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In Situ Oil Spill Countermeasures in Ice-Infested Waters: A Modeling Study of the Fate/Behaviours of Spilled Oil

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ABSTRACT 300131:

The expansion of offshore oil and gas and marine transport activities in the Arctic have raised the level of risk for an oil spill to occur in the Arctic region. Existing technologies for oil spill cleanup in ice-covered conditions are limited and there is a need for improved oil spill countermeasures for use under Arctic conditions. A recent field study has assessed a proposed oil spill response technique in ice-infested waters based on the application of fine minerals in a slurry with mixing by propeller-wash to promote the formation of oil-mineral aggregates (OMA). While it was verified in the experimental study that the dispersion was enhanced and mineral fine additions promoted habitat recovery by enhancing both the rate and extent of oil biodegradation, limited monitoring data provide little insights on the fate of dispersed oil after the response. To help understand the oil transport process following mineral treatment in ice-covered conditions, mathematical modeling was used in this study to simulate the transport of OMA and calculate the mass balances of the spilled oil. To study the effects of ice and minerals on the fate and transport, the result was compared with scenarios without ice and without the addition of mineral fines. The results show general agreement between the modeling results and field observations, and further confirm the effectiveness and potential for using mineral treatment as a new oil spill counter-measure technology. This technique offers several operational advantages for use under Arctic conditions, including reduced number of personnel required for its application, lack of need for waste disposal sites, and cost effectiveness.

Keywords**:** oil mineral fines, modeling, biodegradation, ice

INTRODUCTION:

Marine traffic in the Arctic is predicted to increase with the lengthening of the ice-free season in the Northwest Passage, industrial expansion, eco-tourism and community development. In response to recent oil spill incidents and the announcement of future frontier oil and gas exploration and production activities in the Arctic, the public, industry and regulatory

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resource managers are demanding improved oil spill countermeasures for use under Arctic conditions.

Existing technologies for oil spill cleanup in the ice-packed, open ocean are based on physical recovery and *in situ* burning, which are limited by logistical constraints such as ease of access, availability of equipment and response personnel, and environmental factors such as interference by the presence of ice and inclement weather. Enhanced dispersion has also been considered as an alternative oil spill response countermeasure for use in the Arctic. Chemical dispersants have been developed to enhance the oil-in-water emulsification, however, a number of concerns have been raised over the potential application of such products with respect to human health and potential toxic effects on sensitive species of biota that could change ecosystem dynamics.

Suspended particulate matter (SPM) has long been recognized as an important factor in the transport of spilled oil from one environmental compartment to another (Poirier and Thiel, 1941; Muschenheim and Lee. 2002; Sørensen et al., 2014; Gong et al., 2014). Bragg and Owens (1995) suggested that mineral-oil interactions may have been insrumental in the natural cleansing of shorelines oiled in Prince William Sound, Alaska, following the *Exxon Valdez* spill. As the basis of an active oil spill countermeasure technique, the active generation of oil-mineral-aggregates (OMA) in the field first employed "surf-washing," which exposes stranded oil to mineral fines and wave-energy when contaminated sediments are transported into the surf-zone (Lee et al., 1999; Owens, 1999). In subsequent modelling studies of oil sediment interaction in nearshore waters, Bandara et al. (2011) concluded that oil removed due to sediment interaction could be useful in the development of oil spill countermeasures. Scenario simulations showed that up to 65% of released oil could be effectively removed from the water column in the form of oil-sediment aggregates (OSA). Furthermore, in terms of potential impacts on the benthic environment, the model simulations showed that the amount of oil partitioned into sediments is 4–5 orders of magnitude smaller than the amount of OSAs formed.

The potential use of OMA as a spill countermeasure in ice-packed waters was illustrated in the late 1990's following an accidental release of oil onto ice from the tanker *Saraband* in the Saguenay Fjord, Canada (Blouin, 2001). More recently, Lee et al. (2011) have assessed an oil spill response technique in ice-infested waters based on the application of fine minerals in a slurry with mixing by propeller-wash to promote the formation of oil-mineral aggregates (OMA). Although it was verified in the field and follow-up laboratory studies that treatment with mineral fines in the presence of a high energy environment (provided by propeller wash) enhanced the dispersion of the oil and promoted habitat recovery by enhancing both the rate and extent of oil biodegradation, limited monitoring data provide little insights on the fate of dispersed oil after the response. On the other hand, mathematical models have been proven useful to simulate the subsequent fate/transport of OMA after its formation under a wide range of hydrodynamic conditions (Niu et al. 2009, 2010, 2011).

To complement the experimental study of Lee et al. (2011) and help the understanding of the fate of spilled oil after mineral addition and propeller-wash, the purpose of this study is to conduct mathematical modeling to simulate the transport of OMA under ice-covered conditions.

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The mass balances of the oil with OMA treatment will be studied and compared with scenarios without ice and without mineral treatment.

MATERIALS AND METHODS:

The same model approach by Niu et al. (2011) is adopted here to study the fate/transport of oil under eight different scenarios (Table 1). The oil spill model used by Niu et al. (2011) is the OSCAR model developed by SINTEF (Reed et al., 2012). For all scenarios, 200 L of Heidrun crude oil was released and its subsequent transport was simulated for a period of 5 days. Scenario 1 is a case that simulates the open water conditions without mineral treatment. While there was also no mineral treatment in scenario 2, the case was under ice-covered conditions and it was assumed that oil will be trapped under ice and no evaporation was possible. Scenarios 3, 5, and 7 are open water conditions with mineral treatment and scenarios 4, 6, and 8 are ice-covered conditions with mineral treatment. The comparison of modeling results from scenarios 1, 3, 5 and 7 with scenarios 2, 4, 6 and 8 shows the effects of ice on the transport. The comparison of scenario 1 with scenarios 3, 5, and 7 shows the effects of mineral treatment under open water conditions while the comparison of scenario 2 with scenarios 4, 6 and 8 indicates the effects of mineral treatment on oil fate under ice-covered conditions. The main difference between open water scenarios (3, 5, and 7) and ice-covered scenarios (4, 6, and 8) are the particle size distribution of OMAs as explained below.

Table 1. Scenarios for the modeling study.

Conditions	1	2	3	4	5	6	7	8
Mineral	-	-	+M1	+M1	+M2	+M2	+M3	+M3
Ice Cover	-	+	-	+	-	+	-	+

+/-: with/without, M1=Mineral 1 (Mean Diameter=52 μm), M2=Mineral 2 (Mean Diameter=81 μm), M3=Mineral 3 (Mean Diameter=111 μm).

To account for the range of OMA particle sizes likely to be encountered in field operations under various environmental conditions (including different energy dissipation rates), three different mean particle sizes (M1=52 µm, M2=81 µm, and M3=111 µm) were selected from the results of wave tank experiments (Lee et al., 2012) for the modelling of OMA transport. Lee et al. (2012) also found that the minerals can combine and remove approximately 30% to 70% of the surface oil (oil removal percentage, ORP) depending on the temperature, oil type and mineral-oil-ratio (MOR). In this study, an ORP value of 46% was used for low water temperature conditions.

The settling velocities for the three mean OMA diameters are based on an analysis of experimental data obtained by Khelifa et al. (2008) (Figure 1). The ocean currents, as illustrated in Figure 2 for the study period were obtained from the outputs of a 3-dimentional ocean circulation model (Saucier and Chassé, 2000; CHS, 2010).

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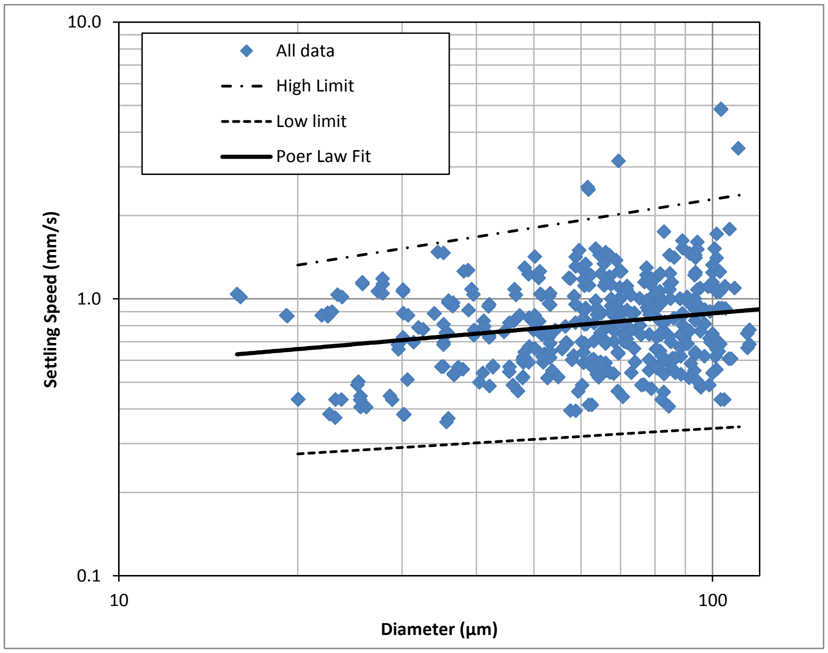

Figure 1. Settling velocities of OMAs (after Khelifa et al., 2008).

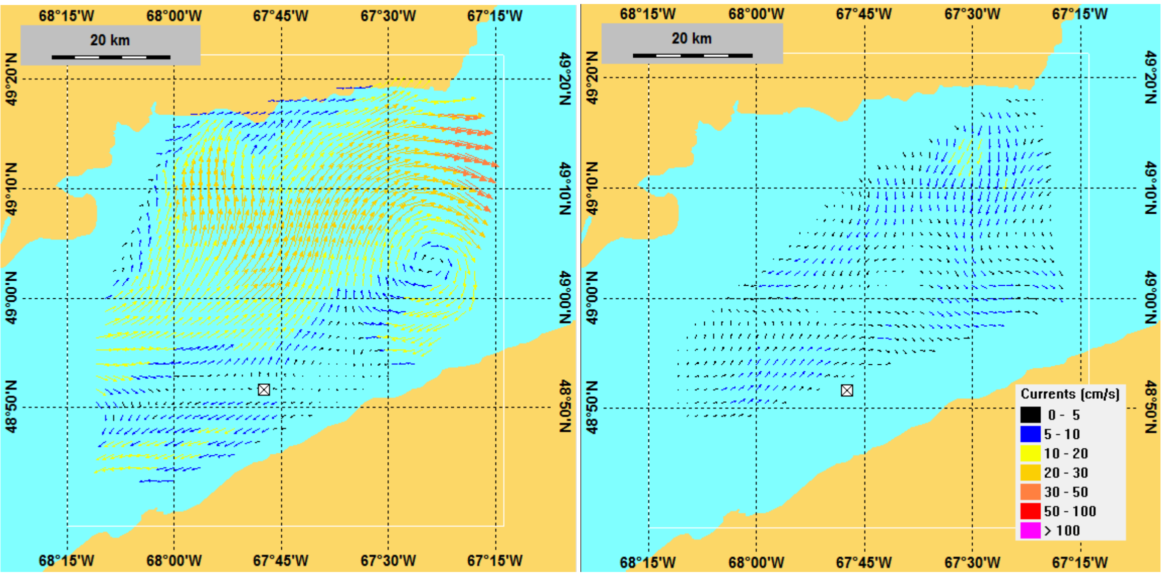

Figure 2. Currents for the study area: 20 m (Left), 200m (right).

For all scenarios (2, 4, 6, and 8) with ice cover, continuous ice coverage was used in the model. This is because the majority of the study area was covered with continuous ice and only the areas near the spill site were partially covered with broken ice (Figure 3).

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Figure 3. Addition of mineral fines to spilled oil.

RESULTS AND DISCUSSION:

The extent of oil for the two scenarios 2 (ice, - Mineral) and 4 (ice, + M1) after 5 days are shown in Figure 4. It can be seen from the figure that oil has dispersed away from the spill site after 5 days. The vertical profile shows that without mineral treatment, most oil remains at the surface (trapped under ice). With the application of mineral fines, a significant portion of the oil was dispersed into the water column and another portion settled to the bottom.

The mass balances for the eight scenarios are plotted in Figure 5. It can be seen that the open water condition in scenario 1 enabled evaporation and approximately 30% was evaporated at the end of 5-day simulation period. However, the remaining oil (~68%) stays on surface with little mixing with water and therefore the amount decayed is very small (0.7%). For scenario 2, the ice-cover has inhibited the evaporation, and the total amount remaining at the surface under ice (87%) is much higher than that of the scenario 1 (68%). However, the biodegradation was enhanced (6.7%) in scenario 2 compared with 0.7% in scenario 1. This may be due to differences in the interaction between oil and water under ice cover.

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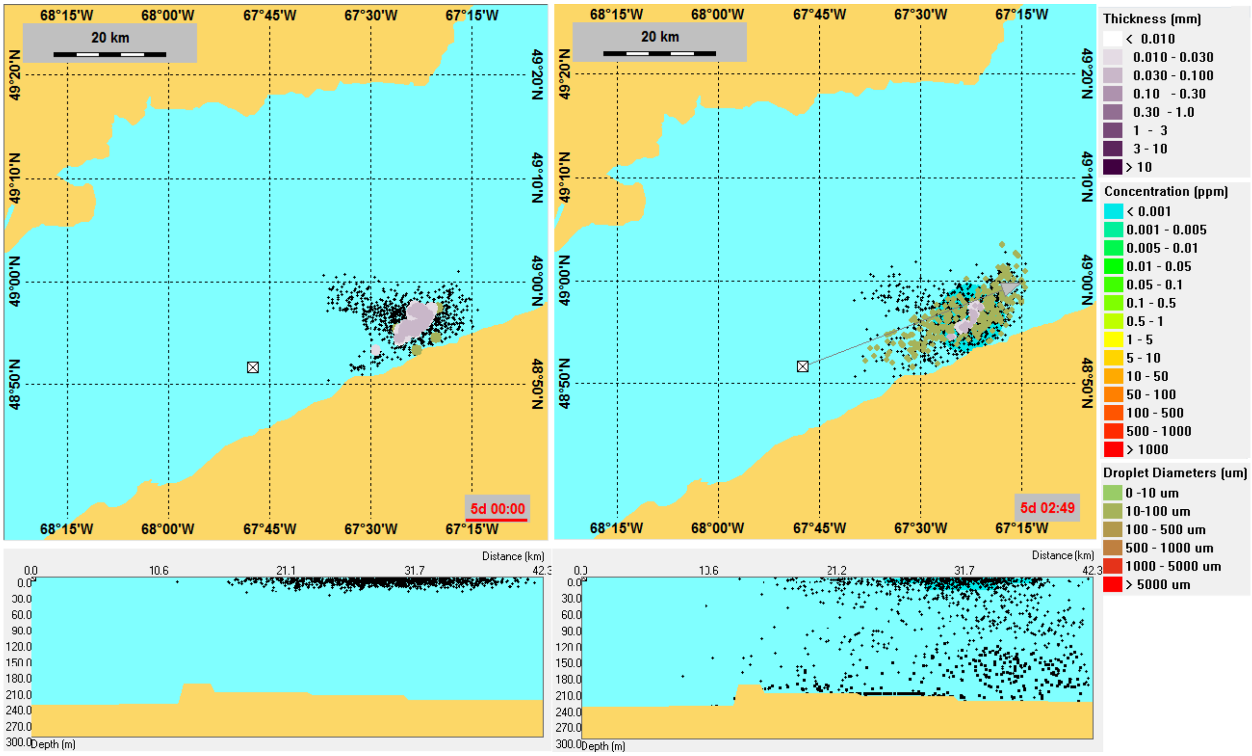

Figure 4. Extent of oil after 5 days: Scenario 2 (left), Scenario 4 (right). The black dots represent surface and submerged oil. The green colored dots are related to the OMA sizes. The white/grey color indicate the surface slick thickness.

For scenario 3 with no ice and the application of mineral fines (mean diameter: 52 µm) a significant amount of oil was transported from surface to water column. For example, the amount of oil on the surface was 77% in scenario 1, but it was reduced to 42% in scenario 3 (time=12 hours). The amount of oil in the water column increased from 0.9% to 43% (time=12 hours). The amount lost to evaporation was reduced in scenario 2 due to reduced amount of oil on the surface. Compared with scenario 1, the increased amount of oil (dispersed) in the water column also enhanced biodegradation from 0.1% to 7.1% (time=5 days). It should be noted that some of the oil in the water column settled out to the seabed starting from 94 hours after discharge. The amount in sediment was 7.3% at the end of the 5-day period.

Similar with the case without mineral treatment (scenarios 1 and 2), the entrapment of oil under ice for the cases with mineral treatment increased the biodegradation from 7.1% (scenario 3) to 13.9% (scenario 4). By comparing scenario 4 with 2, it can be seen that mineral treatment significantly enhanced the dispersion of oil into the water column under ice-covered conditions. This is consistent with the open water conditions (scenario 3 versus scenario 1) where dispersion was also enhanced. The biodegradation was also increased from 6.7% (scenario 2) to 13.9% (scenario 4).

As the same ORP of 46% was used in scenarios 4, 6, and 8 (scenarios with different mean OMA diameter), the amounts that remained on the surface were approximately same (47.6%,

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47.7%, and 47.6%) after 5 days. The fractions in the water column or that degraded, were similar for the three cases initially. For example, the fractions in the water column were 43.7%, 43.8%, and 43.9% at 60 hours (2.5 days) for scenarios 4, 6, and 8 respectively. The corresponding decayed fractions were 8.1%, 7.9%, and 7.8%. However, as time progressed, some OMAs started to settle out of water column and deposited as sediment at the bottom. The time for OMAs to reach the seabed was 98, 86, and 80 hours for scenario 4, 6, and 8, respectively. This difference is caused by the change in settling velocity that increases with the size of the OMA. Due to the differences in settling out to the seabed, the fractions in the water column and degradation showed differences for the three scenarios after 5 days. The fractions in the water column at the end of 5 days were 32.6%, 23.1% and 17.6% and the fractions decayed were 13.9%, 13.4%, and 13.3%. In comparison to the fractions delayed, significant differences between treatments were observed for the water column fractions. The corresponding fractions in the sediment were 5.9%, 15.5%, and 21.3% for the three scenarios. The differences in mean particle sizes (52 µm, 81 µm and 111 µm) caused significant differences in OMA deposition.

Due to limited field data and the difference between model setup (intended to predict fate for a longer duration) and field experiments (intended to provide observations for short periods), it is difficult to have a quantitative comparison between modeling and field experiments. However, the modeling results agree qualitatively with observations. For example, the experimental data show that oil can be detected at ~9m deep below the surface after 150 minutes for the cases with mineral treatment (Test 1) but it was non-detectable for the case (Test 3) without mineral treatment. The model results confirmed that the oil associated with OMAs helps to disperse the oil to deeper depth and therefore can be detected at 9m depth at t=150 min.

Mineral application can help to disperse oil and therefore enhance degradation compared with the case without mineral application. However, due to the relatively higher density of OMAs than oil and possibly seawater, some OMAs would settle (depending on the type of minerals used, oil properties and the conditions they were formed) and ultimately deposit onto the seabed. This may raise a concern that the form of OMA may potentially affect the benthic organisms. Although this concern is valid, Niu et al. (2011) have found that the amount of oil that settles from the water column is not the deciding factor in decision making regarding the use of OMA formation as a spill countermeasure; instead, a case by case risk assessment is more appropriate. Thus, although identical amounts of oil may settle between spills; differences in site conditions, such as ocean currents and depth of water, may result in quite different risks. A deeper site with stronger currents is favourable for mineral treatment.

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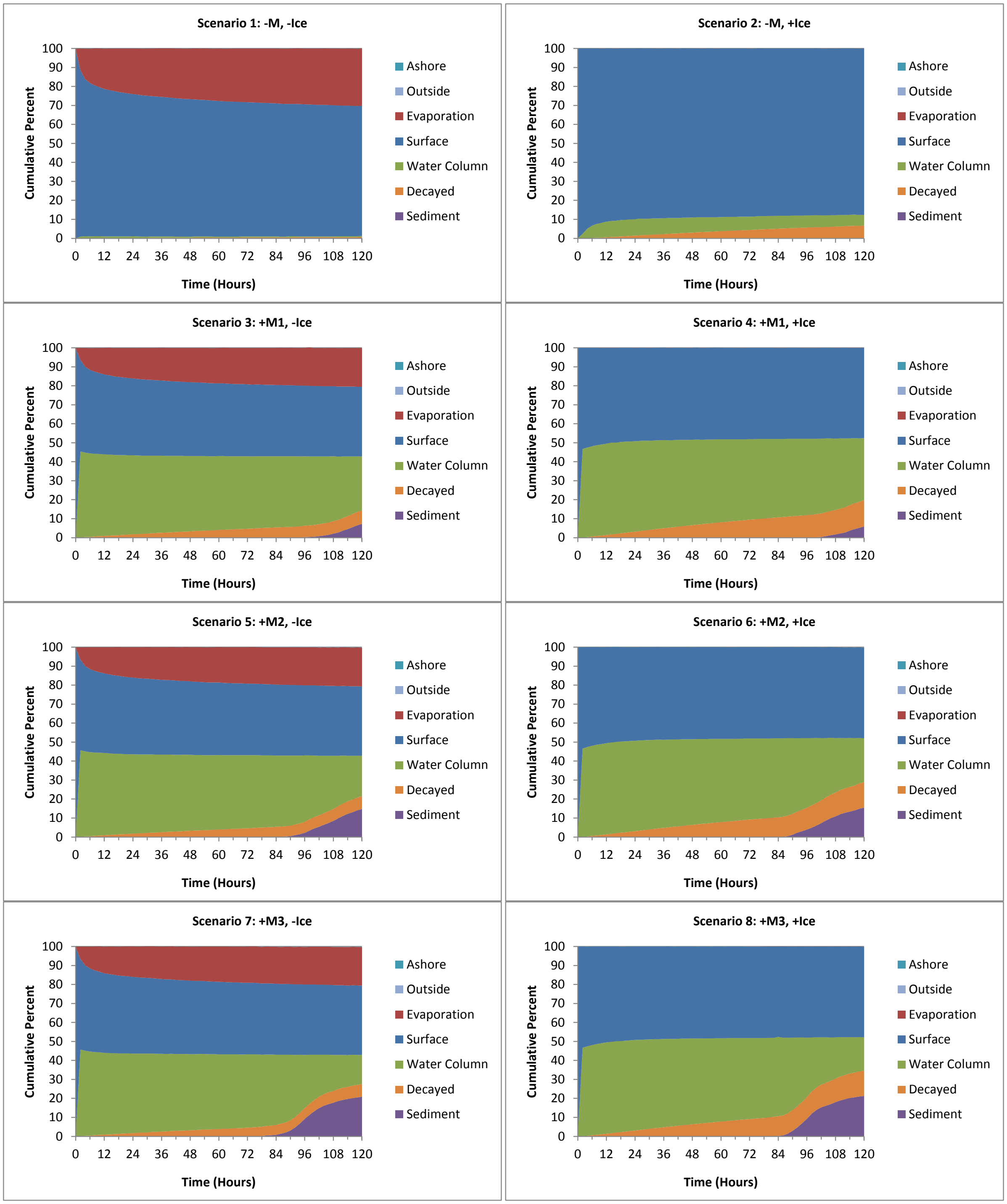

Figure 5. Mass balance for the 8 scenarios: M=minerals, +/1=with/without, M1=Mineral 1 (Mean Diameter=52 µm), M2=Mineral 2 (Mean Diameter=81 µm), M3=Mineral 3 (Mean Diameter=111 µm).

The modeling results also show that larger particles will cause more oil to settle out of the water column. Therefore, using minerals that can form smaller OMAs are preferable. In this

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regard, results of preliminary experiments in our laboratory have shown that OMAs formed with kaolin are much smaller and may therefore have greater potential to be used for mineral treatment.

CONCLUSIONS:

A mathematical modeling study was conducted to help understand the fate of spilled oil within a field of broken ice after receiving mineral fine treatment from a unique field trial in Quebec, Canada. Eight scenarios of oil spills under open water and ice-covered conditions have been studied. The modeling results indicate that significant portions of oil have been transferred from surface to water column and biodegradation was enhanced for cases with mineral treatment. The limited comparison of modeling result with field experiment shows general agreement.

The modeling results confirm the effectiveness of using minerals for oil spill counter-measure. However, due to the possibility of oil sinking to the bottom, the application of this method should be evaluated case-by-case. Further experimental data on optimal mineral-types and conditions that favor the form of smaller OMAs are important because it will reduce the transfer of oil to sediment and enhance biodegradation.

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