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EVALUATION OF SUBSEA INJECTION OF DISPERSANT

ABSTRACT

The present study has used OSCAR with the improved model for droplet size predictions (modified Weber scaling) and improved prediction of oil temperature and resulting viscosity during droplet formation. The objective with this study is to evaluate the potential for injecting dispersants during subsurface releases, and to investigate implications for the improved model for prediction of droplet sizes, in particular with regards to the surface impact for å subsea release of an oil-gas mixture. In total, 30 different subsea releases of oil and gas mixtures with varying release depths (50, 150, 300, 700 and 1 000 m), with three different wind speeds (0, 5 and 10 m/s) and with/without subsea injection of dispersants (SSDI) have been simulated.

The OSCAR simulations indicated that SSDI could be a very effective response method, especially when taking into account the significantly reduced lifetime and surface signature of the resulting thin surface oil slicks. There is a notable difference in the surface slick formed for a release treated with SSDI compared to a non-treated release. SSDI results in both less oil and wider/thinner oil slicks on the surface compared to oil alone scenarios. These thinner, non-emulsifying surface oil slicks are expected to have very short life time due to enhanced natural dispersion.

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1 INTRODUCTION

Based on recently obtained data from droplet breakup experiments at the tower tank facility at SINTEF (Brandvik et al. (2013)), a new consistent method for prediction of droplet size distributions of oil emerging from subsea blowouts, both with untreated oils and oils treated with dispersants, has been derived by Johansen et al. (2013). This model (modified Weber scaling) has been implemented into the oil spill model OSCAR (Oil Spill Contingency And Response) developed by SINTEF.

The objectives of this study were to evaluate the potential for injecting dispersants during subsurface releases, and to investigate implications of the new modified Weber scaling model for prediction of droplet sizes, in particular to the surface impact of a subsea release of an oil and gas mixture.

This study was an extension of the previous study performed in 2013/2014. The results from the previous study were presented in a draft report dated February 4, 2014.

The present study has used a research version of OSCAR (based on version 8.0)[1] including the improved model for droplet size predictions, as well as a viscosity-scaling based on the release temperature, to model different scenarios of subsurface release of oil and gas mixtures. These scenarios include variations of parameters assumed to affect the surface impact: Varying release depth (50 m – 1 000 m), with/without subsea injection of dispersants. This study further included modelling of subsequent exposure to waves on the surface to investigate the fate of a surface slick after treatment of subsea injection of dispersants.

All scenarios were simulated under open water conditions. Due to the available current profile (ASL, 2013), the location of the release was in the Beaufort Sea.

[1] Commit number f08c25837fb

2 THEORY

2.1 Near-field plume

A subsea release of oil and gas will form a plume in the water column formed by the momentum and buoyancy of the released oil and gas, commonly referred to as the near-field. Deep-water blowouts are more sensitive to cross-flow and ambient density stratification than blowouts in moderate to shallow water. This is due to reduced buoyancy caused by the strong compression of the gas in deep water, together with other factors such as non-ideal gas behaviour and the potential for a substantial fraction of gas dissolved in the oil phase.

Oil and gas that escape the near-field plume, either due to surfacing, trapping or separation from the plume will transition into the far-field model as described below. Figure 2.1 shows a diagram of such a plume, and illustrates how the buoyancy driven plume may be trapped at a depth due to stratification and subsequent loss of momentum. This depth is often referred to as a trapping layer, even though individual oil droplets and gas bubbles may rise further due to their buoyancy. Oil and gas may also escape the plume prior to trapping.

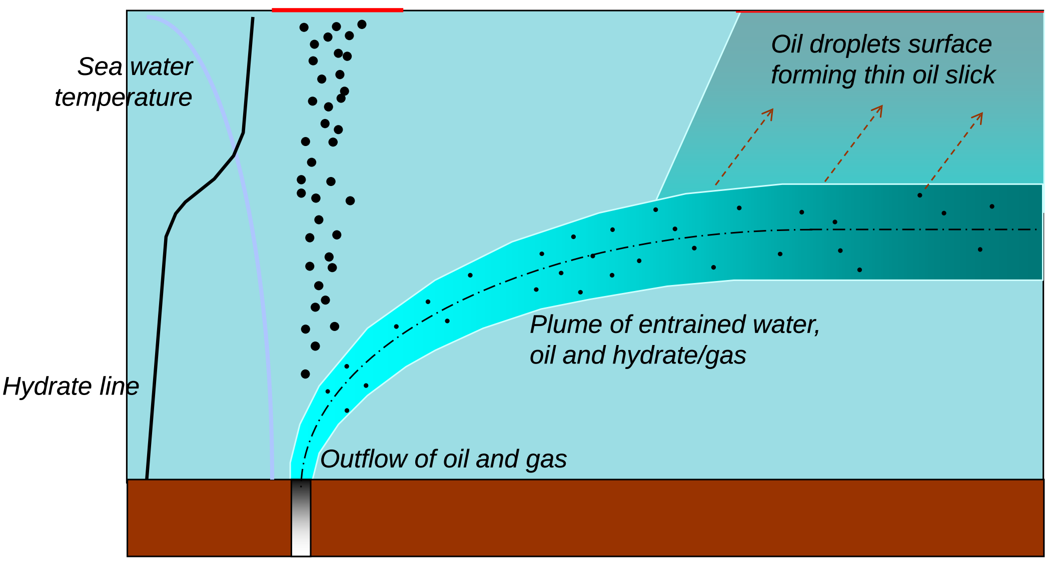

Figure 2.1 Diagram of a modelled plume. The oil and gas forms a buoyancy driven plume which may be trapped at a depth, as in this figure. Oil droplets escape the plume and are transported to the surface as a function of their size and corresponding buoyancy.

A near-field plume model is described by Johansen (2000 and 2003). The implementation of this model goes under the name Plume3D (previously referred to as DeepBlow) and is a part of the oil spill model OSCAR.

Table 2.1 gives an overview of the different quantities reported by Plume3D used throughout this report.

Table 2.1 Overview of results produced by Plume3D.

Result	Description
Estimated droplet size (d_{50} and d_{95})	Median and 95 percentile droplet size estimated by the OSCAR model for a release.
Release velocity at droplet break-up	Outlet velocity of released oil and gas.
Plume status	Indicator for the termination of the plume, either surfaced or trapped.
% of release period	Percentage of the release period (first 2 days of simulation) the plume is either surfaced or trapped
Plume surfacing time	The time it takes for the plume to reach the surface.
Plume trapped depth	The depth at which the plume is trapped, if applicable.

2.2 Effects of droplet size in subsurface releases

The size distribution of oil droplets formed in deep water oil and gas blowouts is known to have strong impact on the subsequent fate of the oil in the environment (Johansen, 2003).

Large droplets (> 0.1 mm) will rise relatively rapidly and come to the surface relatively close to the discharge location, while small droplets (< 0.1 mm) will rise more slowly and can be transported long distances from the discharge location with ambient currents before reaching the sea surface. The smaller droplets will be kept suspended in the water column for a longer time than predicted by their rise velocity due to turbulence in the ocean. Oil droplets in the water column are subjected to enhanced dissolution and biodegradation compared to surface oil. Releases which are predominantly producing large droplets (in the millimetre size range) may thus result in relatively thick surface oil slicks, while thin surface films may be expected from releases producing small droplets (micrometre range). Thin oil films may not form water-in oil emulsions and will thus be more susceptible to natural dispersion. This implies that thin films will have distinctly shorter persistence on the sea surface than thicker oil slicks, and the possibility of oiling of adjacent shorelines may thus be strongly reduced (Johansen et al., 2013). However, factors like vertical turbulence mixing in the water column and cross flows will contribute to keep such fine droplets submerged for even prolonged periods (Johansen et al., 2003).

Depending on the depth, the release rate, and the amount of gas in the release, a plume generated from a subsurface blowout may terminate in the water column or reach the sea surface. In blowouts from moderate to shallow depths with a large amount of gas, the buoyancy generated by the expanding gas will tend to bring the plume of entrained water to the sea surface together with dispersed oil droplets and gas bubbles regardless of the initial oil droplet size generated at the source. A relatively thin surface oil slick will then form as the dispersed oil droplets settle out of the outward flow of the surfacing entrained water. A deepwater plume (with reduced buoyancy, due to gas compression and dissolution of the gas) is more likely to be trapped by the ambient density stratification or bent over by cross-flow. In this case oil droplets will separate from the plume and rise to the surface with their own terminal velocities determined by the size of the droplets as indicated in Figure 2.1.

2.3 Prediction of droplet size distributions

A model for the prediction of oil droplet size distribution during a mixed oil and gas release, with and without subsea injection of dispersants, is described in Johansen et al., 2013.

This droplet size distribution follows a Rosin-Rammler (Weibull) distribution and can be characterized by a median droplet size d_{50}, given by a modified Weber number (We*) scaling:

$$\frac{d_{50}}{D} = A\mathrm{We}^*(\rho, U, \sigma_{ow}, \mu)^{-\frac{3}{5}} \qquad (1)$$

Where $We^* = We / [1 + B\, Vi\, (d_{50}/D)^{1/3}]$.

D is here the outlet diameter, A and B are empirical constants and V_i is the viscosity number (μ/σ_{ow}). Thus, the modified Weber number takes into account the oil density ρ, outlet velocity U, oil-water interfacial tension σ_{ow} and oil viscosity μ.

The model presented in Eq. 1 covers cases with momentum jets and single fluid releases (oil only). For combined releases with gas and oil, a void fraction correction of the release velocity (U_n) as described in Eq. 2 is used.

$$U_n = U_{oil} / (1 - n)^{1/2}, \qquad (2)$$

Where n is the gas volume fraction.

To adjust for releases that are buoyancy dominated, an exit Froude number correction is applied, as described in Eq. 3.

$$U_C = U_n\,(1 + Fr^{-1}), \qquad (3)$$

Where $Fr = U_n / (g' D)^{1/2}$ with $g' = g\,[\rho_w - \rho_{oil}\,(1 - n)]/\rho_w$. Further details are found in Johansen et al., 2013.

The implementation of the modified Weber scaling in OSCAR takes into account the adjustments of outlet velocity U as given in equations 2 and 3 above. In this text this velocity is referred to as the buoyancy corrected velocity.

The modified Weber algorithm is based on a sound physical understanding on the involved physical processes and extensive datasets from laboratory testing with combined releases, various scales and testing under high pressure with combined releases with natural gas and live oil (Brandvik et al., 2016a, 2016c, and 2017).

2.4 Determining the viscosity parameter for subsea blowouts

Droplet formation for a subsea blowout happens in several stages, where the initially separated oil becomes subsequently broken down into smaller and smaller droplets. Droplet formation occurs at the highest rate close to the discharge point, where turbulence is highest, and ceases at some distance from the wellhead where turbulence is no longer strong enough to separate oil into smaller fractions. During the successive rounds of break-up, the oil's temperature will gradually decrease as the oil, emerging from the well with a typically high temperature up to 80-

120 °C, encounters ambient water at 4-10 °C. This means that the initial stages of breakup will occur at higher temperatures and lower viscosities than later stages. At the same time, the Weber scaling model requires a single viscosity parameter. To bridge this gap, SINTEF developed a model that produces an effective temperature for droplet formation (Skancke et al., 2016). This model averages the temperature of cooling oil using the drop of turbulence with distance from the wellhead. The resulting temperature is used to determine the corresponding viscosity. For this, two viscosity-temperature data points are required in order to find the matching viscosity using a regression model.

2.5 Far field

The transition from near-field to far-field happens when the rising oil is no longer being influenced by the buoyancy and momentum from the blowout plume. This may occur in the water column, in which case oil droplets will continue to rise and spread as droplets. If on the other hand the plume buoyancy and momentum continues until the sea surface, oil from the plume will be transported further as surface oil. Further transport of oil is determined by advection by ocean currents and wave-induced currents, wind and the buoyancy of oil. The oil will be subject to dissolution into the water column and evaporation to the atmosphere. Dissolved components, droplets and surface slicks are further subject to biodegradation by bacteria. Droplet clouds and dissolved components are spread by turbulent diffusion, while oil slicks on the surface are also subject to gravitational spreading, natural dispersion by waves and emulsification. All of these processes depend on the properties of the oil, such as density, viscosity and composition.

The oil spill model OSCAR simulates the transition from near-field to far-field and captures all of the processes mentioned above. It can model subsea releases at varying depths globally with 3D ocean currents and weather conditions (Reed et al., 2001; Reed et al., 1999).

An important output from the OSCAR model is the mass balance of a release. This allows inspection of the fate of oil and respective quantities. The example given in Figure 2.2 demonstrates the relative mass balance as a function of time, accounting for the total amount evaporated, amount of oil on surface, amount of oil in the water column either as droplets or dissolved into the water (dispersed), amount of oil biodegraded and amount of oil escaping the modelled area (outside). The mass balances as a function of time for all simulations are given in Appendix A.

The example given in Figure 2.3 demonstrates a comparison of mass balances, all taken at the same time (5 days into the simulation period). Note that the mass balance at day 5 in Figure 2.2 corresponds to the last column. This provides a tool to compare the overall fate of oil in over different scenarios.

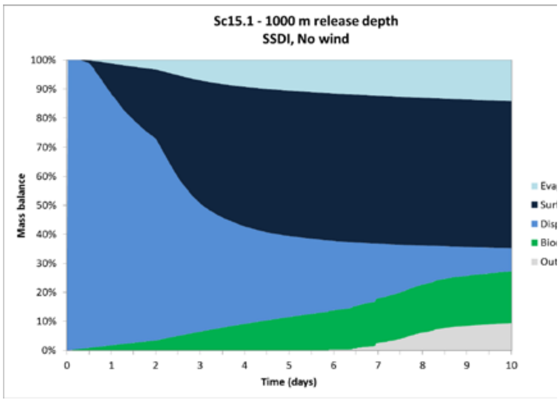

Figure 2.2 Example of mass balance for a simulation without wind and with subsea dispersant injection as a function of time, from start of release to end of release (day 2) and continued to the end of simulation (day 10).

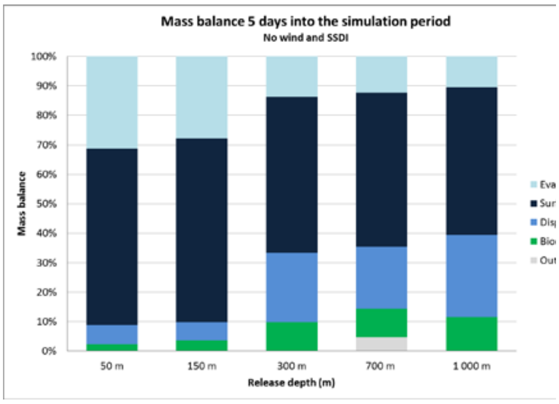

Figure 2.3 Example of mass balance comparison between several simulations without wind and with subsea injection, where the mass balance is obtained 5 days into the simulation period. The legend "outside" represents the oil that is outside the geographical grid defined for the modelling.

2.6 Subsea injection of dispersants

Down-scaled experiments simulating different subsea dispersant injection techniques were performed at SINTEF (Brandvik et al., 2013) to study the effectiveness of different dispersant injection techniques used during the Deepwater Horizon release. The different injection methods gave similar results (reduction in interfacial tension and smaller droplets) whether the dispersant was injected immediately before the outlet (simulated injection tool) or immediately after the outlet (simulating injection wand). A dispersant injection of 1-2 % lowered the interfacial tension between oil and water by a factor of 100 (Brandvik et al., 2016b).

2.7 Surface dispersion of oil treated with dispersant subsurface

In some cases with subsurface dispersant treatment, reduction in droplets sizes could be limited. This could be caused by lack of sufficient energy (e.g. low flow rates), very low dosage of dispersant or demanding oil properties (e.g. very high viscosity). These droplets of treated oil could form a surface slick that will be exposed to wave energy on the surface. Breaking waves can break up the surface oil into smaller droplets. Smaller droplets are more easily entrained into the water column (natural dispersion). This process is governed by wave energy, oil viscosity and oil film thickness: High wave energy, low viscosity and a thin oil slick give the most effective natural dispersion. This process occurs also for oil treated with dispersants, in particular in cases where dispersants have contributed to producing a thinner oil slick, i.e. during a subsea release with subsea injection of dispersants.

3 METHOD

3.1 Choice of model

For this project a research version of SINTEF OSCAR model system with Plume3D version 8.0 with the addition of a recently developed sub-model for scaling viscosity based on outlet temperature, was used.

3.2 Modelling sub-surface application of dispersants

It is assumed that the primary effect of oil treated with dispersants is a reduction in the oil-water interfacial tension (IFT). As described in Section 2.6, a reduction in the oil-water interfacial tension will reduce the median droplet size of the release.

The oil-water interfacial tension for the droplet size calculation can be specified in OSCAR, thereby simulating a treatment with dispersants.

For this study, an IFT reduction factor of 100 was chosen. Figure 3.1 shows the estimated median droplet size for release depths at 150 and 700 m depth versus different interfacial tension reduction factors. This figure shows that for a reduction of the IFT by a factor of 100 to 200, the median droplet size is converging towards a fixed value. This means that the break-up is entering a viscosity dominated regime and is no longer governed by the IFT. The simulations performed in this study can therefore assume that the dispersant to oil dosage is near optimal and that variation of dosage, application method and oil- and dispersant type have minimal impact on the droplet size distribution and subsequent simulation results (Brandvik et al., 2016b).

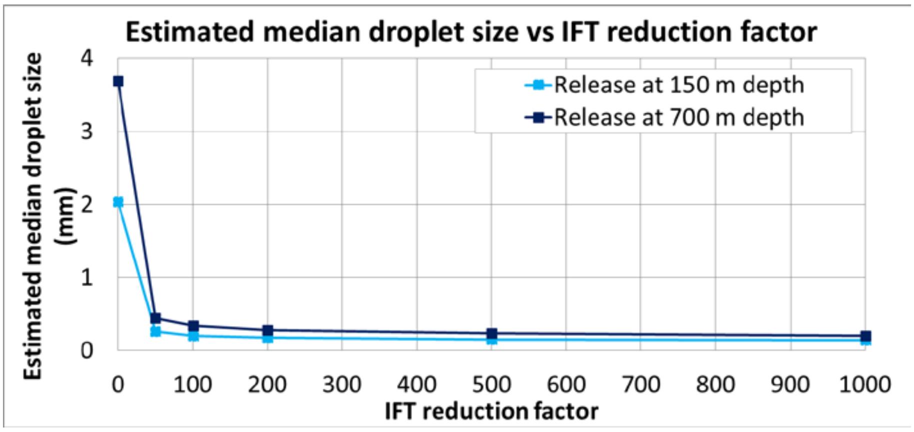

Figure 3.1 Estimated median droplet size for release depths at 150 and 700 m depth versus different interfacial tension (IFT) reduction factors. For this study, a reduction factor of 100 was chosen.

3.3 Modelling oil on the surface previously treated by sub-surface applied dispersants

The version of OSCAR (8.0 VT) used in this study does not track residual dispersants still present in the oil droplets after a subsea application. This means that oil rising to the surface will not retain information of being treated with dispersants, apart from being distributed into smaller droplets and consequently forming thinner oil slicks. This results in surface slicks that do not have any reduction in interfacial tension to further enhance dispersion. This is likely a conservative assumption, particularly for shallow to moderate water depths where the oil can rapidly surface due to the buoyancy of the entrained gas.

However, a new algorithm for surface dispersion (Johansen et al., 2015) is now implemented in a research version of OSCAR. This algorithm covers both natural and chemically enhanced dispersion and opens up for reducing the surface tension of surfaced oil from a SSDI scenario. This new algorithm is not thoroughly tested, and for this reason not used in the present study.

In order to investigate the effect of the wind on the surface slick, all 10 base scenarios were modelled with a constant and unidirectional wind of 5 m/s and 10 m/s during the entire duration of the scenarios. The wave energy is calculated in OSCAR based on the wind speed and fetch.

3.4 Scenario parameters

The common scenario parameters for all simulations are given in Table 3.1.The location of the release is chosen to be the same as the location of the current profile mooring. Figure 3.2 shows this position on the map. The release rate for the simulations is shown in Figure 3.3.

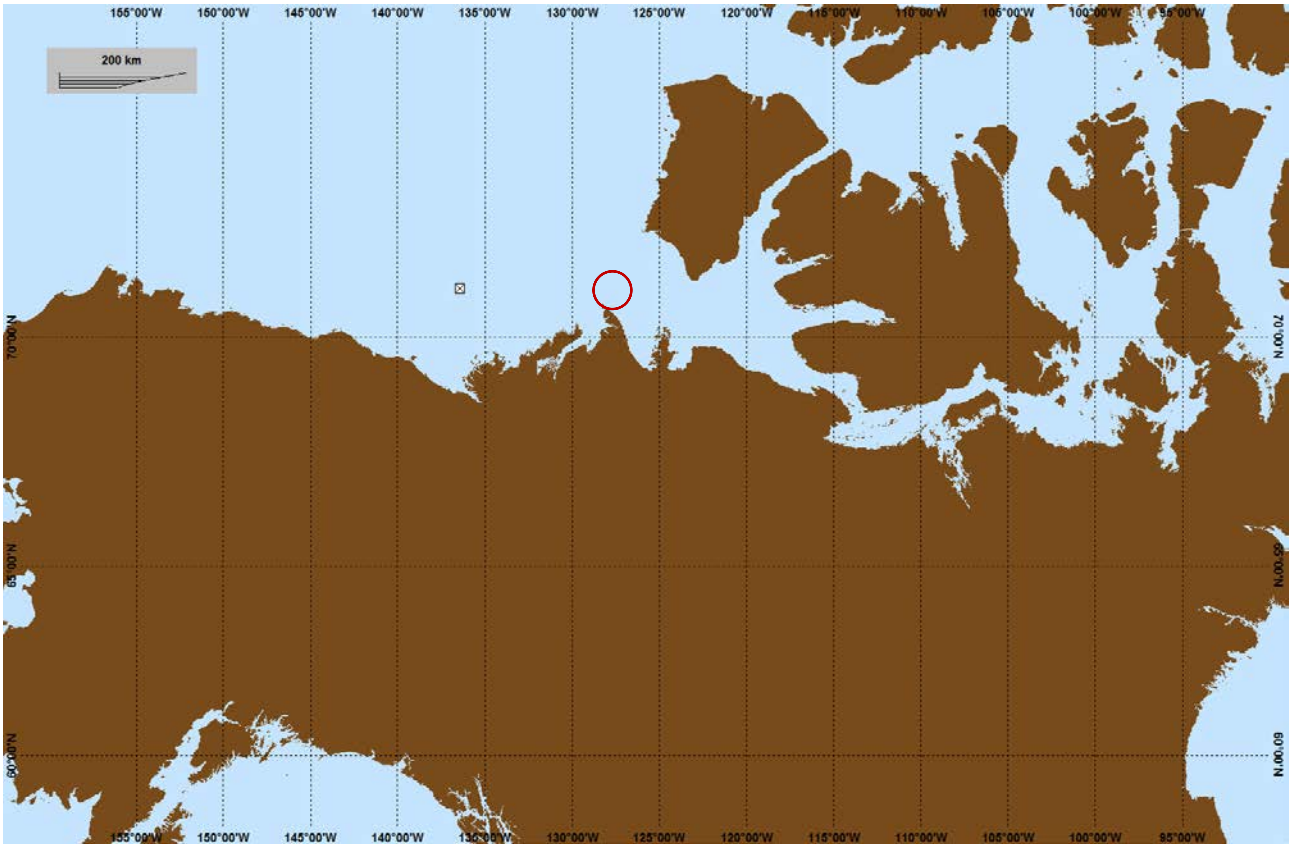

Figure 3.2 Map with the location of the release site/current profile mooring position (Beaufort Sea).

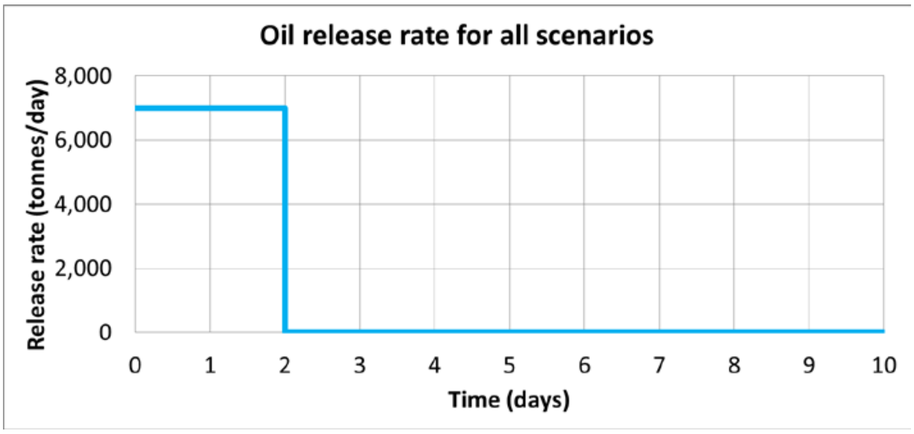

Figure 3.3 The oil release rate used for all scenarios. The release is constant for the first two days and then completely stopped.

Table 3.1 Scenario parameters

Parameter	Value
Start time	2009-09-16 12:00 UTC
Duration	10 days
Oil profile	Oseberg Blend (light paraffinic)
Oil density	0.839 (kg/l)
Release location	Beaufort Sea
Longitude	136° 24.688' W
Latitude	70° 55.856' N
Release rate	7 000 tonnes/day (52 478 barrels/day)
Release duration	2 days
Salinity of formation water in the release	0 (no formation water in release)
Temperature of release	60 °C
Release diameter	0.25 m
GOR	100
Gas density	0.8 kg/Sm^3
Air temperature	10 °C

3.5 Model parameters

The model parameters are given in Table 3.2. These parameters are the same for all scenarios, and are important in order to reproduce the OSCAR simulations. A key difference in the setup defined by the table compared to a normal OSCAR setup is the usage of the temperature-viscosity model (Skancke et al., 2016). This model requires two temperature-viscosity data-pairs (indicated in Table 3.2). This data is used to fit an equation that predicts the viscosity at other temperatures than the specified ones, as described in Skancke et al., (2016).

Table 3.2 Model parameters

Parameter	Value
Liquid/Solid particles	10 000
Dissolved particles	10 000
Horizontal grid resolution (cell size [m])	200x200
Vertical resolution (number of cells)	10
Output interval	30 minutes
Internal time step	5 minutes
Use distance to Nearest Neighbour	ON
Approx. ext. conc.	ON
Stretch current depth	ON
Adjust surfacing thickness	ON
Enable temp-visc model	ON
Temperature 1 [°C]	30.1
Temperature 2 [°C]	60.6
Viscosity 1	4.08
Viscosity 2	2.67

3.6 Environmental parameters

3.6.1 *Current profile time series*

Measured current profile time series have been provided by ASL (2013). The current mooring consisted of two DVS (Doppler Volume Sampler) current meters (989 m and 864 m), a Long Ranger ADCP (Acoustic Doppler Current Profiler) with measurements from 410 to 130 m depth, and a Quartermaster ADCP with measurements from 106 m to 20 m depth. Images of the current and speed profiles with time are shown in Figure 3.4.

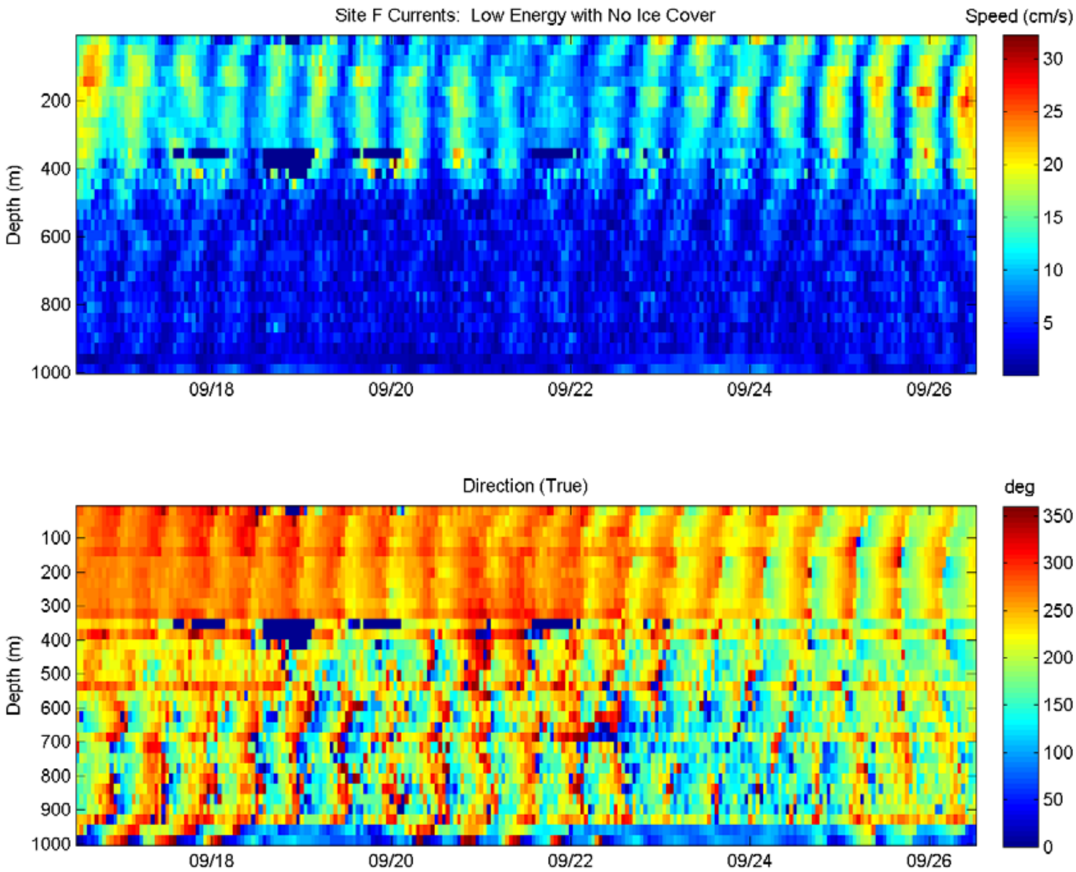

Figure 3.4 Current profile time series with weak/normal current conditions (from ASL, 2013).

3.6.2 *Temperature and salinity profiles*

September monthly mean temperature and salinity data from the National Virtual Ocean Data System (NVODS, accessed 14 August 2013) at position 145.5° W, 71.5° N was used. This was the only available dataset close to the release site (Figure 3.5 and Table 3.3). The density is calculated from the temperature and salinity with a reference pressure at sea level (p=0).

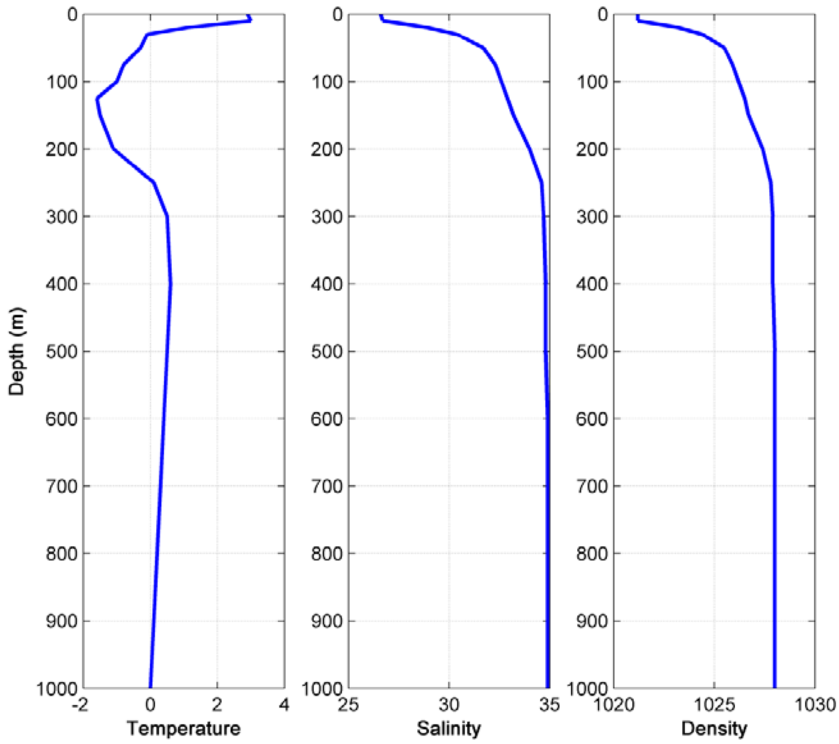

Figure 3.5 Temperature, salinity and density profiles used in the model scenarios.

Table 3.3 September monthly mean temperature, salinity and density (from the NVODS database) close to the release site.

Depth	Temperature [°C]	Salinity	Density [kg/m^3]
0	2.9	26.6	1021.2
10	3.0	26.7	1021.2
20	1.1	28.9	1023.2
30	-0.1	30.4	1024.4
50	-0.3	31.7	1025.5
75	-0.8	32.3	1025.9
100	-1.0	32.6	1026.2
125	-1.6	32.9	1026.5
150	-1.5	33.2	1026.7
200	-1.1	34.0	1027.4
250	0.1	34.6	1027.8
300	0.5	34.7	1027.9
400	0.6	34.8	1027.9
500	0.5	34.8	1028.0

600	0.4	34.9	1028.0
700	0.3	34.9	1028.0
800	0.2	34.9	1028.0
900	0.1	34.9	1028.0
1000	0.0	34.9	1028.0

3.7 Overview over the modelled scenarios

A total of 30 different scenarios have been modelled and compared with each other. The scenario names and variations are given in Table 3.4.

Table 3.4 The description of the scenarios.

No	Scenario name	Depth [m]	Wind [m/s]	Dispersant	Interfacial Tension Oil/Water [mN/Mm]
1.1	Sc1.1-MEMW8.0ViscTemp-50m-NoDisp-NoWind	50	0	No	15.5
1.2	Sc1.2-MEMW8.0ViscTemp-50m-NoDisp-5msWind	50	5	No	15.5
1.3	Sc1.3-MEMW8.0ViscTemp-50m-NoDisp-10msWind	50	10	No	15.5
2.1	Sc2.1-MEMW8.0ViscTemp-150m-NoDisp-NoWind	150	0	No	15.5
2.2	Sc2.2-MEMW8.0ViscTemp-150m-NoDisp-5msWind	150	5	No	15.5
2.3	Sc2.3-MEMW8.0ViscTemp-150m-NoDisp-10msWind	150	10	No	15.5
3.1	Sc3.1-MEMW8.0ViscTemp-300m-NoDisp-NoWind	300	0	No	15.5
3.2	Sc3.2-MEMW8.0ViscTemp-300m-NoDisp-5msWind	300	5	No	15.5
3.3	Sc3.3-MEMW8.0ViscTemp-300m-NoDisp-10msWind	300	10	No	15.5
4.1	Sc4.1-MEMW8.0ViscTemp-700m-NoDisp-NoWind	700	0	No	15.5
4.2	Sc4.2-MEMW8.0ViscTemp-700m-NoDisp-5msWind	700	5	No	15.5
4.3	Sc4.3-MEMW8.0ViscTemp-700m-NoDisp-10msWind	700	10	No	15.5
5.1	Sc5.1-MEMW8.0ViscTemp-1000m-NoDisp-NoWind	1000	0	No	15.5
5.2	Sc5.2-MEMW8.0ViscTemp-1000m-NoDisp-5msWind	1000	5	No	15.5
5.3	Sc5.3-MEMW8.0ViscTemp-1000m-NoDisp-10msWind	1000	10	No	15.5
11.1	Sc11.1-MEMW8.0ViscTemp-50m-SSDI-NoWind	50	0	Yes	0.155
11.2	Sc11.2-MEMW8.0ViscTemp-50m-SSDI-5msWind	50	5	Yes	0.155
11.3	Sc11.3-MEMW8.0ViscTemp-50m-SSDI-10msWind	50	10	Yes	0.155
12.1	Sc12.1-MEMW8.0ViscTemp-150m-SSDI-NoWind	150	0	Yes	0.155
12.2	Sc12.2-MEMW8.0ViscTemp-150m-SSDI-5msWind	150	5	Yes	0.155
12.3	Sc12.3-MEMW8.0ViscTemp-150m-SSDI-10msWind	150	10	Yes	0.155
13.1	Sc13.1-MEMW8.0ViscTemp-300m-SSDI-NoWind	300	0	Yes	0.155
13.2	Sc13.2-MEMW8.0ViscTemp-300m-SSDI-5msWind	300	5	Yes	0.155
13.3	Sc13.3-MEMW8.0ViscTemp-300m-SSDI-10msWind	300	10	Yes	0.155
14.1	Sc14.1-MEMW8.0ViscTemp-700m-SSDI-NoWind	700	0	Yes	0.155
14.2	Sc14.2-MEMW8.0ViscTemp-700m-SSDI-5msWind	700	5	Yes	0.155
14.3	Sc14.3-MEMW8.0ViscTemp-700m-SSDI-10msWind	700	10	Yes	0.155
15.1	Sc15.1-MEMW8.0ViscTemp-1000m-SSDI-NoWind	1000	0	Yes	0.155
15.2	Sc15.2-MEMW8.0ViscTemp-1000m-SSDI-5msWind	1000	5	Yes	0.155
15.3	Sc15.3-MEMW8.0ViscTemp-1000m-SSDI-10msWind	1000	10	Yes	0.155

4 RESULTS

4.1 Droplet sizes and rising rate

Table 4.1 shows the difference in median droplet size and time to reach the surface with and without SSDI, as well as the outlet release velocity. SSDI caused approximately a 10-fold reduction in droplet size (Table 4.1). However, in addition to the droplet size the release depth and the plume rise velocity also affects the time it takes for oil to reach the surface. The droplet rise time for the median droplet size was calculated by combining the velocity provided by the plume with the buoyant rise velocity of the droplet. For the two shallowest releases, there was no difference in rise time as the plume reached the surface with high velocity. For the three remaining depths, the rise time to the surface increased with SSDI. Further description of the plume is given in section 2.1.

Table 4.1 Results from the plume calculations for the different release depths (both for oil only and with SSDI).

Depth [m]	Estimated droplet size d_{50} Oil only [mm]	Estimated droplet size d_{50} SSDI [mm]	Reduction factor in droplet size after SSDI has been applied [%]	Outlet release velocity (both oil only and SSDI) [m/s]	Time to reach surface for d_{50} droplet Oil only [h]	Time to reach surface for d_{50} droplet SSDI [h]
50	1.29	0.140	89.1	10	0.005	0.005
150	2.04	0.207	89.9	7.0	0.03	0.03
300	2.70	0.263	90.3	5.5	0.53	6.86
700	3.69	0.343	90.7	4.2	1.30	11.8
1 000	3.90	0.379	90.3	3.8	2.18	19.1

4.2 Mass balance for all scenarios at 2, 5 and 10 days

The mass balance 2, 5 and 10 days into each of the 30 simulations is shown in Figure 4.1 – Figure 4.3, respectively.

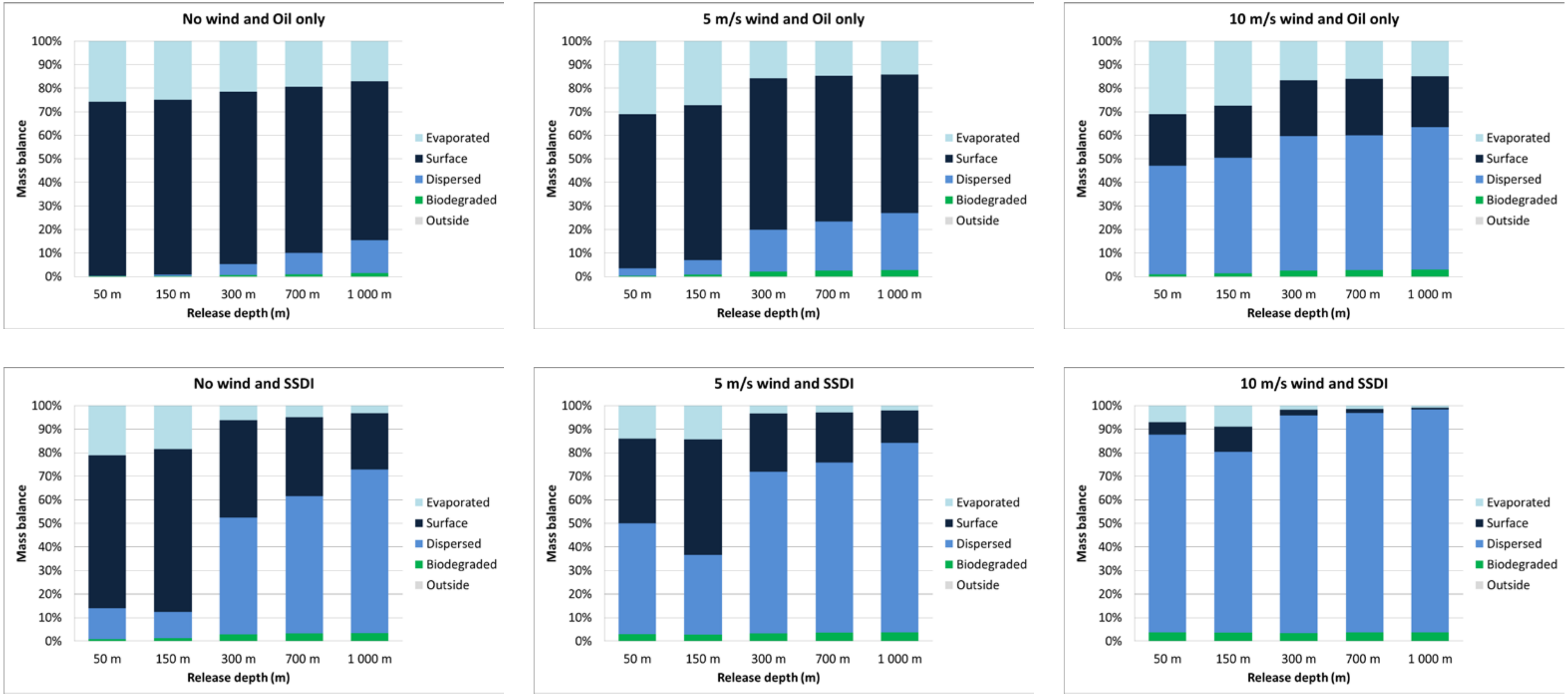

Figure 4.1 Mass balance 2 days into the simulation period (at the end of the release) for all scenarios. The upper pictures show the results for the scenarios without SSDI, whereas the lower pictures are the scenarios with SSDI. Left: No wind. Middle: 5 m/s wind. Right: 10 m/s wind.

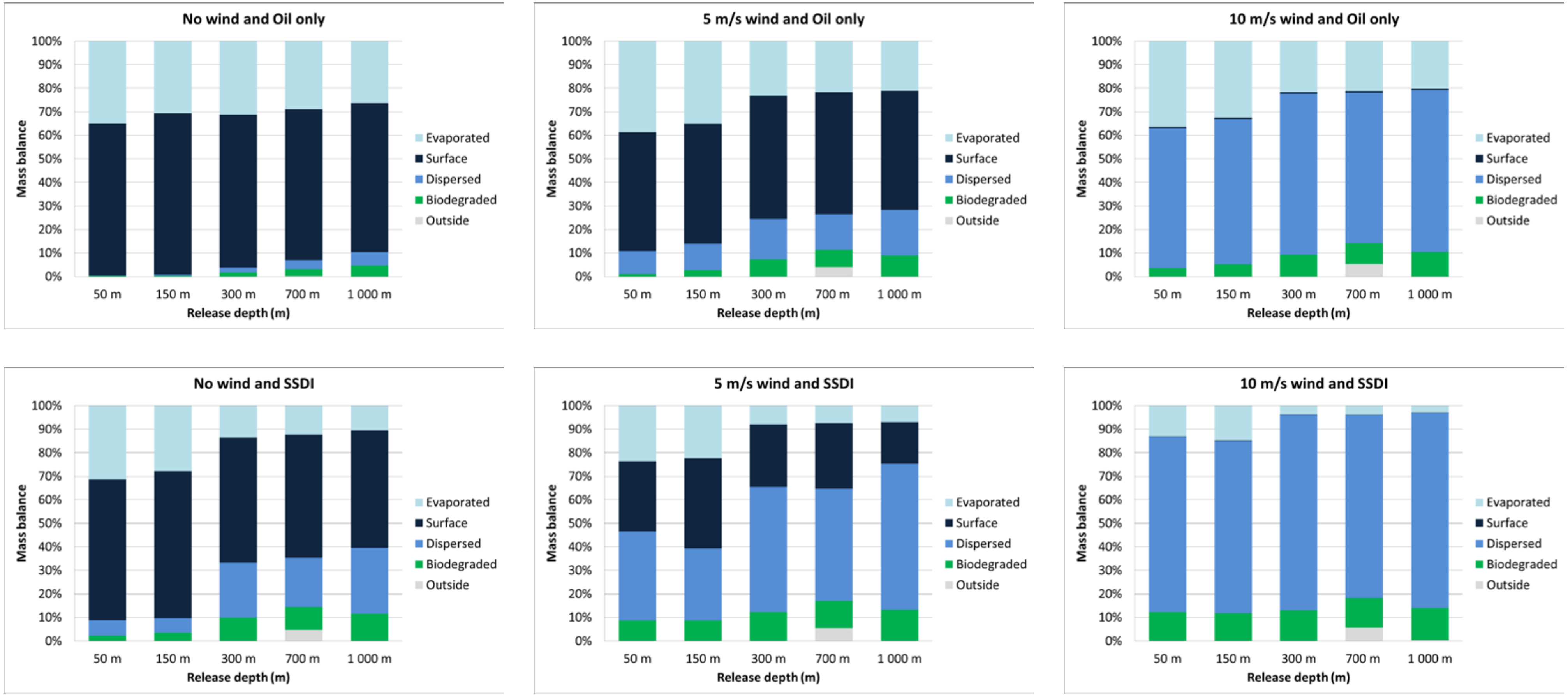

Figure 4.2 Mass balance 5 days into the simulation period (3 days after the end of the release) for all scenarios. The upper pictures show the results for the scenarios without SSDI, whereas the lower pictures are the scenarios with SSDI. Left: No wind. Middle: 5 m/s wind. Right: 10 m/s wind.

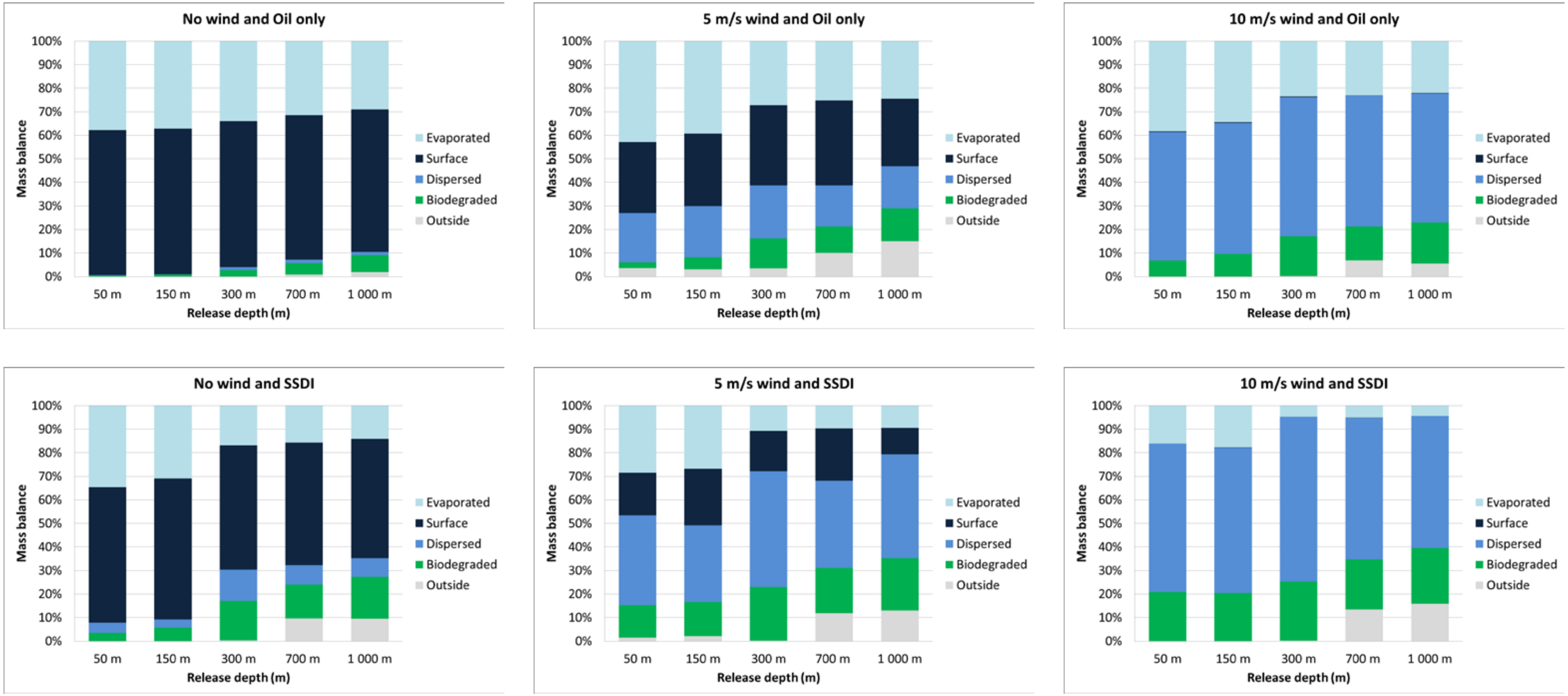

Figure 4.3 Mass balance at the end of the simulation period (10 days) for all scenarios. The upper pictures show the results for the scenarios without SSDI, whereas the lower pictures are the scenarios with SSDI. Left: No wind. Middle: 5 m/s wind. Right: 10 m/s wind.

4.3 Impacted surface area (scenarios without wind)

The overall maximum surface oil thickness (impacted area) for the scenarios with oil only is given in Figure 4.4. The figure shows the maximum oil thickness at any surface grid cell at any time during the 10-day simulation period for all five release-depths. The same results from the scenarios with SSDI are given in Figure 4.5.

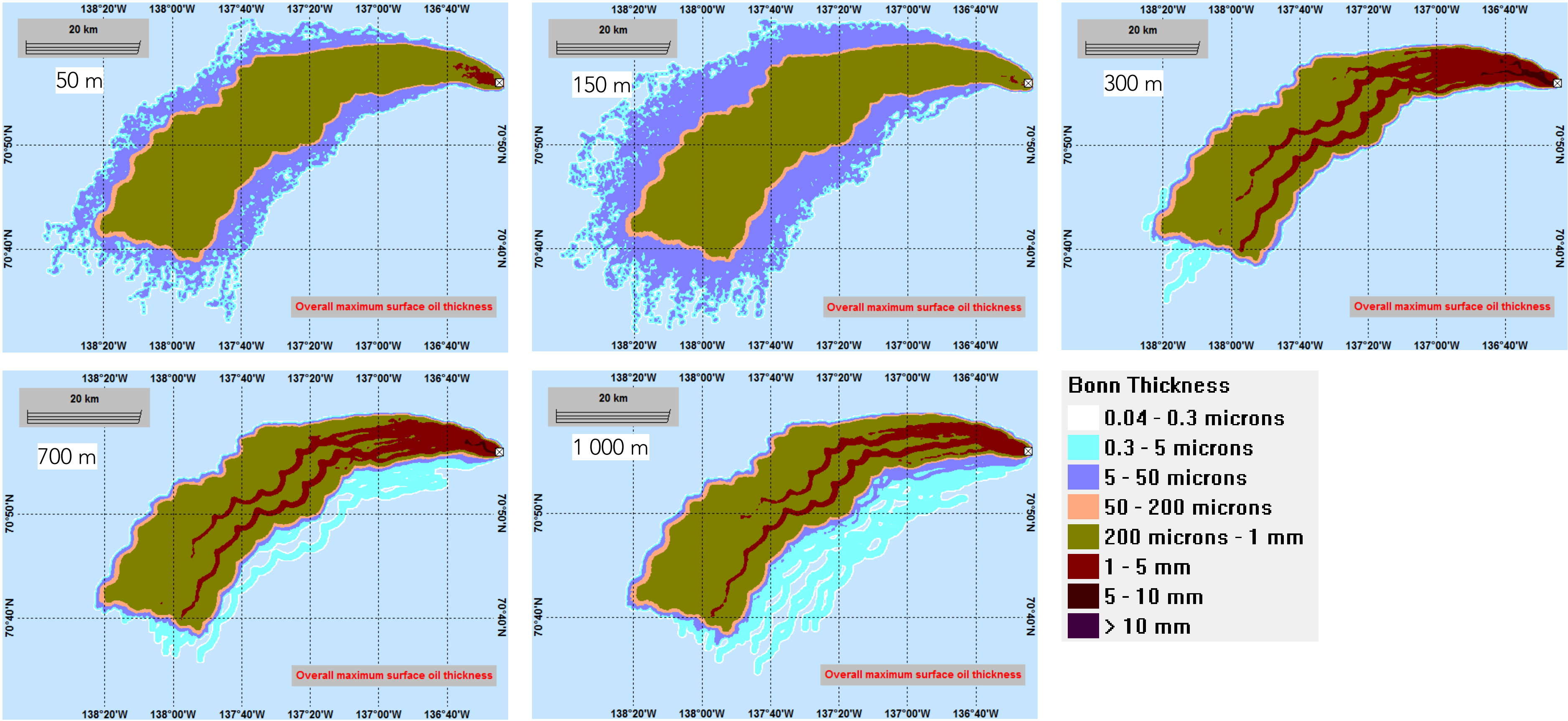

Figure 4.4 Overall maximum surface oil thickness (impacted surface area) for all release depths (scenarios 1.1-5.1), without wind and with oil only.

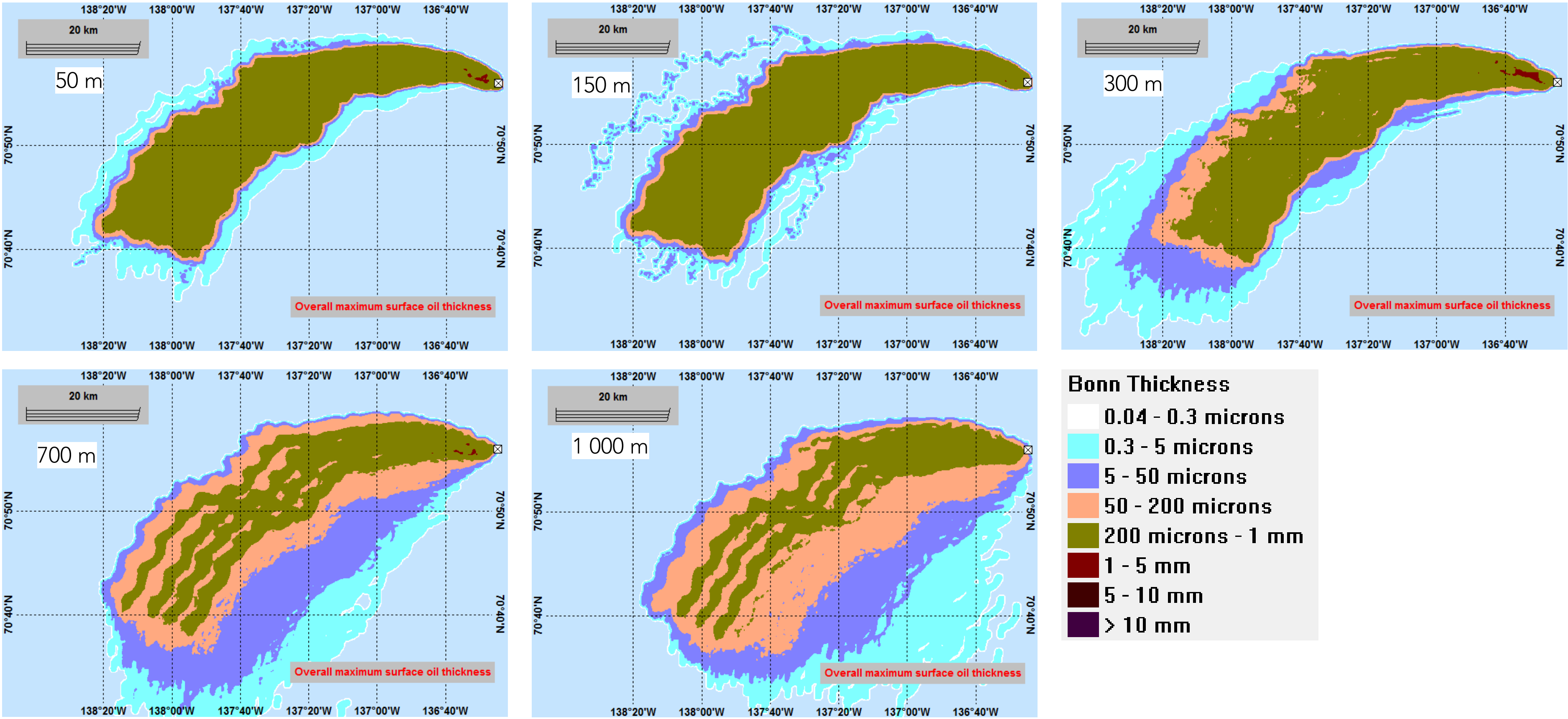

Figure 4.5 Overall maximum surface oil thickness (impacted surface area) for all release depths (scenarios 11.1-15.1), without wind and with SSDI.

4.4 Comparison of surface oiling

The scenarios with release depth 150, 300 and 700 m were selected for further studies and the results from these predictions are presented in this section. The distribution of the resulting surface oil slick for these three depths are presented in the next two sections. The scenarios with release depth 50 and 1 000 m are not discussed, but the mass balances are provided in Appendix A.

4.4.1 Results for releases at 150 m depth

4.4.1.1 Surface oiling at the end of the release period (2 days)

Snapshots of surface oil at the end of the release for all scenarios with release at 150 m are given in Figure 4.6. It can be seen that there is no significant difference in the thickness and spreading of the surface oil when comparing the scenario without SSDI to the scenario with SSDI for this release depth when there is no wind. When there is a gentle breeze, it can be seen that the oil that has been treated with SSDI will spread over a larger area in a thinner layer than untreated oil. A similar effect can as for the situation with 5 m/s can be seen when the wind speed is increased to 10 m/s; the surface oil is thinner and spread over a larger area when treated with SSDI.

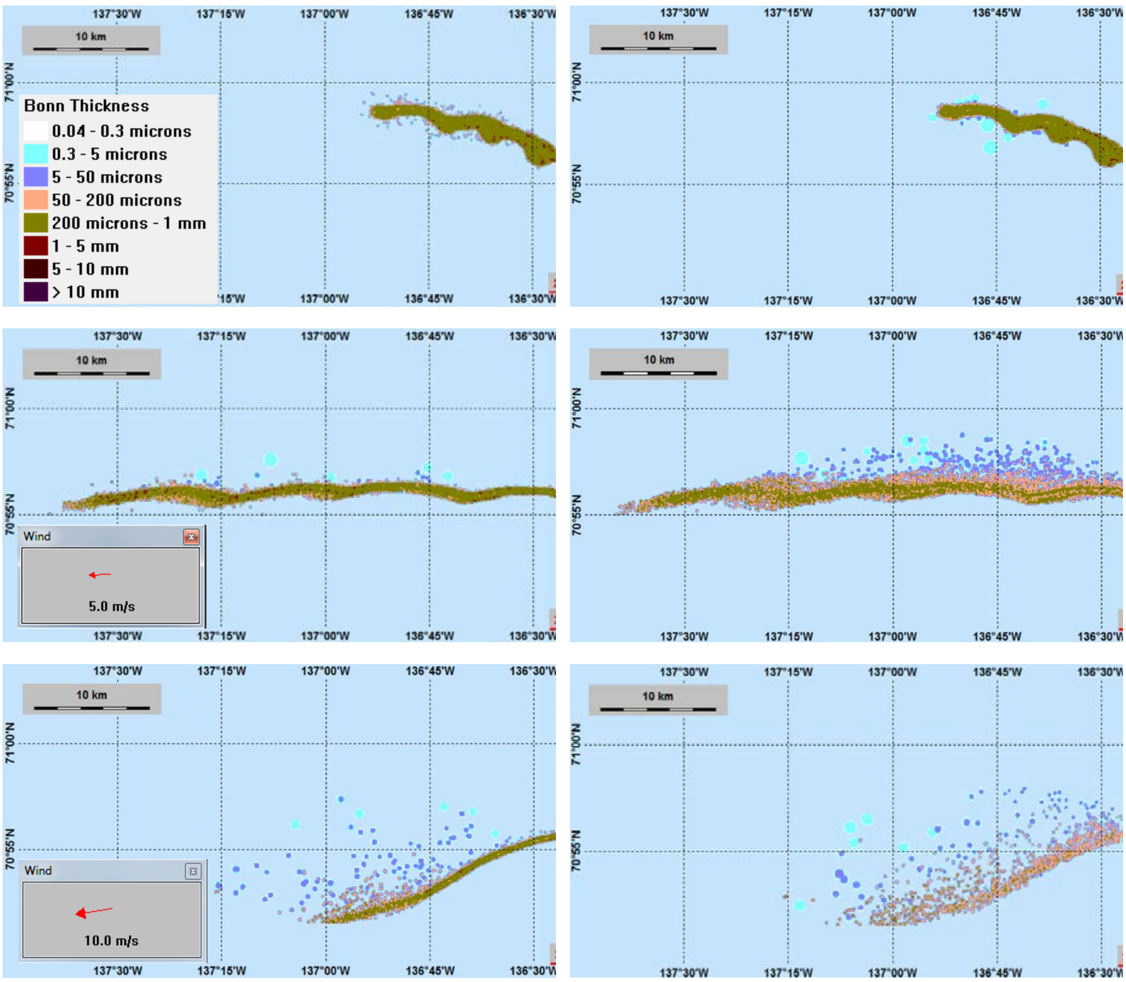

Figure 4.6 Surface oil at the end of the release (2 days) for releases at 150 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.1.2 Surface oiling 5 days into the simulation period

Snapshots of surface oil 5 days into the simulation period (3 days after the end of the release) for all the scenarios with release at 150 m are given in Figure 4.7. The same behaviour as at the end of the release (2 days) can be seen for the situation at 5 days for the cases with no wind and 5 m/s wind: There is no significant difference in the thickness and spreading of the surface oil when comparing the scenario without SSDI to the scenario with SSDI for this release depth when there is no wind. When there is a gentle breeze, it can be seen that the oil that has been treated with SSDI will spread over a larger area in a thinner layer than untreated oil. When the wind is blowing at a constant speed of 10 m/s, there is little oil left on the surface for both the scenario with oil only and when SSDI has been applied.

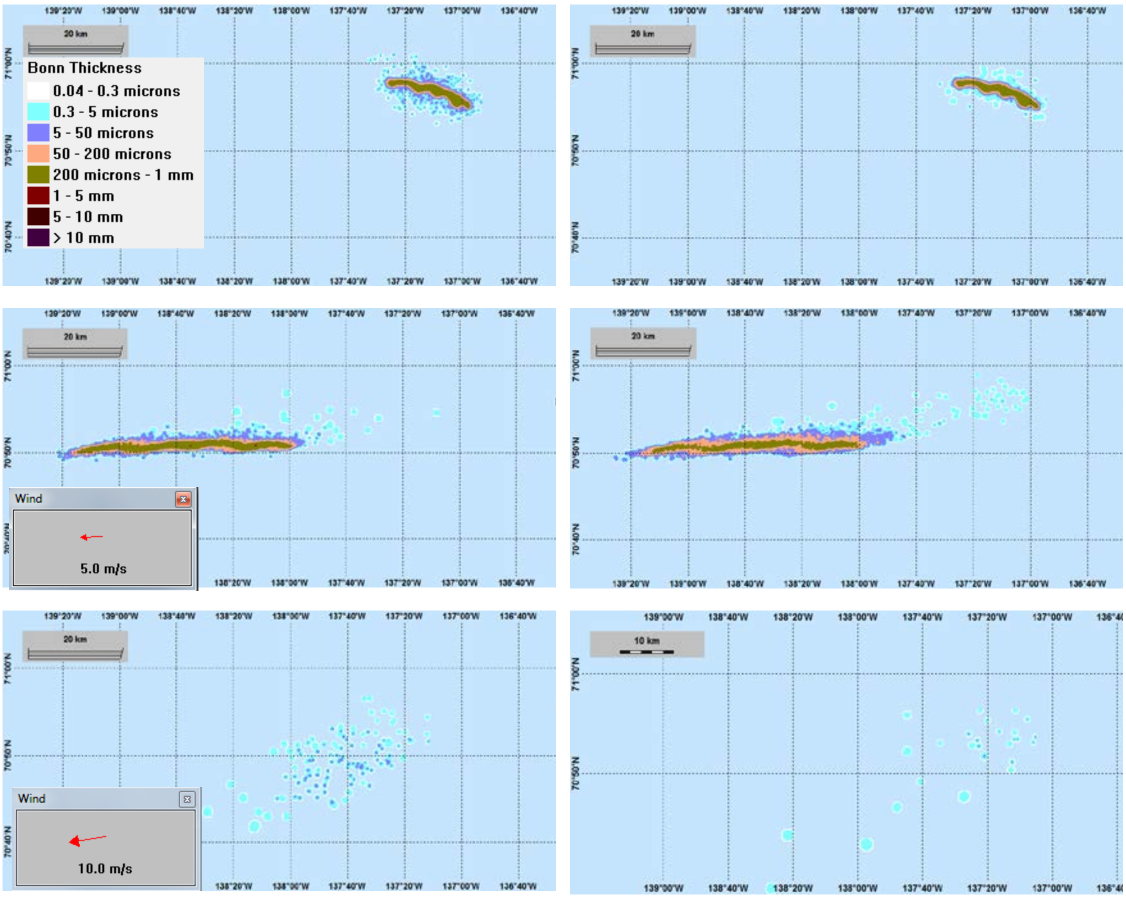

Figure 4.7 Surface oil 5 days into the simulation period (3 days after the end of the release) for releases at 150 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.1.3 Surface oiling 10 days into the simulation period

Snapshots of surface oil 10 days into the simulation period (8 days after the end of the release) for all the scenarios with release at 150 m are given in Figure 4.8. For the scenarios without wind, there is little change in the surface oil signature than is was at the end of the release period and at 5 days into the simulation. The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario with oil only shows thicker surface slick than when SSDI has been applied. When the wind is blowing at a constant speed of 10 m/s, there is hardly any oil left on the surface for both the scenario with oil only and when SSDI has been applied.

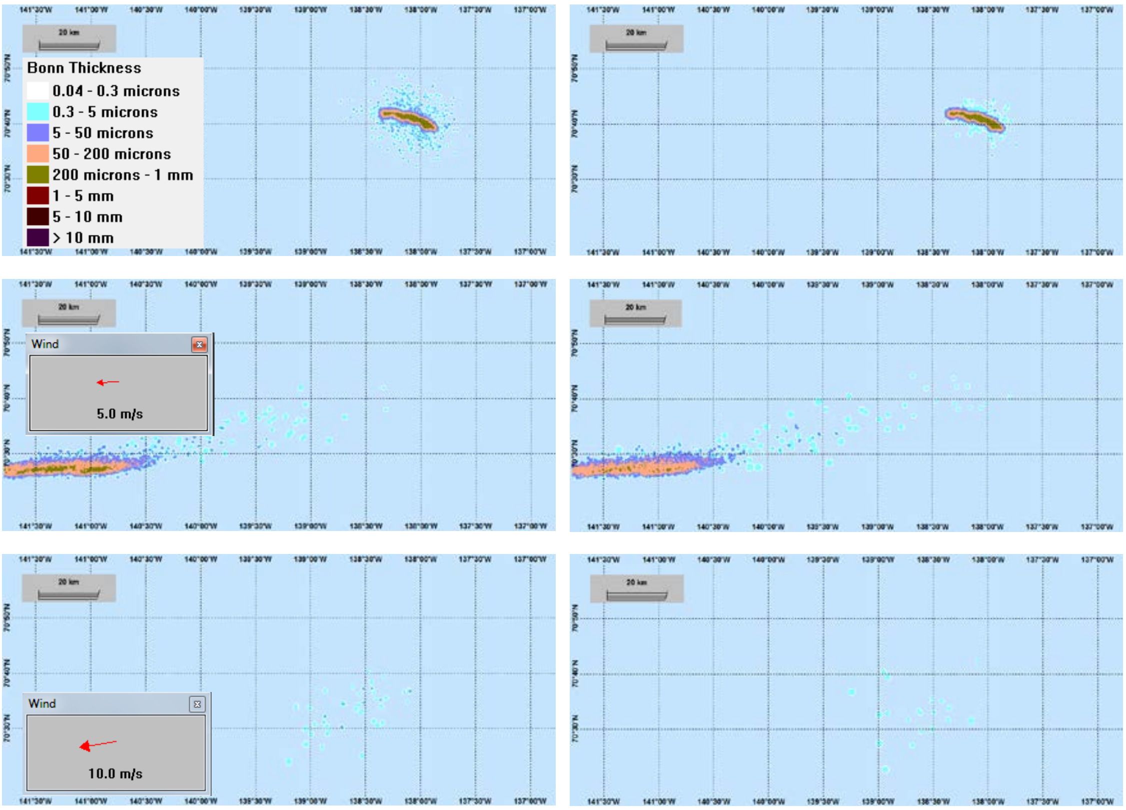

Figure 4.8 Surface oil at the end of the simulation period (10 days) for releases at 150 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.1.4 Mass balance for the release at 150 m depth

The mass balance for all the releases at 150 m depth are presented in Figure 4.9. The mass balance show that when there is no wind and oil only, nearly all the released oil is either on the surface or has evaporated. When SSDI has been applied, the oil remains longer in the water column before it surfaces, thus leading to enhanced biodegradation compared to the oil only scenario. There is less evaporation in this case since more of the total released oil is submerged.

When there is a gentle breeze of 5 m/s, the mass balance show that there is more oil being mixed into the water column, both with oil only and SSDI applied. However, there is still 31 % of the total released oil left on the surface for the scenario with oil only, and 24 % when SSDI has been applied. This means that there will still be a chance for emulsification of surface oil with 5 m/s wind.

For the releases when there is blowing a constant wind of 10 m/s, the wind is strong enough to mix the surfaced oil down into the water column after the release has finished. During the release, there is much more oil at the surface when there is oil only compared to when SSDI has been applied.

A closer comparison of the mass balance 2, 5 and 10 days into the simulation period is shown in Figure 4.10.

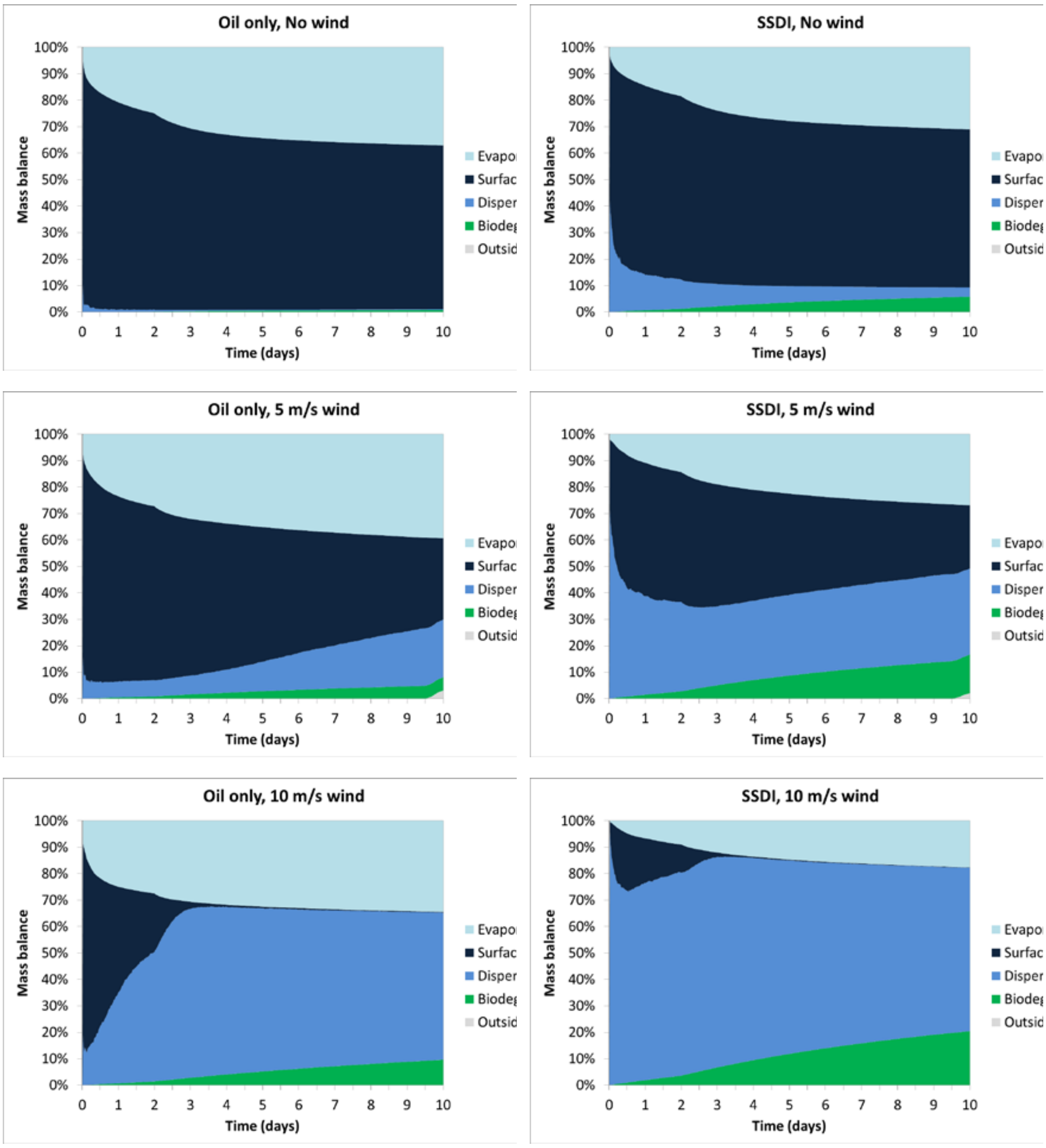

Figure 4.9 Mass balance for all scenarios with releases at 150 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

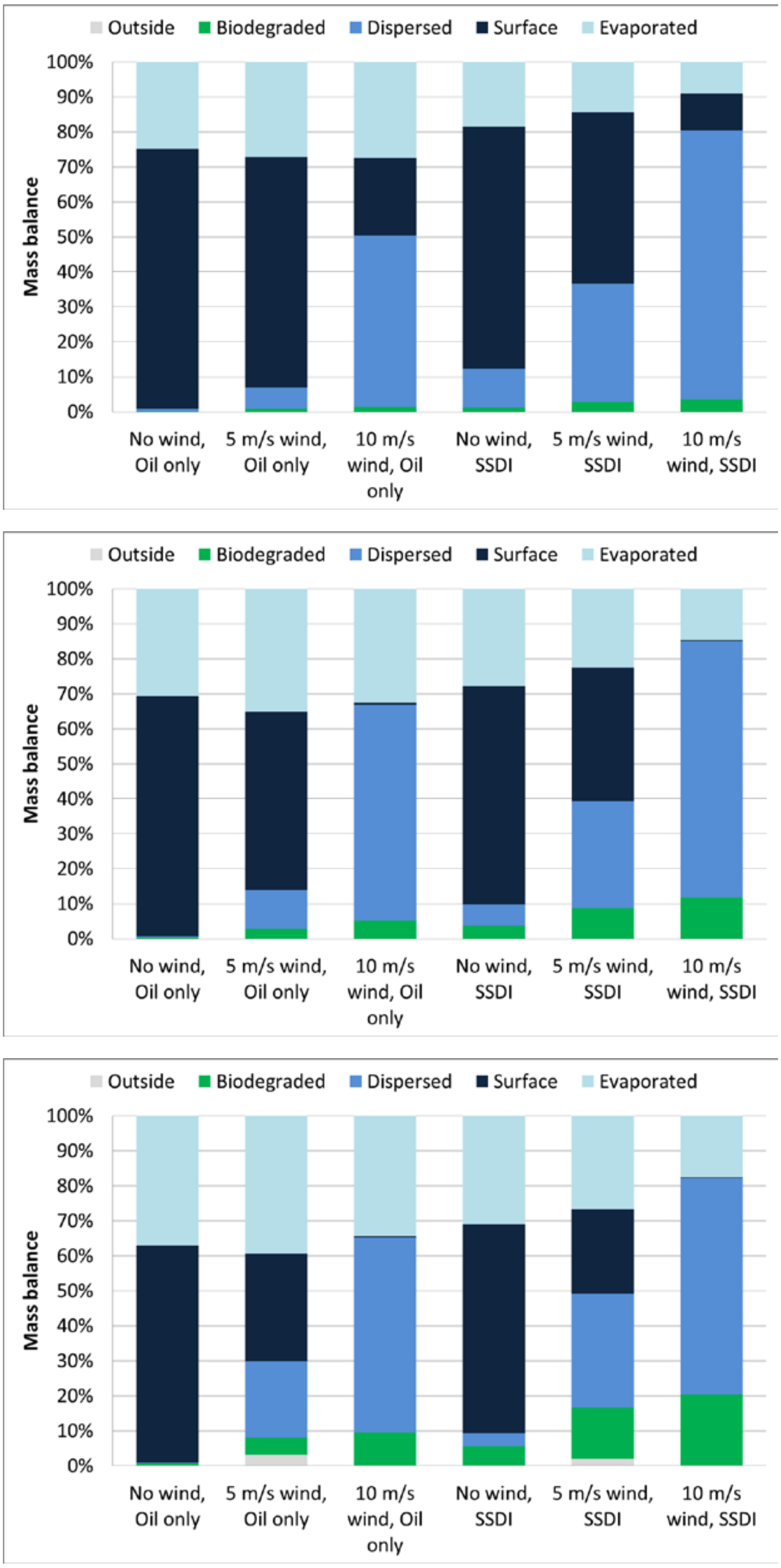

Figure 4.10 Mass balance at the end of the release (2 days into the simulation) (upper), 5 days (middle) and 10 days (lower) into the simulation period at 150 m depth with and without the presence of wind and SSDI.

4.4.1.5 Impacted surface area

Figure 4.11 show the maximum oil thickness at any surface grid cell at any time during the 10-day simulation period for all scenarios with release at 150 m. The figure shows that there is little difference when there is no wind, only a small area close to the release point has experienced thicker surface oil (1 – 5 mm) when there is oil only. This is not seen in the SSDI results. When there is a gentle breeze of 5 m/s, it can be seen that the surface oil is thicker for the scenario with oil only compared to with SSDI. The same results can be seen for the 10 m/s scenarios. It can also be seen that when there is a gentle breeze, the oil is transported over a larger area. This is because the energy transferred from the wind is not large enough to generate breaking waves that mixes the surface oil into the water column.

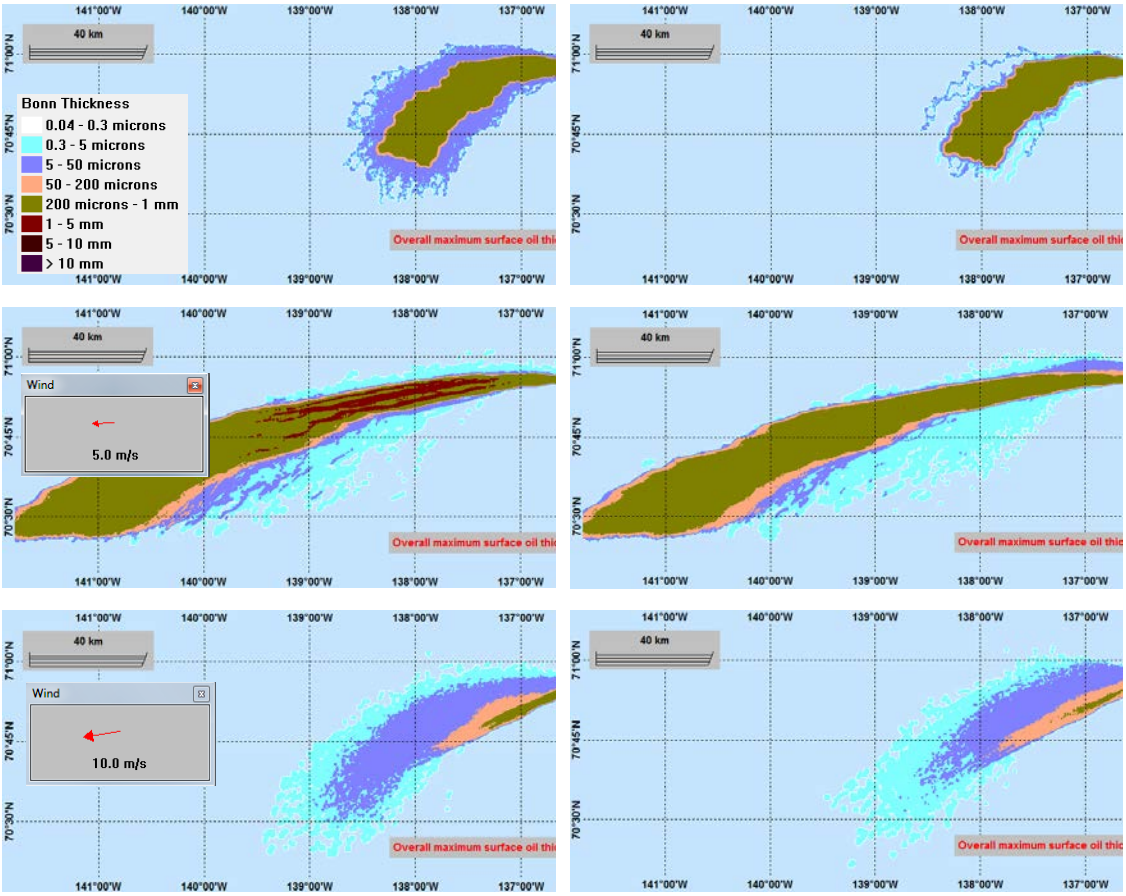

Figure 4.11 Overall maximum surface oil thickness (impacted area) for all scenarios with release at 150 m. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.2 Results for releases at 300 m depth

4.4.2.1 Surface oiling at the end of the release period (2 days)

Snapshots of surface oil at the end of all the scenarios with release at 300 m are given in Figure 4.12. It can be seen that the surface oil is thicker in a more confined area for the case with only oil when compared to the scenario with subsea injection of dispersant. The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface spread over a narrower band than when SSDI has been applied. However, the wind transports the oil over a larger area in the scenario without SSDI. When the wind is blowing at a constant speed of 10 m/s, the scenario without SSDI shows a narrower area with thicker oil than when SSDI has been applied. In addition, the wind is more effective in dispersing the surface oil, leading to little oil on the surface after treatment with SSDI.

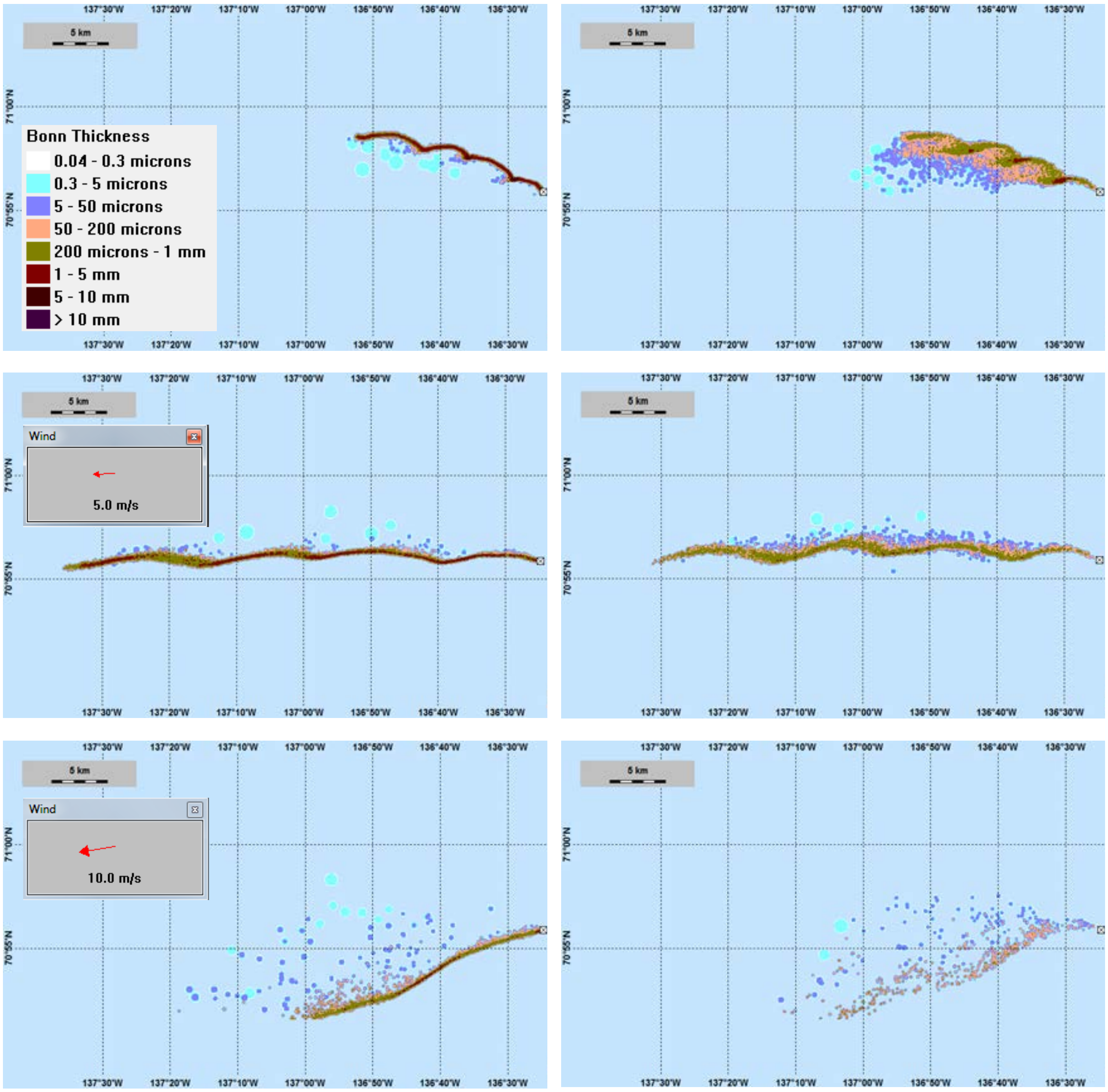

Figure 4.12 Surface oil at the end of the release for releases at 300 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.2.2 Surface oiling 5 days into the simulation period

Snapshots of surface oil 5 days into the simulation period (3 days after the end of the release) for all the scenarios with release at 300 m are given in Figure 4.13. For the scenarios without wind, there is little change in the surface oil signature than is was at the end of the release period (3 days previous). The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface spread over a narrower band than when SSDI has been applied. However, the wind transports the oil over a larger area in the scenario without SSDI. When the wind is blowing at a constant speed of 10 m/s, there is little oil left on the surface for both the scenario with oil only and when SSDI has been applied.

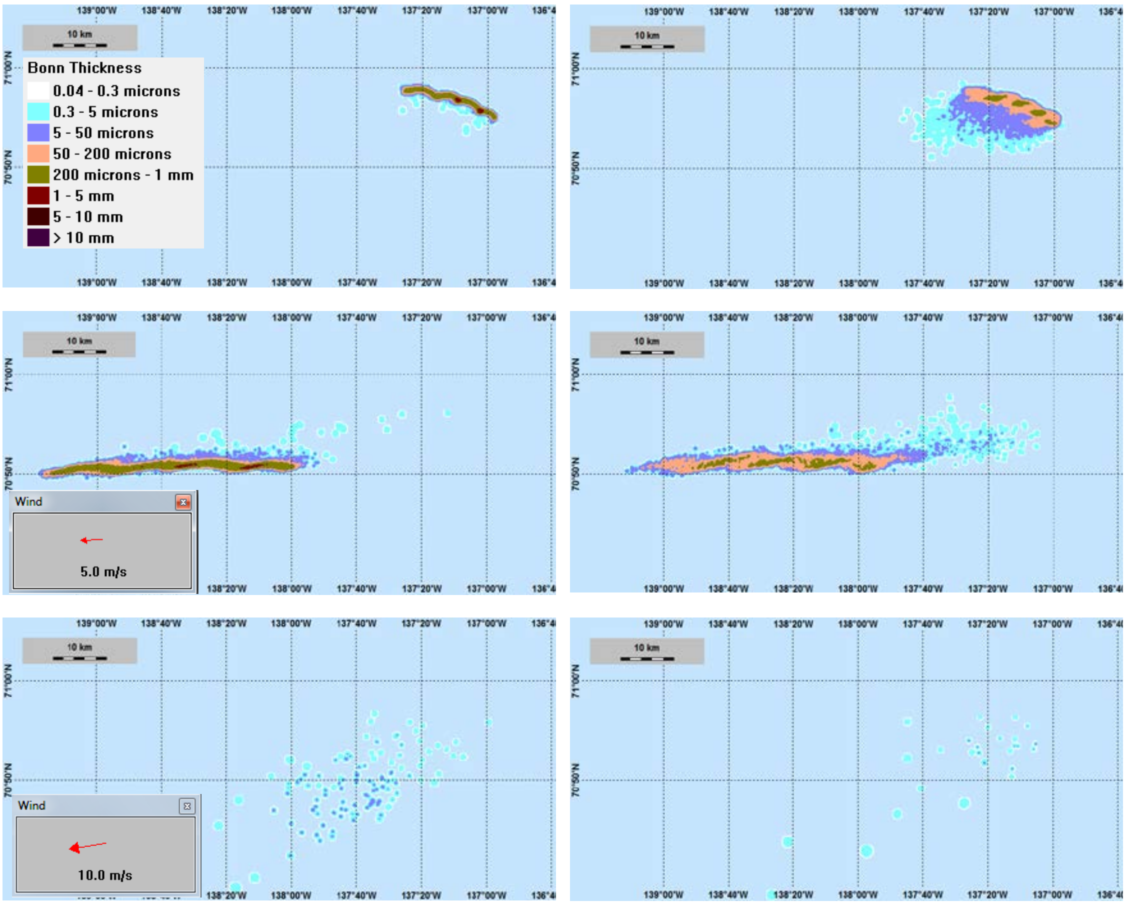

Figure 4.13 Surface oil 5 days into the simulation period (3 days after the end of the release) for releases at 300 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.2.3 Surface oiling 10 days into the simulation period

Snapshots of surface oil 10 days into the simulation period (8 days after the end of the release) for all the scenarios with release at 300 m are given in Figure 4.14. For the scenarios without wind, there is little change in the surface oil signature than is was at the end of the release period and at 5 days into the simulation. The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface slick than when SSDI has been applied. When the wind is blowing at a constant speed of 10 m/s, there is hardly any oil left on the surface for both the scenario with oil only and when SSDI has been applied.

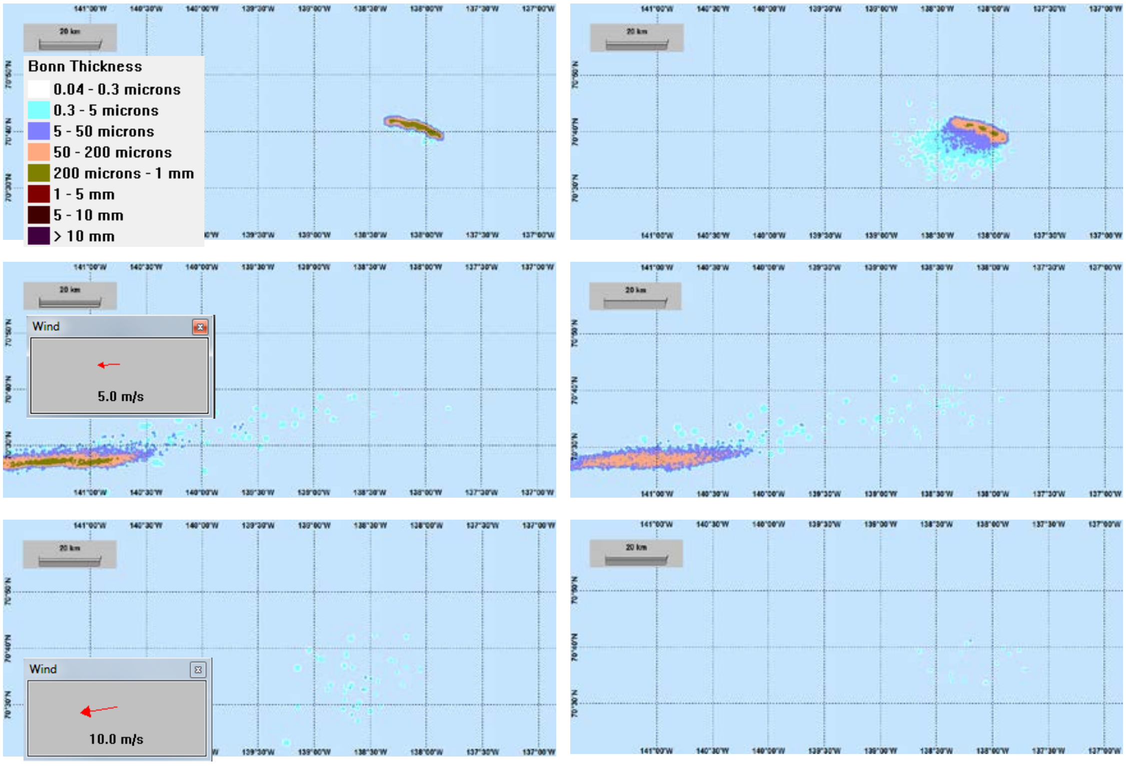

Figure 4.14 Surface oil at the end of the simulation period (10 days) for releases at 300 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.2.4 Mass balance for the release at 300 m depth

The mass balance for all the releases at 300 m depth are presented in Figure 4.15. The mass balance show that when there is no wind and oil only, nearly all the released oil is either on the surface or has evaporated. When SSDI has been applied, the oil remains longer in the water column before it surfaces, thus leading to enhanced biodegradation compared to the oil only scenario. There is less evaporation in this case since more of the total released oil is submerged.

When there is a gentle breeze of 5 m/s, the mass balance show that there is more oil being mixed into the water column, both with oil only and SSDI applied. However, there is still 34 % of the total released oil left on the surface for the scenario with oil only, and 17 % when SSDI has been applied. This means that there will still be a chance for emulsification of surface oil with 5 m/s wind.

For the releases when there is blowing a constant wind of 10 m/s, the wind is strong enough to mix the surfaced oil down into the water column. For the scenario with oil only, the wind needs more time to accomplish this, than when SSDI has been applied.

A closer comparison of the mass balance 2, 5 and 10 days into the simulation period is shown in Figure 4.16.

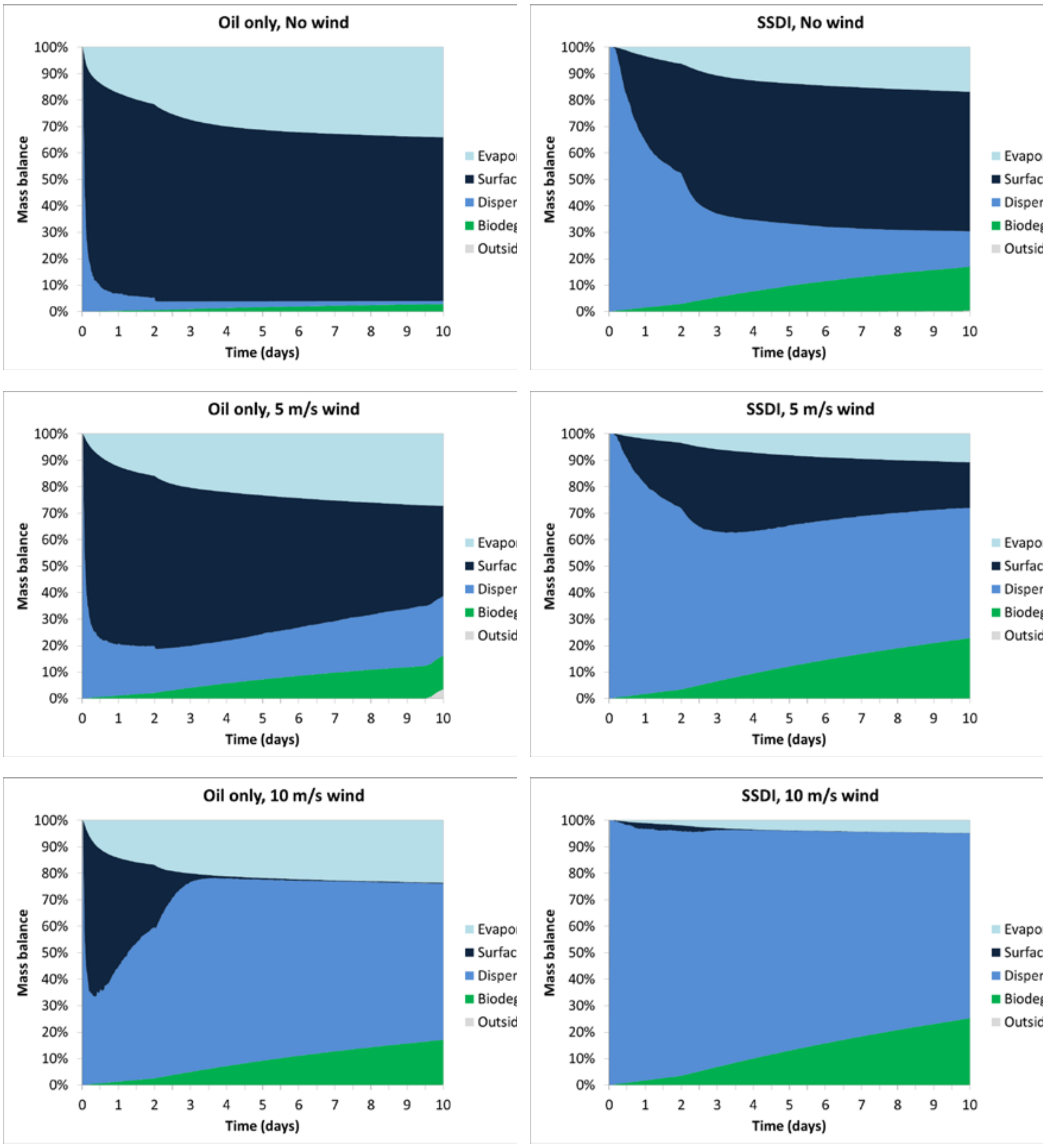

Figure 4.15 Mass balance for all scenarios with releases at 300 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

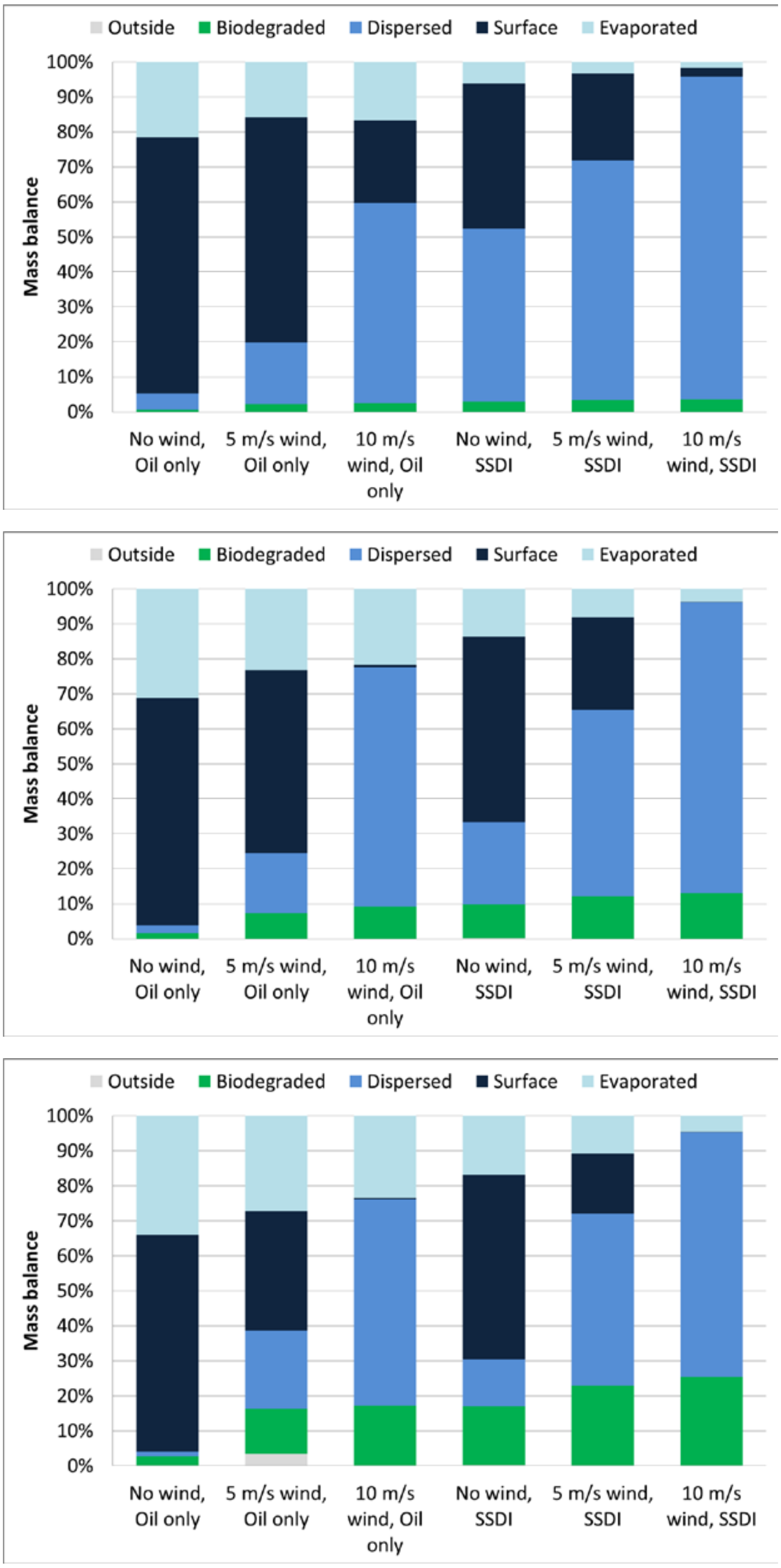

Figure 4.16 Mass balance at the end of the release (2 days into the simulation) (upper), 5 days (middle) and 10 days (lower) into the simulation period at 300 m depth with and without the presence of wind and SSDI.

4.4.2.5 Impacted surface area

Figure 4.17 show the maximum oil thickness at any surface grid cell at any time during the 10-day simulation period for all scenarios with release at 300 m. The figure show that there is thicker oil (especially in the range 1 – 5 mm) present at the surface for all three scenarios with oil only than for the SSDI scenarios. For the scenario with 10 m/s wind and SSDI, the thickest oil present during the 10-day simulation period is in the range 50 – 200 µm. It can also be seen that when there is a gentle breeze, the oil is transported over a larger area. This is because the energy transferred from the wind is not large enough to generate breaking waves that mixes the surface oil into the water column.

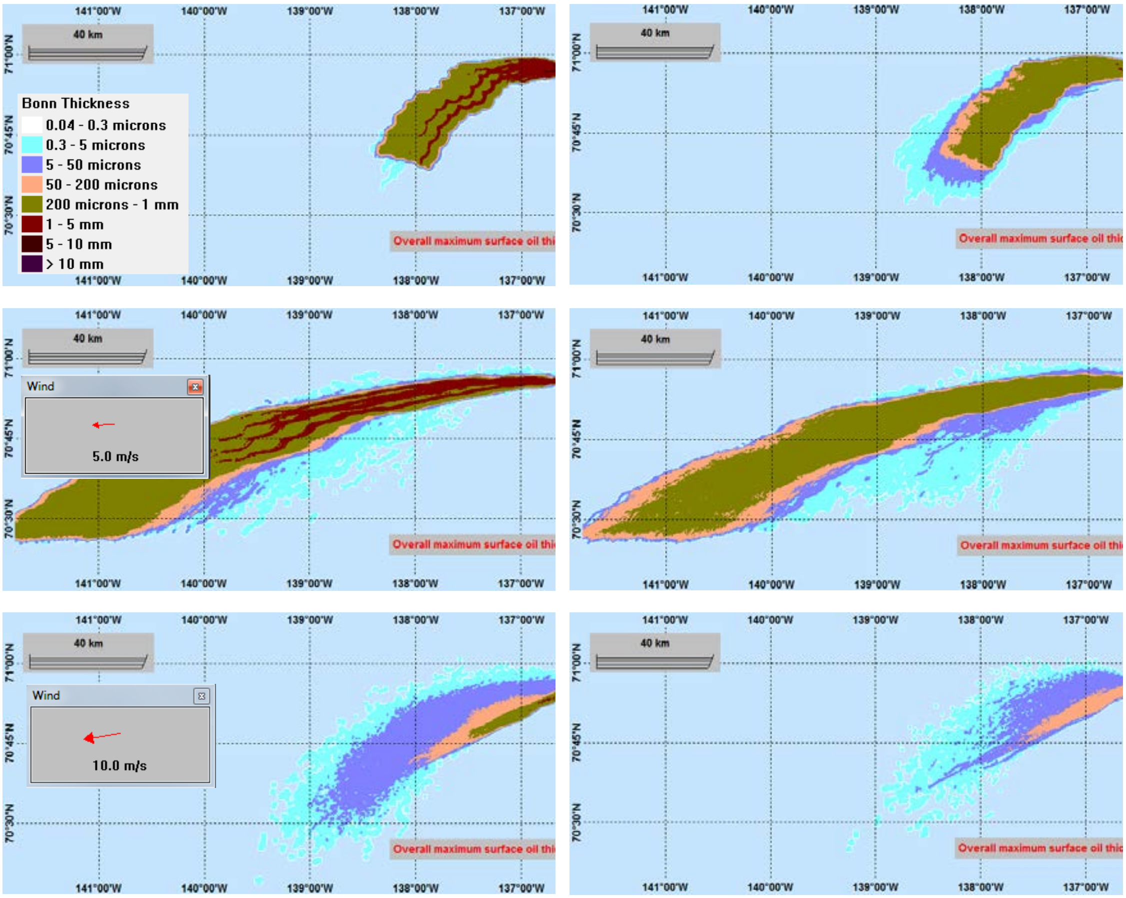

Figure 4.17 Overall maximum surface oil thickness (impacted area) for all releases at 300 m. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.3 Results for releases at 700 m depth

4.4.3.1 Surface oiling at the end of the release period (2 days)

Snapshots of surface oil at the end of all the scenarios with release at 700 m are given in Figure 4.18. It can be seen that the surface oil is thicker in a more confined area for the case with only oil when compared to the scenario with subsea injection of dispersant. The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface spread over a narrower band than when SSDI has been applied. However, the wind transports the oil over a larger area in the scenario without SSDI. When the wind is blowing at a constant speed of 10 m/s, the scenario without SSDI shows a narrower area with thicker oil than when SSDI has been applied. In addition, the wind is more effective in dispersing the surface oil, leading to little oil on the surface after treatment with SSDI.

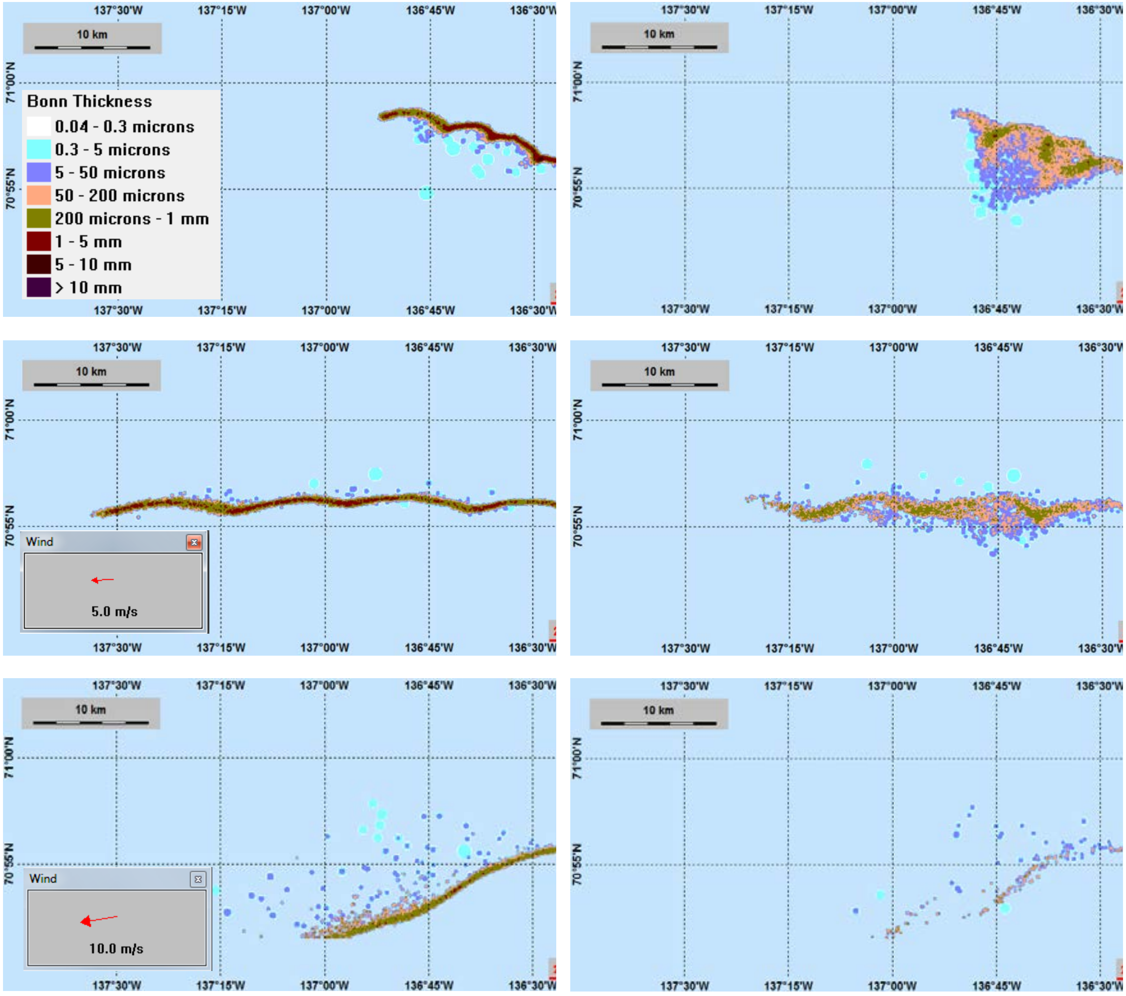

Figure 4.18 Surface oil at the end of the release for releases at 700 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.3.2 Surface oiling 5 days into the simulation period

Snapshots of surface oil 5 days into the simulation period (3 days after the end of the release) for all the scenarios with release at 700 m are given in Figure 4.19. For the scenarios without wind, there is little change in the surface oil signature than is was at the end of the release period (3 days previous). The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface spread over a narrower band than when SSDI has been applied. However, the wind transports the oil over a larger area in the scenario without SSDI. When the wind is blowing at a constant speed of 10 m/s, there is little oil left on the surface for both the scenario with oil only and when SSDI has been applied.

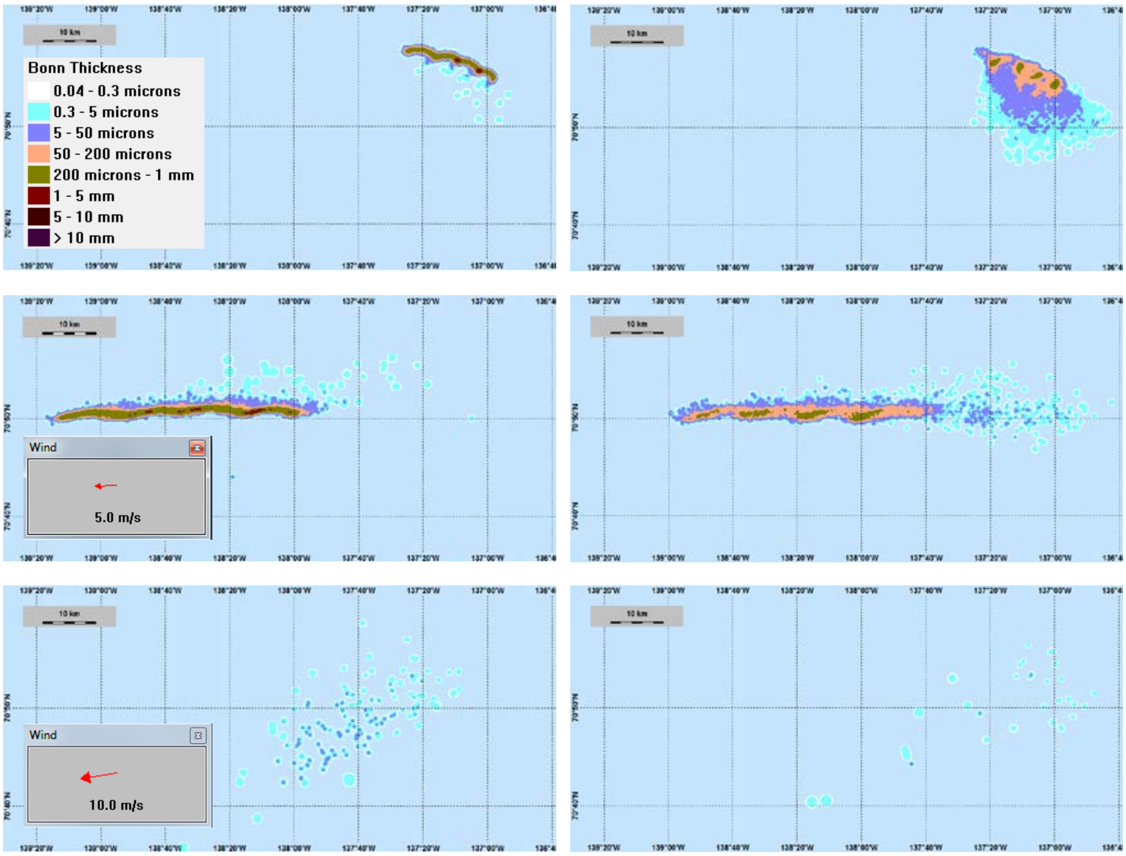

Figure 4.19 Surface oil 5 days into the simulation period (3 days after the end of the release) for releases at 700 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.3.3 Surface oiling 10 days into the simulation period

Snapshots of surface oil 10 days into the simulation period (8 days after the end of the release) for all the scenarios with release at 700 m are given in Figure 4.20. For the scenarios without wind, there is little change in the surface oil signature than is was at the end of the release period and at 5 days into the simulation. The same results as for the situation without wind can be seen when a gentle breeze of 5 m/s is applied. The scenario without SSDI shows thicker surface slick than when SSDI has been applied. When the wind is blowing at a constant speed of 10 m/s, there is hardly any oil left on the surface for both the scenario with oil only and when SSDI has been applied.

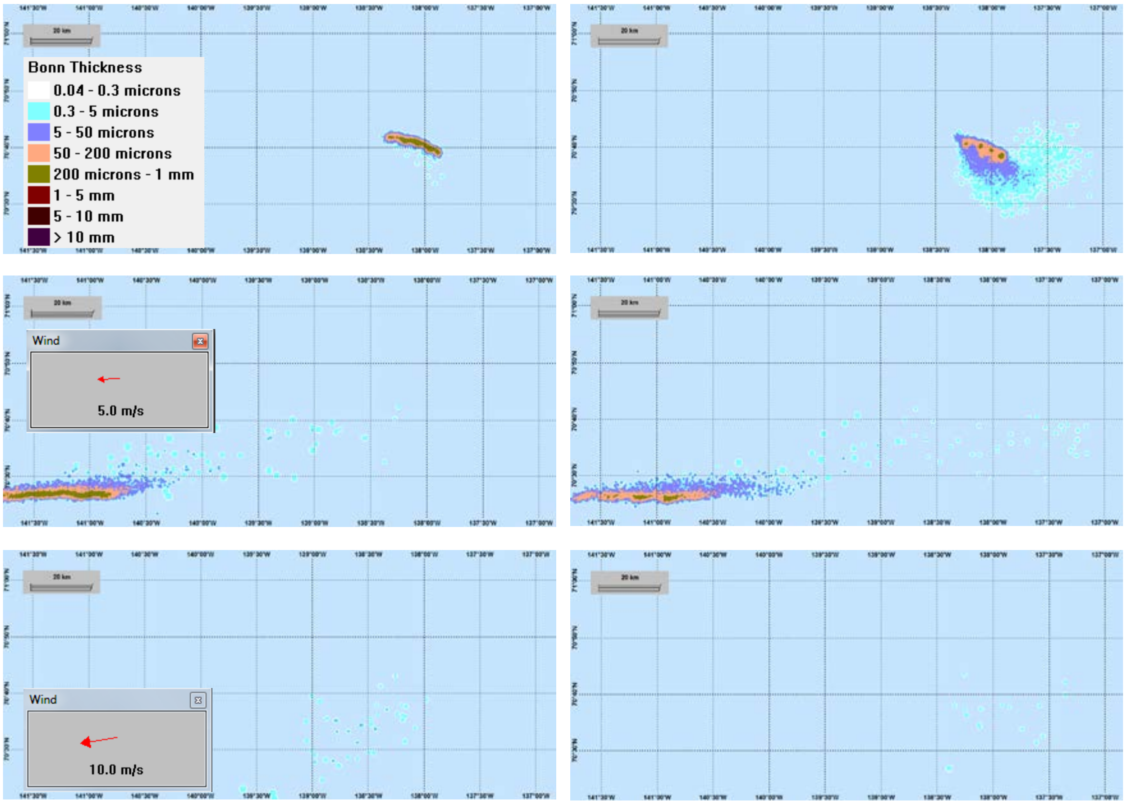

Figure 4.20 Surface oil at the end of the simulation period (10 days) for releases at 700 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

4.4.3.4 Mass balance for the release at 700 m depth

The mass balance for all the releases at 700 m depth are presented in Figure 4.21. The mass balance show that when there is no wind and oil only, nearly all the released oil is either on the surface or has evaporated. When SSDI has been applied, the oil remains longer in the water column before it surfaces, thus leading to enhanced biodegradation compared to the oil only scenario. There is less evaporation in this case since more of the total released oil is submerged.

When there is a gentle breeze of 5 m/s, the mass balance show that there is more oil being mixed into the water column, both with oil only and SSDI applied. However, there is still 36 % of the total released oil left on the surface for the scenario with oil only, and 22 % when SSDI has been applied. This means that there will still be a chance for emulsification of surface oil with 5 m/s wind.

For the releases when there is blowing a constant wind of 10 m/s, the wind is strong enough to mix the surfaced oil down into the water column. For the scenario with oil only, the wind needs more time to accomplish this, than when SSDI has been applied.

A closer comparison of the mass balance 2, 5 and 10 days into the simulation period is shown in Figure 4.22.

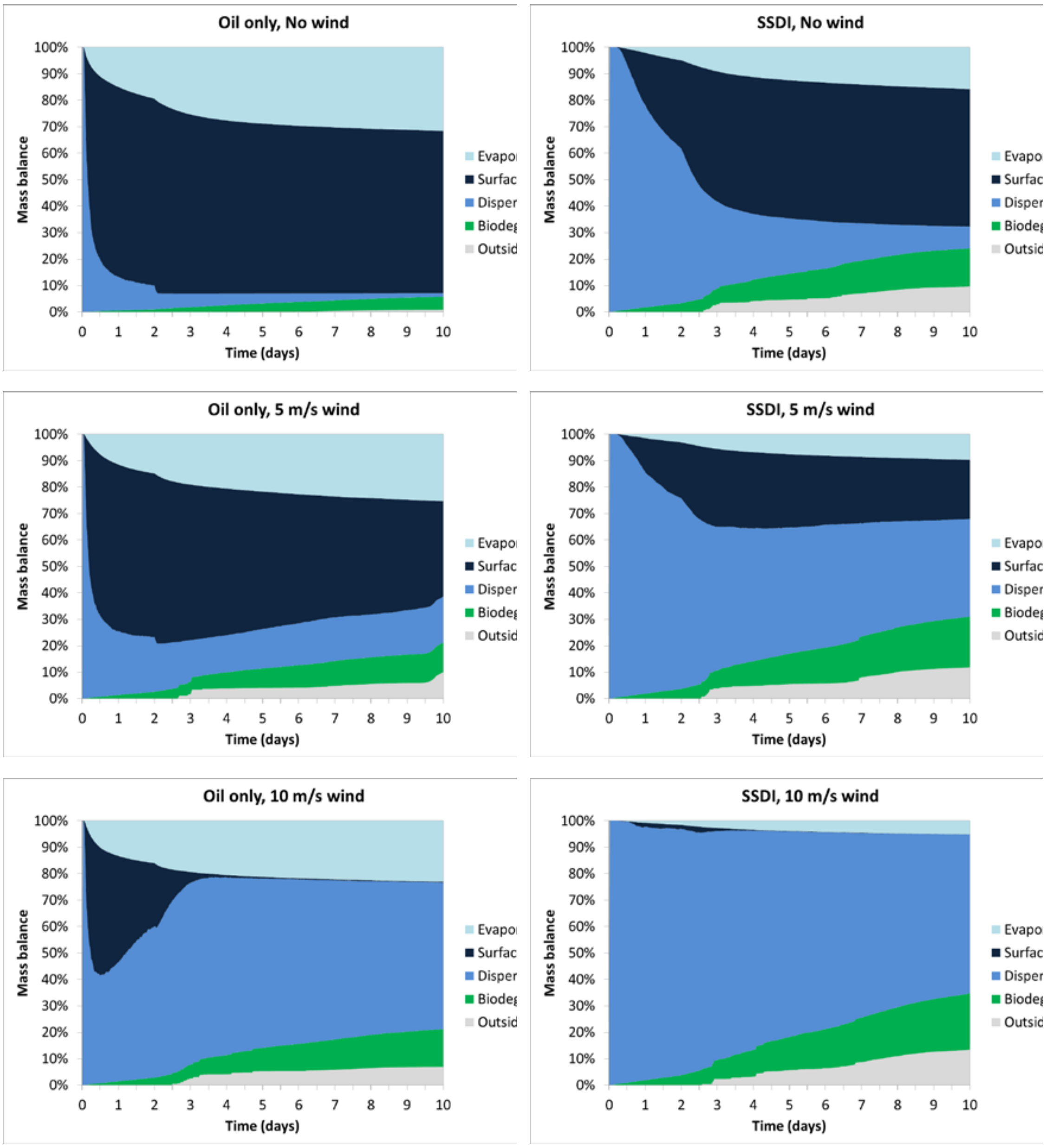

Figure 4.21 Mass balance for all scenarios with releases at 700 m depth. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

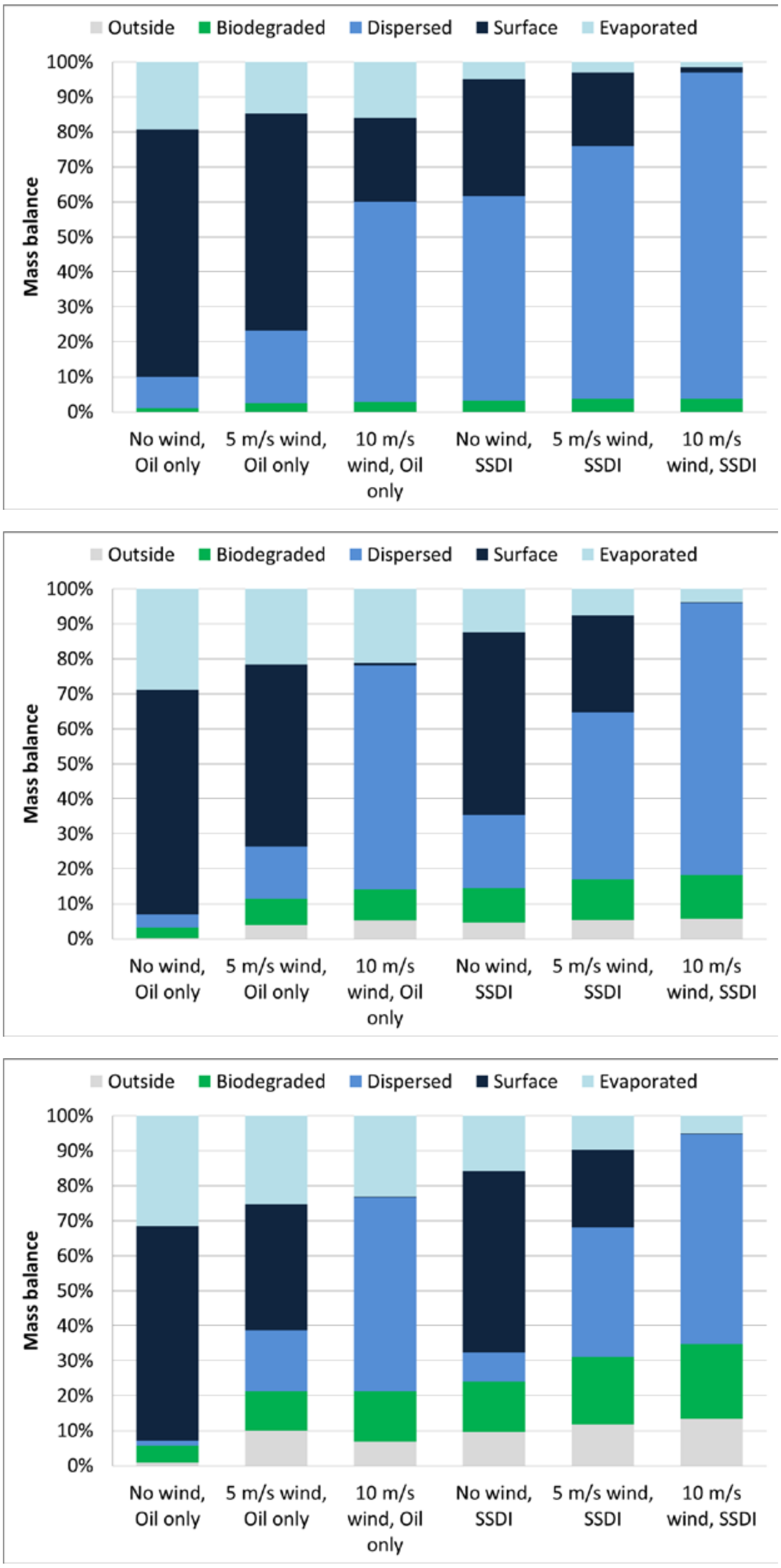

Figure 4.22 Mass balance at the end of the release (2 days into the simulation) (upper), 5 days (middle) and 10 days (lower) into the simulation period at 700 m depth with and without the presence of wind and SSDI.

4.4.3.5 Impacted surface area

Figure 4.23 show the maximum oil thickness at any surface grid cell at any time during the 10-day simulation period for all scenarios with release at 700 m. The figure shows that the oil is thicker over a longer time period for the releases with oil only compared with the scenarios when SSDI has been applied. It can also be seen that when there is a gentle breeze, the oil is transported over a larger area. This is because the energy transferred from the wind is not large enough to generate breaking waves that mixes the surface oil into the water column.

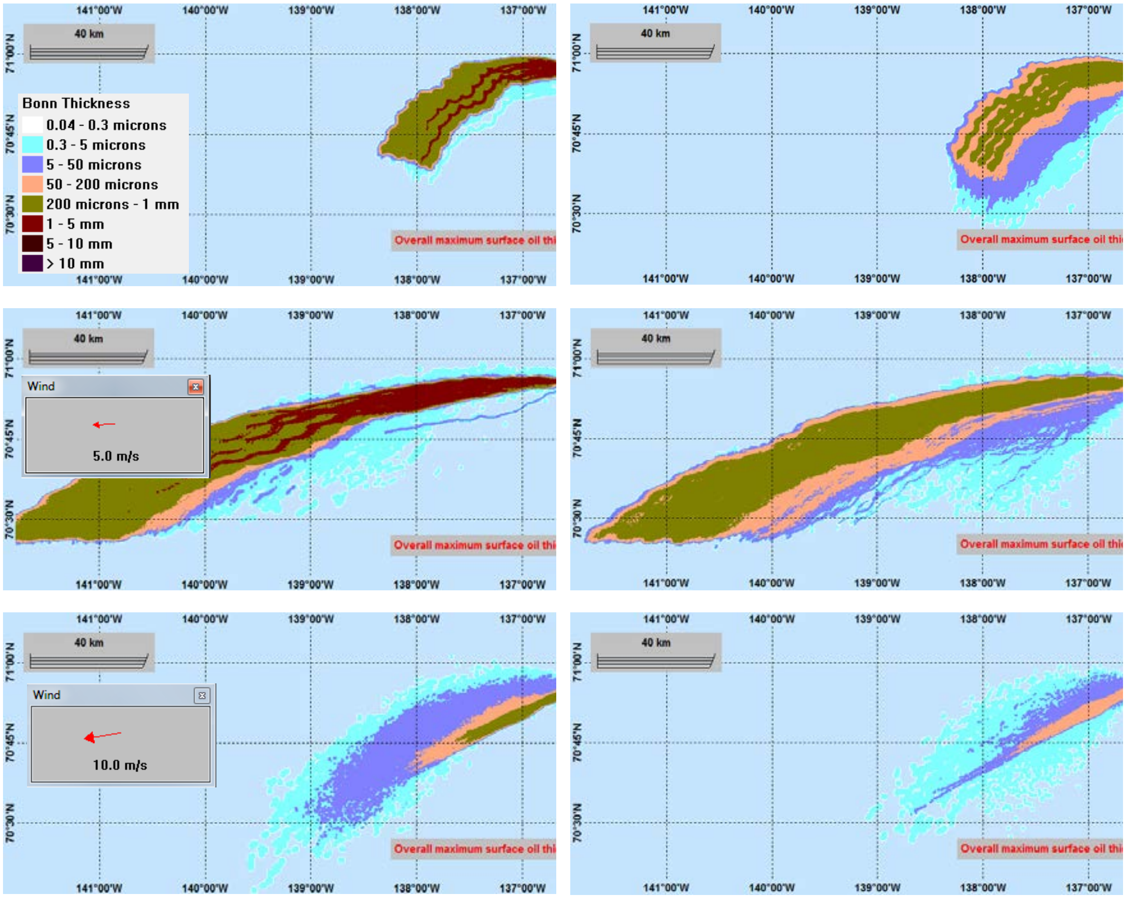

Figure 4.23 Overall maximum surface oil thickness for all releases at 700 m (impacted area. Left – oil only: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

5 DISCUSSION

The results presented in Chapter 4 are discussed here. In this chapter, droplet size distributions are discussed with regards to depth and subsea injection of dispersion in Section 5.1 and the effects of subsea injection of dispersants with regards to surfacing of oil are discussed in Section 5.2 whereas the effect of surface wind is discussed in Section 5.3.

5.1 Droplet size variation by increasing depth

For all scenarios, the maximum stable droplet size was determined by the formula proposed by (Hu & Kintner, 1955). This reflects the maximum stable size of a rising oil droplet outside of the turbulent regime causing the initial droplet break up. As the 95-percentile droplet size (d_{95}) in all of the scenarios were below this maximum stable droplet size (d_{max}), as shown in Figure 5.1, it can be concluded that break-up of droplets is only caused by turbulence at the outlet and not by droplets exceeding their maximum stable size. The d_{95} for the releases at 1 000 m depth approaches the maximum stable droplet size, but is still somewhat smaller (d_{95} = 3.725 mm and d_{max} = 3.894 mm).

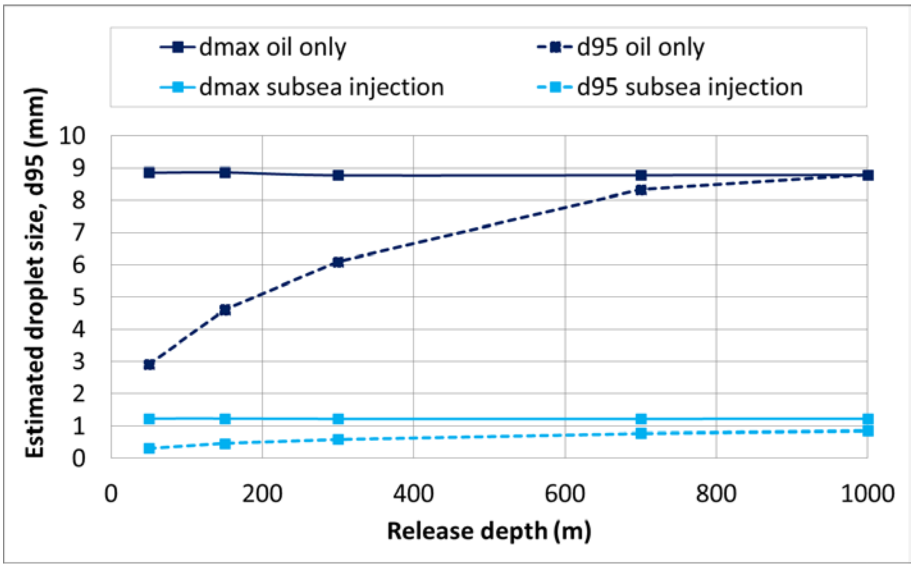

Figure 5.1 Estimated d_{95} and d_{max} at the different release depths for the scenarios with and without subsea injection of dispersants.

Figure 5.2 demonstrates that as the depth increases, the median droplet size d_{50} of the released oil also increases. This is because the droplet sizes are directly dependent on the turbulence in the release, being reduced as the gas is compressed due to increasing hydrostatic pressure (reduced velocity, U, as described in Section 2.3, Eq. 2). Oil in the OSCAR model is considered as incompressible, while the non-ideal gas is compressible and has a flow volume greatly dependent on the depth and pressure.

The oil droplet sizes for the treated oil (SSDI) does not show the same large variation with depth as the untreated oil since they are less turbulence dependant at such low interfacial tensions, see Eq. 1 and Johansen et al. (2013) for further details.

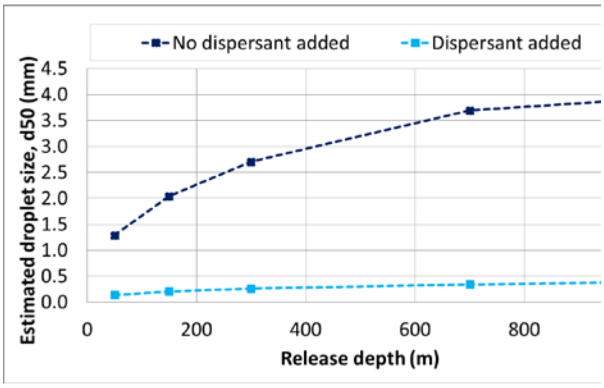

Figure 5.2 Estimated median droplet size for the different release depths with and without subsea injection of dispersants.

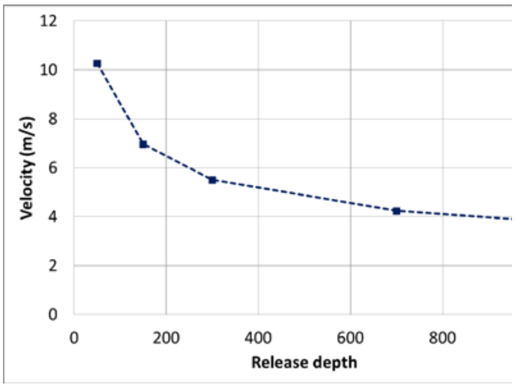

Figure 5.3 Buoyancy corrected release velocity for the different release depths.

Figure 5.3 illustrates the release velocity as a function of depth. Here it can be observed that the flow rate is dependent on the depth of release: A deeper release leads to more compression of the gas, leading to less buoyancy and smaller outlet flow volume. This reduces the outlet velocity and leads to less generated turbulence. It can be observed that the buoyancy of gas has the largest effect on the outlet flow at 50 m depth and little to no effect on the deeper releases (700 and 1000 m release depths).

5.2 Effects of subsea injection of dispersants

Oil treated with SSDI reduced the droplet sizes typically by a factor of ten (see Table 4.1). This reduction in droplet size strongly influences the buoyancy of the oil droplets and reduces the volume of oil coming to the surface especially close to the release site.

However, it can be seen from the mass balances (Figure 4.1 – Figure 4.3) that even with SSDI substantial volumes of oil will surface. For the scenarios with "No wind" only a minor reduction is observed for 50-150 m depths and still is 20-30% of the released volume surfacing for the deeper releases (300-1000 meters depth). None of the simulated releases completely removed surface oil with SSDI applied.

It is important to take the distribution of the oil on the surface into account, not only the surfaced volumes. The untreated oil volumes tended to surface over a smaller area and form oil slicks thick enough to emulsify. Emulsified oil usually results in more persistent slicks with a longer life time (weeks). The small oil droplets caused by SSDI surface over a larger area due to significantly reduced rising velocity and form thinner surface slicks. These are often too thin to emulsify and have a very limited life time (hours) due to breaking waves and naturally dispersion.

This is summarized in Figure 4.4 and Figure 4.5 that show the swept area (shown as maximum thickness) of oil for releases at all depths without wind for the scenarios with oil only and with SSDI, respectively. These figures demonstrate that releases with subsea injection of dispersants form a surface slick that has a smaller maximum thickness and cover larger areas than a release with no dispersant added. This behaviour is consistent for all depths.

The difference in surface oil slick persistency is clearly illustrated in Figure 4.1 – Figure 4.3 when comparing the "no wind" simulations with corresponding simulations with 5 and 10 meters surface wind. The thinner surface oil slicks formed by the smaller droplets are more susceptible to natural dispersion by surface waves. More details on this in the next section. Enhanced entrainment is observed on oil previously treated with dispersants even if the dispersants no longer are considered mixed with the oil. OSCAR does not include reduces IFT from any residual surfactant in the surfaced oil in the modelling of surface dispersion.

Figure 5.4 further illustrates this effect by displaying a snapshot of the surface oil 2 days after the start of release (at the end of the release period). This scenario is for a release at 700 m depth without wind. It can clearly be seen that the oil is spread to a larger area and generally thinner when applying subsea injection of dispersants. This is explained by the reduced rise velocity of the smaller oil droplets in the SSDI scenario. These smaller droplets are affected by a time-varying current profile for a longer time than the larger droplets in the oil only scenario, and are therefore more spread out before surfacing.

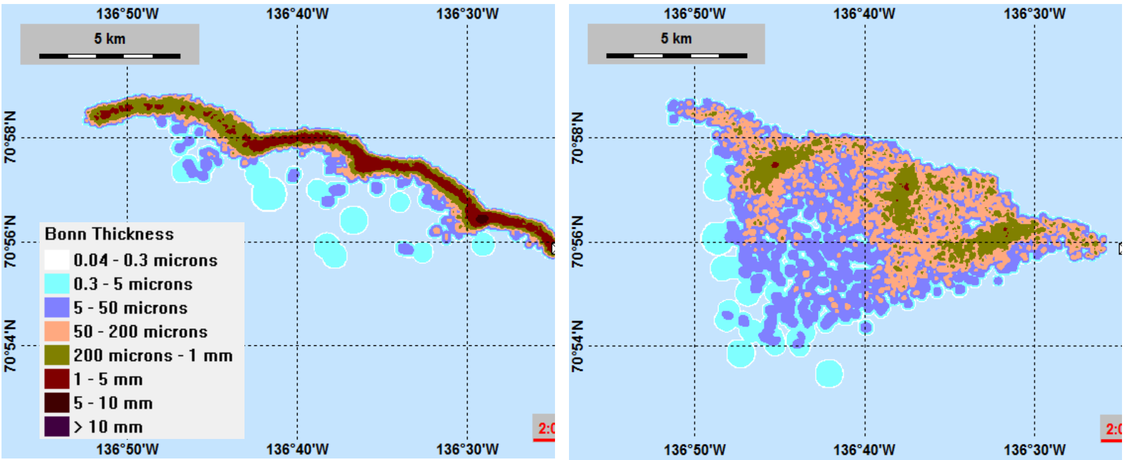

Figure 5.4 Surface oil at the end of the release (2 days into the simulation period) for the scenarios with release depth 700 m and without wind. Left: Oil only. Right: SSDI applied.

5.3 Effect of surface wind

In this study, all scenarios have been modelled both without wind, and with 5 and 10 m/s wind. When the model runs with wind, the surfacing oil slicks are impacted by the wind and wind-generated waves as soon as they reach the surface. This implies that the thicker oil slicks have a higher tendency to emulsify, forming viscous, stable and persistent emulsions (see example in the left snapshot in Figure 5.4 above). The thinner oil slicks resulting from the SSDI scenarios (see example in the right snapshot in Figure 5.4 above), tended to be too thin to emulsify, and tended to naturally re-disperse after surfacing resulting in a low persistency and short drifting time.

This difference in surface oil persistency is also illustrated in Figure 4.6, Figure 4.12 and Figure 4.18 where the surface oil at the end of the release period for releases at 150, 300 and 700 m depth are shown. The results from 700 m are repeated in Figure 5.5 to easier compare the effect of the thin surface slicks caused by SSDI and natural dispersion at the surface (or entrainment). The upper pictures show the scenarios without wind, the middle with 5 m/s wind and the lower with 10 m/s wind. The pictures to the left show the situation without SSDI whereas the right ones show the situation with SSDI. The figure show that when waves are applied to these scenarios, the thinner oil slicks from the SSDI scenarios have a shorter surface signature. This is an effect of the wave induced natural dispersions or entrainment of the oil.

Furthermore, it can be seen that when there is a gentle breeze of 5 m/s, the oil that has been treated with SSDI will spread over a larger area in a thinner layer than untreated oil. However, the wind is not strong enough to create waves with enough energy to avoid creating a surface slick even when SSDI has been applied. For the simulations with 10 m/s wind, the energy of the wind is high enough to create waves that are more effective in dispersing the surface oil, leading to little oil on the surface after treatment with subsea dispersants.

The surface oil at 5 days into the simulation for 150, 300 and 700 (Figure 4.7, Figure 4.13 and Figure 4.19) and at the end of the simulation period of 10 days (Figure 4.8, Figure 4.14 and Figure 4.20) show the same trends as at the end of the release period (2 days).

It is important to note that these scenarios represent cases with a constant wind of either 0, 5 or 10 m/s wind for the entire duration of the simulation. In a real case, it is expected that the wind will vary during and after the release period, depending on the geographical location and time of year.

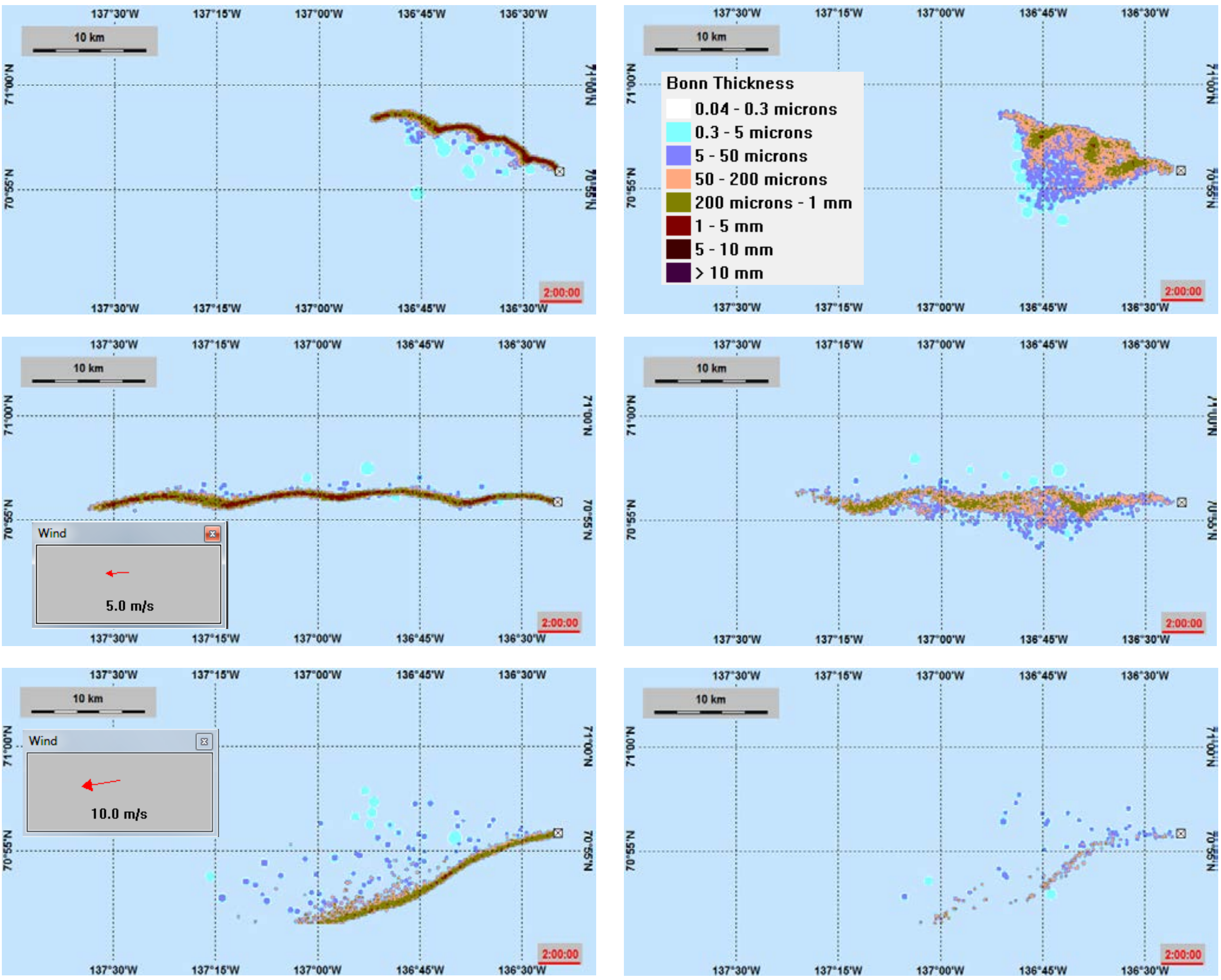

Figure 5.5 Surface oil at the end of the release for releases at 700 m depth. Left – no SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower). Right – with SSDI: No wind (upper), 5 m/s wind (middle) and 10 m/s wind (lower).

5.4 Possible relationship between oil film thickness and tar ball formation

As seen from e.g. Figure 4.18 and Figure 4.21, the surface film thickness is important for the persistence and lifetime for an oil slick. Slicks with sufficient thickness to emulsify increase in viscosity, which cause less natural dispersion. On the other hand, oil slicks too thin to emulsify will maintain the low viscosity and preferable naturally disperse.

This implies that oil film thickness also should influence the formation of tar balls. Tar balls are regarded as the ultimate endpoint of the weathering of a surface oil slick. However, the descriptions in the literature are very conflicting both concerning a definition of a tar ball and possible theory of their formation. Both Godman (2002), Owens et al. (2001) and Owens later work for API (e.g. API, 2014) discuss several possible definitions and theories for tar ball formation. Owens (2002) describe tar balls as "black spherical objects, which when crushed emit a strong petroleum odour", but alternatively as "lumps of oil weathered to a semi-solid or solid consistency, feel sticky and difficult to remove from contaminated surfaces". Several theories for tar ball formation are also discussed by Owens with "generated from the water in oil emulsions (chocolate mousse), one of the final stages of weathering" as one of the more likely ones.

OSCAR does not include the process of tar ball formation as an end product for an oil spill. Today natural dispersion and physical disintegration are the main processes breaking down the surface oil slicks. However, based on SINTEFs experience from multiple experimental field releases and real cases (Faksness et al., 2016), it is very likely that tar ball formation is connected to the thick, viscous and very stable patches of emulsion observed after long time weathering at sea (the "emulsion theory"). Interaction with other materials available at the sea surface or in the upper water column (e.g. debris or sediment particles) could also promote tar ball formation.

SINTEF assisted Statoil with a 4000 m^3 spill of crude in 2007. The oil was released during a transfer operation offshore in 15-20 m/s wind and oil sampling and surveillance at the spill site two days later only revealed smaller patches (1-10 cm) of oil surrounded by thin sheen (Moldestad et al., 2008). The initial strong wind and corresponding heavy waves dispersed most of the oil and formed very thin oil slicks over a wide area, possible due to surfacing large droplets. These thin sheens promoted further natural dispersion and emulsification was only observed sporadically. No thick oil slicks were observed after 2-3 days and the potential for tar ball formation, even from this large surface oil slick, was believed to be very small.

With the "emulsions theory" as the most likely theory for tar ball formation combined with SINTEFs experience from experimental field releases and real cases, we would assume that thinner oil slicks would reduce tar ball formation and thicker (emulsifying) oil slicks would promote tar ball formation. This would lead to the assumption that SSDI, which usually produce thinner surface oil slicks, also has the potential to reduce tar ball formation.

6 CONCLUSION

Using the OSCAR oil spill model with; (1) improved prediction of droplet size distributions (modified Weber scaling) and (2) improved prediction of oil temperature and resulting viscosity during droplet formation, 30 different subsea releases of oil and gas mixtures with varying release depths (50, 150 300, 700 and 1 000 m), with three different wind speeds (0, 5 and 10 m/s) and with/without subsea injection of dispersants (SSDI) have been simulated.

The surface impact of the release oil volumes is shown to be strongly dependent on the depth of the release due to the following factors:

- Compression of the gas as a function of depth reduce release velocity and turbulence in the release,
- Compression of the gas as a function of depth reduce the buoyancy of the plume,
- Trapping of the plume is dependent on gas buoyancy and was only observed for the three deepest releases.
- SSDI causes a tenfold reduction in oil droplet sizes that strongly influenced the oil volume in the trapped plume, the oil droplet rising time and the position/thickness of the resulting surface oil slick.

The simulations show that even with SSDI and trapped plumes substantial oil volumes might reach the surface. For the scenarios with "No wind" only a minor reduction in surfaced oil is observed for 50-150 m scenarios and still is 20-30% of the released oil volume surfacing for the deeper releases. None of the simulations with SSDI completely prevented oil from surfacing.

However, it has been demonstrated that in the case of oil reaching the surface, there is a notable difference in the surface slick formed for a release treated with SSDI compared to a non-treated release. SSDI results in both less oil and thinner oil slicks over a larger area compared to oil only scenarios (no SSDI). These thinner, non-emulsifying surface oil slicks are expected to have very short life time due to enhanced natural dispersion.

These OSCAR simulations indicate that SSDI can be a very effective response method, especially when taking into account the significantly reduced lifetime and surface signature of the resulting thin surface oil slicks. With the "emulsions theory" as the most likely theory for tar ball formation, it is assumed that thinner oil slicks would reduce tar ball formation and thicker (emulsifying) oil slicks would promote tar ball formation. This would lead to the assumption that SSDI, which usually produce thinner surface oil slicks, also has the potential to reduce tar ball formation.

7 REFERENCES

API, 2014. Subsurface Oil Detection and Delineation in Shoreline Sediments: Phase 2 – Final Report. API Technical Report 1149-1, Washington DC, 34 pp.

ASL. 2013. Data set submitted to SINTEF as a zip-file in e-mail from Keath Borg, ASL Environmental Science Inc, June 26, 2013.

Brandvik, P.J., Ø. Johansen, F. Leirvik, U. Farooq, and P.S. Daling. 2013. Droplet breakup in sub-surface oil releases – Part 1: Experimental study of droplet breakup and effectiveness of dispersant injection. Marine Pollution Bulletin 73: 319-326.

Brandvik, P.J., Ø. Johansen, E.J. Davies, F. Leirvik; D.F. Krause, P.S. Daling, D. Dunnebier, S. Masutani, I. Nagamine, C. Storey, C. Brady, R. Belore, T. Nedwed, C. Cooper, A. Ahnell, O. Pelz, and K. Anderson. 2016a. Subsea Dispersant Injection - Summary of Operationally Relevant Findings from a Multi-Year Industry Initiative. SPE-179401. In proceedings from SPE HMS Conference Stavanger, Norway, April 2016.

Brandvik P.J., Ø. Johansen F. Leirvik , D. Krause and P.S. Daling. 2016b. Subsea injection of dispersants, effectiveness of different dispersant injection techniques – An experimental approach (In preparation).

Brandvik, P.J., E. Davies, C. Brady, C. Storey and F. Leirvik. 2016c. Subsurface oil releases – Verification of dispersant effectiveness under high pressure - A scaled experimental approach using the SINTEF Tower Basin and SwRIs 90" high pressure chamber. SINTEF report no: A27469. Trondheim Norway 2016. ISBN: 978-821405857-4.

Brandvik, P.J., E. Davies, C. Storey and F. Leirvik. 2017. Subsurface oil releases – Verification of dispersant effectiveness under high pressure using combined releases oil live oil and natural gas. SINTEF report no: OC2017 A-090. Trondheim Norway 2017. ISBN: 978-82-7174-282-9.

Faksness, L.G., P.J. Brandvik, P.S. Daling, I. Singsaas, and S.E. Sørstrøm. 2016. The value of offshore field experiments in oil spill technology development for Norwegian waters. Marine Pollution Bulletin 11:402-410.

Goodman, R. 2003: Tar Balls: The End State – Short Communication. Spill Science & Technology Bulletin, 8 (2): 117-121.

Hu, S. and R.C. Kintner, 1955. The fall of single drops through water, AIChE J, Vol. 1, pp. 42.

Johansen, Ø., 2000. DeepBlow – A Lagrangian Plume Model for Deep Water Blowouts. Spill Science & Technology Bulletin 6 (2): 103 – 111.

Johansen, Ø., 2003. Development and verification of deep-water blowout models. Marine Pollution Bulletin 47: 360-368.

Johansen, Ø., H. Rye, C. Cooper. 2003. Deep spill – field study of a simulated oil and gas blow-out in deep water. Spill Sci. Technol. Bull. 8: 333-343.

Johansen, Ø., P.J. Brandvik, and U. Farooq. 2013. Droplet breakup in subsea oil releases – Part 2: Predictions of droplet size distributions with and without injection of chemical dispersants. Marine Pollution Bulletin 73: 327-335.

Johansen, Ø., M. Reed, and N.R. Bodsberg. 2015. Natural dispersion revisited. Marine Pollution Bulleting 93: 20-26.

Moldestad, M.Ø., M. Reed, and A. Follestad. 2008. Studies in the aftermath of the oil spill on the Statfjord field December 12, 2007. Final report (In Norwegian). SINTEF report A7130 (Unrestricted), June 2008, Trondheim, Norway.

National Virtual Ocean Data System (NVODS), http://ferret.pmel.noaa.gov/NVODS/UI.vm, accessed 14 August 2013

Owens, E.H., G.S. Mauseth, C.A. Martin, A. Lamarche. and J. Brown. 2002. Tar ball frequency data and analytical results from a long-term beach monitoring program, Marine Pollution Bulletin 44: 770–780.

Reed, M., P.J. Brandvik, P. Daling, A. Lewis, D. Mackay, and R. Prentki. 1999. Oil Spill Modeling towards the Close of the 20th Century: Overview of the State of the Art. Spill Science & Technology Bulletin 5(1) 3-16.

Reed, M., I. Singsaas, P.S. Daling, L.G. Faksness, O.G. Brakstad, B Hetland, J. Hokstad. 2001. Modeling the Water-Accommodated Fraction in OSCAR2000. Proceedings 2001 International Oil Spill Conference, pp. 1083 – 1091.

Skancke, J., Ø. Johansen, P.J. Brandvik, O.G. Brakstad. 2016. Implementing New Features in OSCAR; Oil Temperature and Viscosity during Droplet Formation and Area Specific Biodegradation. SINTEF report A27807. Unrestricted. Trondheim, Norway.

APPENDIX A MASS BALANCE FOR SIMULATIONS OF RELEASES AT 50 M AND 1000 M

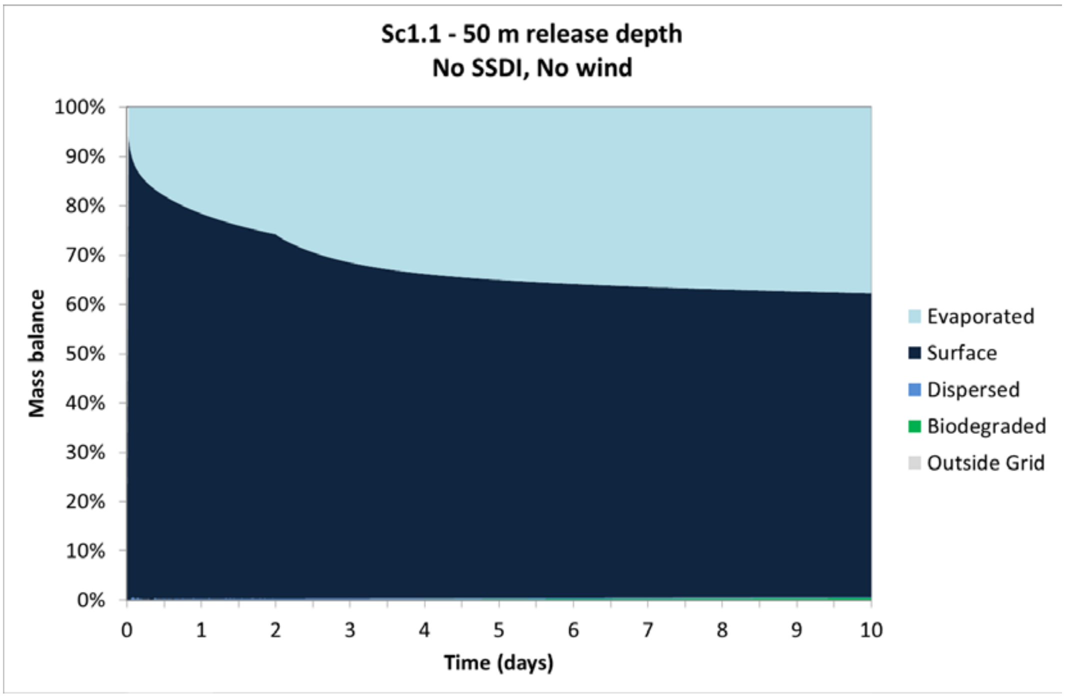

Figure A 1 Mass balance scenario 1.1

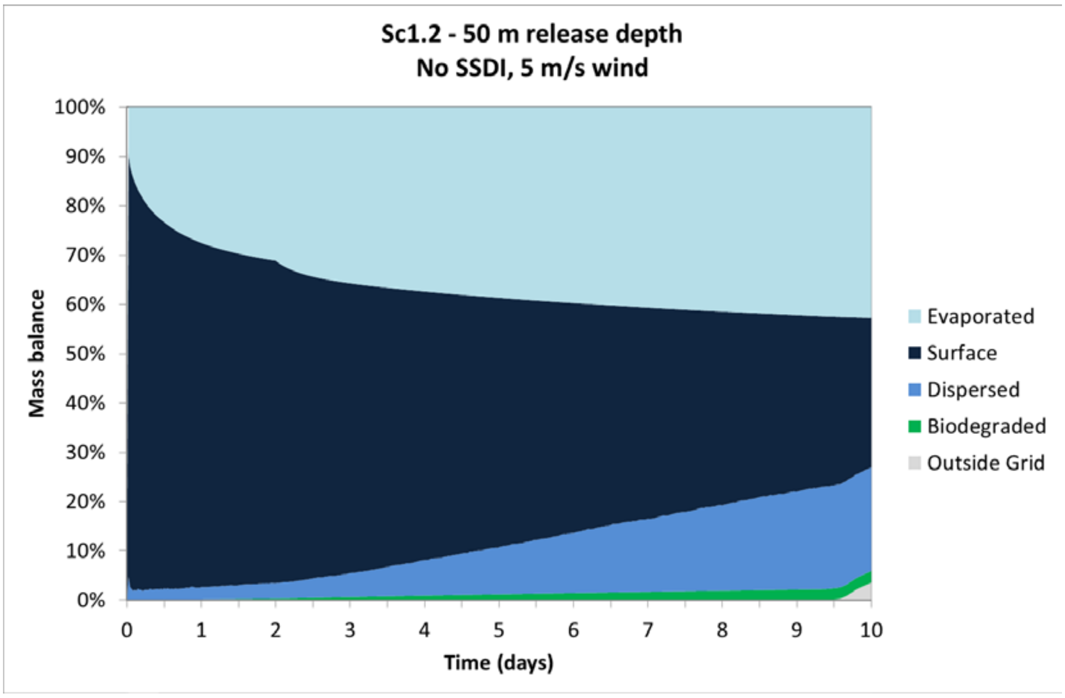

Figure A 2 Mass balance scenario 1.2

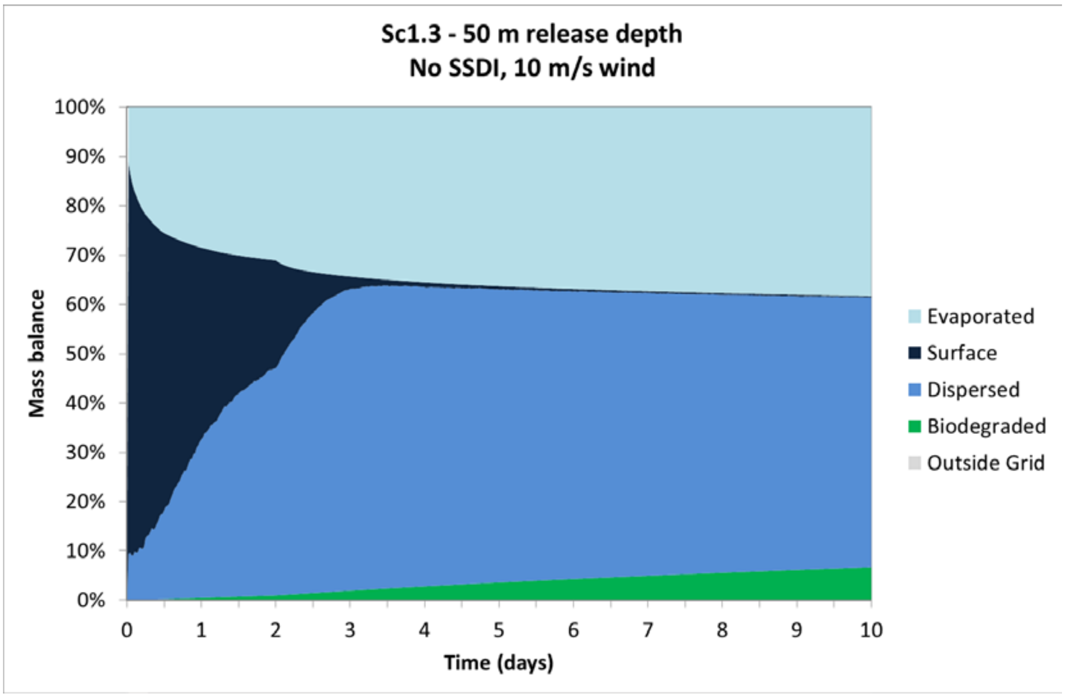

Figure A 3 Mass balance scenario 1.3

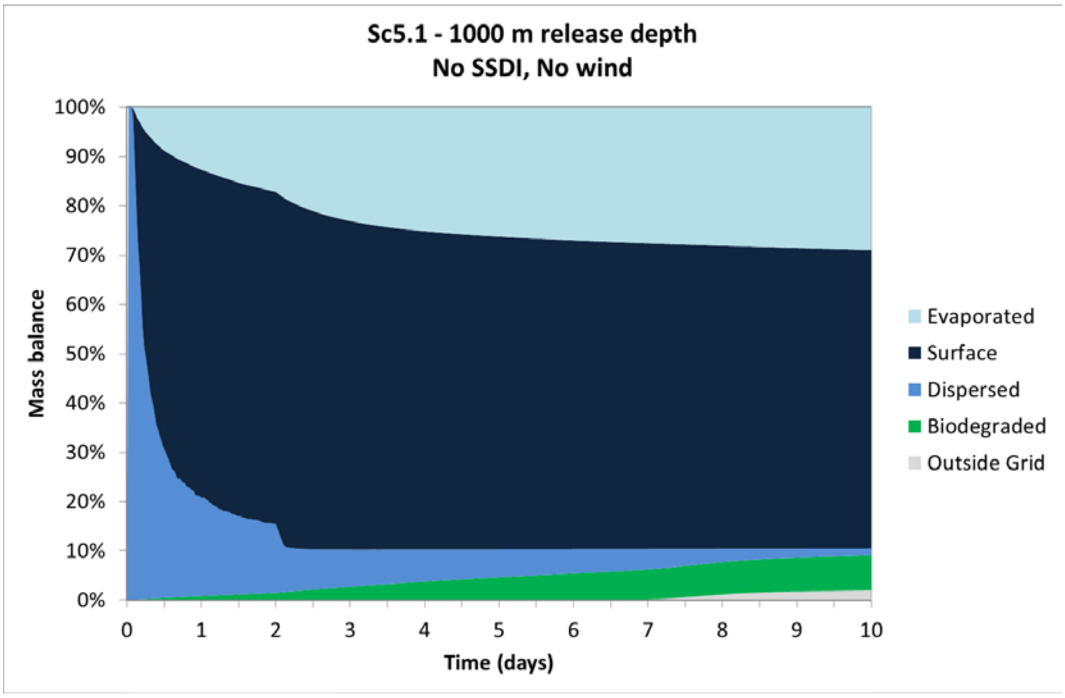

Figure A 4 Mass balance scenario 5.1

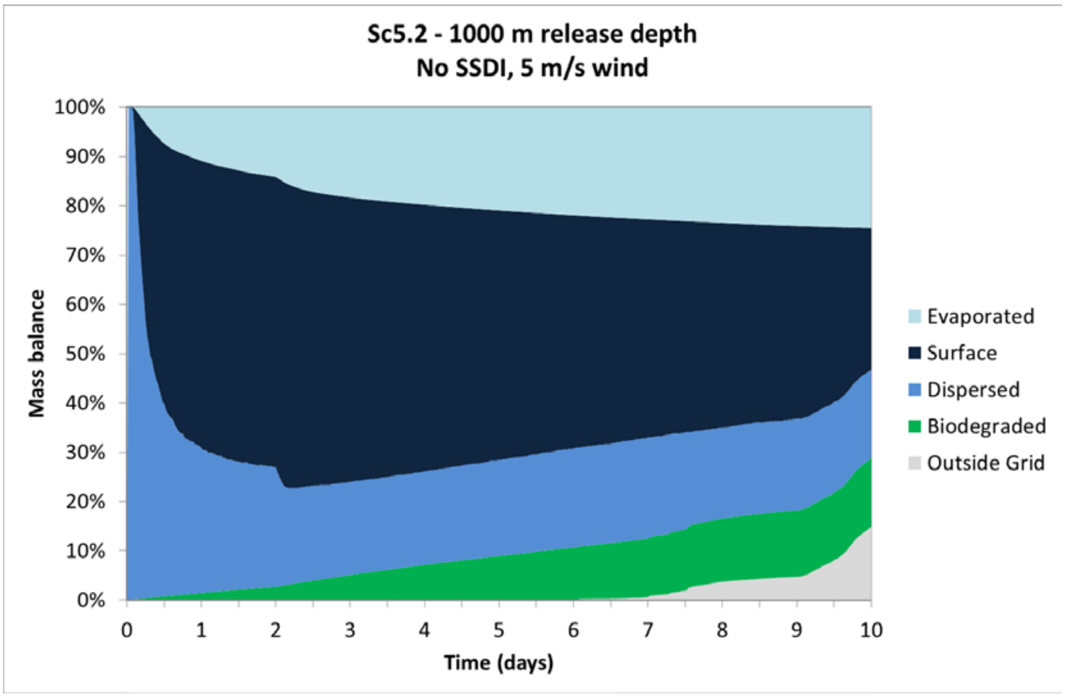

Figure A 5 Mass balance scenario 5.2

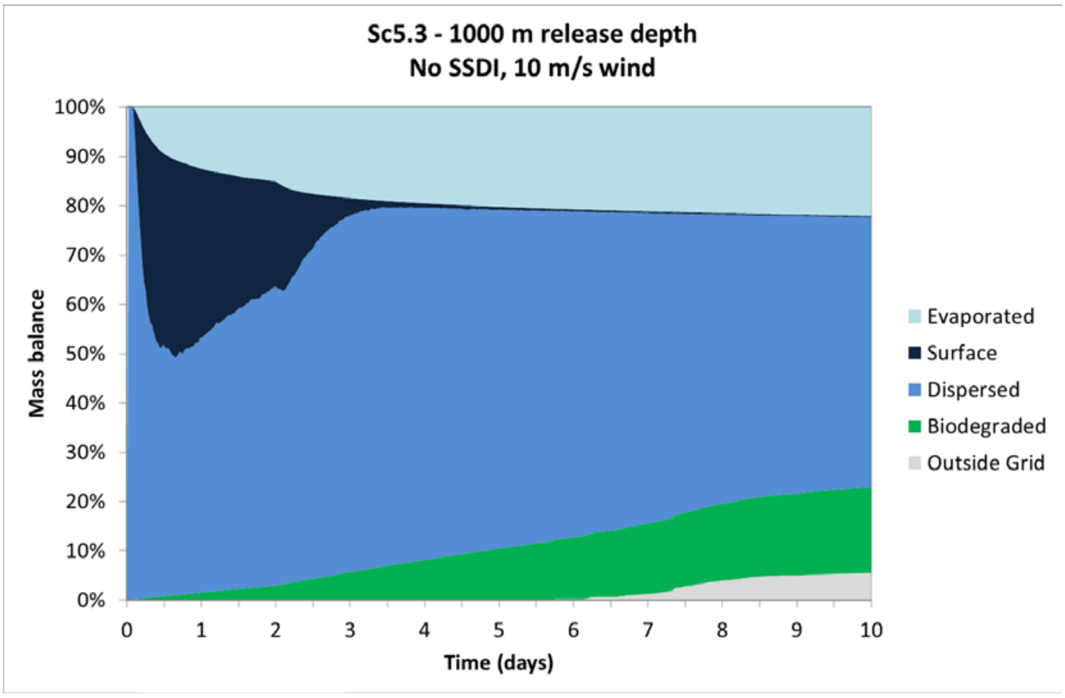

Figure A 6 Mass balance scenario 5.3

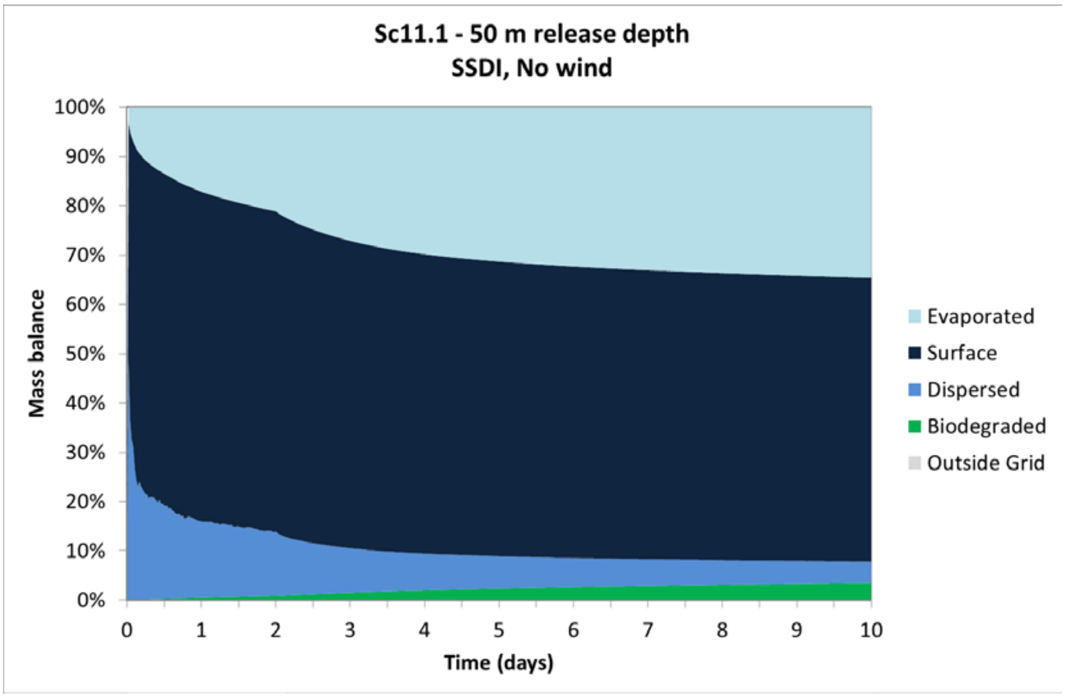

Figure A 7 Mass balance scenario 11.1

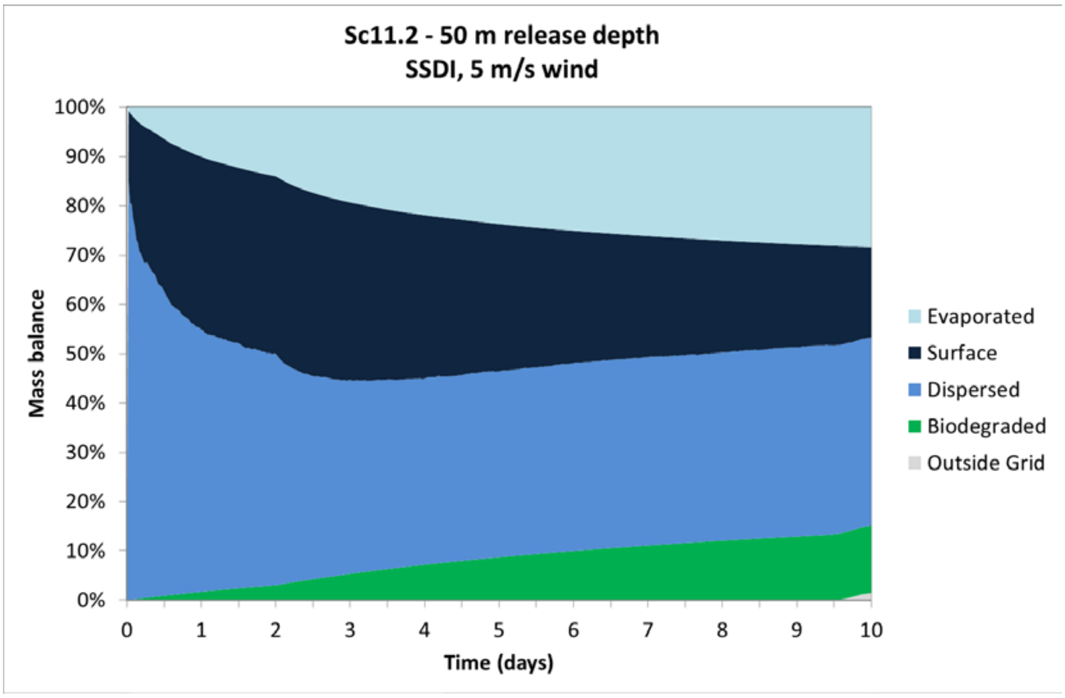

Figure A 8 Mass balance scenario 11.2

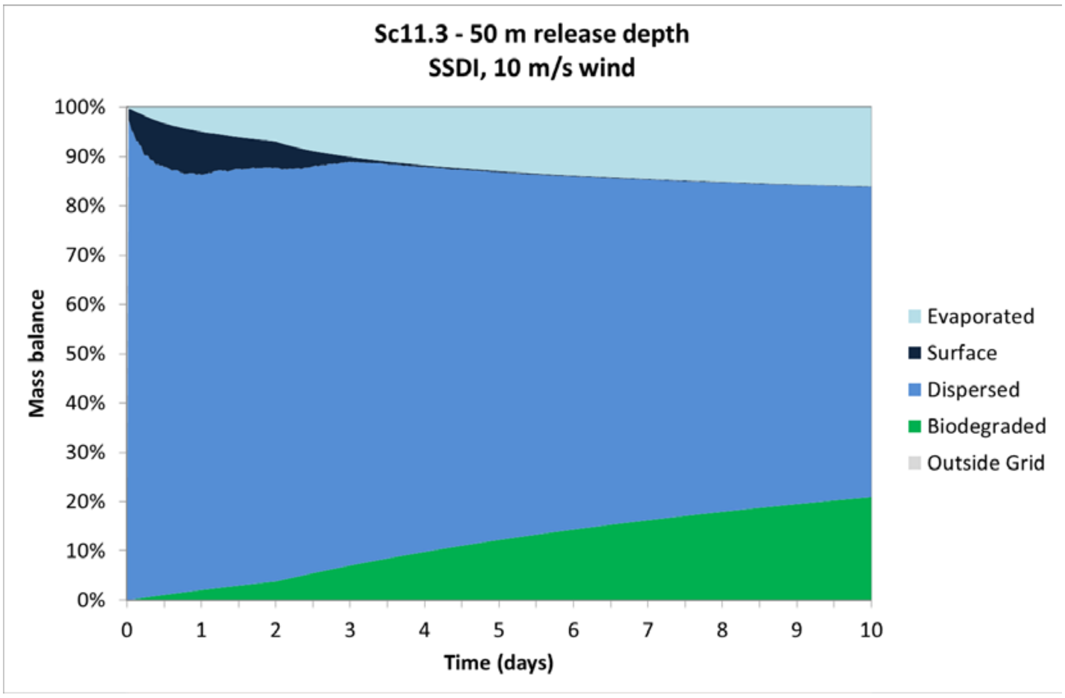

Figure A 9 Mass balance scenario 11.3

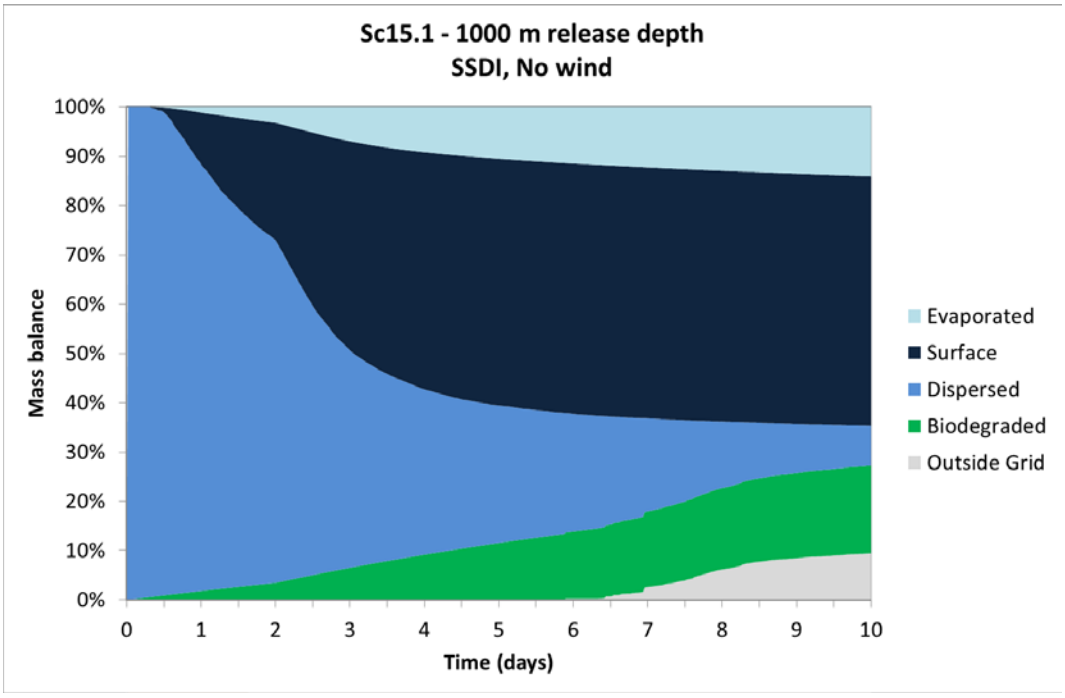

Figure A 10 Mass balance scenario 15.1

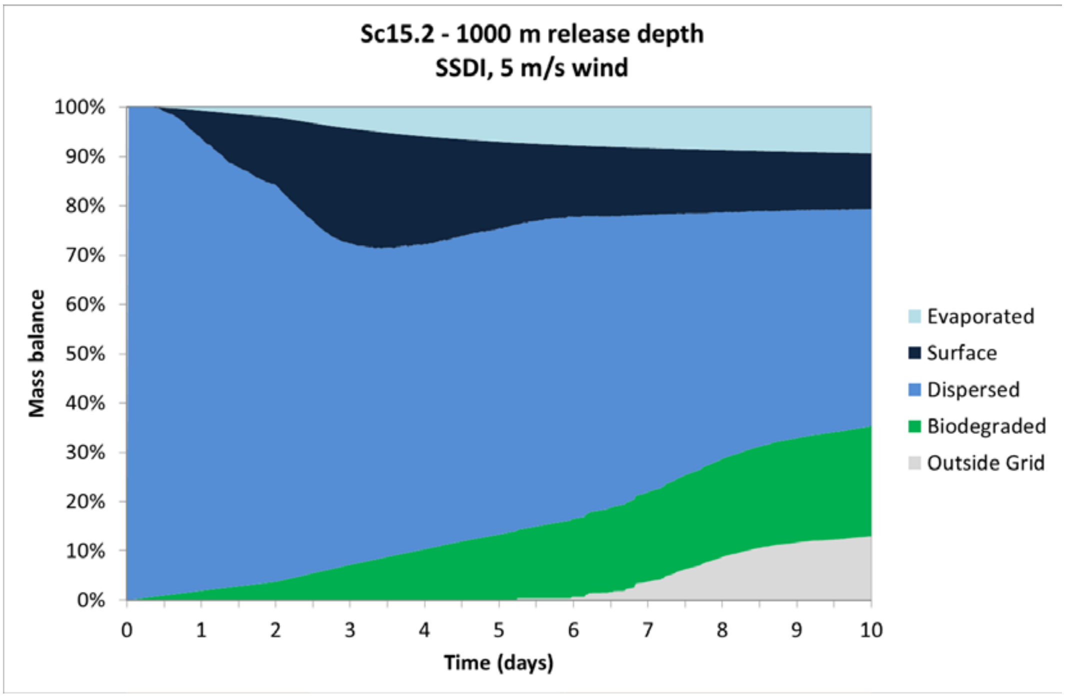

Figure A 11 Mass balance scenario 15.2

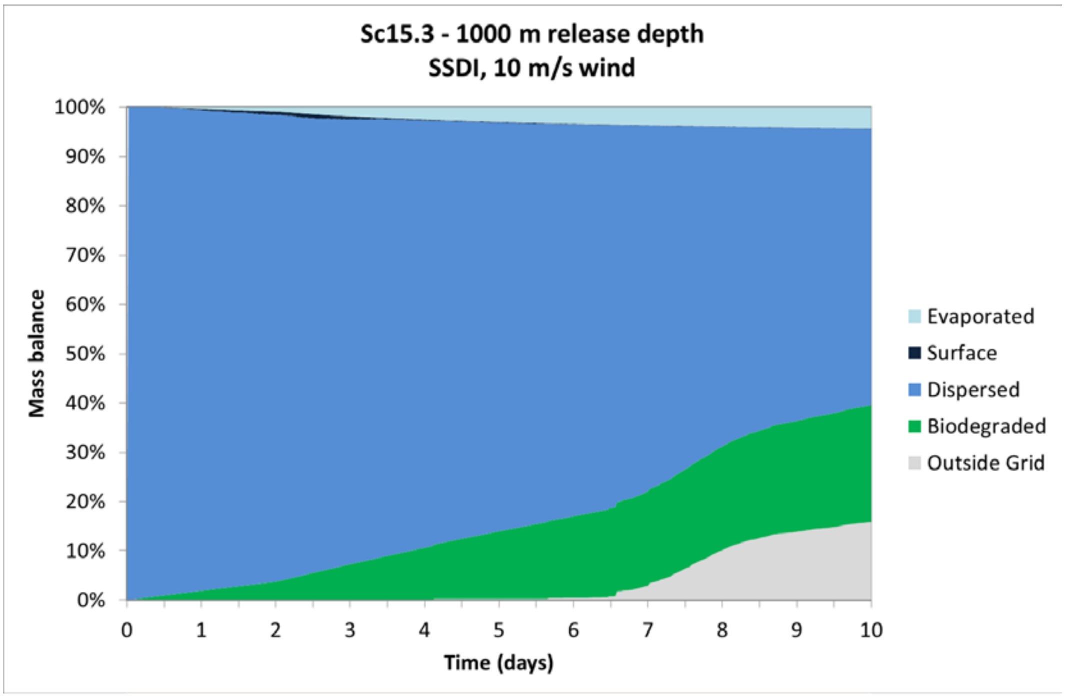

Figure A 12 Mass balance scenario 15.3