The sensitivity of the surface oil signature to subsurface dispersant injection and weather conditions

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Abstract

Subsea blowouts have the potential to spread oil across large geographical areas, and subsea dispersant injection (SSDI) is a response option targeted at reducing the impact of a blowout, especially reducing persistent surface oil slicks. Modified Weber scaling was used to predict oil droplet sizes with the OSCAR oil spill model, and to evaluate the surface oil volume and area when using SSDI under different conditions. Generally, SSDI reduces the amount of oil on the surface, and creates wider and thinner surface oil slicks. It was found that the reduction of surface oil area and volume with SSDI was enhanced for higher wind speeds. Overall, given the effect of SSDI on oil volume and weathering, it may be suggested that tar ball formation, requiring thick and weathered oil, could possibly be reduced when SSDI is used.

Keywords:

Oil spill modelling, Subsea release, Dispersants, Subsea Dispersant Injection (SSDI)

Introduction

Subsea oil development over the course of the past decades has resulted in the drilling of a large number of oil wells on the ocean floor, and technological advances are pushing exploration still further into deeper waters. The major Deepwater Horizon (DWH) and Ixtoc oil spills showed that releases from subsea wells can be large in volume, hard to control, and can lead to extensive environmental damage (Boehm and Fiest, 1982; Fisher et al., 2014; Jernelöv and Lindén, 1981; Ryerson et al., 2012; Valentine et al., 2014). During an oil spill at sea, chemical dispersants are routinely applied to surface oil slicks to reduce the potential for environmental damage, as dispersants facilitate increased oil dispersal under breaking waves (Chapman et al., 2007). In the case of the DWH oil spill, dispersants were additionally injected into the turbulent oil flow as it emerged above the wellhead (Lehr et al., 2010). The purpose of using subsea dispersant injection (SSDI) is to reduce the size of the oil droplets generated in the turbulent oil jet. Smaller droplets rise more slowly, and thereby have greater potential for dispersion, dissolution, and biodegradation, which may reduce the total impact of the oil spill, especially with regard to the fate of the surface slick and subsequent shoreline oiling. For the DWH spill there was not sufficient *in situ* measurements of the plume to document the effect of SSDI (Kujawinski et al., 2011). However, a theoretical studies of the DWH spill estimated that SSDI reduced the median droplet size from the millimeter range to the sub-millimeter range, which would have greatly increased the rise time and dwell time of the droplets in the water column (Zhao et al., 2015; Testa et al., 2016). Since SSDI has the potential to alter the outcome of a subsea oil spill, it is important to identify the spill characteristics and environmental conditions under which SSDI is an effective response option.

Field experience with SSDI is, fortunately, scarce. On the other hand, much research has recently been done to understand this response option in a laboratory setting. The droplet size reduction that is obtained with SSDI has been extensively characterized in experiments with downscaled blowout models (Brandvik et al., 2013). To transfer these results to the field, Johansen et al. (2013) developed an equilibrium model referred to as modified Weber scaling where dimensionless variables are used to predict droplet sizes. In addition to the data from Brandvik et al. (2013), the modified Weber scaling model was also fitted to data from the DeepSpill experiment, the only large scale experiment performed so far for subsea blowouts (Johansen et al., 2003). SSDI can be simulated in the modified Weber scaling model by reducing the oil-water interfacial tension (Johansen et al., 2013), which although variable between oil types, has been found to decrease by roughly 100 fold for 1 % injected dispersant (Brandvik et al., 2013). Another equilibrium droplet size model was developed by Li et al. (2016), who used experimental downscaled blowout and surface entrainment data to fit their model, which could fit data from both blowouts and from breaking waves depending on a scale parameter (Li et al., 2016). The idea behind the equilibrium models is that the droplet size distribution produced by the model should represent the situation after droplet breakup and coalescence have ceased. Others have instead developed dynamic droplet size models, where a time series of droplet breakup and coalescence is calculated with a population balance equation based on the blowout jet mixing energy (Nissanka and Yapa, 2016a; Zhao et al., 2014). Although very different in approach, the above-mentioned equilibrium and dynamic models all predict that the DWH spill generated droplets with a size up to several millimeters without SSDI, and on the sub millimeter scale with SSDI (Li et al., 2016; Nissanka and Yapa, 2016b; Testa et al., 2016; Zhao et al., 2014). On the other hand, other authors have argued that blowouts on the scale of the DWH generate droplets that are significantly smaller, between 1 µm and 300 µm (Aman et al., 2015a; Paris et al., 2012a). These studies derive the droplet size distribution not from a turbulent jet, but from experiments that produce a constant shear that is not representative of the rapidly decreasing shear that droplets would encounter in a blowout (Aman et al., 2015b; Boxall et al., 2012). Not surprisingly, the models that predict the initial untreated small droplets found that SSDI did not lead to large differences in the amount of oil reaching the surface (Aman et al., 2015; Paris et al., 2012). Ultimately, experimental deep water subsea releases with large release diameters and SSDI are needed in order to validate the different droplet size models.

The utility of a droplet size model is best achieved when used to set the initial condition of a subsea blowout in an oil spill model. Studies of particle tracking using the small droplets predicted by the stirred cell experiments found that SSDI did not lead to large differences in the amount of oil reaching the surface (Aman et al., 2015b; Paris et al., 2012b). Another study (Testa et al., 2016), used modified Weber scaling to predict large untreated droplets in order to investigate the effect of SSDI on oil dispersal for the DWH spill. They found that it took longer for the oil to reach the surface when SSDI was applied (8 hours vs 4 hours), and that the total volume of oil on the surface was greatly reduced when SSDI was applied, as more was retained under water. Focusing on short-term effects, the particle model used by Testa et al. (2016), did not include several processes that are known to affect the fate of oil at sea, such as evaporation, biodegradation, dissolution, emulsion formation, and entrainment of surface oil by breaking waves. These processes, previously reviewed in detail for oil spill modelling, (Afenyo et al., 2016; Reed et al., 1999; Spaulding, 2017, 1988), can have a large effect on the outcome of an investigation of the efficiency of SSDI. One aspect is that smaller oil droplets will be subjected to more rapid biodegradation and dissolution (Brakstad et al., 2015). Furthermore, oil that reaches the surface when SSDI has been applied may form thinner slicks as it surfaces over a larger area, and may therefore be less emulsified after a certain time at sea. In turn, a lower degree of emulsification will affect the extent of dispersion, as emulsified oil is more resistant to natural dispersion by wave action (Johansen et al., 2015). Due to the large impact of surface processes on the fate of an oil spill, it is of interest to investigate the effectiveness of SSDI application using an oil spill model that includes the above-mentioned physical and chemical processes.

The objective of this work was to use a state of the art oil spill model to investigate how SSDI affects the surface signature of oil from a deepwater blowout. Importantly, the aim was in particular to investigate the impact of varying weather conditions, as represented by different wind speed. As exemplified by the DWH spill, weather conditions during an oil spill may alternate between wind-still conditions and hurricane force winds, which greatly affect the moment to moment evolution of the spill (MacDonald et al., 2015).

Methods

The OSCAR oil spill model

The OSCAR model is a three-dimensional Lagrangian oil spill trajectory model for predicting the transport, fate and effects of released oil. The model development is closely linked to laboratory and field activities at SINTEF. OSCAR covers the key physical and chemical processes that affect oil spilled at sea, including evaporation, surface spreading and transport, entrainment into the water column, emulsification, sedimentation and shore interaction (Reed et al., 1995). The varying solubility, volatility, and aquatic toxicity of oil components are accounted for by representing the oil in terms of 25 pseudo-components (Reed et al., 2000). Subsurface oil spills are initialized with a jet and plume model (Johansen, 2000) that uses a Weber-scaling method to calculate droplet sizes based on outlet conditions (Johansen et al., 2013). Oil viscosity during subsea blowouts, which is an important parameter in the Weber-scaling droplet size calculation, is obtained by adjusting the oil viscosity to a temperature found as a function of the released oil temperature and ambient water temperature, using a method described elsewhere (Skancke et al., 2016).

The ocean current data used in this study corresponds to a measured current profile from a location in the Beaufort Sea and has been provided (“ALS,” 2013). The average current speed in the modelling period was 7.1 cm/s for the total water column, and 11.7 cm/s for the upper 100 m. The maximum current speed in the upper 100 m was 27.2 cm/s. Temperature and salinity profiles were obtained from the National Virtual Ocean Data System (“World Ocean Atlas 2005,” 2013).

Results

Model setup

The effect of SSDI and the fate of the surface oil slick were investigated during different weather conditions for a deepwater oil blowout. The blowout was set at 700 m, deep enough to ensure a trapping of the plume in the subsurface layer and therefore a sensitivity in the outcome to differences in the initial droplet size distribution. Six simulations were performed, where the two parameters of variation were the wind speed (0, 5 and 10 m/s) and whether SSDI was applied or not (SSDI vs. oil only). To establish a baseline condition of an uninterrupted spill, a 2-day constant release was simulated, and then the oil was tracked for an additional 8 days in order to investigate the evolution of the surface slick after the subsea release was over.

The oil spill simulation parameters for this study are given in Table 1. We have modelled the application of SSDI assuming that an injection of 1 % dispersant reduces the interfacial tension between oil and water by a factor of approximate 100, as supported by experimental data (Brandvik et al., 2013). For comparison, the average dispersant to oil ratio during the SSDI during the Deepwater Horizon blowout was estimated to 0.5 %, lower than was is recognized as to achieve maximum effect (Lehr et al., 2010).

Oseberg Blend is a light paraffinic crude with a low asphaltene and wax content (0.2 & 2.7 wt.%). Such a low viscosity oil would is highly relevant for a high flow rate scenario like this. Further details regarding oil properties are given in Brandvik et al., 2013.

With the given release parameters (Table 1), oil treated with SSDI reduced the median droplet size by 90 %, from 3.69 mm to 0.434 mm. This reduction corresponds to a reduction in rise velocity from approximately 270 m/hour to 20 m/hour. The release generated a momentum and buoyancy driven plume with an outlet velocity of 4.6 m/s, an outlet gas volume fraction of 58 %, and a plume trapping height of 260 m +/- 1.8 m. The small variation of +/- 1.8 m observed in the plume trapping height is due to variation in strength of horizontal currents that cause the plume to bend to a greater or lesser extent.

Surface area oiling

When SSDI was applied, a significant difference in the subsurface transport of oil droplets was observed. The smaller droplets that were obtained with SSDI (0.43 versus 3.7 mm) had a comparatively prolonged residence time in the water column and surfaced around 1.7 km away from the release site, compared to 700 m for the oil only simulations (Figure 1). This affected the surface oil signature in a weather-dependent manner. At the end of the 2-day release, when wind was absent, SSDI led to a larger surface oil slick area, but the slick consisted of thinner oil (Figure 2). In conditions of 5 m/s wind, the surface areas were similar in size, but again the case with SSDI led to thinner oil that was more rapidly entrained (Figure 2). For 10 m/s wind, SSDI led to a near disappearance of surface oil in comparison with the case with oil only, where some surface oil persisted in spite of the wind (Figure 2).

When observing the drifting surface oil slicks, the trends from Figure 2 in terms of surface area generally persisted, but showed some variation depending on the thickness of the oil. For the case without wind, the surface area when using SSDI continued to increase relative to when SSDI was not used (Figure 3A). This implies that the initially thinner oil spread more rapidly due to surface transport and diffusion. However, the difference in area between the two scenarios was reversed when considering only the thick part of the oil (> 200 µm) (Figure 3D). Thus, while SSDI led to a larger surface slick in the absence of wind, the area of thick oil was smaller. For the case with 5 m/s wind and SSDI, the total slick area was larger until day 5, after which it became smaller than the release with only oil and gas (Figure 3B). However, the thick part of the slick was also here markedly smaller with SSDI (Figure 3E). This describes a situation where with SSDI the oil initially spread out more thinly over a larger area, but since thin oil is more efficiently entrained, this area was eventually reduced to a smaller slick by wave action. For 10 m/s winds the wave energy alone was sufficient to remove most of the oil from the surface, although with SSDI the oiled area is smaller than when SSDI was not used (Figure 3C). When considering the thick oil, SSDI effectively eliminated slicks thicker than 200 µm, while with oil only thick oil persisted until day 3 (Figure 3F). It was observed that the total oiled area did not reduce to zero with time for persistent 10 m/s wind, which may have been expected for a 10 day period (Figure 3C). This was caused by occasional resurfacing of small droplets over a large ocean area to form very thin and spread out sheen. This can be seen as the oil volume on the surface decreased much more rapidly than the oil area (comparing Figure 3C with Figure 4C).

Effect of SSDI and wind on the persistence of oil and emulsion volume on the surface

The effect of SSDI on the surface area is important for the likelihood of interaction between surface oil and aquatic sea surface organisms, and the areal information may be compared with satellite imagery of oil slicks. However, in terms of oil spill response, such as skimming, it is also of importance to evaluate the effect of SSDI on oil emulsion volume. Figure 4 shows the effect of wind speed and SSDI application on the time-series of the volume of emulsion and the volume of oil on the sea surface. In this figure, the oil volume was found as the volume of emulsion minus the volume of water in the emulsion. In the absence of wind and with oil only, the surface oil volume increased steeply up to the end of the release at two days, after which it slowly decreased due to evaporation (Figure 4A). In contrast, when SSDI was applied, the volume of oil on the surface continued to increase after the end of the release, peaking around day five, three days after the release had ended (Figure 4A). This difference was due to the smaller oil droplets associated with SSDI taking more time to reach the surface. With their prolonged rise-time, the smaller droplets associated with SSDI had dissolved volatile compounds in the water column that instead evaporated to the atmosphere for the oil only scenario. This can be seen in the mass balance as the volume of surface oil was more stable for the SSDI case than for the oil only case (Figure 4A). Delayed volume peak and reduced evaporation were also observed for the cases with 5 m/s and 10 m/s wind, in addition to a distinct reduction of oil volume with the increase in wind speed (Figure 4B and Figure 4C).

There was a similar delay in the volume peak with SSDI for the emulsion volume for the case of no wind (Figure 4D). In zero wind speed, the model accounts for some emulsion formation, representing stochastic variation in the wind field. This baseline water uptake (see Table 2 for an overview of emulsion water uptake) balanced the loss of oil from the emulsion, causing the surface volumes to plateau (Figure 4A vs Figure 4D). The case with 5 m/s wind showed a steady increase in oil emulsion volume on the surface both with and without SSDI lasting several days after the release had ended, owing to ongoing emulsion formation (Figure 4E). An increase in emulsion volume was observed for the simulation with 5 m/s compared to the simulation without wind (Figure 4E vs Figure 4D), in contrast to the oil volume which decreased for 5 m/s wind (Figure 4A vs Figure 4B). The reason for this difference is that surface mixing at this relatively low wind speed increases the mass uptake of water into oil faster than it is entraining surface emulsion. For the case with 10 m/s wind, there was less overall emulsion formation due to more rapid entrainment, and especially so for the case with SSDI application due to the thinner surface oil slicks (Figure 4F and Table 2).

The model does not explicitly simulate tar ball formation, so this phenomenon could not be compared between the simulations. However, in terms of weathering, substantially lower water content and viscosity were predicted of the 0 m/s wind and 10 m/s wind when SSDI was used, as shown in Table 2. Further, the total remaining oil volume was lower in all scenarios when SSDI was used. With less remaining oil, and with the oil having lower viscosities, it may be inferred that the likelihood of tar ball formation would be reduced for the SSDI cases, the extent of which depending on weather conditions, as oil weathering with and without SSDI was more similar for the 5 m/s scenarios.

The findings highlight the complex weather-dependent effect SSDI may have on surface oil area and volume and how it can be visualized through simulations in an oil spill model. Our finding that SSDI has a strong impact on the surface oil signature stands in contrast to some previous work where much smaller droplet sizes are assumed both with and without SSDI (Aman et al., 2015b; Paris et al., 2012b). On the other hand, the results agree with the effects of SSDI in delaying and reducing a surface slick as observed by Testa et al. (2016) for the DWH scenario, and extend their work by considering the effect of wind-induced turbulence and the most relevant mass transfer processes that spilled oil undergoes at sea. However, there are still processes that may influence the fate of a subsea oil release that were not account for. The most notable processes are dispersant retention in rising droplets and tip streaming. It is likely that with SSDI some dispersant remains associated with the droplets as they rise through the water column, possibly causing the phenomenon of tip streaming, where small droplets, along with dispersant, are shed from larger ones (Gopalan and Katz, 2010). If dispersant remains associated with the droplets until they form a slick on the surface this could lead to enhanced surface dispersion by wave action. However, the experimental knowledge of droplet shedding and dispersant retention is not yet sufficient in the literature to quantify how these processes affect the fate of oil from a subsea blowout. Specifically, it is necessary to know more about how these processes depend on oil droplet size, turbulence, surfactant properties, and oil rheology. The study and inclusion of these processes to oil spill models would increase the accuracy of SSDI modelling.

Here, a deep-water blowout at 700 m was considered. For blowouts in more shallow depths, such as less than 400 m, there is an increased probability that the plume will reach the surface, especially if the release contains large amounts of gas. In this case, one may expect that both small and large droplets are transported in the plume to the surface, reducing the effect of prolonged dwell time for small droplets that we found for deep-water blowouts. However, for a shallow release scenario, SSDI may still have an effect on the fate of the surface oil slick, since the reduced droplets size could cause wider spreading at the surface and retained dispersant could lead to enhanced surface dispersion. In this work, we have studied the effect of SSID using a single oil type at a single depth with a single rate. An improvement on this work would be to use ensemble simulations to investigate multiple oil types, release depths, GOR ratios, and oil release rates, and even geographic locations.

Conclusion

Using modified Weber-scaling to predict initial oil droplet sizes in a state of the art oil spill model, it was found that SSDI causes a tenfold reduction in oil droplet size that strongly influenced the oil droplet rising time, location, area and thickness of the resulting surface oil slick. SSDI did not completely trap oil in deep water, but it kept oil in the water column longer than the release without SSDI, resulting in less oil reaching the surface. Additionally, SSDI in general resulted in thinner oil slicks covering a larger area compared to oil alone scenarios. These thinner, non-emulsifying surface oil slicks had a shorter lifetime due to enhanced natural dispersion.

It was shown that the untreated releases generally formed a thicker oil slick. When these thicker oil slicks were subject to wind-generated waves, they had a higher tendency to form stable, viscous and persistent emulsions. However, when the wind speed is too low to naturally disperse the surface oil, as seen in the 5 m/s scenarios, even the oil slicks from the treated release emulsified. The volume of this surface emulsion was still smaller than the resulting emulsion from the untreated oil. The thinner oil slicks resulting from the SSDI scenario with higher wind speed (10 m/s) tended to be too thin to emulsify, and to naturally re-disperse after surfacing, resulting in a lower persistency and shorter drift time on the surface.

In the present study, an oil spill occurring at 700 m depth was simulated. However, the overall conclusion obtained from this work is expected to be similar for deep-water blowouts in general where the conditions are such that SSDI leads to a marked reduction in droplet sizes and the plume is trapped below the sea surface. These simulations indicate that SSDI can be an effective response method, especially when taking into account the significantly reduced lifetime caused by the thinner oil slicks. The shift in surfacing location (1 km further away from the release site) may also offer a significant advantage regarding safety and working conditions for personnel working on the sea surface on waters above the release site. Given the effect of SSDI on surface oil volume and weathering, it may be suggested that tar ball formation, requiring thick and weathered oil, could possibly be reduced when SSDI is used.

Acknowledgement

This project was funded by the International Association of Oil and Gas Producers and was supported by the nine international oil and gas companies BP, Chevron, ConocoPhillips, Eni, ExxonMobil, North Caspian Operating Company, Shell, Statoil, and Total.

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Figures:

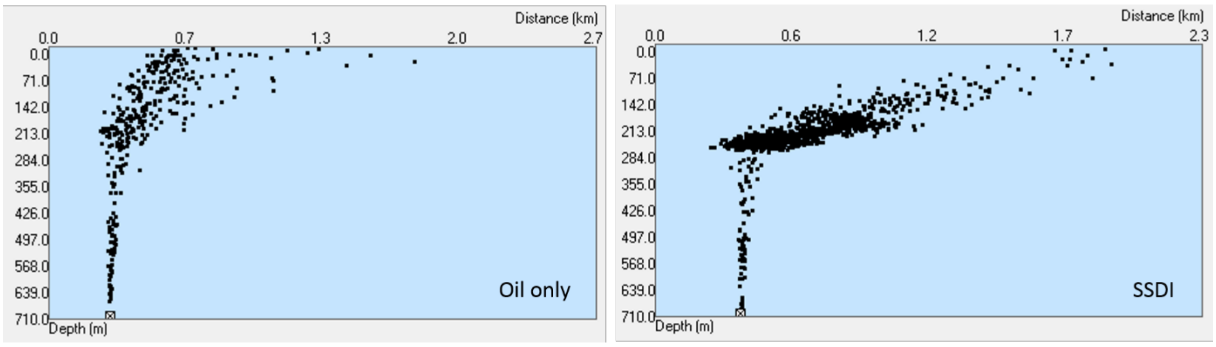

Figure 1. Rising oil droplets during the release with oil only (left) and with SSDI (right). With SSDI the smaller droplets stay with the trapped plume for a longer period.

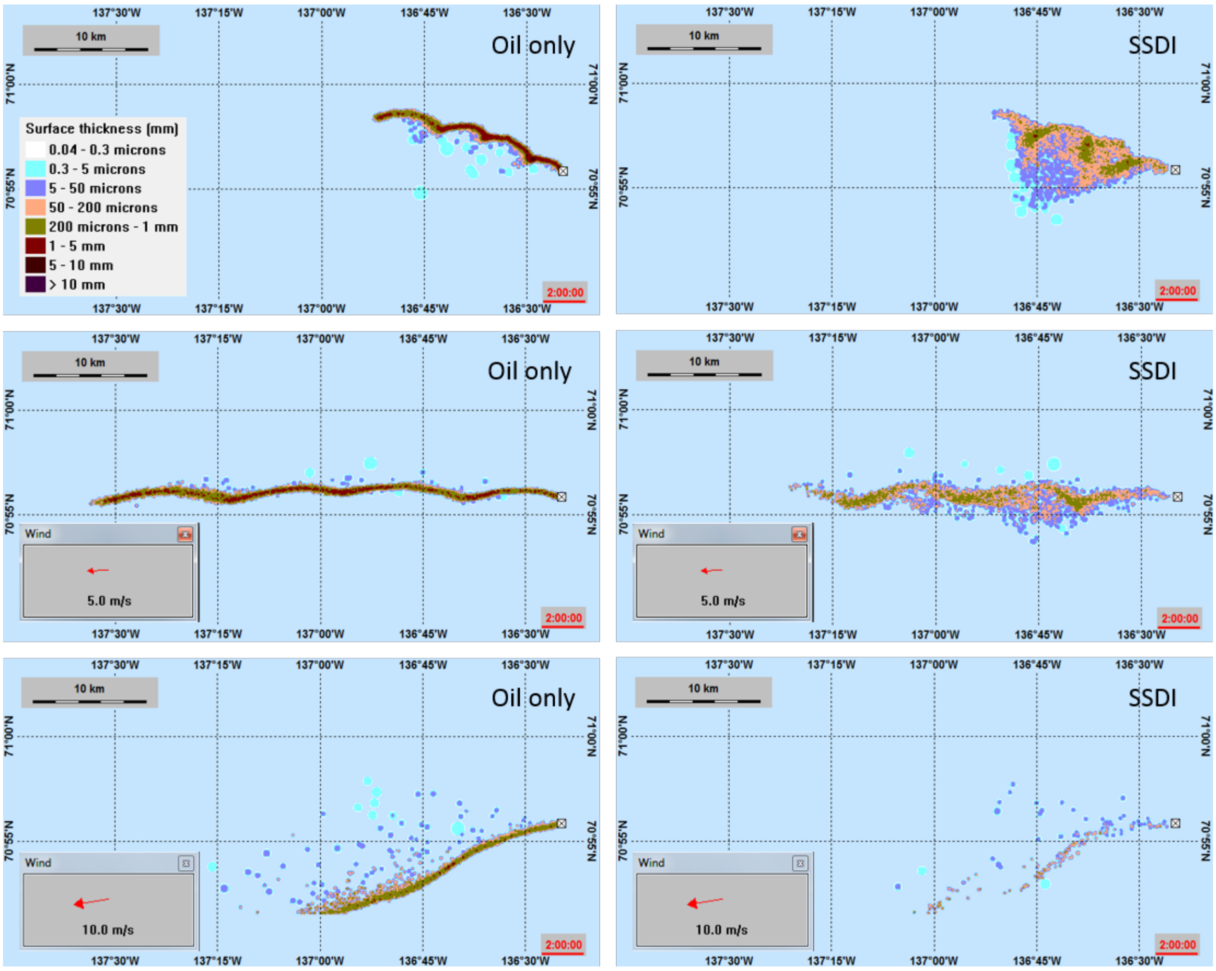

Figure 2. Distribution of surface oil at the end of the 2-day release. The surface slick is shown for the following conditions: oil alone (left) and with SSDI (right), no wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). The legend showing the colors for the thickness of the oil is given in the upper left figure.

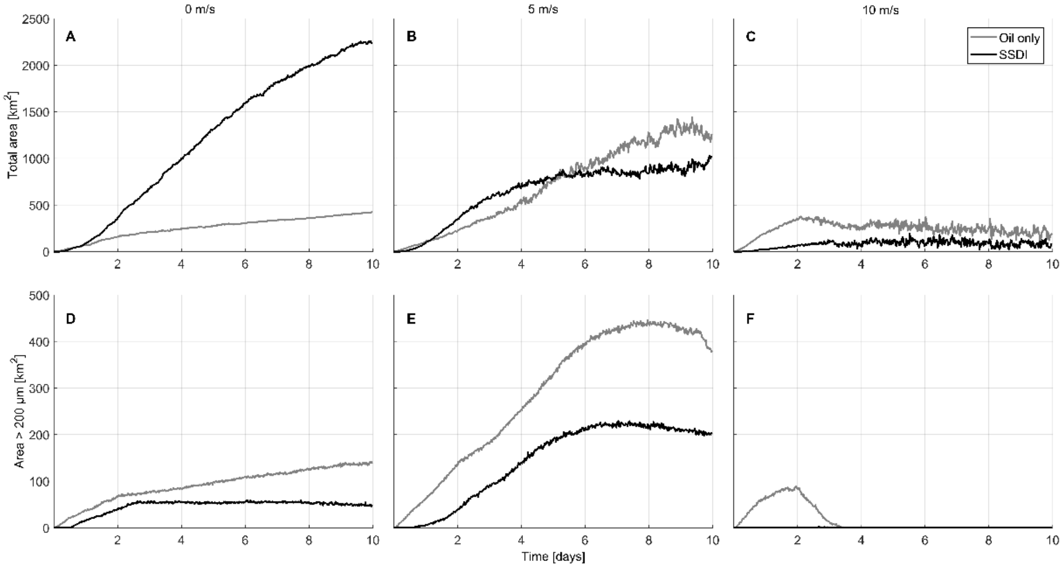

Figure 3. A to C: Total oiled surface area for wind speeds of 0 m/s (A), 5 m/s (B), and 10 m/s (C). D to F: Oiled surface area for oil thicker than 200 µm for wind speeds of 0 m/s (E), 5 m/s (E), and 10 m/s (F). Grey lines show results from simulations with oil only, and dark lines show results from simulations with SSDI.

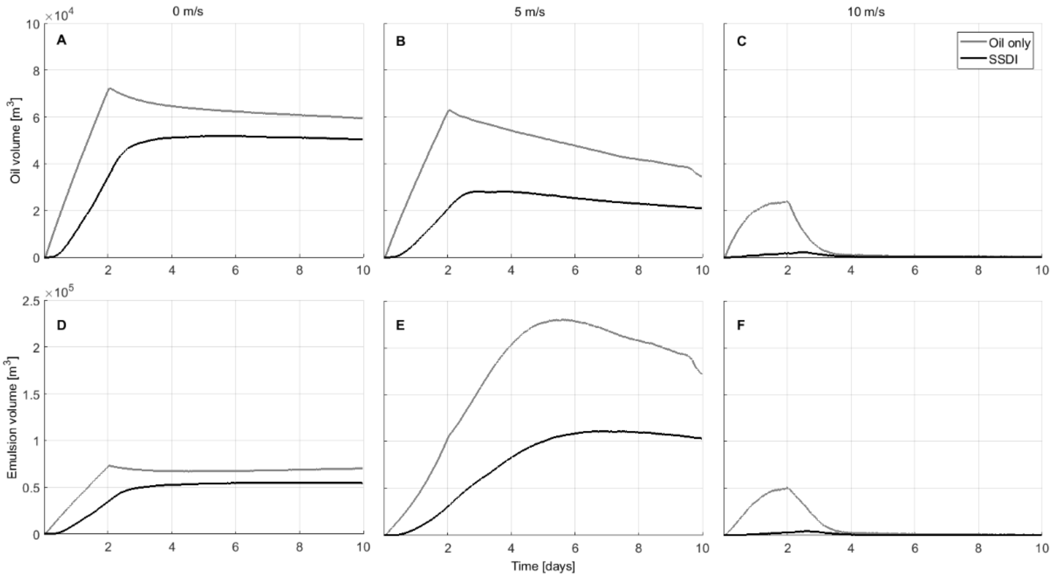

Figure 4. A to C: Total surface oil volume for wind speeds of 0 m/s (A), 5 m/s (B), and 10 m/s (C). D to F: Surface emulsion volume (volume of oil and water) for oil thicker than 200 µm for wind speeds of 0 m/s (D), 5 m/s (E), and 10 m/s (F). Grey lines show results from simulations with oil only, and dark lines show results from simulations with SSDI.

Tables:

Table 1. Simulation parameters.

Parameter	**Value**
Release depths	700 m
Surface wind	0, 5 and 10 m/s (constant)
Duration of simulation	10 days
Oil type	Oseberg Blend
Oil density	0.839 (kg/l)
Release location	Beaufort Sea
Release rate	7 000 tonnes/day (52 478 barrels/day)
Duration of release	2 days
Temperature of release	60 °C
Droplet formation temperature	33.2 °C (Skancke et al., 2016)
Oil viscosity at droplet formation	3.9 cP
Release diameter	0.25 m
Gas-to-oil Ratio (GOR)	100 at standard conditions (1 atm)
Gas density	0.8 kg/Sm^3

Table 2. Average viscosity, water content, and remaining oil mass at day 10 (end of the simulation period).

Simulation	**Average viscosity (cP)**	**Average water content in emulsion (%)**	**Remaining oil volume (% of total release)**
No SSDI, 0 m/s wind	1263	13	61
SSDI, 0 m/s wind	244	1.6	52
No SSDI, 5 m/s wind	12720	78	35
SSDI, 5 m/s wind	12055	68	22
No SSDI, 10 m/s wind	5548	64	0.2
SSDI, 10 m/s wind	1574	22	0.1