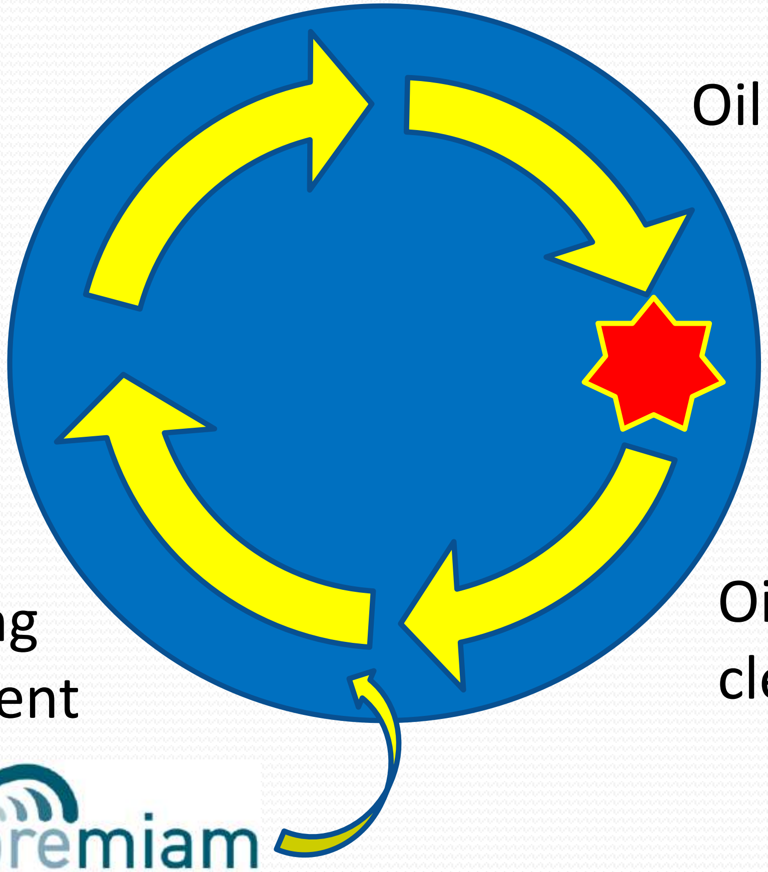
Connecting environmental studies to NEBA / SIMA: appropriate use of science and data

Alun Lewis
Oil Spill Consultant

Virtuous cycle of continuous improvement



Knowledge gained

Oil spill contingency planning

Incident or exercise

Oil spill response and clean-up

Post-spill monitoring and impact assessment

Follow-up scientific studies

premiam

Impact assessment and response effectiveness

- **Impact assessment** is the retrospective measure of the impact/damage caused by a particular oil spill
  - This quantification can be used for various purposes

- **Response effectiveness** could be quantified by the amount of impact/damage <u>prevented</u> by oil spill response
  - This is therefore a measure of something that did <u>not</u> occur
  - It is very difficult to accurately quantify the effectiveness of oil spill response at real oil spills

Real and hypothetical oil spills

- Large oil spills are rare events and are getting more rare
  - Obviously a ‘good thing’, but means that there is a limited knowledge base derived from actual observation and measurement
- There is a regulatory requirement to prepare oil spill contingency plans for certain activities
  - Hypothetical - most often computer modelled - oil spills ‘occur’ at a much higher frequency than real oil spills
- How can we ensure that the computer models used accurately reflect what would really occur in the modelled oil spill scenarios?

NEBA and SIMA

- **Net Environmental Benefit Analysis (NEBA)**
  - NEBA is a structured approach to compare the environmental benefits of potential response tools and develop a response strategy that will reduce the impact of an oil spill on the environment
- **Spill Impact Mitigation Assessment (SIMA)**
  - SIMA is a [NEBA] methodology, developed to help facilitate the selection of the most appropriate response options to effectively combat an oil spill

The SIMA process

1. Compile and evaluate data for relevant oil spill scenarios including fate and trajectory modelling, identification of resources at risk and determination of feasible response options

2. **Predict outcomes/impacts for**
    a. **the ‘no intervention’ (or ‘natural attenuation’) option and**
    b. **the effectiveness (i.e. relative mitigation potential) of the feasible response options for each scenario**

3. Balance trade-offs by weighing and comparing the range of benefits and drawbacks associated with each feasible response option, including no intervention, for each scenario

4. Select the best response option(s) to form the strategy for each scenario, based on the combination of techniques that will minimize the overall ecological, socio-economic and cultural impacts and promote rapid recovery

Some large oil spills of the last 50 years

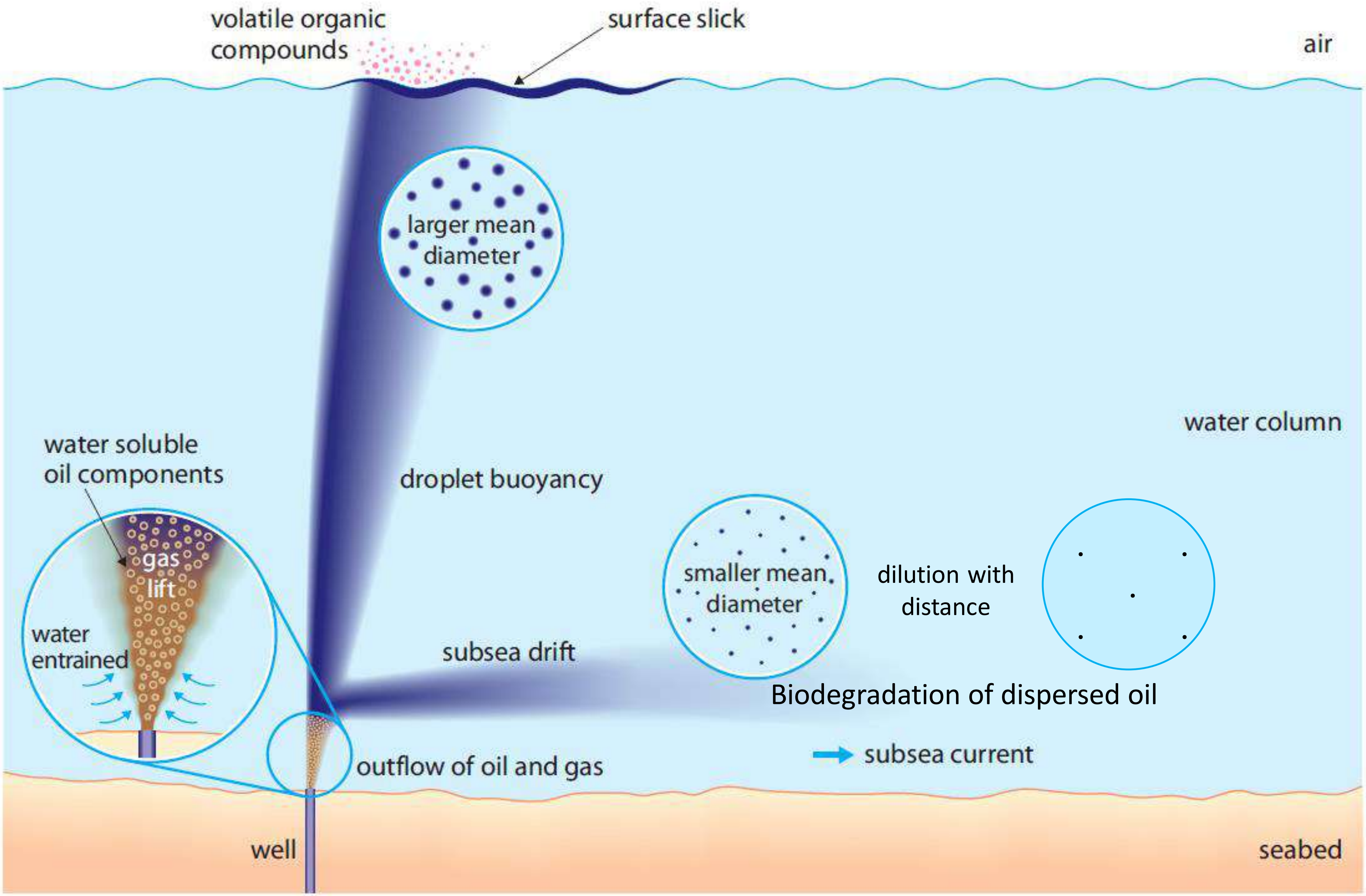
Incident Name	Year	Incident type	Oil spill size (tonnes)	Oil type
Torrey Canyon	1967	Oil tanker grounding	119,000	Kuwait crude oil
Amoco Cadiz	1978	Oil tanker grounding	223,000	Saudi light crude oil
Exxon Valdez	1989	Oil tanker grounding	37,000	Prudhoe Bay crude oil
Haven	1991	Oil tanker explosion and fire	144,000	Iranian heavy crude
Braer	1993	Oil tanker grounding	85,000	Gullfaks (Norway) crude oil
Sea Empress	1996	Oil tanker grounding	72,000	Forties crude oil
Erika	1999	Product tanker break up	20,000	Heavy Fuel Oil
Prestige	2002	Product tanker break up	63,000	Heavy Fuel Oil
Hebei Spirit	2007	Oil tanker collision	11,000	Middle East crude oils
Deepwater Horizon	2010	Subsea gas and oil blowout	430,000	Macondo crude oil

Similarities and differences

- What was learned from these oil spills?
  - Many lessons learned at *Torrey Canyon* about oil spills in general and the inadvisability of using of toxic industrial detergents
  - Dispersant used at *Braer* and *Sea Empress* incidents
    - Extremely rough sea and oil type dominated oil fate at *Braer*
  - Dispersant use not appropriate at *Erika* or *Prestige*
  - Shoreline clean-up significant at most spills

- How much information gained from one oil spill be usefully transferred to the circumstances of another?

The *Deepwater Horizon* incident



Biodegradation of dispersed oil

The Deepwater Horizon incident

- 3.19 million barrels (~ 430,000 tonnes) of oil released into waters of Gulf of Mexico over a period of 87 days

- 1.84 million US gallons (6,631 m^3) of dispersants were used
  - 53% sprayed from aircraft, 42% injected subsea and 5% sprayed from ships

- Very extensive post-spill monitoring and impact assessment conducted for several reasons including
  - NRDA (Natural Resource Damage Assessment) under OPA 90

Dispersant use at *Deepwater Horizon*

- “Traditional” dispersant spraying onto oil on the sea surface:
  1. Oil **dispersed** into water column
  2. Dispersed oil **diluted** to low concentration in water
  3. Dispersed oil **biodegraded** by naturally-occurring microorganisms

- Novel subsea injection of dispersant
  - Much more targeted way of using dispersant
  - Lower dispersant treat rate needed
  - Same general principles: disperse, dilute and biodegrade

Influence of media and the internet

- Internet permitted almost instant propagation of:
  - Information, misinformation (unintentionally false), and disinformation (intentionally false or inaccurate information that is spread deliberately)
- Concern - bordering on hysteria - about the potential effects of the oil spill and the response actions spread widely
  - Stoked by the mis /disinformation and the prolonged nature of the incident
- A wide range of misunderstandings about purpose and effects of dispersant use were put forward
  - And these misunderstandings were not only in the minds of the general public
  - Politicians and regulators were also confused

Oil spills are not scientific experiments

- There are too many uncontrolled variables
    - Small experimental oil spills require pre-planning and organisation

- Too many unknowns
    - In many cases the amount of oil released is not known
        - And cannot be measured either as oil on sea surface or as oil dispersed into water column
        - Water samples can be taken and measurements (e.g. fluorometry) made, but there will be insufficient resolution in distance or time to construct a mass balance
    - If the resources have not been catalogued in the pre-spill state impact assessment can be difficult

Dealing with unknowns

- Not being able to adequately answer questions about the unknowns can look like weakness or incompetence
  - Politician and regulators do not like that

- There is a widespread belief (often propagated by researchers) that conducting carefully controlled scientific studies will make the unknowns known

- There are often “R&D funding blooms” after large oil spills
  - The *Deepwater Horizon* incident was a very large incident
  - $3.55 billion have been allocated for R&D

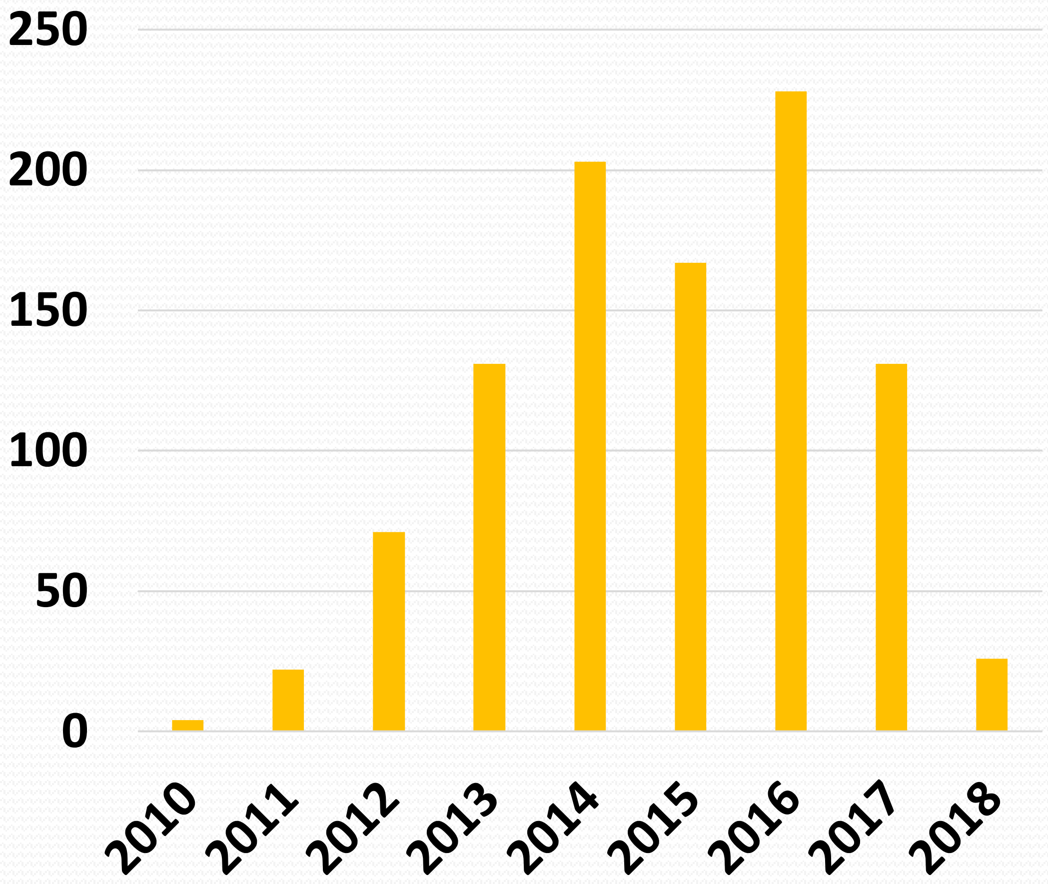
Funding for R&D after *Deepwater Horizon*

Penalties and reparations from the 2010 *Deepwater Horizon* spill have enriched three US non-governmental organizations that support research.				
Organization	Source	Amount	Objectives	Funding start/end
GoMRI Gulf of Mexico Research Initiative	BP donation	US$500 million	Oil dispersion and degradation studies; ecological and health effects	2010–20
NFWF National Fish and Wildlife Foundation	BP and Transocean plea agreements	US$2.55 billion	Restoration and risk-reduction projects; construction of barrier islands	2013–until depleted
NAS National Academy of Sciences	BP and Transocean plea agreements	US$500 million	Environmental protection and human health studies; education and environmental monitoring	2013–43

GoMRI (Gulf of Mexico Research Initiative)

- All $500 million of GoMRI funding has been committed and ongoing projects will end in 2020
  - Research programme conducted primarily at US Gulf Coast States research institutions
  - Thousands of researchers involved and hundreds of students qualified
  - Over 1,000 peer-reviewed scientific papers have been published so far

Number of published GoMRI-funded papers



Findings from GoMRI funded studies

- Very many of the studies have confirmed what was already known
  - Oil spills can have a wide range of negative effects on a range of organisms
    - Studies have been more specific to GoM species
  - The concentration and exposure regimes used in toxicity and biodegradation studies may have contributed to some surprising results

- What new or novel has been discovered so far?

Two of the more surprising “new science” findings

- **MOSSFA (Marine Oil Snow Sedimentation and Flocculent Accumulation)**
  - Hypothesis is that marine snow interacted with the Macondo crude oil and caused very significant quantities of the crude oil to be deposited on the seabed to the detriment of the benthos

- **Claim that dispersants inhibit biodegradation of dispersed oil**
  - Dispersant use is much more normally considered to facilitate the rapid biodegradation of dispersed oil by increasing the oil / water contact area available for microorganisms to colonize

MOSSFA

- **Basis of argument**
  - ‘Fresh’ Macondo crude oil has a density of 0.833 gm/ml at 5°C and could not sink in seawater with a density of 1.025 gm/ml
  - Therefore “something” must have caused the oil to sink
  - The something was marine snow generated by oil on the sea surface

- **Alternative explanation**
  - ‘Fresh’ Macondo crude oil can have neutral buoyancy if dispersed as very small oil droplets
  - ‘Fresh’ Macondo crude oil rapidly lost some components by dissolution and was biodegraded
  - Converted into much smaller quantity of recalcitrant residue
  - Microscopic particles of this residue diffusely deposited on seabed under path of subsea plume
  - Not bioavailable

Fallout plume of submerged oil from Deepwater Horizon
by Valentine et al. 2014

- Used concentrations of hopane in seabed sediment samples
  - Hopane present at 69 ppm in ‘fresh’ Macondo crude oil and 1 gm hopane derived from 15 Kg of ‘fresh’ oil
- Total amount of ‘fresh’ Macondo crude oil released estimated at ~5.0 million barrels with ~2 million barrels being dispersed oil in the subsea plume
- Hopane concentrations on sediment over 3,200 km^2 of seabed represented ~12% (a range 4% to 31%) of the total of 2 ± 0.2 million, i.e. 240,000 barrels of ‘fresh’ Macondo crude oil (with a range of 80,000 to 620,000 bbl) had been deposited on the seabed

Because hopane is used as a proxy for oil, the estimate does not account for biodegradation or dissolution of other petroleum hydrocarbons

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Fallout plume of submerged oil from *Deepwater Horizon*

David L. Valentine[a,b,1], G. Burch Fisher[a,b], Sarah C. Bagby[a,b], Robert K. Nelson[c], Christopher M. Reddy[c], Sean P. Sylva[c], and Mary A. Woo[d]

[a]Department of Earth Science and [b]Marine Science Institute, University of California, Santa Barbara, CA 93106; [c]Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole MA 02543; and [d]Department of Earth System Science, University of California, Irvine, CA 92697

Edited by Derek C. G. Muir, Environment Canada, Burlington, ON, Canada, and accepted by the Editorial Board September 26, 2014 (received for review August 5, 2014)

The sinking of the *Deepwater Horizon* in the Gulf of Mexico led to uncontrolled emission of oil to the ocean, with an official government estimate of ~5.0 million barrels released. Among the pressing uncertainties surrounding this event is the fate of ~2 million barrels of submerged oil thought to have been trapped in deep-ocean intrusion layers at depths of ~1,000–1,300 m. Here we use chemical distributions of hydrocarbons in >3,000 sediment samples from 534 locations to describe a footprint of oil deposited on the deep-ocean floor. Using a recalcitrant biomarker of crude oil, 17α(H),21β(H)-hopane (hopane), we have identified a 3,200-km^2 region around the Macondo Well contaminated by ~1.8 ± 1.0 × 10^6 g of excess hopane. Based on spatial, chemical, oceanographic, and mass balance considerations, we calculate that this contamination represents 4–31% of the oil sequestered in the deep ocean. The pattern of contamination points to deep-ocean intrusion layers as the source and is most consistent with dual modes of deposition: a “bathtub ring” formed from an oil-rich layer of water impinging laterally upon the continental slope (at a depth of ~900–1,300 m) and a higher-flux “fallout plume” where suspended oil particles sank to underlying sediment (at a depth of ~1,300–1,700 m). We also suggest that a significant quantity of oil was deposited on the ocean floor outside this area but so far has evaded detection because of its heterogeneous spatial distribution.

Macondo Well blowout | Gulf of Mexico | ocean pollution | petroleum spill | deep plumes

The sinking of the *Deepwater Horizon* in the Gulf of Mexico led to the discharge of ~5.0 million barrels of petroleum from the Macondo Well. The discharge occurred at a water depth of ~1,500 m and gave rise to intrusion layers (1) in the deep ocean that included both water-soluble hydrocarbons in the dissolved phase (2–6) and small particles of water-insoluble hydrocarbons (7–11). These intrusion layers were found primarily at a depth of 1,000–1,300 m and may have hosted the majority of the environmental discharge, including all the natural gas and ~2 million barrels of liquid oil (12). Although the most abundant of the water-soluble hydrocarbons underwent rapid biodegradation during the spill (4, 6, 8, 9, 13–15), the fate and impacts of the insoluble hydrocarbons in the deep ocean have remained uncertain (16).

The intrusion layers that hosted hydrocarbon contamination persisted for 6 mo or more and at distances >300 km from the well, but available evidence suggests that particles of submerged oil were particularly concentrated during the first 6 wk of discharge and within ~15 km of the well (8, 9, 11). Thus, initial partitioning of hydrocarbon particles to the intrusion layers appears to have given way to transport or removal by undefined deep-ocean processes. Such processes might include sedimentation, buoyant rise toward the sea surface, incorporation into pelagic biota, biodegradation, or interventions at the wellhead. Mechanisms exist that support several of these options (9, 17–20), but uncertainty as to oil's actual partitioning, the effect of chemical dispersant (21), and the impacts of a changing microbial community (6, 8, 9, 13–15, 17, 22–24) have precluded further understanding of the processes that acted on the oil.

In this study we focus on testing the hypothesis that oil particles suspended in the deep intrusion layers were deposited on the sea floor over a broad area. To do so, we use publicly available data generated as part of the ongoing Natural Resource Damage Assessment (NRDA) process (*Supporting Information*) to assess the spatial distribution of petroleum hydrocarbons in the deep-ocean sediments of the Gulf of Mexico. We focus on the recalcitrant compound 17α(H),21β(H)-hopane (hereafter referred to as “hopane”) as a conserved tracer for crude oil deposition to sediments (25); we treat hopane as a degradation-resistant proxy for Macondo's liquid-phase oil (26). Analysis of the spatial distribution of hopane allows us to define both a regional background level and a depositional footprint of oil from the *Deepwater Horizon* event. In combination with other lines of evidence, this analysis leads us to conclude that significant quantities of particulate oil sank from the intrusion layers to rest on the underlying sea floor.

Results and Discussion

Hopane Distribution Is Consistent with Macondo as the Source. Our first goal was to determine if the distribution of hopane in the Gulf of Mexico's deep-water sediments could be used quantitatively as a tracer of Macondo discharge. Because hopane is not unique to Macondo Well oil, we investigated its spatial distribution (Fig. 1) for indications of its origin. To help determine

Significance

Following the sinking of the *Deepwater Horizon* in the Gulf of Mexico an unprecedented quantity of oil irrupted into the ocean at a depth of 1.5 km. The novelty of this event makes the oil's subsequent fate in the deep ocean difficult to predict. This work identifies a fallout plume of hydrocarbons from the Macondo Well contaminating the ocean floor over an area of 3,200 km^2. Our analysis suggests the oil initially was suspended in deep waters and then settled to the underlying sea floor. The spatial distribution of contamination implicates accelerated settling as an important fate for suspended oil, supports a patchwork mosaic model of oil deposition, and frames ongoing attempts to determine the event's impact on deep-ocean ecology.

Author contributions: D.L.V., R.K.N., C.M.R., S.P.S., and M.A.W. designed research; D.L.V., G.B.F., and S.C.B. analyzed data; and D.L.V. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. D.C.G.M. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. Email: valentine@geol.ucsb.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1414873111/-/DCSupplemental.

15906–15911 | PNAS | November 11, 2014 | vol. 111 | no. 45

www.pnas.org/cgi/doi/10.1073/pnas.1414873111

Characterization and flux of marine oil snow settling toward the seafloor ….. by Stout and German 2018

Conclusions

The volume of oil deposited on the seafloor was 217,700 to 229,900 barrels, representing 6.8 to 7.2% of the total of 3.19 million barrels of oil released into the waters of the Gulf of Mexico

- Approx. 224,000 barrels of ‘fresh' Macondo crude oil was deposited on the sea bed? OR
- A much lesser amount of the wax-rich, severely weathered and highly biodegraded recalcitrant residue derived from that volume of Macondo crude oil was deposited

Weathering (dissolution loss) and biodegradation of dispersed oil not taken into account in the estimated amounts

Marine Pollution Bulletin 129 (2018) 695–713

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Characterization and flux of marine oil snow settling toward the seafloor in the northern Gulf of Mexico during the *Deepwater Horizon* incident: Evidence for input from surface oil and impact on shallow shelf sediments

Scott A. Stout[a], *, Christopher R. German[b]

[a] *NewFields Environmental Forensics Practice, LLC, Rockland, MA, United States*
[b] *Woods Hole Oceanographic Institution, Woods Hole, MA, United States*

ARTICLE INFO

Keywords:
Sediment trap
Chemical fingerprinting
Biomarkers
Gulf of Mexico
Benthos

ABSTRACT

Sediment trap samples from the shelf edge area (400-450 m water depth), 58 km northeast of the failed Macondo well, were collected before, during and after the *Deepwater Horizon* oil spill. Detailed chemical analyses of particulates revealed that fluxes of spill-derived TPH (2356 μg/m^2/day), total PAH (5.4 μg/m^2/day), and hopane (0.89 μg/m^2/day) settling to the seafloor directly beneath the surface-plume were 19- to 44-times higher during the active spill than pre- and post-spill background values. The oil was variably biodegraded, evaporated and photo-oxidized indicating that it derived from the sinking of surface oil. The hopane-based oil flux that we calculate (10 bbl/km^2) indicates that at least 76,000 bbl of Macondo oil that reached the ocean surface subsequently sank over an area of approximately 7600 km^2. We explore how this flux of sunken surface oil contributed to the total volume of oil deposited on the seafloor following the *Deepwater Horizon* incident.

1. Introduction

Between April 20 and July 15, 2010 the *Deepwater Horizon* oil spill introduced approximately 4 million barrels of oil to the northern Gulf of Mexico (GoM) at a depth of approximately 1500 m (Crone and Tolstoy, 2010). One fraction of the Macondo crude oil that was released remained at depth in the ocean in a combination of dissolved material and physically- or chemically-dispersed droplets, all of which were advected away from the source in the form of a laterally dispersing non-buoyant plume centered at approximately 1000–1300 m depth (Camilli et al., 2010; Socolofsky et al., 2011). Importantly, however, a second fraction of the oil released from the Macondo well was sufficiently buoyant to rise all the way to the ocean surface where it was dispersed by wind and currents over vast areas of the northern GoM over a period of nearly three months (Graettinger et al., 2015).

Some fraction of the dispersed oil from the deep-sea plume and/or buoyant oil from the sea surface was ultimately deposited on the seafloor as evidenced by the widespread accumulation of oily “floc” in sediments (Valentine et al., 2014; Brooks et al., 2015; Chanton et al., 2015; Hastings et al., 2015; Romero et al., 2015; Schwing et al., 2015; Stout et al., 2016a, 2016b) and on deep-sea corals (White et al., 2012; Hsing et al., 2013; Fisher et al., 2014a, 2014b). Although impingement of oil from the dispersing deep-sea plume directly onto topographic obstacles likely occurred, the dominant mechanism by which the oily “floc” was carried to the seafloor is hypothesized to have been the formation and sinking of marine oil snow (Kinner et al., 2014). The marine oil snow formed from aggregates of oil with microbially-mediated, mucous-rich marine snow particles that formed following the proliferation of oil-degrading bacteria, in both the deep-sea and near the ocean surface, in response to the spill (Hazen et al., 2010; Valentine et al., 2010; Baelum et al., 2012; Passow et al., 2012, Ziervogel et al., 2012; Passow, 2014; Fu et al., 2014; Daly et al., 2016; Passow and Ziervogel, 2016).

The numerous sediment and coral studies mentioned above have already established the impact of sinking marine oil snow on seafloor sediments and coral communities found at depths > 1000 m. This initially had led to a broad expectation that oil dispersed through the deep-sea plume, which never penetrated upward shallower than 1000 m, was the overwhelming and perhaps exclusive source of oil found in the oily floc. Evidence that marine oils snow formed at the surface had impacted the shallower seafloor < 1000 m deep (i.e., above the depth of the deep sea plume) was varied. For example, two colonial coral sites shallower than 1000 m and immediately north of the Macondo wellhead (VK906 and VK826; Fig. 1) did not exhibit visible signs of impact (Fisher et al., 2014a,b). Hydrocarbon analysis of sediment cores collected at < 1000 m depth, while limited in number and

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* Corresponding author.
E-mail address: sstout@newfields.com (S.A. Stout).

http://dx.doi.org/10.1016/j.marpolbul.2017.10.059
Received 21 November 2016; Received in revised form 20 October 2017; Accepted 21 October 2017

Chemical dispersants can suppress the activity of natural oil-degrading microorganisms Kleindienst *et al* 2015

In laboratory experiments, we simulated environmental conditions comparable to the hydrocarbon-rich, 1,100 m deep plume that formed during the Deepwater Horizon discharge

Not a good simulation

- Dispersant in seawater concentrations used in the microcosms are **790 and 1,410 times higher**, respectively, than the 19 µg/L said in the paper to be "*comparable to concentrations observed in the DWH plume*".
- Dispersant concentrations used are **2,500 and 4,466 times higher** than the actual maximum of 6 µg/L (6 parts per billion) of dispersant in seawater measured in the deep water plume at the DWH incident.

The microbial populations developed to preferentially biodegrade the surfactants in the vast excess of dispersant

ENVIRONMENTAL SCIENCES

Chemical dispersants can suppress the activity of natural oil-degrading microorganisms

Sara Kleindienst[a,1], Michael Seidel[a,2], Kai Ziervogel[b], Sharon Grim[c,3], Kathy Loftis[a,4], Sarah Harrison[a], Sairah Y. Malkin[a], Matthew J. Perkins[d], Jennifer Field[d], Mitchell L. Sogin[c], Thorsten Dittmar[e,f], Uta Passow[g], Patricia M. Medeiros[a], and Samantha B. Joye[a,5]

[a]Department of Marine Sciences, University of Georgia, Athens, GA 30602; [b]Department of Marine Sciences, University of North Carolina, Chapel Hill, NC 27599; [c]Josephine Bay Paul Center, Marine Biological Laboratory, Woods Hole, MA 02543; [d]Department of Environmental and Molecular Toxicology, Oregon State University, Corvallis, OR 97331; [e]Research Group for Marine Geochemistry, Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky University, 26129 Oldenburg, Germany; [f]Max Planck Institute for Marine Microbiology (MPI), 28359 Bremen, Germany; and [g]Marine Science Institute, University of California, Santa Barbara, CA 93106

Edited by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved September 25, 2015 (received for review April 15, 2015)

During the *Deepwater Horizon* oil well blowout in the Gulf of Mexico, the application of 7 million liters of chemical dispersants aimed to stimulate microbial crude oil degradation by increasing the bioavailability of oil compounds. However, the effects of dispersants on oil biodegradation rates are debated. In laboratory experiments, we simulated environmental conditions comparable to the hydrocarbon-rich, 1,100 m deep plume that formed during the *Deepwater Horizon* discharge. The presence of dispersant significantly altered the microbial community composition through selection for potential dispersant-degrading *Colwellia*, which also bloomed in situ in Gulf deep waters during the discharge. In contrast, oil addition to deepwater samples in the absence of dispersant stimulated growth of natural hydrocarbon-degrading *Marinobacter*. In these deepwater microcosm experiments, dispersants did not enhance heterotrophic microbial activity or hydrocarbon oxidation rates. An experiment with surface seawater from an anthropogenically derived oil slick corroborated the deepwater microcosm results as inhibition of hydrocarbon turnover was observed in the presence of dispersants, suggesting that the microcosm findings are broadly applicable across marine habitats. Extrapolating this comprehensive dataset to real world scenarios questions whether dispersants stimulate microbial oil degradation in deep ocean waters and instead highlights that dispersants can exert a negative effect on microbial hydrocarbon degradation rates.

oceanography | microbial dynamics | hydrocarbon cycling | chemical dispersants | oil spills

Crude oil enters marine environments through geophysical processes at natural hydrocarbon seeps (1) at a global rate of ~700 million liters per year (2). In areas of natural hydrocarbon seepage, such as the Gulf of Mexico (hereafter, the Gulf), exposure of indigenous microbial communities to oil and gas fluxes can select for microbial populations that use petroleum-derived hydrocarbons as carbon and energy sources (3, 4). The uncontrolled deep-water oil well blowout that followed the explosion and sinking of the *Deepwater Horizon* (DWH) drilling rig in 2010 released about 750 million liters of oil into the Gulf. Seven million liters of chemical dispersants were applied (5) with the goal of dispersing hydrocarbons and stimulating oil biodegradation. A deep-water (1,000–1,300 m) plume, enriched in hydrocarbons (6–11) and dioctyl sodium sulfosuccinate (DOSS) (12, 13), a major component of chemical dispersants (14), formed early in the discharge (7). The chemistry of the hydrocarbon plume significantly altered the microbial community (11, 15–17), driving rapid enrichment of low-abundance bacterial taxa such as *Oceanospirillum*, *Cycloclasticus*, and *Colwellia* (18). The natural hydrocarbon degraders in Gulf waters were either in low abundance or absent in DWH deep-water plume samples (18).

Chemical dispersants emulsify surface oil slicks, reduce oil delivery to shorelines (19), and increase dissolved oil concentrations, which should make oil more bioavailable (20) and stimulate biodegradation (21). The efficacy of dispersants in stimulating oil biodegradation is debated (22) and negative environmental effects have been documented (23). Dispersant application often requires ecological tradeoffs (24). Surprisingly little is known about the impacts of dispersants on the activity and abundance of hydrocarbon-degrading microorganisms (25). This work addressed three key questions: (*i*) Do dispersants influence microbial community composition? (*ii*) Is the indigenous microbial community as effective at oil biodegradation as microbial populations following dispersant/dispersed oil exposure? (*iii*) Does chemically dispersed oil stimulate hydrocarbon biodegradation rates?

Laboratory experiments were used to unravel the effects of oil-only (supplied as a water-accommodated fraction, "WAF"), Corexit 9500 ("dispersant-only"), oil–Corexit 9500 mixture (chemically enhanced

Significance

Oil spills are a significant source of hydrocarbon inputs into the ocean. In response to oil spills, chemical dispersants are applied to the oil-contaminated seawater to disperse surface slicks into smaller droplets that are presumed to be more bioavailable to microorganisms. We provide evidence that chemical dispersants applied to either deep water or surface water from the Gulf of Mexico did not stimulate oil biodegradation. Direct measurement of alkane and aromatic hydrocarbon oxidation rates revealed either suppression or no stimulation of oil biodegradation in the presence of dispersants. However, dispersants affected microbial community composition and enriched bacterial populations with the ability to use dispersant-derived compounds as growth substrates, while oil-alone amendments enriched for natural hydrocarbon degraders.

Author contributions: S.K., S.H., S.Y.M., and S.B.J. designed research; S.K., M.S., K.Z., K.L., S.H., S.Y.M., M.J.P., J.F., and U.P. performed research; S.G., K.L., M.J.P., J.F., M.L.S., T.D., and P.M.M. contributed new reagents/analytic tools; S.K., M.S., K.Z., S.G., S.H., S.Y.M., M.J.P., J.F., M.L.S., T.D., U.P., P.M.M., and S.B.J. analyzed data; and S.K., M.L.S., P.M.M., and S.B.J. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: 16S rRNA amplicon Illumina sequencing data were deposited in the GenBank database (BioProject accession no. PRJNA253405).

[1] Present address: Center for Applied Geosciences, Eberhard-Karls-University Tuebingen, 72074 Tuebingen, Germany.

[2] Present address: Research Group for Marine Geochemistry, Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky University, 26129 Oldenburg, Germany; and Max Planck Institute for Marine Microbiology (MPI), 28359 Bremen, Germany.

[3] Present address: Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI 48109.

[4] Present address: Center for Applied Isotope Studies, University of Georgia, Athens, GA 30602.

[5] To whom correspondence should be addressed. Email: mjoye@uga.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1507380112/-/DCSupplemental.

Conclusions

- Large oil spills are becoming increasingly rare – which is good
  - Obtaining hard data from actual spills is therefore becoming less frequent
  - Accurate and effective post-spill monitoring and impact assessment by environmental monitoring is therefore needed more than ever

- There will always be some unknowns at real oil spills
  - Oil spills are not scientific experiments
  - Follow-up studies are often required

Conclusions

- Conducting laboratory or mesocosm-scale experiments under controlled and defined conditions can be very useful
  - But such studies must obviously be scientifically rigorous, accurate and transparent
  - Academic scientists must be capable of accurately explaining their results to a non-academic audience
  - **Otherwise NEBA/SIMA considerations may be skewed, leading to less effective response strategy at future spills**