Deepwater oil-spill modeling for assessing environmental impacts

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Abstract

Oil and gas activities in deepwater (areas deeper than 340 meters) have proceeded at an unprecedented rate, and have led to concerns about oil released by accidents near the seafloor. Oil and natural gas releases in deep water behave much differently than in shallow water. This is primarily because of the density stratification, high pressures, and low temperatures found in deep water. Some physical and chemical changes that occur in deepwater environments may significantly reduce the buoyancy of the plume and keep large amounts of the oil submerged for an extended time. This has significant implications for environmental impact assessment, oil-spill cleanup, contingency planning, and source tracing.

The Minerals Management Service (MMS) performs an oil-spill risk analysis (OSRA) to estimate the probability of oil spills occurring and the risks of contact to environment resources. The Clarkson Deepwater Oil and Gas Blowout Model (CDOG model) is a jet/plume model that simulates the behavior of oil and gas accidentally released in deepwater areas. The OSRA model and the CDOG model are used to estimate the contact of deepwater oil spills to the environmental resources. Real-time current data from Acoustic Doppler Current Profilers (ADCP's) deployed on offshore platforms are used to drive the models.

Preliminary results indicate that the OSRA model and the CDOG model can provide important information on the behavior of oil spills in the deep water. Ultimately, this information will be used in the pertinent environmental impact statements and in the development of deepwater oil-spill response plans.
Keywords: deepwater oil spill, environmental impact, oil spill risk analysis, trajectory model, plume model.

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1 Introduction

As a Federal agency within the U.S. Department of the Interior (DOI), the Minerals Management Service (MMS) maintains a leasing program for commercial oil and gas development on the U.S. Outer Continental Shelf (OCS). The MMS evaluates the development of mineral resources by analyzing the environmental consequences prior to making decisions regarding lease sales or approval of industry's action plans by publishing either an environmental impact statement or an environmental assessment.

Offshore drilling for oil and gas has been conducted since the early 1900's. Oil and gas under the seabed continue to be an important part of the energy resources of the United States. The OCS provides approximately 30 percent of the domestically produced crude oil and 25 percent of the domestic natural gas. The western and central portions of the northern Gulf of Mexico (GOM) make up one of the world's major oil and gas production areas, and have been a steady and reliable source of crude oil and natural gas for more than 50 years. Approximately $4-6 billion per year in minerals revenue is collected from offshore and onshore leases. The need to balance the value of these resources against the potential for environmental damage is an important concern, and has become increasingly recognized in Federal laws and national debates over energy, LaBelle [1].

Oil and gas activities in deep water (areas deeper than 340 meters) have proceeded at an unprecedented rate, and have led to concerns about oil released by accidents near the seafloor. Oil and natural gas releases in deep water behave much differently than in shallow water. This is primarily because of the density stratification, high pressures, and low temperatures found in deep water. Figure 1 is a sketch of some physical features in a subsurface plume. Preliminary calculations suggest that a plume of gas and/or oil could travel beneath the surface for many kilometers before surfacing many hours after release. Recent field experiments showed, however, that oil released at a depth of 840 meters surfaced within a few hours. Some physical and chemical changes that occur in this deepwater environment, such as the formation of frozen gas hydrates from gas bubbles, could significantly reduce the buoyancy of the plume and keep large amounts of the oil submerged for an extended time. Recently, it has also been shown that there are strong currents at water depths between 1,000 and 2,000 meters. These strong flows affect oil and gas operations and MMS assessments of subsurface spills. All of these features have significant implications for environmental impact assessment, oil-spill cleanup, contingency planning, and source tracing.

2 Models for oil-spill simulation

At the MMS, two models are used for oil spill studies: the Oil-Spill Risk Analysis (OSRA) model (Smith *et al* [2]) for oil spilled on the surface water and the Clarkson Deepwater Oil and Gas Blowout Model (CDOG model) (Yapa *et al* [3]) for spills in the deepwater.

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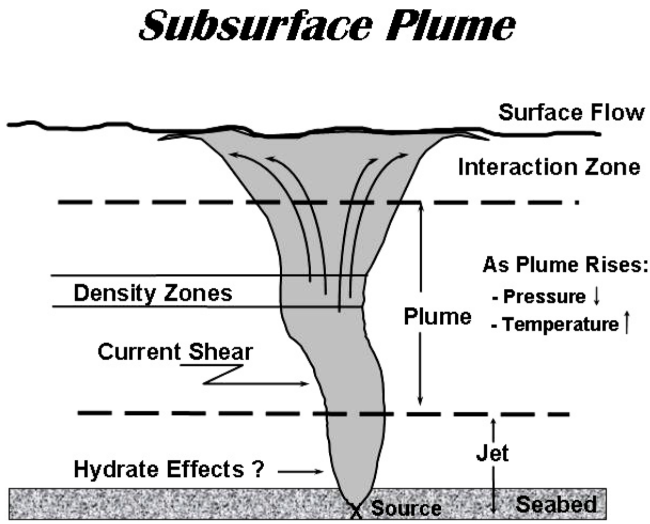

Figure 1: A sketch of some features in a subsurface plume in deep water.

2.1 OSRA model

The OSRA model, originally developed by Smith *et al* [2] and enhanced by MMS over the years (LaBelle and Anderson [4] and Ji *et al* [5]), is applied to study oil spilled on surface water. The OSRA model produces probabilistic estimates of oil-spill occurrence and contact to biological and economic resources using historical records of oil spills, winds, and surface ocean currents. The model initiates thousands of oil-spill simulations at hundreds to thousands of hypothetical spill locations to generate an ensemble of oil-spill trajectories, which can statistically characterize oil-spill risk over a large area. The spill locations are in areas of prospective drilling and production, and along projected pipeline and tanker routes.

The oil-spill risk analysis depends on the meteorological, geographical, and oceanographical conditions of the study area, the environmental resources that are at risk, and the estimated volumes of oil resources that are assumed to be discovered, produced, and transported. The MMS works closely with States and other Federal agencies to obtain the best available geographic information regarding natural resources and the shoreline, which is represented by one or more equal-distant partitions called land segments.

The analysis is usually conducted in three parts corresponding to different aspects of the overall problem:

- The first part addresses the probability of oil-spill occurrence (Anderson and LaBelle [6] [7])
- The second part addresses the trajectories of oil spills from hypothetical spill locations to various environmental resources (LaBelle and Anderson [4]).

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- The third part combines results of the first two to estimate the overall oil-spill risk if there is oil development.

Projection of potential oil-spill impacts is based on results generated by the OSRA model. The OSRA results provide information for imposing stipulations or deleting certain tracts from leasing where there is a high probability that any oil spilled would affect particularly sensitive areas and valuable resources.

An oil spill on the ocean surface moves around by the complex surface ocean currents exerting a shear force on the spilled oil from below. In addition, the prevailing wind exerts an additional shear force on the spill from above, and the combination of the two forces causes the transportation of the oil spill away from its initial spill location. In the OSRA model, the velocity of a hypothetical oil spill is the linear superposition of the surface ocean current and the wind drift. The model calculates the movement of hypothetical spills by successively integrating time sequences of two spatially gridded input fields: the surface ocean currents and the sea-level winds, both of which were generated by other computer models using many observations of relevant physical parameters. In this fashion, the OSRA model generates time sequences of hypothetical oil-spill locations–essentially, oil-spill trajectories.

At each successive time step, the OSRA model compares the location of the hypothetical spills against the geographic boundaries of shoreline and designated offshore environmental resources. The model counts the occurrences of oil-spill contact to these areas during specific time periods. Finally, the frequencies of oil-spill contact are computed for designated oil-spill travel times (e.g., 3, 10, or 30 days) by dividing the total number of oil-spill contacts by the total number of hypothetical spills initiated in the model from a given hypothetical spill location.

In the trajectory simulation portion of the OSRA model, many hypothetical oil-spill trajectories are produced by numerically integrating a temporally and spatially varying ocean current field and superposing on that an empirical wind-induced drift of the hypothetical oil spills. Collectively, the trajectories represent a statistical ensemble of simulated oil-spill displacements produced by a field of winds derived from observations and numerically derived ocean currents.

The OSRA model has been used successfully to hindcast several documented oil-spill incidents including the Argo Merchant incident (off Nantucket Island, 1976), the Santa Barbara Channel blowout (1969), and the IXTOC-I spill (1979-1980). The spill trajectories generated by the OSRA model closely matched the observed movement of the spilled oil during these incidents. Recent applications of the OSRA model include the analyses in the Gulf of Mexico (Ji *et al* [8] [9]).

2.2 CDOG

The CDOG model (Yapa *et al* [3]) simulates the behavior of oil and gas accidentally released in deep water. The model formulation integrates the hydrodynamics and thermodynamics of the jet/plume, the thermodynamics and kinetics of hydrate formation and decomposition, and gas dissolution. In deep water, the ultra-high pressure and cold temperature cause phase changes in gases. These effects, combined with deepwater currents in some regions, present extraordinary challenges to modeling jets/plumes from deepwater oil and gas blowouts. The model uses an improved, integrated formulation for computing the buoyant velocity of oil droplets, gases and hydrates. Each module in the CDOG model has been tested by comparing the computational results with available data. The model results show a good agreement with data from the field experiments (Yapa *et al* [3]).

3 Modeling of deepwater spills

3.1 The Deepblow Experiment

In June 2000, a series of field experiments on a deepwater spill (called the deepblow) was successfully completed off the Norwegian coast, and provided important information on how oil and gas from subsea leaks or blowouts will behave in deep water (Johansen *et al* [10]). The experiments were a joint effort involving the MMS and 22 oil companies with interests in exploration and development in deepwater areas of the U.S. Gulf of Mexico and Norwegian Sea. The experiments were conducted at a depth of 84-meters in the Helland Hansen region in the Norwegian Sea, about 250 kilometers northwest of Kristiansund. The experiments released 60 cubic meters of marine diesel and 60 cubic meters of crude oil, together with 18 cubic meters of liquefied natural gas equivalent to 10,000 cubic meters of gas at atmospheric pressure.

In this study, the CDOG model is used to simulate the deepwater spill events. Figure 2 is the modeled oil thickness 124 minutes after the release of oil from the seabed. The horizontal axis represents distance in the south-north direction, and the vertical axis represents water depth. The oil thickness gives the total amount of oil accumulated in the west-east direction and indicates the amount of oil mass in the water column. The arrows on the right give the current speeds in the south-north direction near the spill site. Figure 2 also shows that the oil spilled at the 844-meter water depth reached the surface after 2 hours or so, which is consistent with the observation.

Figure 3 is the modeled oil thickness on the water surface after 5 hours from continuous oil release. The horizontal axis is in the west-east direction, and the vertical axis is in the south-north direction. It shows that the oil spreads more than 1 kilometer in the south-north direction and about 800 meters in the west-east direction, a result that is also comparable to the experimental observation.

3.2 Modeling deepwater spilled in the GOM

In this study, current data from Acoustic Doppler Current Profilers (ADCP's) deployed on offshore platforms are used to drive the CDOG model. The data are measurements collected at 2-minute time intervals, in waters up to 1,800 meters deep, and include more than 80 bins in the vertical; they provide excellent current profiles for the CDOG model.

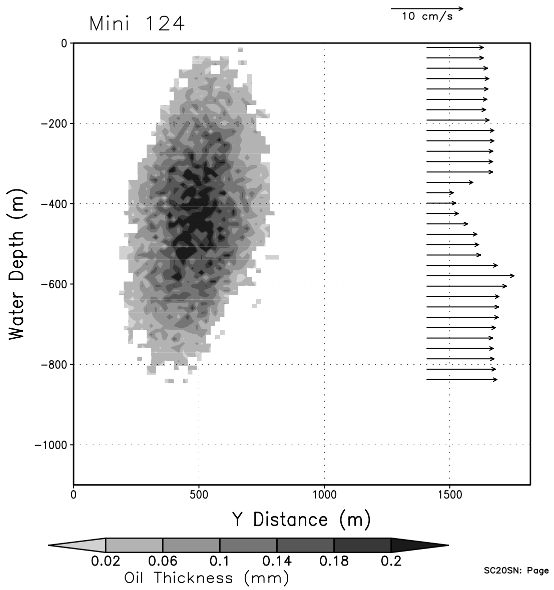

Figure 2: Modeled oil thickness 124 minutes after release of oil from the sea bed.

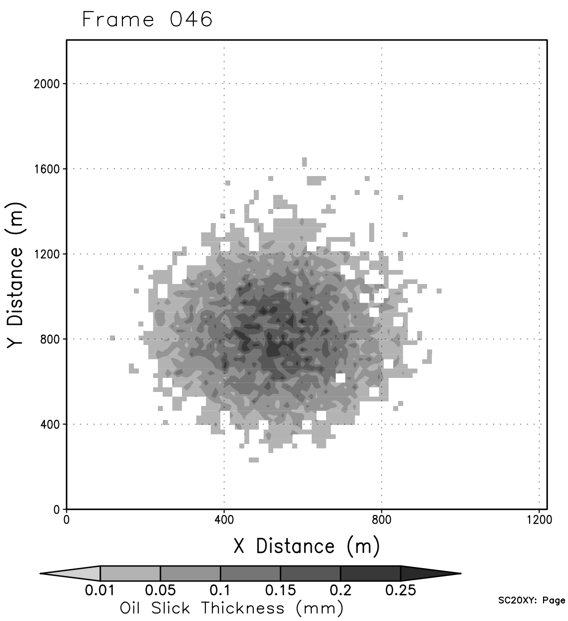

Figure 3: Modeled oil thickness on the water surface after 5 hours from continuous oil release.

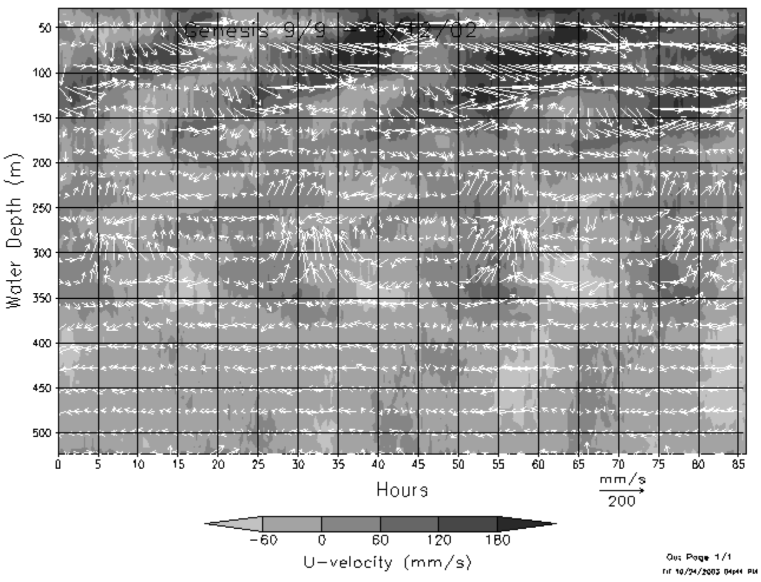

Figure 4: Measured u-velocity at the Genesis station (9/9-12/02).

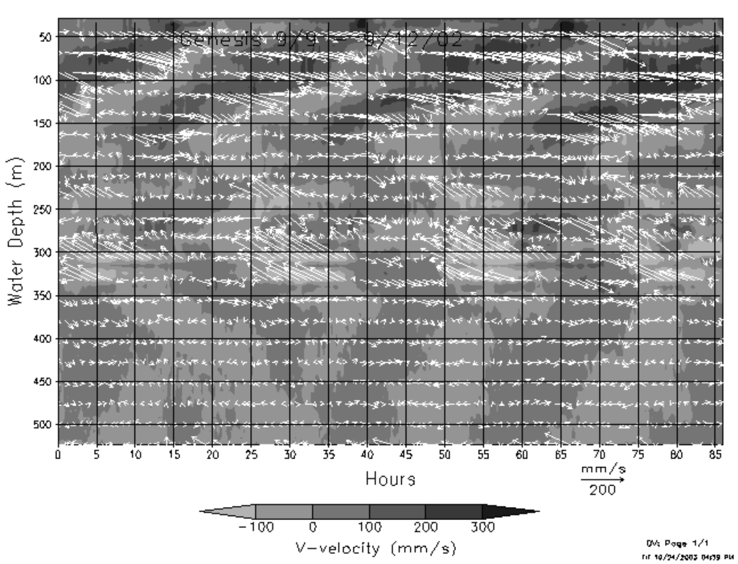

Figure 5: Measured v-velocity at the Genesis station (9/9-12/02).

Figure 4 is the u-component of the measured current at the Genesis station (91.5° W, 27.7° N) for 85 hours between September 9 and 12, 2002. Figure 5 is the corresponding v-component. Both figures indicate strong periodic signals of

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25 hours or so, the signals produced by the initial motion. The surface current speeds can measure more than 40 centimeters per second from time to time. This set of ADCP data is used to drive the CDOG model to simulate the hypothetical oil spills in the area. Figure 6 is the modeled surface oil thickness after 86 hours of continuous oil release at 800 meters below the water surface. Figure 6 shows that the surface oil slick spreads more than 20 kilometers in the south-north direction and more than 10 kilometers in the west-east direction.

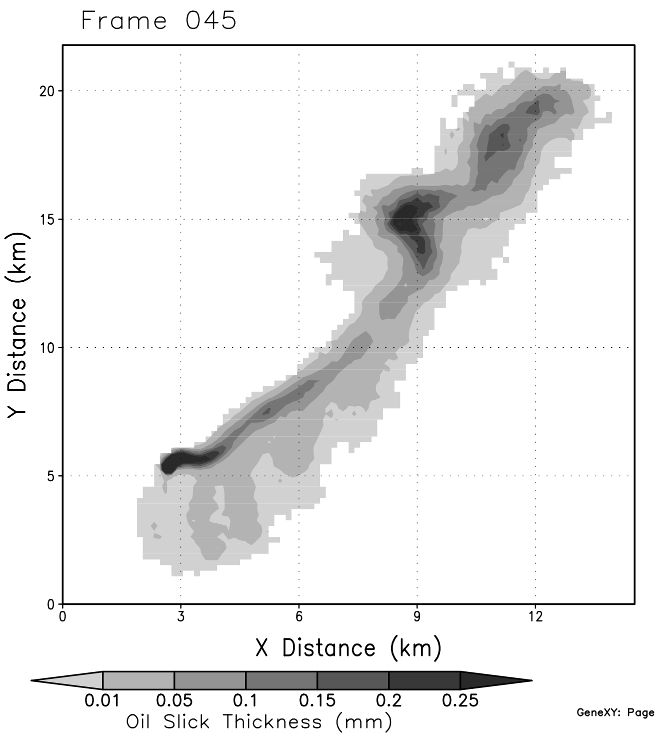

Figure 6: The modeled oil thickness on the water surface after 85 hours of continuous oil release.

4 Summary and conclusions

In addition to the OSRA model for modeling oil spills on the water surface, the MMS also uses the newly developed CDOG model for the simulation of oil spilled in deep water. The combination of the two models provides a useful tool for estimating the oil spill trajectories and for analyzing the environmental impacts of potential spills.

In this study, the CDOG model is applied to simulate deepwater oil spills in the Norwegian coast and in the GOM. The model results are consistent with the experimental observations obtained from the Deepblow experiments

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(Johansen *et al* [10]). Results from the study indicate that the OSRA model and the CDOG model can provide important information on the behavior of oil spills in deep water and the environmental risks. An on-going study is to directly couple the two models for assessing the environmental impacts of deepwater spills. This information will be used in the pertinent environmental impact statements and in the development of deepwater oil-spill response plans (Ji [11]).

Acknowledgements

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