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Modeling oil weathering and transport in sea ice

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ABSTRACT

This paper presents a model of oil weathering and transport in sea ice. It contains a model formulation and scenario simulation to test the proposed model. The model formulation is based on state-of-the-art models for individual weathering and transport processes. The approach incorporates the dependency of weathering and transport processes on each other, as well as their simultaneous occurrence after an oil spill in sea ice. The model is calibrated with available experimental data. The experimental data and model prediction show close agreement. A sensitivity analysis is conducted to determine the most sensitive parameters in the model. The model is useful for contingency planning of a potential oil spill in sea ice. It is suitable for coupling with a level IV fugacity model, to estimate the concentration and persistence of hydrocarbons in air, ice, water and sediments for risk assessment purposes.

1. Introduction

Oil spill preparedness and response in the Arctic has become a main focus for potential oil exploration and production and Arctic shipping activities (Walker et al., 2014; Dickins, 2011). It is projected that these activities will increase and therefore so will the possibility of an oil spill in the Arctic (Dickins, 2011; Yapa and Chowdhury, 1990). Accidental oil spills in open water represent 5% of total oil pollution, but the impact on the environment is high (Janeiro et al., 2008). An oil spill in the Arctic presents higher risks. This is because such an ecosystem is sensitive and presents challenges for the response and mitigation of the spilled oil. The harsh nature of the environment, limited response capacity, remoteness, complex nature of oil–ice interaction, and the lack of daylight are some of the factors responsible for these challenges (Dickins, 2011; Lissauer and Murphy, 1978).

The capacity to predict weathering and transport processes is key to aiding contingency planning, clean up, and the assessment and risk evaluation of environmental impact of accidental releases of oil and gas in sea ice (Daling and Strøm, 1999; Yapa and Chowdhury, 1990).

Different accidental release scenarios result in different behaviors of spilled oil. A blowout beneath the ice cover may result in the spread of the oil beneath the ice. The blowout may force the plume of oil and gas through the ice cover, creating a broken ice–oil interaction (Gjøsteen and Løset, 2004). In the event of an oil spill from a ship or a rig in open water, a possible outcome is an oil slick on the surface of the water. An accidental release from a ship in the Arctic could result in the spilled oil moving between the floes. The oil may move below the floes as well. The oil may also become encapsulated by ice due to the nature of the ice cover (Drozdowski et al., 2011; Gjøsteen and Løset, 2004). These interaction and movement of oil are illustrated in Fig. 1. In the presence of snow and leads, the oil–ice interaction becomes even more complex (Afenyo et al., 2015).

Weathering and transport processes of an oil spill in ice-covered waters are studied through experiments and oil spill models (Sebastião and Soares, 1995; Gjøsteen and Løset, 2004). Laboratory experiments may be appropriate for studying a single or limited number of factors and their effects, but modeling provides more flexibility for studying multiple factors and their effects concurrently (Gjøsteen and Løset, 2004). Oil spill modeling makes use of both weathering and transport algorithms. Both processes influence each other. The complex, interactive nature of the processes makes numerical models a good tool for solving the interactions at varying time scales (Janeiro et al., 2008). The weathering processes include evaporation, emulsification, photo-oxidation, biodegradation, and dissolution. The transport processes are spreading, dispersion, sedimentation, advection and encapsulation. These processes are functions of the environment in which the spill occurs and the oil characteristics (Reed et al., 1999; Fingas, 2015). Fig. 2 shows the structure of a typical oil spill model, which is made up of an input section, calculation section, and an output section (Afenyo et al., 2015; Reed et al., 1999).

Spill models are used to predict the physical and chemical properties of weathered oil, the location of spilled oil at a particular time, and the oil mass balance (Fingas, 2015; Reed et al., 1999). In the past, models based on “mixing rules” have been used and were found to be inadequate and less successful for predicting most oil properties. “Mixing rules” refer to the use of physical properties of oil, based on the transformation of the composition of oil, as a consequence of evaporation of the lighter fraction of the oil. Such models were only successful for

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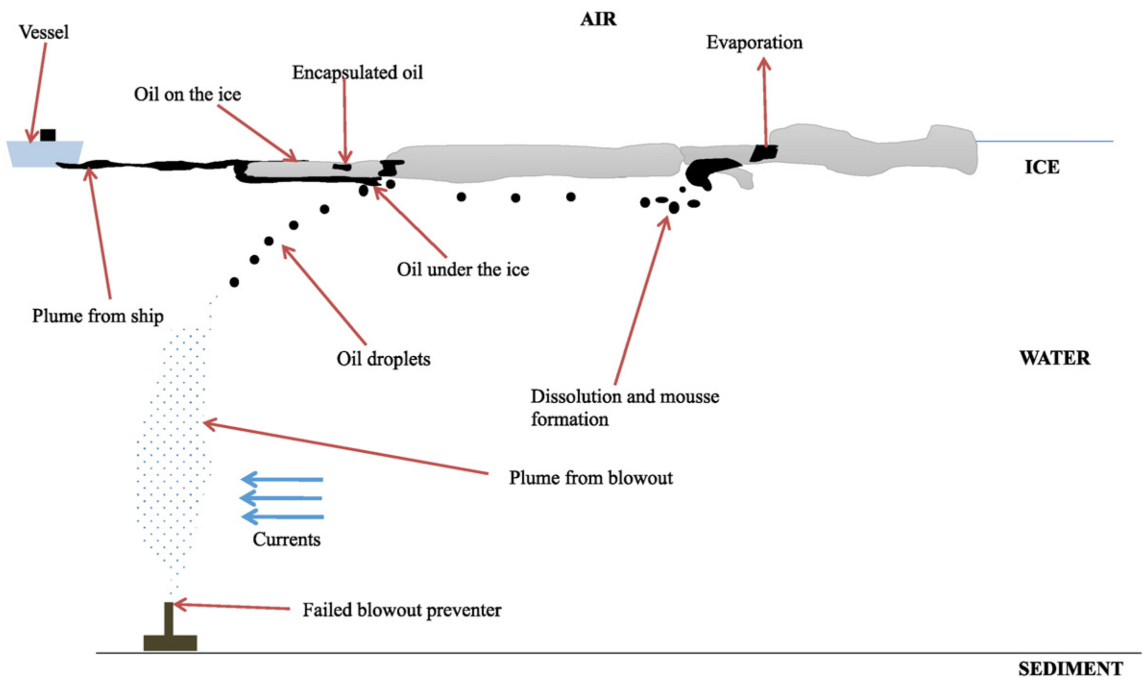

Fig. 1. Oil–ice interaction during Arctic shipping and an offshore blowout scenario.
After Afenyo et al. (2015) and Drozdowski et al. (2011).

predicting the density of spilled oil and not properties like pour point and viscosity (Daling and Strøm, 1999). Most oil spill modeling efforts have focused on modeling the processes singularly. In reality, the processes occur simultaneously and are dependent on each other (Sebastião and Soares, 1995).

Modeling weathering and transport of an oil spill in sea ice are complicated. The uncertainties and unknowns about oil–ice interaction make it more challenging. This is because of the scarcity of data and limited studies on the subject, compared to open water conditions. Predicting the weathering and transport processes singularly in ice has been a challenge. Individual processes are still not understood properly (Afenyo et al., 2015; Lee et al., 2015). Modeling these processes simultaneously presents more complexity (Afenyo et al., 2015).

This paper focuses on the simultaneous occurrence and time dependency of weathering and transport process after an oil spill in sea ice. The paper presents the approach adopted for model formulation and its application. A calibration exercise is carried out to match the model output with large-scale field experimental data conducted by SINTEF. This has not been done in previous studies because of the scarcity of data on releases of oil spills in ice-covered waters.

This work is structured as follows: Section 2 describes two perspectives for oil spill modeling. In Section 3, the methodology adopted is presented. Section 4 presents a description of the scenario of the large-scale experiment conducted by SINTEF. The experiment is used as a numerical example, and the results obtained from the experiment are compared with those of the model. Section 4 also includes a sensitivity analysis of the parameters of the model. In Section 5, the outcome of the study is discussed and the conclusion of the work is presented in Section 6.

2. Weathering and transport modeling of oil spill

Two approaches are used for modeling the weathering and transport of spilled oil. These are referred to in this paper as the Singular Process Modeling Approach (SPMA) and the Multi-processes Modeling Approach (MPMA). The SPMA refers to a modeling approach in which the interdependencies and linkage effects of processes after an oil spill are not considered; modeling is performed for a single process. This is illustrated in GjØsteen (2004) where the data from Sayed and Løset (1993) is used to model oil spreading in cold waters. This model does not consider the effect of other weathering and transport processes. The MPMA considers the effects of linkages and the interdependences of relevant processes to a particular oil spill scenario. The success of both approaches is dependent on the availability of algorithms describing the processes of interest (Sebastião and Soares, 1995; Yang et al., 2015). SPMA is useful when the goal of the study is to evaluate the effect of individual parameters involved in the description of a particular weathering or transport process (Gjøsteen and Løset, 2004). If this is the case, SPMA presents a more focused approach. From an oil spill contingency planning perspective, the interdependencies among the weathering processes are important. This is because the interactions affect the overall mass balance of the spilled oil, which is important information for the team involved in planning, response, and recovery of the oil spill (Afenyo et al., 2015). MPMA offers a better option for this purpose. Sections 2.1 and 2.2 describe some of the works that have adopted the two approaches.

2.1. Singular process modeling approach—SPMA

Researchers have developed models for individual transport and weathering processes for ice-covered waters. Fingas and Hollebone (2003) and Afenyo et al. (2015) have presented reviews of models for freezing environments. The algorithms developed for these processes through laboratory experiments have focused on studying individual processes (Fingas and Hollebone, 2003; Gjøsteen and Løset, 2004). The preparation of oil samples for the experiments to support the development of the Oil Spill Contingency and Response Model (OSCAR) was done in such a way as to avoid the effect of other processes, so the processes under investigation could be studied individually (Daling et al., 1997; Fingas, 2015).

2.2. Multiple processes modeling approach—MPMA

Sebastião and Soares (1995) and Mishra and Kumar (2015) have adopted an MPMA for modeling spilled oil in open water. Part of this concept will be used in the methodology of this paper. This approach considers the effect of linkages and dependencies between weathering