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Simulating the effects of droplet size, high-pressure biodegradation, and variable flow rate on the subsea evolution of deep plumes from the Macondo blowout

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ABSTRACT

The relative effects of hydrodynamic, thermodynamic, and geochemical factors on the fate and transport of oil in the subsea are not well understood to date. This glaring lack of knowledge in deep-sea spill studies precludes the parameterization of blowout far-field models. Here we use observations from the Macondo blowout to evaluate the importance of input variables in a numerical model of oil transport and fate. We adapt a multi-hydrocarbon fraction module to oil dissolution and run sensitivity analyses under various parameterization scenarios. We find that the inclusion of oil droplet atomization, variable flow rates (VFR), high-pressure biodegradation (HPB), and vertical currents' velocities (VV) affects significantly the subsea oil mass distribution in the water column as well as the evolution of deep plumes. In particular, droplets up to 50 μm are neutrally buoyant and moved by deep currents predominantly driven by the topography, while the depth of the deep plume is very sensitive to the VV of the hydrodynamic model. We find good agreement between CTD cast observations and modeled mean depth of the oil mass, whereby HPB provide increased accuracy of predictions with time. The model suggests that VFR and HPB are mechanisms for the persistence of the southwestern deep plume observed at 1100 m by increasing the residence time of the oil in the water column. Modeled oil concentrations range from 5 to 500 ppb and present the highest values in the western and deepest locations of the subsea plume, which corroborate with field observations. We hypothesize that a substantial amount of subsea oil mass might have interacted with the bottom of the Mississippi Canyon.

1. Introduction

Following the Deepwater Horizon explosion on April 20, 2010, oil and gas gushed from the bottom of the Gulf of Mexico (GoM) at a depth of 1522 m, latitude 28.74°N, and longitude 88.36°W, polluting GoM waters for 87 days before the wellhead was capped (Fig. 1). While the surface slick and the airborne plume represented about 22% of the total leaked gas and oil (Ryerson et al., 2012), a fraction of the oil was trapped at depth (Kessler et al., 2011; Kujawinski et al., 2011; Paris et al., 2012) and in the sediments (Paul et al., 2013). As a result, water column oxygen levels were altered with the potential to cause long-term damage to the ecosystem of the GoM (Adcroft et al., 2010; Camilli et al., 2010; Lubchenco et al., 2010). Though the oil spill was a tragedy on many levels, it was also a rare opportunity to learn about the conditions for the formation of deep oil intrusions, improve subsea oil models, and address the footprint of subsea oil on marine ecosystems; all of which should help improve the emergency response to blowout.

Tracing the transport of surface oil in two dimensions is highly complex, but tracking and forecasting movement of deep plumes in three dimensions is even more challenging. An example of a challenge that the modeling efforts face is that the buoyant plume ejected from Macondo was not only driven by gases but also by the density difference between the oil/gas mixture and the surrounding seawater. The combined buoyancy of the gas and oil created a rising plume but, unlike a single-phase plume, much of the oil and gas separated from the entrained seawater and became trapped by stratification (Socolofsky et al., 2011, Paris et al., 2012).

Another critical challenge is to model the time scales of biodegradation processes to remove hydrocarbons from the water column. Oil is a reactive tracer since it undergoes physical and

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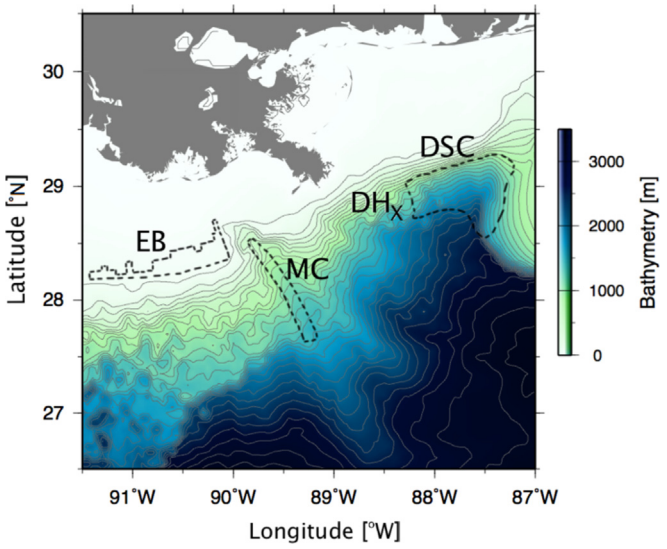

Fig. 1. Study area in the northern Gulf of Mexico encompassing the DeSoto Canyon (DSC), the Mississippi Canyon (MC), the Ewing Bank (EB), and the Deepwater Horizon site (DH). Bathymetric data was retrieved from ETOPO1 1-min Global Relief (Amante and Eakins, 2009) and contours in gray indicate isobaths from 50 to 3500 m with contours intervals of 100 m.

chemical changes called weathering. Predominantly, this process includes evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation (Douglas et al., 1994). Among those changes, biodegradation determines the ultimate fate of the oil (Díez et al., 2005; Prince et al., 2003; Venosa and Holder, 2007). After the Macondo blowout, a plume of hydrocarbon-enriched water was observed at depths of 800–1200 m (Camilli et al., 2010; Joye et al., 2011a; Valentine et al., 2010), at which hydrocarbons stimulated intense heterotrophic microbial activity (Kessler et al., 2011). As a result of millions of years of natural oil seeps from the seafloor, oil residues are a common phenomenon in the GoM (OSAT, 2010). Therefore, it is not surprising that the microbial potential for biodegradation of oil compounds was present when oil was highly dispersed in the water column after the spill.

Hitherto, measurement and modeling of the crude oil and gas chemistry have been presented by Reddy et al. (2011), while estimates of rising fluid composition and velocity have been presented by Ryerson et al. (2011) and Camilli et al. (2010). Recent model simulations of subsea oil transport have used three-dimensional coupled models to capture the major far-field (ca. 300 m above the wellhead) processes involved in the blowout. Those works have demonstrated the importance of droplet size, motion due to ocean dynamics and oil buoyancy, synthetic dispersants, water stratification, upwelling and subduction events (North et al., 2011; Paris et al., 2012) on the dispersion and fate of the oil.

The objective of this study is to evaluate the relative contribution of droplet size, variable flow rate (VFR), high-pressure biodegradation (HPB), and vertical velocity (VV) of the hydrodynamic model on the subsea evolution of the oil plume. This study builds upon the modeling effort of Paris et al. (2012) and the findings of Adcroft et al. (2010) by implementing biodegradation rates derived from laboratory experiments at high pressure and observed time varying flow rates (Griffiths, 2012) to a novel version of the multi-fraction oil module described in Paris et al. (2012). The research presented here includes: (1) a description of the hydrodynamic and oil multi-fraction models; (2) statistical comparison of expected and observed subsurface oil plume location and center of mass; and (3) sensitivity analyses of various near-field blowout parameters on the distribution and fate of oil in the far-field.

2. Data and methods

A newly developed oil spill model (Paris et al., 2012) was calibrated with varying initial conditions of the Macondo blowout. The oil spill model used herein is an application of the Connectivity Modeling System (CMS) of the Rosenstiel School of Marine and Atmospheric Science (RSMAS), a multi-scale biophysical modeling system based on a stochastic Lagrangian framework (Paris et al., 2013). Laboratory experiments on biodegradation were conducted at the high-pressure reactors of the Institute of Technical Biocatalysis, Technical University Hamburg–Harburg (TUHH).

2.1. Biodegradation experiments at high pressure

Biodegradation is hypothesized to remove most of the contaminating hydrocarbons, but it can take months to years in areas of high oil concentrations (Atlas and Hazen, 2011); some light should be shed to constrain those time scales. To incorporate into the model experimental biodegradation rates for the light (F_1), intermediate (F_2), and heavy (F_3) oil fractions simulated in individual oil droplets, biodegradation experiments at high-pressure were carried out for three different alkanes of each oil fraction.

Pseudomonas frederiksbergensis was used as model bacteria for the alkane degradation at high pressure. This strain was isolated from sea-ice samples from Spitzbergen, Norway and was identified by the German Collection of Microorganisms and Cell Cultures by fatty acid analysis and 16S rDNA sequencing (Fredua-Agyeman et al., 2011). These bacteria belong to γ-Proteobacteria class, which is the same class that Hazen et al. (2010) reported to be the only significantly enriched in the plume relative to non-plume samples. Valentine et al. (2012) found that the microbial community dynamics in water parcel were composed of *Colwelliaceae*, *Oceanospirillales*, *Methylococcaceae*, and *Cycloclasticus*. Those bacteria, except *Methylophilaceae*, belong to the γ-Proteobacteria class, as *Pseudomonas frederiksbergensis* does. Recent findings show that γ-Proteobacteria distributes and migrates seasonally, and can bloom as well in very different latitudes ranging from the North Pole to the South Pole, and therefore in many different regions of the marine ecosystem (Ladau et al., 2013). Recently Gutierrez et al. (2013) discovered that several taxa belonging to γ-Proteobacteria are capable of degrading hydrocarbons from plume waters during the DH oil spill.

For the biodegradation experiments at high pressure, five identical high-pressure reactors of 160 mL volume were used. A glass vial containing 20 mL of mineral media was supplied with 1 mM of one of these alkanes: decane ($C_{10}H_{22}$), hexadecane ($C_{16}H_{34}$) or tetracosane ($C_{24}H_{50}$) and inoculated with 10% of P. frederiksbergensis. In order to provide a model with realistic biodegradation rates we used pressure conditions as they occur at the Macondo well. The vials were placed inside the reactors and the air in the reactors was compressed with nitrogen gas until 150 bar. Although obligate barophiles —bacteria that grow exclusively under elevated hydrostatic pressure— only exist at higher pressures, it is still not clear how much influence a pressure of 150 bars on biodegradation of alkanes of chain longer than butane. The reactors were incubated at 200 rpm and room temperature until the stationary phase of the bacterial growth was reached. Pseudomonas frederiksbergensis is a psychrophilic bacterium, that grows optimally at 15 °C. We used room temperature because the growth rates at 4–5 °C are identical to those at 20–22 °C (Abdel-Megeed and Müller, 2009). For each time point, one reactor was used and after incubation, bacterial growth and the alkane amount were quantified.

The number of the bacteria was determined by plate counting in LB agar. The analysis of alkanes was done with a Hewlett-Packard 5890 Series II gas chromatograph (GC), which was equipped with an Agilent HP-5MS column and a Hewlett-Packard 5971A mass selective detector. The oxygen was measured online in the gas phase using

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