Quantified Exposures from Potential Deepwater Releases for Comparative Risk Assessment of Oil Spill Response Options Including Dispersant Use

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ABSTRACT

(ID: 688274) The goal of oil spill response is to mitigate the overall impacts of spilled oil on ecological and socioeconomic resources. Surface and subsea dispersant applications are effective tools that remain controversial after decades of research and discussion. The tradeoff that dispersants potentially increase effects on water column and benthic communities while reducing floating and nearshore/shoreline oil exposure is recognized, but inevitably are qualitatively considered when subjectivity and stakeholder interests prevail. To be objective and transparent, we developed a *quantitative* approach using oil spill modeling to evaluate response alternatives in a Comparative Risk Assessment (CRA) framework where the fractions of resources potentially exposed are compared, along with their recovery potential. The model quantifies exposure as water surface area, shoreline area and water volume exposed above thresholds of concern, multiplied by duration of exposure, in each environmental compartment. These exposure metrics (i.e., area-days or volume-days) are multiplied by relative densities across the environmental compartments to evaluate the fractions of the resources exposed in each modeled scenario. The fractions of resources exposed, along with their recovery potential, inform decisionmakers using a Spill Impact Mitigation Assessment (SIMA) approach with quantitative estimates of potential consequences, which they may consider along with stakeholder values.

Previously, we evaluated a deepwater blowout in the Gulf of Mexico, assuming no intervention or various response options (mechanical recovery, in-situ burning, surface dispersant application, and subsea dispersant injection [SSDI]). The findings were that inclusion of SSDI reduced human and wildlife exposure to volatile organic compounds; dispersed oil into a large water volume at depth; enhanced biodegradation; and reduced surface water, nearshore and shoreline exposure to floating oil and entrained/dissolved oil in the upper water column. Tradeoffs included increased exposures at depth. However, since organisms are less abundant at depth, overall exposure of valued ecosystem components was minimized by use of SSDI. Follow-up modeling shows the benefits of SSDI are due to reduction of the oil droplet sizes released to the water column. Droplet sizes are sensitive to oil and gas release rates, release depth, orifice size and dispersant-to-oil ratio. The exposure metrics resulting from a matrix of scenarios varying these inputs and response actions are expected to be generally representative of the fate and behavior of oil and gas blowouts in the offshore areas of the Gulf of Mexico, as well as other regions with similar oceanographic conditions.

INTRODUCTION

Oil spill responders seek to reduce the negative impact of an oil spill on human health, environmental resources, socioeconomic uses, and cultural values. Most oil spill response activities seek to decrease the amount of floating oil, which reduces exposure of humans and wildlife to volatile emissions and direct contact with oil. Protection strategies are focused on nearshore and shoreline areas where many valued resources and uses are concentrated. In addition, cleanup in nearshore areas can cause additional adverse impacts, so preventing oil from reaching these areas is a primary response objective. To accomplish these goals, mechanical recovery (e.g., using skimmers and booms), in situ burning (ISB), monitored natural attenuation of oil (no intervention), and oil dispersion by chemical dispersants (either through surface or subsurface application) are employed. Response and area contingency plans lay out policies, guidance and needed equipment for response activities in consideration of these and other factors (Walker et al. 2001; NOAA 2010; ITOPF, 2018; NASEM, 2019).

Response actions that remove floating oil (mechanical and ISB) are generally accepted if precautions are taken to prevent additional damage to shoreline/nearshore habitats and human exposure to burn emissions. However, dispersant use remains controversial owing to the potential tradeoff of dispersants increasing effects on water column and benthic resources, as well as human health concerns related to the dispersant (NASEM, 2019). As it is difficult to make response decisions when various stakeholders prioritize different resources, several formalized approaches have been developed to compare the consequences of alternative response options. Net Environmental Benefits Analysis (NEBA; NOAA, 1990; ASTM, 2013; IPIECA, 2105) is a consensus-based process in which responsible parties, regulatory authorities, resource trustees and stakeholders work together to formulate decisions, albeit often subjective, on the best course of action to reduce environmental impacts given the specific circumstances of an oil spill (Efroymson et al., 2004; NASEM, 2019). Consensus Ecological Risk Assessment (CERA; Aurand et al., 2000; Aurand and Essex, 2012; Walker et al., 2016) is an exchange among stakeholders, who consider findings from the scientific literature, local knowledge and experiences of decision makers, agency personnel, risk assessors, and other stakeholders to develop a consensus as to the best course of action for oil spill response. Spill Impact Mitigation Assessment (SIMA) is a recent refinement of the original environmentally-focused NEBA approach that uses decision-support tools to quantify the tradeoffs among different response options aimed at reducing adverse ecological, socioeconomic, and human health consequences. SIMA requires the same basic steps as NEBA: collecting appropriate data, predicting outcomes for various response strategies and environmental conditions, considering tradeoffs between response options, and then selecting the response strategy that mitigates environmental / socio-economic effects and enhances ecosystem recovery (Coolbaugh and Varghese, 2016, Robinson et al., 2017; NASEM, 2019).

Thus, the NEBA, CERA, and SIMA frameworks all involve comparison of alternative spill response strategies and outcomes, considering both potential impacts and stakeholder values. Each of the approaches has built off prior experience to facilitate objective and transparent decision-making. However, if quantitative analyses of the consequences of specific actions are not available, the comparisons will of necessity involve some degree of subjectivity. Recently, a fully-quantitative approach for a Comparative Risk Assessment (CRA) of response options was developed (French-McCay et al. 2018b; Bock et al. 2018; Walker et al. 2018), which can be used to inform a NEBA, CERA or SIMA framework, providing scientific information, quantitative metrics related to oil amount spilled, environmental circumstances, oil fate, resource exposures, and a tool for making comparisons of response consequences considering both possible tradeoffs and stakeholder values of the affected resources and their services. The CRA uses oil spill modeling to simulate the fates and effects of each considered scenario. It employs weighting functions to represent the relative exposure, susceptibility, and importance of resources. The quantification is based on: (1) the surface areas or water volumes and days of exposure above threshold surface oil thickness or water-column oil concentrations, as estimated by oil spill modeling; (2) the relative density distributions of valued ecosystem components (VECs) across environmental compartments (ECs) to determine the fraction of the VECs in the domain exposed to oil above the applicable threshold; (3) the relative ability of the VECs to recover based on life expectancy; (4) the relative amount of volatile exposure in the air; and (5) a method of exploring different assumptions of the value of each VEC based on stakeholder concerns (French-McCay et al. 2018b; Bock et al. 2018; Walker et al. 2018). In order to evaluate relative risks of response actions, it is important to quantitatively consider possible exposure concentrations, potential effects levels and relative fractions of populations exposed in different environments. Otherwise, the comparisons are of necessity qualitative so that they may be viewed as not definitive and more easily overridden by opinions and stakeholders' objections.

This paper summarizes the CRA approach, results for the example deepwater blowout scenario in the northeastern Gulf of Mexico used to develop the methods, and sensitivity studies exploring how the results would vary for other deepwater blowout conditions. We also describe how the CRA approach may be applied to spill risk assessments in various regions with differing protection concerns, considering these and other alternative spill response scenarios.

METHODS

CRA Approach and Prior Studies

The CRA approach is the first to use probabilistic modeling to evaluate the influence of variable metocean conditions (i.e., meteorological and oceanographic conditions, such as winds, currents, salinities, and temperatures) on oil trajectory and fate. Using individual runs representative of specific metocean conditions, several different modeling simulations and combinations of response options are compared to quantify oil fate, the amount of oil surfaced as opposed to dispersed, and the spatial extent of ECs over which oil concentrations exceeded screening thresholds for potential effects.

French-McCay et al. (2017, 2018b) describe the oil spill modeling portion of a CRA for an example offshore deepwater blowout in the Gulf of Mexico. Bock et al. (2018) describes how the oil spill modeling was used to develop exposure metrics quantifying the relative portions of the VEC populations exposed in the model domain, as well as the relative time scales over which affected VECs would recover. First, modeling-based surface areas and water volumes exposed above thresholds of concern for surface oil thickness or water-column oil concentration were multiplied by days of exposure. Second, a relative exposure index was calculated by dividing the surface area-days and water volume-days of exposure by the maximum possible exposure area-days or volume-days in the study area. Third, the exposure index in each EC was multiplied by the fraction of the total VEC population (i.e., relative density) in the EC, yielding a fraction of the population exposed. Forth, this relative exposure index was multiplied by a relative index of recovery time, calculated as the typical life span of the VEC divided by the maximum recovery time for any VEC. Thus, for each oil spill response scenario, the CRA provides an index of the proportion of the VEC in the total model domain exposed above thresholds for potential effects, weighted by its recovery potential. Bock et al. (2018) also explored how the use of relative weighting schemes by stakeholders or decision-makers might influence the comparisons of risks to VECs and ECs. A third paper by Walker et al. (2018) describes the engagement process used to guide the project as it progressed, and then present results to and solicit feedback from external stakeholders upon completion.

The central issue related to dispersant use is weighing the relative risks to surface and nearshore resources and services, as compared to adverse consequences for water column and benthic resources. The purpose for using subsea dispersant injection (SSDI) at the wellhead during the Deepwater Horizon oil spill was to reduce the droplet sizes of oil released into the water column so that less oil would surface and more of the oil would “weather” at depth (OSAT 2010; NASEM 2019). Oil weathering includes dissolution of soluble and semi-soluble components and biodegradation, both of which are facilitated by breaking up oil into smaller droplet sizes with higher surface-area-to-volume ratios (Mackay et al., 1982; NRC, 2003, 2005).

The additional weathering at depth by use of SSDI reduces volatile hydrocarbon amounts reaching the surface and evaporating, particularly in the area of active response near the wellhead where volatiles are a human health risk (Crowley et al., 2018). Thus, the oil droplet size distribution of a subsea release is a major controlling factor of the quantity of oil that surfaces, potentially impacting nearshore and shoreline areas; of volatile emissions to air, potentially exposing humans and wildlife; and of exposure to water column and benthic resources.

Because the CRA approach developed in the original study (French-McCay et al. 2018b; Bock et al. 2018; Walker et al. 2018) was tested with a single spill scenario (one spill site, spill volume, oil type), a next logical step was to evaluate the sensitivity of the oil spill model (and so the CRA) results to key release scenario model inputs, i.e., those related to oil droplet size. For a subsea blowout, oil droplet sizes are functions of oil and gas flow rates, discharge orifice size, dispersant application as a percentage of oil flow rate (including no dispersant use), blowout location (i.e., geographic and environmental conditions), and depth of the release. As summarized in NASEM (2019) and French-McCay et al. (2019), predictions of oil droplet size are uncertain to the degree that the modeled fate of the oil is sensitive to the uncertainty range of the oil droplet size distribution used. French-McCay et al. (2019) presents the methods and results of the sensitivity study varying assumed oil droplet size distribution.

Models Used

In the studies by French-McCay et al. (2017, 2018b, 2019) and Bock et al. (2018), oil spill trajectory and fate modeling was performed using two sequentially-linked models: OILMAP DEEP (OIL Model Application Package for DEEPwater releases; Crowley et al. 2014; Spaulding et al. 2017) and the SIMAP (Spill Impact Model Application Package) oil fate and effects model (French-McCay 2003, 2004; French-McCay et al. 2018a, b). OILMAP DEEP evaluates the nearfield dynamics of a blowout plume, predicting the trap height and the droplet sizes produced subject to the turbulent energy involved and the oil properties, considering the amount of dispersant applied (Spaulding et al. 2000; Crowley et al. 2014; Spaulding et al. 2017; Li et al. 2017). This determines the initial conditions (i.e., oil mass as a function of droplet size and the depth where droplets are released) to be input to the far field model, SIMAP, which calculates transport and fate of, and exposure to, the oil and its components. Summaries of model algorithms and validation studies are available in these publications and in French-McCay et al. (2018b, 2019).

Modeled Scenarios, Inputs and Assumptions

The original study modeled a hypothetical blowout at 1400 m in eastern De Soto Canyon (28.044143^{o}N, 86.511795^{o}W), which is 120 nautical miles (222 km) from the nearest shoreline. The oil volume flow rate was assumed to be 45,000 bbl/day (7,154 m^3/day), a rate in the range of potential worst-case discharges (WCD) reported in offshore response plans (BOEM, 2013b). The duration of the release assumes well shutdown via a capping stack at 21 days after the release start. The assumed gas-to-oil ratio (GOR) was 2000 scf/stb (standard cubic foot per stock tank barrel; 11,229 sm^3/sm^3), which is typical of the range of potential gas contents for reservoirs in the Gulf of Mexico (BOEM, 2013a). A typical and well-characterized Gulf of Mexico light crude oil (HOOPS, API = 34.2, viscosity = 8.4 cP at 20^{o}C) was used for modeling. For all response actions, present international capacities of materials and equipment were assumed available to be brought to bear on the response. Effectiveness of surface actions (begun day 2) were constrained by technical feasibility vis-à-vis weather and sea conditions, and state of the oil. SSDI was assumed to begin on day 6. Details of the model inputs are in French-McCay et al. (2018b).

Based on literature reviews in French-McCay et al. (2018), the two thresholds considered for floating oil exposure of wildlife (birds, mammals and sea turtles) and *Sargassum* were 10 and 100 g/m^2 (~10 and 100 μm of non-emulsified oil, assuming a specific gravity of ~1.0 g/mL). The assumed thresholds for shoreline invertebrates were 0.01 and 0.1 mm (10 and 100 g/m^2) of oil coverage. Aquatic toxicity to fish, plankton and benthic invertebrates has been shown to be strongly related to polycyclic aromatic hydrocarbon (PAH) concentrations in water (NRC 2003). Thresholds for plankton below 20 m, and for fish at all depths, were set to 10 and 100 µg/L total PAH. Thresholds for plankton in the upper 20 m were set to an order of magnitude lower concentrations, i.e., 1 and 10 µg/L total PAH to account for potential phototoxic effects.

In the sensitivity study (French-McCay et al., 2019) the same model inputs and assumptions were used as for the prior work, except for certain inputs altered for the analysis. Two additional spill locations were evaluated: one in 500 m of water and 63 km from the nearest shoreline (89.168^{o}W, 28.476^{o}N); the other in 1400 m of water and 92 km from the nearest shoreline (88.830^{o}W, 28.274^{o}N), both offshore of southern Louisiana. Placing the releases closer to Louisiana than assumed for the first study allowed greater resolution of the shoreline oiling between the various response strategies. The modeling matrix included seven oil flow rates (10k, 20k, 45k, 60k, 80k, 100k and 120k bbl/day; 1590-19,078 m^3/day) and two GORs (500 and 2000 scf/stb; 2807 and 11,229 sm^3/sm^3), which are typical of reservoirs in the Gulf of Mexico (BOEM 2013a). Two orifice diameter sizes were modeled: 18.75 in (47.6 cm) to match the opening on a standard blowout preventor and 6 in (15.2 cm) to simulate a scenario of a restriction at the release point. Results of the far field (SIMAP) modeling were summarized and presented in terms of mass balance and indicative exposure metrics adopted in the earlier CRA analysis.

RESULTS

Figure 1 summarizes the oil fate modeling results presented in French-McCay et al. (2018). Compared to the no-intervention, mechanical-only (not shown) and MBSD (Mechanical, in situ Burning, and Surface Dispersant application) scenarios, the model results showed that inclusion of SSDI reduced the total amount of oil and oil components on the water surface, in the near surface waters, in the air, and on the shoreline by dispersing oil at depth, thereby facilitating biodegradation (by increasing surface area of oil droplets and dissolution, which makes the oil more available to microbial degradation). The cumulative footprint of floating oil was also reduced by SSDI, as compared to other response alternatives. PAH concentrations were reduced in surface waters (< 20 m) because SSDI dispersed more oil at depth, whereas there was greater water volume exposed to PAHs and other components of the oil in deep offshore water. Thus, SSDI reduced human and wildlife exposure to volatile organic compounds; dispersed oil into a large water volume at depth; enhanced biodegradation; and reduced surface water, nearshore and shoreline exposure to floating oil and entrained/dissolved oil in the upper water column.

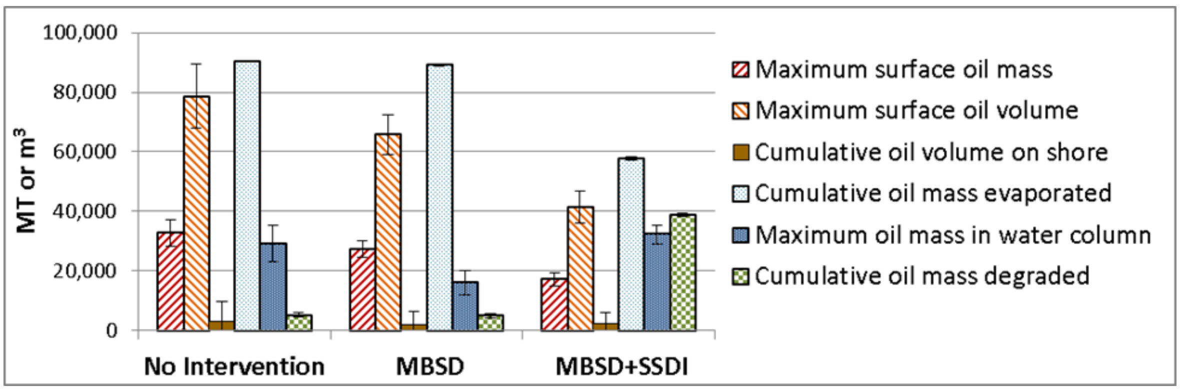

Figure 1. Means (± coefficient of variation) of mass balance metrics based on 100 runs for each response option of the examined scenario under varying metocean conditions (French-McCay et al., 2018; MBSD = mechanical, in situ burning, and surface dispersant application).

As SSDI use increased oil exposures at depth, the CRA method (Bock et al., 2018) was applied to evaluate the implications of this result considering the relative abundance of biota in different ECs (i.e., shoreline and coastal, shelf and offshore waters divided into depth ranges: 0 – 10 cm, 10 cm – 20 m, 20 m – 200 m, >200 m, and <1 m from the seafloor). The results demonstrated the added benefit of SSDI since relative risks to shoreline, surface wildlife and most aquatic life VECs were reduced. The results (summarized in Figure 2) show that adverse environmental consequences of an oil spill are overwhelmingly driven by long-lived wildlife and other biota exposed in surface waters and on shorelines. Since water column organisms are less abundant in deep water below 200 m, SSDI reduced overall exposure to those VECs as well (Figure 3). There were no exceedances of either threshold within 1 m of the sea floor, or in shelf or coastal ECs, for either of the evaluated scenarios in Bock et al. (2018). Thus, benthic communities (including any deep-sea coral communities that might be in the area) were not exposed to water concentrations above the thresholds examined in these particular scenarios.

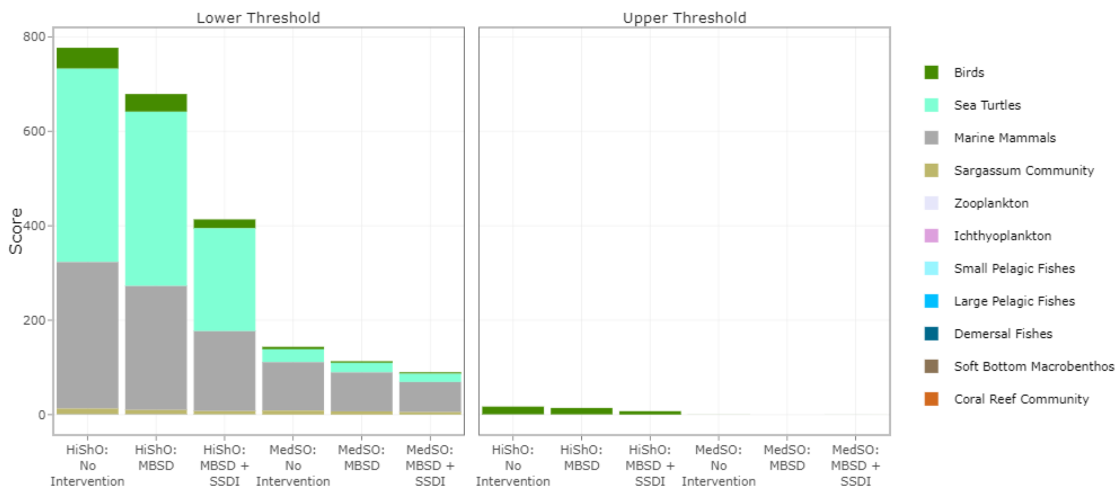

Figure 2. Composite score for all VEC exposures by scenario and response alternative. (HiSho is high shoreline and MedSO is median surface oil exposure scenario; Bock et al. 2018).

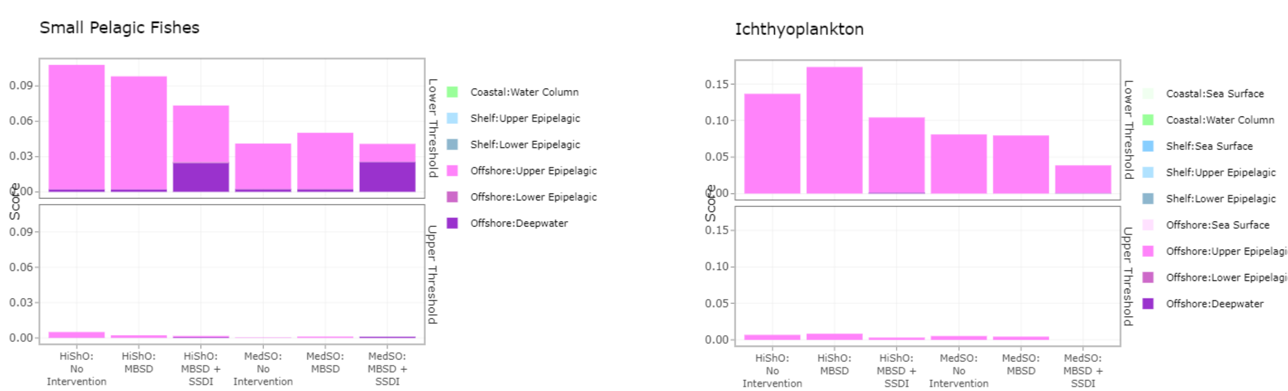

Figure 3. Composite score for water column exposures by scenario and response alternative. (HiSho is high shoreline and MedSO is median surface oil exposure scenario; Bock et al. 2018).

The CRA results shown in Figure 2 assume that all VECs are valued by stakeholders equally. As explored by Bock et al. (2018), some VECs may be considered more valuable or more important for protection because of their protection status, cultural value or socioeconomic importance. The CRA includes a method of exploring different assumptions for VEC value based on stakeholder concerns.

The results of the sensitivity study by French-McCay et al. (2019) are summarized in Figures 4 and 5. In all the simulations of 21-day releases, at 66 days after the spill start, no oil was on the surface and oil had accumulated in sediment, shoreline, degradation, and atmospheric compartments. Oil in the water column at 66 days would ultimately degrade or settle to the sediments. Figure 4 plots the accumulated mass by 66 days for the water column, sediment, shoreline, degradation, and atmospheric compartments, and the peak surface oil mass during the spill period, as a function of the median droplet size of the oil released to the water column. Figure 5 shows the rise time to the surface and the distance oil droplets would travel before surfacing (given ambient currents at the spill site) as a function of median droplet size and depth of the release. These results demonstrate that the fraction of oil surfacing (and potentially going ashore) and potential risks associated with VEC exposures are strongly related to the oil droplet size distribution. When the median droplet diameter is decreased to below about 700 μm for a spill at 1400 m, and below about 400 μm for a spill at 500 m, the amount of surfaced oil, volatile hydrocarbon emissions and oil reaching shorelines substantially decreased (Figure 4). Below these droplet sizes, the percentage of spilled oil surfacing is inversely related to the rise time to the surface (Figures 4 and 5). Rise times of droplets ≤200 μm in diameter from releases below 1100 m are so long that much of the oil would dissolve and degrade before the droplets could reach the water surface. Hence, they may be considered permanently dispersed in the deep water. From shallower depths, such as the modeled releases from 500 m (where the intrusion is trapped at a depth of ~220 m on average), droplets ≤100 μm may be considered permanently dispersed in the water column. Overall, the results indicate that for releases at 500 m, SSDI generally will be less effective in reducing oiling at the surface and at the shore than it would be for releases from 1400 m depth. Above some threshold water depth, SSDI benefits will become negligible.

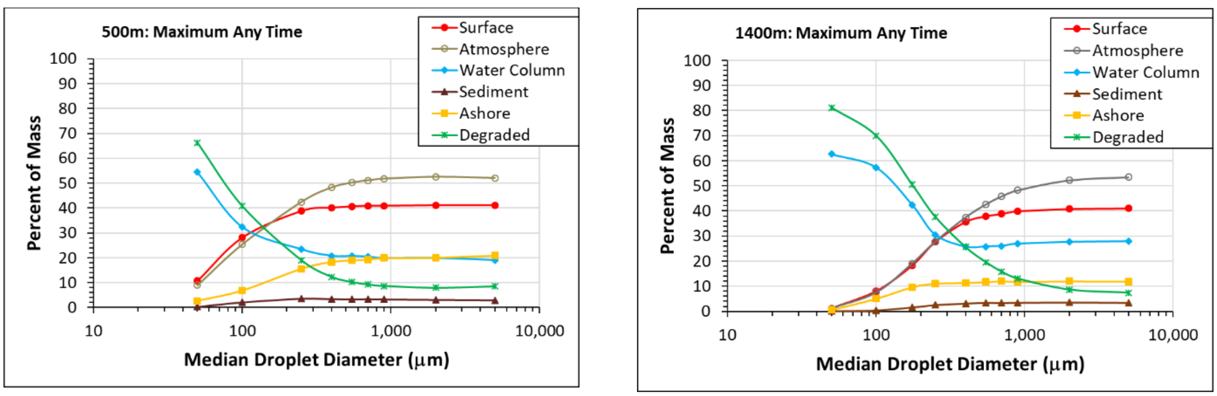

Figure 4. Maximum percent of the released oil mass in each compartment at any time after the spill as a function of median droplet size – 500-m spills with intrusion at 220 m below surface (left panel) and 1400-m spills with intrusion at 1100 m below surface (right panel).

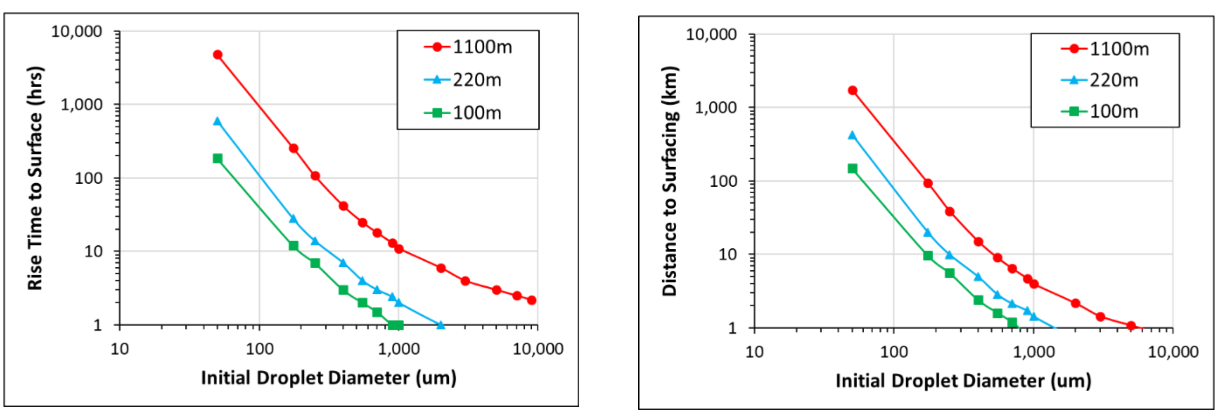

Figure 5. Rise time to the surface (1 m) as a function of initial droplet diameter released at the intrusion depth, compared to percentage of mass reaching the surface (i.e., not weathered at depth; left panel) and distance down current where the droplet size would surface based on the temporally-averaged current profile (right panel).

DISCUSSION AND CONCLUSIONS

Oil spill response decision-making requires an understanding of the effectiveness and tradeoffs of multiple response alternatives. The CRA approach offers an objective and *quantitative* method for evaluating the consequences of various alternatives that may inform and be part of a NEBA, CERA or SIMA. The CRA approach utilizes: (1) surface areas or water volumes and days of exposure above threshold concentrations, which are estimated by oil spill fate and exposure modeling; (2) relative density distributions of VECs across ECs, which determines the proportion of the VEC in the domain evaluated that would be exposed; (3) the relative ability of the VECs to recover; (4) the relative amount of volatile exposure in the air; and (5) the relative weights implicitly or explicitly given by stakeholders to VECs and ECs that are applied when comparing the modeled exposures above thresholds of concern.

The model-based CRA studies of deepwater blowouts summarized herein show that the benefits of SSDI use on deepwater releases are demonstrable through its reduction of the oil droplet size distribution of oil released to the ambient water column. The exposure metrics for a matrix of scenarios varying these inputs and response actions are expected to be generally representative of the fate and behavior of oil and gas blowouts in much of the offshore water areas of the Gulf of Mexico with similar oceanographic conditions. However, distance to land and local current patterns dictate the relative degree of shoreline exposure. Biological distributions in the benthos were not mapped in these reported studies but should be considered in response decision-making. For example, SSDI might increase exposure to sensitive deepwater benthic habitats such as coral reefs if these resources are near a release and downstream.

The CRA approach may be applied to other oil types, regions, spill scenarios, and response activities, including for both surface spills (e.g., vessels, platforms, facilities; such as for a spill scenario matrix like that used by French-McCay and Graham, 2014) and subsurface releases (e.g., from oil and gas blowouts, pipelines, and submerged wrecks). Oil spill modeling (using a model capable of providing exposure-duration weighted exposure metrics such as SIMAP) can utilize appropriate environmental inputs for the location of interest, as well as oil properties and composition data for the oil type evaluated. The ECs and VECs used in the Gulf of Mexico CRA are typical of many marine locations. However, adjustments would need to be made to account for other ECs (such as ice habitats) and VECs of concern locally. The exposure metrics from the oil spill modeling could also be used to estimate human health and socioeconomic impacts. Because the modeling and CRA take some time to set up and perform, its role may be stronger as part of pre-spill planning than as part of a real-time response, particularly for short-duration releases. The main strengths of the approach are that it provides quantitative, relative indices of potential oil exposures (as opposed to more uncertain estimates of impacts), and that results can be used to engage stakeholders, expand awareness, and build confidence and trust in the decision-making process.

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