National Marine Fisheries Service*. Available at http://www.st.nmfs.noaa.gov/st1/fus/fus10/02_commercial2010.pdf. Accessed April 25, 2012.
33. Ylitalo GM, et al. (2012) Federal seafood safety response to the Deepwater Horizon oil spill. *Proc Natl Acad Sci USA* 109:20274–20279.
34. Varanasi U, ed (1989) *Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment* (CRC, Boca Raton, FL).
35. Bolger M, Carrington C (1999) *Evaluating and Communicating Subsistence Seafood Safety in a Cross-Cultural Context: Lessons Learned from the Exxon Valdez Oil Spill*, eds Field LJ, Fall JA, Nighswander TS, Peacock N, Varanasi U (Society of Environmental Toxicology and Chemistry, Pensacola, FL), pp 195–204.
36. Hom T, Brown DW, Stein JE, Varanasi U (1999) *Evaluating and Communicating Subsistence Seafood Safety in Cross-Cultural Contexts: Lessons Learned from the Exxon Valdez Oil Spill*, eds Field LJ, Fall JA, Nighswander TS, Peacock N, Varanasi U (SETAC Press, Pensacola, FL), pp 169–194.
37. Yender R, Michel J, Lord C (2002) *Managing Seafood Safety After an Oil Spill* (Hazardous Materials Response Division, Office of Response and Restoration, National Oceanic and Atmospheric Administration, Seattle).
38. US FDA (2010) *Protocol for Interpretation and Use of Sensory Testing and Analytical Chemistry Results for Re-Opening Oil-Impacted Areas Closed to Seafood Harvesting Due to the Deepwater Horizon Oil Spill*. Available at http://www.fda.gov/Food/ucm217601.htm. Accessed February 25, 2012.
39. Gratz S, et al. (2010) *Screen for the Presence of Polycyclic Aromatic Hydrocarbons in Select Seafoods Using LC-Fluorescence, Laboratory Information Bulletin No. 4475, DHHS*. Available at www.fda.gov/downloads/ScienceResearch/UCM220209.pdf. Accessed February 25, 2012.
40. Flurer RA, et al. (2010) *Determination of Dioctylsulfosuccinate in Select Seafoods Using a Quechers Extraction with Liquid Chromatography—Triple Quadrupole Mass Spectrometry. US Food & Drug Administration*. Available at http://www.fda.gov/downloads/ScienceResearch/FieldScience/UCM231510.pdf. Accessed February 25, 2012.
41. Sloan CA, et al. (2005) *Techniques in Aquatic Toxicology*, ed Ostrander GK (CRC, Boca Raton, FL), pp 631–651.
42. Benner RA, Jr., et al. (2010) *Investigation of Corexit 9500 Dispersant in Gulf of Mexico Seafood Species*. Available at http://www.fda.gov/downloads/Food/FoodSafety/Product-SpecificInformation/Seafood/UCM250307.pdf. Accessed February 25, 2012.
43. Gohlke JM, Doke D, Tipre M, Leader M, Fitzgerald T (2011) A review of seafood safety after the *Deepwater Horizon* blowout. *Environ Health Perspect* 119(8): 1062–1069.
44. 15 *Federal Register* 990.30 (2012).
45. Hsieh PA (2010) *Computer Simulation of Reservoir Depletion and Oil Flow from the Macondo Well Following the Deepwater Horizon Blowout. USGS Open-File Report 2010-1266*. Available at http://pubs.usgs.gov/of/2010/1266/of2010-1266.pdf. Accessed September 30, 2012.
46. Hansen R (2011) Lending a hand to an oily problem. *Science & Technology Review*, March:10–17. Available at https://str.llnl.gov/Mar11/sharpe.html. Accessed September 29, 2012.
47. Camilli R, et al. (2012) Acoustic measurement of the *Deepwater Horizon* Macondo well flow rate. *Proc Natl Acad Sci USA* 109:20235–20239.
48. Redmond MC, Valentine DL (2012) Natural gas and temperature structured a microbial community response to the Deepwater Horizon oil spill. *Proc Natl Acad Sci USA* 109:20292–20297.
49. Valentine DL, et al. (2012) Dynamic autoinoculation and the microbial ecology of a deep water hydrocarbon irruption. *Proc Natl Acad Sci USA* 109:20286–20291.
50. Whitehead A, et al. (2012) Genomic and physiological footprint of the Deepwater Horizon oil spill on resident marsh fishes. *Proc Natl Acad Sci USA* 109:20298–20302.
51. National Science and Technology Council, Subcommittee on Ocean Science and Technology (2012) *Deepwater Horizon Oil Spill Principal Investigator Workshop: Final Report* (National Science and Technology Council, Washington, DC).
52. Machlis GE, McNutt MK (2010) Disasters. Scenario-building for the Deepwater Horizon oil spill. *Science* 329(5995):1018–1019.
53. Oil Spill Commission Action (2012) *Assessing Progress: Implementing the Recommendations of the National Oil Spill Commission*. Available at http://oscaction.org/osca-assessment-report-april-2012/. Accessed September 30, 2012.
54. Gagosian RB, D'Elia CF (July 27, 2010) Research on gulf oil spill shouldn't take a backseat to litigation. *Washington Post*. Available at www.washingtonpost.com/wp-dyn/content/article/2010/07/26/AR2010072604443.html. Accessed November 7, 2012.
55. Board of Editors (2010) *Embargo Policies for* Science. Available at http://www.sciencemag.org/site/feature/contribinfo/faq/index.xhtml#embargo_faq. Accessed April 25, 2012.
56. Garcia HE, et al. (2010) *World Ocean Atlas 2009, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation*, NOAA Atlas NESDIS 70, ed Levitus S (US Government Printing Office, Washington, DC).
57. Wanninkhof R, Park G-H, Berberian G (2011) Oxygen winkler titrations by NOAA/AOML in support of Deep Water Horizon spill monitoring. *NOAA technical memorandum OAR AOML-99*, p 15. Available at www.aoml.noaa.gov/ocd/gcc/co2research/datareports/AOML%20Tech%20Memo-99.pdf. Accessed November 9, 2012.