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Improving environmental assessments by integrating Species Sensitivity Distributions into environmental modeling: Examples with two hypothetical oil spills

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ABSTRACT

A three dimensional (3D) trajectory model was used to simulate oil mass balance and environmental concentrations of two 795,000 L hypothetical oil spills modeled under physical and chemical dispersion scenarios. Species Sensitivity Distributions (SSD) for Total Hydrocarbon Concentrations (THCs) were developed, and Hazard Concentrations (HC) used as levels of concern. Potential consequences to entrained water column organisms were characterized by comparing model outputs with SSDs, and obtaining the proportion of species affected (PSA) and areas with oil concentrations exceeding HC5s ($\text{Area}_{\geqslant \text{HC5}}$). Under the physically-dispersed oil scenario $\leqslant$77% of the oil remains on the water surface and strands on shorelines, while with the chemically-dispersed oil scenario $\leqslant$67% of the oil is entrained in the water column. For every 10% increase in chemical dispersion effectiveness, the average PSA and $\text{Area}_{\geqslant \text{HC5}}$ increases (range: 0.01–0.06 and 0.50–2.9 km^2, respectively), while shoreline oiling decreases ($\leqslant$2919 L/km). Integrating SSDs into modeling may improve understanding of scales of potential impacts to water column organisms, while providing net environmental benefit comparison of oil spill response options.

1. Introduction

Modeling is an essential component of environmental assessments, as it can help guide and scale the mobilization of resources, prioritize protection or mitigation strategies, and inform management decisions (e.g., Castanedo et al., 2006). Oil spill trajectory and effects models, for example, can be used to quantitatively predict the behavior and movement of oil in the environment by using algorithms describing fate processes, while providing information on the relative spatial and temporal extent of potential ecological consequences. These models have proven useful in pre-planning emergency response (MacFadyen et al., 2011; Mearns et al., 2001, 2003), as well as in natural resource damage assessment (French-McCay, 2003; French McCay et al., 2004). Within the context of oil spills, modeling can facilitate analyses of impact to biological resources by considering a set of oil recovery actions and response strategies (e.g., Reed et al., 1999), including the use of chemical dispersants.

With the exception of the Deepwater Horizon oil spill, where an unprecedented volume of dispersants was used, dispersants have rarely been used in response to oil spills. In the US and prior to the Deepwater Horizon oil spill, chemical dispersants were used in the Gulf of Mexico in eight occasions between 1990 and 2005 (Gugg et al., 1999; Henry, 2005; Stoermer et al., 2001) and in two occasions in 2009 (NOAA, 2014). Dispersants were also used during the 1984 Puerto Rican vessel incident off San Francisco Bay (Zawadzki et al., 1987). The use of dispersants has also been approved but never used during other oil spills in the US (17 total; e.g., 2004 MV Selendang Ayu and 2006 MV Cougar Ace oil spills, Alaska), and were minimally used during the 1989 Exxon Valdez oil spill due to limited availability of dispersant products and adequate application equipment, among other reasons (NOAA, 2014). Notable examples of dispersant use outside the US include the 1996 Sea Empress oil spill in Wales (Lunel et al., 1997), the 1996 Braer tanker spill in Scotland (Lunel, 1995), the 2006 Solar 1 tanker oil spill in the Phillipines (Yender and Stanzel, 2010), the 2007 container ship MSC Napoli incident in the UK (Law, 2008), and the 2009 Montara wellhead platform incident in Western Australia (Tan, 2011).

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One important premise on the use of chemical dispersants is that by reducing the surface tension of oil, dispersants reduce the amount of floating oil on the water surface reducing exposure risks to wildlife and sensitive shoreline habitats, and increasing microbial degradation (NRC, 1989, 2005). However, chemical dispersion of oil at the water surface enhances the rate of partitioning of oil into the top few meters of the water column, particularly of the lighter oil fractions (e.g., benzene, toluene, ethylbenzene, xylenes, etc.), resulting in higher oil concentrations compared to oil physically dispersed by currents, wind and waves (NRC, 1989, 2005). As a result, organisms entrained in water masses containing chemically dispersed oil are exposed to potentially toxic oil concentrations, though exposures may generally be of short duration because of the rapid dilution and water column mixing occurring in open waters. In addition, the use of dispersants increase the concentration of small oil droplets (generally <70 μm in diameters), which are not only readily biodegradable but also remain entrained in the water column because of their slow rising velocities (Cormack and Nichols, 1977; NRC, 2005). Yet, the relative contribution of oil droplets to the overall toxicity to entrained water column organisms is largely unknown partially because little empirical information exists on the link between oil droplet size and concentration, and toxicological effects (reviewed in Bejarano et al., 2014b).

Characterizing *in situ* impacts to entrained water column organisms is challenging, resulting in reliance of laboratory toxicity tests with a small number of species to infer potential impacts to a broader number of species. Comparisons of relative sensitivities across species and derivation of levels of concern can be achieved via cumulative distributions of existing physically or chemically dispersed oil toxicity data (e.g., median lethal, LC50 and effects concentrations, EC50), commonly known as Species Sensitivity Distributions (SSDs) (Posthuma et al., 2002). This type of approach has been used in oil spill research and assessments (Barron et al., 2013; Bejarano et al., 2013; de Hoop et al., 2011), but have not previously been incorporated into oil trajectory models. Consequently, the primary objective of this study is to demonstrate how SSDs can be used to improve model-based assessments of oil spill impacts under different chemical dispersant use scenarios. For the purpose of these analyses, hypothetical spill scenarios were developed for two areas: off San Francisco Bay, and off Charleston Harbor, South Carolina, and modeled oil concentrations in the water column compared to SSDs.

2. Methods

2.1. Oil mass balance and environmental concentrations

One of the tools used to model the fate, surface and subsurface transport, and three dimensional trajectories of spilled oil is the General NOAA Oil Modeling Environment (GNOME) (NOAA/ERD, 2013). While a number of related models are also available (e.g., SIMAP, French-McCay, 2004), the selection of GNOME was driven by its availability in the public domain. GNOME predicts the trajectory and spreading of oil, and generates trajectory outputs based on site-specific parameters, wind-driven currents and horizontal and vertical mixing (i.e., wind, local hydrodynamics, water column turbulence), while accounting for best guess (trajectories created assuming that all model inputs are correct) and minimum regret (trajectories created accounting for possible forecast errors in model inputs) forecast solutions (Beegle-Krause, 2001; Simecek-Beatty et al., 2002). Because GNOME incorporates oil-specific fate and behavior information (e.g., evaporation, dispersion, sedimentation) from an oil weathering model (Automated Data Inquiry for Oil Spills, ADIOS2) (Lehr et al., 2002), oil trajectories can be used to quantitatively describe the distribution of oil across several components (i.e., air, surface water and water column, shorelines), including estimates of average oil concentrations (Total Hydrocarbon Concentration, THC; hereafter) in the water column. Consequently, GNOME models environmental concentrations of physically or chemically dispersed oil in the water column, allowing for quantitative estimates of the potential footprint of oil impacts.

Oil trajectories for two hypothetical spills involving the release of 795,000 L (5000 barrels) of oil (major spill volume) were developed using GNOME with site-specific input parameters. For the purpose of demonstrating the flexibility of this approach, two oils with different chemical and physical characteristics (intermediate fuel oil [IFO] and Qua Iboe oil) were used in simulations. Only one oil type was used at each spill location: the Gulf of the Farallones (an area offshore San Francisco Bay), and an area offshore Charleston Harbor, South Carolina. Each of these hypothetical spills was modeled under two scenarios: a scenario involving natural (physical) dispersion of oil, and a scenario involving the use of chemical dispersants. The latter was further modeled assuming a 35% dispersant operational effectiveness, which is the upper level of dispersant effectiveness reported under field conditions (5–30%; NRC, 2005), and assuming a 80% dispersant effectiveness, which is considered to be an extreme case scenario under field conditions. Here, dispersant effectiveness is defined, from an operational perspective (not laboratory), as the amount of oil that is dispersed into the water column relative to the amount of oil that is dispersed by physical processes alone (wind, currents, waves). Modeled conditions, and oil and dispersant characteristics (e.g., oil type, physicochemical characteristics, dispersant effectiveness) are summarized in Table 1. For each of these scenarios, GNOME was used to produce outputs containing information on oil trajectory, oil mass balance, oil concentrations in the water column (from the water surface to the pycnocline), and oil loadings on shorelines over space and time (120 h). Because of model uncertainty, oil concentrations in the water column were bounded by upper and lower limits defined as 5× and 0.2× of the mean value, respectively. GNOME generates oil concentrations by grid summarized as mean and maximum THC concentrations. Grid sizes ranged from 0.25 to 1.0 square kilometers (km^2) in the case of Gulf of the Farallones scenario, and from 0.25 km^2 near the source to 3–5 km^2, 10–15 km down coast in the case of the Charleston Harbor scenario.

Table 1
Model inputs of two hypothetical oil spills, each involving the release of 795,000 L of oil (major spill volume). In all cases, models scenarios were run under physical dispersion only (no dispersants), and chemical dispersion with dispersant effectiveness of 35% (operational case) or 80% (extreme case).

Characteristics	Off San Francisco Bay, CA	Off Charleston Harbor, SC
Location	37°51′N, 122°46′W	32°41.6′N, 79°45.72′W
	25 km WNW Golden Gate (39 m isobath)	11.4 km SE Charleston Harbor entrance (10 m isobath)
Oil type	IFO 380 (API 18.3)	Qua Iboe (API 35.8)
Wind velocity (knots)	10 West	15 South
Water column mixing depth/pycnocline depth (m)	10	5
Breaking wave height (m)	1	1