Predicting the Consequence of Natural and Chemical Dispersion for Oil Slick Size over Time

Marieke Zeinstra-Helfrich
Wageningen University

Wierd Koops
NHL University of Applied Sciences

Albertinka Murk
Wageningen University

Follow this and additional works at: https://scholarcommons.usf.edu/cimage_pubs

Part of the Marine Biology Commons

Scholar Commons Citation
Zeinstra-Helfrich, Marieke; Koops, Wierd; and Murk, Albertinka, "Predicting the Consequence of Natural and Chemical Dispersion for Oil Slick Size over Time" (2017). C-IMAGE Publications. 77.
https://scholarcommons.usf.edu/cimage_pubs/77

This Article is brought to you for free and open access by the C-IMAGE Collection at Scholar Commons. It has been accepted for inclusion in C-IMAGE Publications by an authorized administrator of Scholar Commons. For more information, please contact scholarcommons@usf.edu.
Predicting the consequence of natural and chemical dispersion for oil slick size over time

Marieke Zeinstra-Helfrich, Wierd Koops, and Albertinka J. Murk

1Maritime, Marine, Environment and Safety Management, NHL University of Applied Sciences, Leeuwarden, Netherlands, 2Marine Animal Ecology Group, Wageningen University, Wageningen, Netherlands

Abstract Application of dispersants aims to enhance the natural dispersion process in order to reduce the size of the slick and the amount of oil at the surface. This study presents an approach for modeling the development of the surface oil slick as a function of the wind speed, oil viscosity, and dispersant application. We modeled the oil slick mass distribution across a transect through the slick over time taking into account the continuous entrainment of oil, resurfacing process of the different oil droplet size classes and horizontal transport. Outcomes show distinctively different oil slick features, depending on how favorable conditions are for dispersion. A large comet-shaped slick is formed in the case of suboptimal dispersion. Optimal dispersion yields a small surface oil slick, with a large mass of oil suspended. The benefit of dispersants is limited to conditions with suboptimal natural dispersion, with the exception of extremely unfavorable conditions in which the slick size would be increased. The oil slick length, fraction of oil still floating, lifetime of the slick, and wind drift are highly influenced by wind speed and related mixing conditions, and to a lesser extent by oil properties. In the newly defined "Dispersibility Factor" (DF) the oil slick properties and environmental conditions can be combined into one value that correlates with the simulation outcomes and therefore can be used as an indicator of favorability of natural dispersion and likelihood of added value of chemical dispersion.

Plain Language Summary In certain conditions, (part of) an oil spill can disappear from the water surface through a process called natural dispersion. One available oil spill response option is to enhance this process by addition of dispersants (chemical dispersion). An informed decision for such response requires insight in the oil slick size WITH and WITHOUT treatment. This paper aims to enable such assessment of net effectiveness, by providing a strategy for modeling the dispersion process. The findings of earlier laboratory investigations were applied in a model that simulates submergence of oil by breaking waves, rise of the separate oil droplets and concurrent wind-driven differential transport between the floating slick and suspended droplets. The simulation outputs help assess the added value (or not) of dispersant application in reducing the potential adverse effects of the surface oil slick for different oil types and conditions.

1. Introduction

Deciding on application of chemical dispersants remains a complex trade-off between the adverse effects of floating oil and those of suspended/dissolved/sunken oil. In order to make more informed decisions, extensive information on local conditions as well as the (potential) effects of the dispersants on the oil slick fate is needed. Current dispersion algorithms require expert estimation on dispersant effectiveness and do not provide information on the added value of dispersants compared to only natural dispersion [National Research Council of the National Academies, 2005; Zeinstra-Helfrich et al., 2015].

Chemical dispersants can enhance the natural dispersion process by reducing the oil-water interfacial tension. This stimulates oil entrained by breaking waves to be broken up into smaller droplets. The droplet size affects the fate of the oil, as smaller droplets remain in the water column before resurfacing. Generally, droplets with sizes below 70 μm are considered to remain in the water column indefinitely [French-McCoy, 2004]. Considering the random and chaotic processes that make up the dispersion process, such a sharp (and fixed) cut-off seems inappropriate.
As the main goal of dispersant application is to remove the oil from the water surface as fast as possible, the success of such action should be defined from its effectiveness in reducing the mass of floating oil and the surface slick area over time. The surface area of an oil slick is determined by the portion of oil still floating (as opposed to evaporated, dissolved, or suspended), the spreading of the oil slick under the influence of gravity and interfacial tension [Fay and Hoult, 1971] and the wind shear. Wind shear causes the slick to elongate as entrained oil resurfaces upwind of the original slick [Elliott, 1986; Elliott et al., 1986]. As this wind shear process is dependent on dispersion, an understanding of how a dispersant response impacts it is crucial. The wind-shear mechanism is not/hardly described in the literature, as it can only be observed in sea-trials: the differential transport between floating and suspended oil is not present in any of the other test systems. Unfortunately, sea-trials are hard to perform and control. Therefore, in this paper we develop a model for simulating the oil slick elongation and lengthwise volume distribution resulting from dispersion and wind shear. Based on the presented model, the influence of key parameters in dispersion (wind speed, oil type, and interfacial tension) on the volume balance and oil slick appearance is investigated for three wind speeds, three oil types and with or without dispersants added.

2. Methods

We consider a lengthwise cross-section of an oil slick, moving across a "grid" at a speed depending on the wind speed. Within each time step and within each grid cell, oil is continuously entrained.

At any given time, an area (fraction) \( A_{\text{mix}} \) each grid cell is (newly) hit by breaking waves. Upon impact, the floating oil is entrained, broken up into droplets, and assumed to be distributed evenly across mixing depth \( z_i \). During the following quiescent period (while other areas are mixed/entrained) part of the oil resurfaces. After a time period \( T_{\text{res}} \) the same location is hit by a breaking wave again, redistributing the (predominantly small) oil droplets still suspended across \( z_i \) together with newly entrained oil.

Following these steps, we calculate the evolution of the oil slick thickness under continuous agitation by estimating the volume entrained and resurfacing as a function of time and location.

2.1. Process Inputs

Equations cited in this section are listed in Table 1.

2.1.1. Wave Field Characteristics

Simulating the intermittent entrainment and resurfacing of oil requires two parameters for the timing of breaking waves: the area fraction agitated by breaking waves per unit of time (for the oil volume flux) and the time period between successive breaking waves hitting exactly the same location (the “quiescent” time for resurfacing).

### Table 1. Formulas Introduced and Referred to in the Text

<table>
<thead>
<tr>
<th>Equation</th>
<th>Quantity</th>
<th>Units</th>
<th>Formula</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WhiteCap coverage (fraction)</td>
<td>s(^{-1})</td>
<td>( A_{\text{mix}} = 0.46 , U_{\text{sl}}^{0.26} )</td>
<td>Salisbury et al. [2014]</td>
</tr>
<tr>
<td>2</td>
<td>Agitated area fraction</td>
<td>s(^{-1})</td>
<td>( A_{\text{mix}} = \frac{WCC}{C_{16}/C_{17}} )</td>
<td>Phillips [1985] and Kleiss and Melville [2011]</td>
</tr>
<tr>
<td>3</td>
<td>Breaking wave period</td>
<td>s</td>
<td>( T_{\text{b}} = \frac{1}{U_{\text{b}}(z)} )</td>
<td>Phillips [1985] and Kleiss and Melville [2011]</td>
</tr>
<tr>
<td>4</td>
<td>Breaking wave height</td>
<td>m</td>
<td>( H_{\text{b}} = 0.02854 , U_{\text{sl}}^{0.5} )</td>
<td>Galt and Overstreet [2009]</td>
</tr>
<tr>
<td>5</td>
<td>Free fall height</td>
<td>m</td>
<td>( H_{f} = 0.35 , H_{\text{b}} = 0.009989 , U_{\text{sl}}^{0.5} )</td>
<td>Own observations and equation (4)</td>
</tr>
<tr>
<td>6</td>
<td>Significant wave height</td>
<td>m</td>
<td>( H_{\text{sp}} = 0.02244 , U_{\text{sl}}^{0.5} )</td>
<td>Galt and Overstreet [2009]</td>
</tr>
<tr>
<td>7</td>
<td>Droplet injection depth</td>
<td>m</td>
<td>( z_i = 1.4 , H_{\text{b}} )</td>
<td>Li and Garrett [1998]</td>
</tr>
<tr>
<td>8</td>
<td>Stokes-induced velocity</td>
<td>m s(^{-1})</td>
<td>( \nu_{\text{stokes}} = 0.016 , U_{\text{w}} , e^{-3.6} ), with ( k = 8.33 , \frac{z_i}{H_{\text{b}}} )</td>
<td>Garrett and Li [1993]</td>
</tr>
<tr>
<td>9</td>
<td>Wind-induced velocity</td>
<td>m s(^{-1})</td>
<td>( \nu_{\text{wind}} = 0.03 , U_{\text{w}} , \left( 1 - \frac{H_{\text{b}}}{H_{\text{b}} + \frac{z_i}{H_{\text{b}}}} \right) ), with ( z_0 = 0.0001 ), and ( z_i = 20 )</td>
<td>Elliott [1986]</td>
</tr>
<tr>
<td>10</td>
<td>Total slick velocity</td>
<td>m s(^{-1})</td>
<td>( U_{\text{sl}} = \nu_{\text{stokes}} \left( 0 \right) + \nu_{\text{wind}} \left( 0 \right) = 0.046 , U_{\text{w}} )</td>
<td>From equations (8) and (9)</td>
</tr>
<tr>
<td>11</td>
<td>Relative velocity of a droplet at depth ( z ) compared to the surface slick</td>
<td>m s(^{-1})</td>
<td>( U_{\text{d}}(z) = (\nu_{\text{stokes}}(z) + \nu_{\text{wind}}(z)) - U_{\text{b}} )</td>
<td>From equations (8) and (9)</td>
</tr>
<tr>
<td>12</td>
<td>Mass median diameter</td>
<td>m</td>
<td>( \text{MMD} = h_{\text{b0}} \left[ 18.41 \left( \frac{h_{\text{b0}}}{h_{\text{b0}} + \frac{z_i}{H_{\text{b}}}} \right)^{0.6} + 0.64 \left( \frac{h_{\text{b0}}}{h_{\text{b0}} + \frac{z_i}{H_{\text{b}}}} \right)^{2.0} \right] )</td>
<td>Johansen et al.[2015] and Zeinstra-Helfrich et al. [2016]</td>
</tr>
<tr>
<td>13</td>
<td>Bouyant rise velocity</td>
<td>m s(^{-1})</td>
<td>( \nu = \text{d} , g , \left( 1 - \frac{\rho_{\text{w}}}{\rho_{\text{oil}}} \right) / 18 , \text{psu}, \text{ for } \text{d} &lt; 9 , 25 , \text{psu} / g , (1 - \frac{\rho_{\text{w}}}{\rho_{\text{oil}}})^{3/3} )</td>
<td>Stokes’ law</td>
</tr>
</tbody>
</table>
Whitecap coverage (the area fraction covered by breaking waves at any given time) is often investigated as an important parameter in climatology, determining visible albedo, Sea Salt Aerosol flux, and air-sea gas exchange. Direct parameterization with wind speed, however, proves to be difficult [Anguelova and Webster, 2006] due to differences in measurement techniques and the influence of parameters other than wind speed [Salisbury et al., 2013] causing variation in whitecap lifetime [Callaghan et al., 2012]. In this paper, whitecap coverage is calculated based on a recent parameterization for active breaking waves (equation (1)) [Salisbury et al., 2013, 2014], as this is valid for a wide range of conditions. Based on field observations, we approximate the characteristic lifetime (τ) of this active breaking wave phase at 1 s [Monahan and Woolf, 1989; Callaghan, 2013].

Dividing the whitecap coverage by the lifetime of the breaking wave phase (τ) yields the whitecap area formation rate (equation (23)) [Monahan, 1971; Monahan and Callaghan, 2015]. This is the agitated area fraction per unit time (Amix, s⁻¹) in our context, as the newly forming whitecaps are considered to impose the vertical impact necessarily for entrainment of floating oil into the water column. As the agitated area fraction also expresses the number of breaking waves passing a given location per unit time [Phillips, 1985; Kleiss and Melville, 2011], the time between two consecutive “mixing incidents” in one location is \( T_{bw} = 1/Amix \) (equation (3)).

The breaking wave jet free fall height is required as input for the droplet size equation. Taking into account that this jet falls partly on the wave’s own front face, the free fall height is less than the wave height. Photographic measurements indicate fall height is between 0.2 and 0.5 \( H_{bow} \) [Chanson and Cummings, 1994], of which we take the median value of 0.35 in our plunge height (equation (5)) with the breaking wave height based on a fully developed Pierson and Moskowitz wave spectrum [Galt and Overstreet, 2009] (equation (4)).

The mixing depth, or the thickness of the layer below the water surface over which the droplets are distributed, determines how long it takes for suspended oil droplets to resurface. Generally, a value of 1.5 times the wave height is assumed based on two sources [National Research Council of the National Academies, 2005]: Delvigne and Sweeney [Delvigne and Sweeney, 1988] who found their smaller droplet sizes to be homogeneously distributed across a depth of \( (1.5 \pm 0.35) \ H_{bow} \) below the water surface. Li and Garrett [1998] define a surface layer of constant turbulent dissipation rate (c) with a thickness 1.4 \( H_{sign} \), yet do not necessarily relate this to droplet entrainment depth. These values might seem high, yet literature regarding air bubble entrainment suggests values in the same order of magnitude: Air bubble injection by breaking waves is estimated to occur in a layer of thickness up to 0.25–2 times the wave height [Gemmrich, 2009; Chiba and Baschek, 2010].

We base our mixing depth (equation (7)) on the Li and Garrett’s turbulent dissipation rate layer [Li and Garrett, 1998], with the so-called significant wave height based on a fully developed Pierson and Moskowitz wave spectrum (equation (6)) [Galt and Overstreet, 2009].

### 2.1.2. Wind-Induced Velocity of Floating Slick and Suspended Droplets

The most common mechanisms causing differential movement between the (floating slick on the) water surface and the underlying water are the vertical structure of the currents, stokes drift, and wind forcing [Elliott, 1986; Elliott et al., 1986]. Elliott’s work on elongation of oil slicks as a result of near-surface velocity shears [Elliott, 1986; Elliott et al., 1986], considers a 3.5% wind-induced surface velocity additional to the stokes drift-induced velocity. Others add a smaller wind-driven transport factor to the stokes drift [Lehr et al., 2002; Arduhin et al., 2009; Heinaff et al., 2012]. The latter option results in a total contribution of wind (via stokes and direct forcing) on the oil slick transport, closer to the commonly assumed wind drift factor of 3–4% of the wind speed [Lee et al., 2015].

We calculate the forward velocity of the slick and suspended particles due to stokes drift based on the approximation by Garrett and Li [1993]. The stokes drift on the water surface equals 1.6% of the wind speed. The exponential decline of velocity with depth is characterized by the so-called e-folding depth in relation to wind speed: 0.12 \( U_{m} \)/g. The average Lagrangian forward velocity on account of the stokes drift, as a function of depth (below the water surface), is then \( u_{s}(z) = 0.016 \ U_{m} \ e^{-kz} \), with \( k = 8.33 \ g/U_{m}^{2} \) (equation (8)).

The additional wind drift factor (wind-driven surface transport other than stokes drift) in our model is set to 3% at the water surface, and decays logarithmically down from a depth of 0.1 mm–20 m (equation (9)) [Elliott, 1986]. Adding together stokes and wind drift, makes the total wind-induced velocity of our floating slick 4.6% of \( U_{m} \) (equation (10)). This wind drift factor might seem quite high, but the resulting actual
observable displacement of the slick over time will be lower as the entrainment process gradually makes the upwind edge disappear.

Currents are not included in this calculation as they affect suspended and floating oil in the same way, and our interest is in the differential movement by the wind. (Our grid moves along with the currents.)

### 2.1.3. Oil Droplet Breakup

The droplet size distribution is calculated with the Weber and Reynolds relationship developed by Johansen and colleagues [Johansen et al., 2015], with adapted constants \((A_h = 18.41, B = 0.64)\) to yield Mass Median Diameters [Zeinstra-Helfrich et al., 2016] (equation (12)). The standard deviation for this lognormal droplet size distribution is \(\log_{10}(0.38)\).

This particular algorithm is based on measurements of instantaneous droplet sizes, making validation with field measurements extremely difficult [Zeinstra-Helfrich et al., 2016]. The calculation results do follow expected trends with oil properties.

### 2.1.4. Resurfacing

In the presented model, an individual droplet with a diameter \(d\) is assumed to rise to the back surface with a velocity as dictated by Stokes’ law (equation (13)). The mass of oil entrained in larger droplets \((v(d) > z/T_{bw})\) will resurface before the next breaking wave impact. Of droplets that are smaller, a fraction \(1 - T_{bw}v(d)/z\) will still be suspended when the next breaking wave hits. As the remainder of oil mass is redistributed across \(z\), with each new breaking wave, the resurface rate of these smaller droplets at time periods exceeding the first breaking wave periods can be based on exponential decay.

### 2.2. Implementation in the Model

Equations cited in this section are listed in Table 2. A 1-D grid is defined by the total length that accommodates the oil slick maximum travel distance in the given timeframe. The grid cell length, \(\Delta x\), is set to be around 10 m, and adjusted for each case so that the number of grid cells traveled in one breaking wave period \(T_{bw}\) is an integer. The time step length, \(\Delta t\), is set equal to the time it takes the slick to travel exactly one grid cell.

In one time step, the oil layer moves exactly one grid cell downwind, an oil volume \(\Delta A_{mix}\) is removed by entrainment, an oil volume \(V_{res}\) resurfaces (back) into the cell. This \(V_{res}\) is an addition of linear resurfacing of droplets entrained for periods \(< T_{bw}\) from the same grid cell and near upwind cells \((V_{res})\) and resurfacing as a result of quasi-exponential loss of the volume of oil in suspension for longer periods of time \((V_{res})\).

Twenty droplet size classes are defined to properly display the different resurfacing characteristics between small and large droplets. Nineteen of these classes are evenly distributed between MMD \((h_{oil}) = -2.326\sigma\) and the droplet size that resurfaces within a quarter of the breaking wave period \((0.25T_{bw})\). Oil in droplets larger than that is bunched into a twentieth size class, as this oil will all resurface very fast and not far from the point of entrainment.

The oil volume entrained per droplet size class is calculated with the probability density function for the lognormal distribution around MMD (as a function of \(h_{oil}\)) from the lower limit of the size class to the upper limit (equation (15)).

### Table 2. Implementation of the Processes in the Oil Slick Model

<table>
<thead>
<tr>
<th>Equation</th>
<th>Quantity</th>
<th>Units</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Oil layer thickness after a time step</td>
<td>(m (m^3 m^{-2}))</td>
<td>(h_{oil}(t,x) = h_{oil}(t-\Delta t, x - \Delta x) \binom{1}{1} + V_{res} / \Delta t)</td>
</tr>
<tr>
<td>15</td>
<td>Entrainment rate per size class D (ranging from (d_{mix}) to (d_{oil}))</td>
<td>(m^3 m^{-2} s^{-1})</td>
<td>(Q_{entr}(D) = F_v(D) A_{mix} h_{oil}) with (F_v(D) = P(d_{mix} &lt; d &lt; d_{oil}))</td>
</tr>
<tr>
<td>16</td>
<td>Maximum length (distance) of resurfacing</td>
<td>(m)</td>
<td>(dx \sim \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (F_{res}(t - T_{bw}, x) + F_{res}(t, x)) / \Delta x)</td>
</tr>
<tr>
<td>17</td>
<td>Total volume resurfacing per time step per up-wind grid cell</td>
<td>(m^3 m^{-2})</td>
<td>(V_{res}(t, x) = \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (1 - \frac{e^{-k \Delta t}}{k}))</td>
</tr>
<tr>
<td>18</td>
<td>Volume (per size class) still suspended after 1 (T_{bw})</td>
<td>(m^3 m^{-2} s^{-1})</td>
<td>(V_{susp}(t, x) = \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (1 - \frac{e^{-k \Delta t}}{k}))</td>
</tr>
<tr>
<td>19</td>
<td>Total volume suspended after time step</td>
<td>(m^3 m^{-2})</td>
<td>(V_{susp}(t, x) = \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (1 - \frac{e^{-k \Delta t}}{k}))</td>
</tr>
<tr>
<td>20</td>
<td>Total volume resurfacing in one time step</td>
<td>(m^3 m^{-2})</td>
<td>(V_{res}(t, x) = \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (1 - \frac{e^{-k \Delta t}}{k}))</td>
</tr>
<tr>
<td>21</td>
<td>Fraction of suspended oil droplets (per size class) that moves to the downwind grid cell during one time step</td>
<td>(F(D) = \frac{1}{\Delta x} \sum D \Delta t Q_{entr}(D, h) (\rho_{oil} / \rho_{water}) \binom{1}{1} (1 - \frac{e^{-k \Delta t}}{k}))</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Largest droplet diameter that can remain suspended for (T_{bw})</td>
<td>(m)</td>
<td>(d_{mix} = 5.1 \times 10^{-5} (\rho_{oil} - \rho_{water})^{0.5} (\mu_k)^{1.1})</td>
</tr>
</tbody>
</table>
The relationship between entrained oil droplet size distribution and oil layer thickness (with the constant oil properties and wind speed) is calculated at the start of the simulation, to avoid extensive calculations in each time step and each location. This precalculation is performed for a series of 20 oil layer thicknesses ranging from near zero to the maximum oil layer thickness (\(h_{oil,0}\)). During the main simulations, the volume entrained in each size class is based on a linear interpolation of these results.

One oil droplet of size \(d\), initially entrained to depth \(z\), resurfaces \(z = v(d)\) seconds after entrainment. The water column velocity relative to the slick velocity integrated over depth \(z\), with rise velocity as residence time in each location, yields the distance behind the entrainment location in the (moving) slick that this droplet resurfaces (equation (16)).

As the volume of oil entrained is assumed evenly distributed across the top water depth \(z_i\), the volume distribution due to resurfacing within the first breaking wave period after entrainment is obtained by numerically integrating (equation (16)) for entrainment across the time step, across the grid cell length and across the droplet size classes.

The short-term (<\(T_{bw}\)) resurfacing is determined by the volume of oil initially entrained per size class and can therefore be directly related to the (entrained) layer thickness. This enables precalculation of the (total of all size classes) oil volume resurfacing per time step per (upwind) location for the 20 oil layer thicknesses (\(h_{oil,0}\)). During each step of the simulation, \(V_{res,1}\) is obtained from linear interpolations based on the layer thicknesses of the oil slick (grid cells) passing the location in the previous time steps.

The above calculations of \(V_{res,1}\) include the large oil droplets resurfacing within a breaking wave period as well as a portion of the smaller droplets that resurfaces due to its shallow intrusion depth. The volume of entrained oil that does not resurface within the first breaking wave period (\(V_{susp,T_{bw}}\)) is subsequently dealt with per separate droplet size class \(d < d_{lim}\). The (initial) magnitude of \(V_{susp,T_{bw}}\) is precalculated as a function of oil layer thickness (equation (18)) and linearly interpolated for the actual layer thickness in the time step. As a fixed fraction of the oil volume per size class resurfaces per breaking wave period, the resurfacing rate of these longer suspended droplets can be estimated based on exponential decay (equation (20)).

Since entrainment occurs during the whole time step, the first time step needs to account for the time difference between the start and end of the time step (as shown by the right-hand term in equations (19) and (20)).

The horizontal movement of the quickly resurfacing droplets is included in the calculation for \(V_{res,1}\), and the volume suspended for longer periods is also subjected to forward movement in the water column. Per droplet size class, the fraction of the suspended volume transferred to the next downwind grid cell during the course of one time step, is calculated based on the velocity profile a droplet \(d\) at depth \(z\) passes during its journey to depth \(z - v(d)\Delta t\) (equation (21)).

### 2.3. Tested Conditions

Using the described model, the oil slick evolution over time is analyzed for three wind speeds (\(U_w = 5, 10, 15\) m/s), three oil types, and two dispersant conditions (natural and chemical dispersion), yielding 18 cases in total. The three oil types considered have the physical properties as in Table 3.

These properties are assumed to remain unchanged after dispersant dosage; the application of dispersants only affects the oil-water interfacial tension, which is 0.03 N/m for natural dispersion and 0.003 N/m for chemically treated oil. For the above tests, the slick is set to be 250 m long and 1 mm thick at the start of the simulation, and the simulation lasts for 24 h.

In addition, for the medium oil type with 10 m/s wind, a set of initial lengths and thicknesses is tested (\(l_0 = 250\) m, with \(h_{oil,0} = 0.5\) and 2 mm; \(l_0 = 500\) m, with \(h_{oil,0} = 0.5\) and 1 mm).

### 3. Results and Discussion

Each of the simulations results in a graph of the slick evolution over time (Figure 1) and some characteristic metrics of the slick after 24 h (Figure 2). (The output data and slick graphs for all simulations can be found in supporting information)

<table>
<thead>
<tr>
<th>Table 3. Physical Properties of the Simulated Oil Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Type</td>
</tr>
<tr>
<td>Light</td>
</tr>
<tr>
<td>Medium</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
</tbody>
</table>
Figure 1. Simulation results for the least (left) and most (right) favorable conditions for dispersion. (top) The distribution of oil mass over time. (bottom) Slick lengthwise mass distribution (thickness shown as appearance according to the Bonn Agreement Appearance Code) and wind-induced displacement over time. Wind direction is upward.

Figure 2. Oil slick metrics after 24 h as a function of dispersibility factor (equation (23)). Symbol shape indicates wind speed: □ 5, ○ 10, ▲ 15 m/s), color indicates oil type (■ heavy, ■ medium, ■ light oil) in which unfilled symbols represent dispersant treated and filled symbols untreated. (Other symbols indicate variation in lengths and layer thicknesses (Figure 3))
3.1. General Observations

The slick behavior shows two distinctly different regimes for favorable and unfavorable dispersion (Figure 1): Conditions least favorable for dispersion are the heavy oil combined with the low wind speed (Figure 1, left). The oil slick clearly develops a tail over time (Figure 1, bottom). After 24 h, the downwind edge is formed by a patch of "true oil color" of a length just over twice the initial slick length (506 m), followed by an upwind tail that decreases in thickness as we move further from the thick patch. The total slick length after 24 h is 10.2 km, and still increasing (although the growth levels off slightly). The fraction of oil suspended in the water column (Figure 1, top) shows a sharp initial increase (0.5 h), after which it continues to steadily increase (almost linear).

Conditions most favorable for dispersion are the light oil, treated with dispersants, combined with the high wind speed (Figure 1, right). A very large portion of the oil mass is transferred to the water column in only the first half hour, and slowly increases after that (Figure 1, top). Consequently, the surface expression of the remaining mass is very limited. The "true oil color" is only visible in the first 15 min, followed by a brief flash of "metallic" and a period of "rainbow color" transitioning to "sheen" from the front and back edge of the slick. The length of the oil slick has slowly increased over time, but appears to stabilize at 1.0 km after 24 h. We expect that this remaining sheen will diminish into an invisible oil layer (<0.04 μm) in a similar way as the change from rainbow to sheen (from the up and down-wind edges toward the middle). The wind-driven transport has moved the downwind edge 15.3 km in 24 h, this is very little compared to the 59.6 km that would result from (equation (10)) without entrainment. This is consistent with earlier observations oil slick wind-driven transport being reduced in conditions with a lot of entrainment [Reed et al., 1994]. In such cases, the surface slick is only a (temporary) expression of the underwater plume, repeated mixing ensures an oil packet is not available on the surface long enough to be transported. The resulting effective (wind and stokes) drift factor for this simulation, 1.18%, does match with the lowest observed wind drift factor in the field of 1% [Lehr and Simecek-beatty, 2000].

The slick of the first, least favorable case spreads much further than can be explained by circular slick gravity-spreading: When assuming an oil volume based on an initial circular slick $V = (0.25πh_{oil}^2)0$, spreading according to Fay’s [Lehr et al., 1984] formulae would result in a maximum slick diameter of 1.5 km (with an average thickness of $h_{oil} \approx 26 \mu m$) in just over 8 h. The least favorable case exceeds this spreading by 6 times. The "optimal" dispersion case does not reach this predicted diameter, the oil volume remaining on the surface is not sufficient to form such a slick. Additionally, one can question whether such a gravity-spreading phenomenon would take place on this slick where continuous mixing also prevents wind drift to occur.

It must be noted that in this simulation, all mass is assumed to be preserved in a 1-D stretch. In reality, mass will also disappear from the slick by the lateral spreading, and be lost from the slick by evaporation and dissolution. Suspended droplets can also be lost from the mass balance by turbulent diffusion outside the "area of interest" or sinking to the sediment after interaction with particles or marine snow [Vonk et al., 2015; van Eenennaam et al., 2016].

3.2. Output Parameters

Based on the input parameters, we can quickly calculate how susceptible for dispersion each of the combinations of conditions is. Using the oil properties, the environmental conditions and the initial thickness, the volume fraction of oil droplets smaller than the limiting diameter (largest diameter that can stay suspended for longer than $T_{bw}$) is calculated. This parameter indicates the oil fraction that is relatively stable suspended; the dispersibility factor (DF):

$$DF = \int_{0}^{\lambda_{min}} \frac{1}{\pi \sqrt{2\pi}} e^{-\frac{(v_{surf} - \text{wind}(0, t))}{d_{ref}}} \frac{1}{dd}. \quad (23)$$

As this factor considers both the oil as the mixing conditions, it provides an overview of the situation at hand for the period that the mixing conditions persist.

The dispersibility factor (DF) provides a good indication of the four main output parameters after 24 h (Figure 2): (a) Volume fraction of oil in the visible slick, (b) visible slick length, (c) effective drift factor, (d) lifetime of the thick "true oil color" slick.
For cases with high DF (>0.4), outputs after 24 h do not differ much between settings. For cases with lower DF all four shown output parameters are much more sensitive to changes in DF, in this region, dispersion is not optimal.

Slick length after 24 h generally increases with decreasing DF, but decreases again for very low DF values. If there is little entrainment of fast resurfacing droplets slick elongation is maximal. In even less favorable conditions with very little entrainment and very fast resurfacing droplets, the slick elongation mechanism occurs slower.

The wind speed clearly has a large influence on the slick fate (Figure 2). The medium and high wind speed (\( \mu_1 \) 10 m/s and \( \Delta \) 15 m/s) leave hardly any (>5%) oil on the surface (Figure 2a). With the low wind speed (\( \mu_0 \) 5 m/s) 10–70% of oil remains afloat. Slick length, effective drift factor, and life time of the “thick” slick decrease with increasing wind speed (Figures 2b–2d). The presented outcomes are based on constant weather conditions. Consequences of variations in wind speed can be included in the model, for example a following calm period could result in partial refloating of the oil.

The effect of oil type on the oil slick thickness and length after 24 h is less obvious than that of wind speed. At low wind speed, the influence of oil type best visible, yet the absolute difference in outcome after 24 h is very limited. Although the light oil type clearly has a higher DF than the heavy oil type, the influence of oil type on the slick length, transport and oil volume, is hardly noticeable (Figure 2, supporting information). Although increasing oil viscosity does increase the mean droplet size (equation (12)), the effect on the droplet’s rise-speed is largely compensated by the intrinsic higher density of this oil.

With the same layer thickness, doubling the slick length (in otherwise identical conditions) has no noticeable effect on the fraction of oil in the slick nor on wind drift. Slick length increase (\( l_{24h} - l_0 \)) is at maximum a factor 1.03, with only a very small effect on the lifetime of the thick slick (Figure 3).
The initial oil slick thickness has a larger effect on the slick evolution (Figure 3) than slick length. It is clear that thicker slicks are harder to disperse; a larger fraction of oil remains in the slick, slick length is larger, and the lifetime of the black slick is longer. As a result, the effective wind drift remains larger.

A curious observation is that initial slick thickness has a larger influence on slick length after 24 h than the initial slick length does. With an equal initial mass of oil in the cross section, a longer thinner slick will dissipate more easily than a thicker shorter slick. This is a result of the oil-layer-thickness-dependent droplet size distribution we employ, and matches with observations in the field.

This also means that, although oil properties as such did not affect the simulation result much (Figure 2), in reality they could have a serious indirect effect on the slick development through their influence on the initial slick spreading, and thus, thickness. The consequences of other spreading mechanisms on the elongation process can be included in the model but is beyond the scope of this paper.

### 3.3. Influence of Chemical Dispersion

It is clear that effective dispersion reduces the wind-driven transport of an oil slick. That is why chemical dispersion can be used to alter the transport of the slick [Lee et al., 2015]. Our modeling outputs reveal that dispersant application only provides added benefit in two of the cases (Figure 4 and supporting information), namely the low wind speed and medium and light oil. In 24 h, the light oil treated with dispersants and subjected to 5 m/s wind speed, moves 73% of the distance the untreated version did. For the medium oil, this is 85%. In the seven other cases dispersion is already very successful, and the additional reduction in transport by dispersants is less than 10%. Notice the relatively low transport distances at higher wind speeds, due to the lower effective drift factor caused by the dispersion.

Most well-known motive for dispersant use is to reduce the oil on the water surface. The benefit of dispersion is greatest in the ‘critical region’ of dispersion, where naturally occurring dispersion is only little (Figure 2). Conversely, for the least favorable situation (heavy, 5 m/s), slick length after 24 h was increased by dispersants (Figure 5). The high oil viscosity and low energy levels in this case resulted in formation of only very large oil droplets, hampering wind shear spreading of this slick. As the addition of dispersants reduced the droplet sizes, the wind shear spreading was enhanced.

### 3.4. Potential for Oil Slick Impacts

The impact of a surface slick is mostly due to the physical effects. Therefore, impact is proportional with oil slick area yet largely independent of oil slick thickness. On the other hand, it is unlikely that presence of just a trace of oil could cause these impacts. A floating oil layer is considered to cause physical effects at layer thicknesses above 25 μm [Jongbloed et al., 2002]. In order to assess the total potential adverse impact of the
surface slick, we calculated the slick length with a thickness exceeding this effects threshold, during its lifetime (Figure 6).

This parameter, too, correlates nicely with DF, and shows a sharp decrease in the critical region (0.17 < DF < 0.4). In this region, a clear benefit of dispersant application is visible in reducing the thick slick area that can cause adverse effects over time. As one would expect, this time-integrated slick length correlates with the volume of oil still floating after 24 h (Figures 2a; R2: 0.95), and even more so with the time-integrated floating oil volume (R2: 0.97). This means that the choice of the response goal (decrease mass afloat or decrease slick size) will not result in a different decision on dispersant application (except for very rare occasions, such as #7 (red square in Figure 2a)).

3.5. Sensitivity Analysis

Of course, the presented model presents a simplification of reality. This enables fast predictions during spill situations with little time for decision making. In this paragraph, we briefly discuss to what extent the end-results would be affected by different choices of processes or parameters.

The fact that the droplet size distribution is dependent of oil layer thickness has a tremendous influence on the end result. The simulations of the most and least favorable dispersion conditions (Figure 1) were duplicated with the droplet size distribution for the average thickness (supporting information). The transport of the slicks is very similar, yet the elongation process occurs at a much slower rate if the droplet size does not decrease with layer thickness. Ignoring the layer thickness dependence causes the total transition to sheen in the most favorable condition to take longer, and the least favorable condition to hardly develop a tail. The dependence of droplet size on layer thickness explains why a thin initial tail disperses more efficiently.

The presented model does not incorporate the simple droplet size cut-off assuming that droplets smaller than 70 \( \mu \text{m} \) are suspended indefinitely; all droplets are subject to resurfacing. Our results, however, show that individual droplet behavior is quite similar to this rule of thumb: For the 10 and 15 m/s wind speed, less than 2% of oil droplets (<70 \( \mu \text{m} \)) resurface per breaking wave period. For the 5 m/s wind speed, the resurface percentages for the first breaking wave period range from 6.1 to 21.9%. This would mean that at least 78.1% of the oil is redistributed by the next breaking wave impact. So, during the mixing, droplets with diameters below 70 \( \mu \text{m} \) indeed tend to accumulate in the water column.

Even though droplets of 70 \( \mu \text{m} \) or less indeed spend a lot of time underwater, we found that these droplets do affect the slick elongation process: Removing the droplets smaller than 70 \( \mu \text{m} \) from the mass balance when they are formed, causes the modeled slicks to disappear much quicker (supporting information). Due to the loss of volume, the remaining slick is thinner, cascading into much quicker disappearance as more and more oil is removed. Although only a small fraction of these droplets resurfaces, this oil volume does have an important contribution to the oil slick thickness, and thereby the slick behavior. Ignoring these small droplets in the model calculations overestimates the slick disappearance.

In the above model, the wind drift and stokes drift both form their own forward water velocity profile with water depth (equations (8) and (9)). Two alternative calculations are performed: In one case the wind drift only moves the floating slick and does not affect the suspended droplets (\( u_{\text{wind}}(z > 0.0001) = 0 \)), and in the second case both wind and stokes drift have no influence on suspended droplets (\( u_{\text{wind}}(z > 0.0001) = u_{\text{stokes}}(z > 0.0001) = 0 \)). The outcome for both alternative calculations shows seriously decreased slick transport, yet hardly affected extent of slick spreading or appearance (supporting information).

Slick elongation is driven by the difference between (main) water column transport and the surface layer. Both velocity profiles show a sharp decline: the velocity drops below 50% of the surface velocity within the top 1/5 of the mixing depth. Setting the water column velocity to 0, the overall difference between water column transport and slick transport is only slightly enhanced compared to the original profile.
These results indicate that although the surface (stokes and wind) drift itself is the main driver for slick elongation, the choice of the velocity profile in the water column hardly affects the elongation process. However, the water column velocity profile is an important factor in the forward motion of the slick.

The choice of the value for breaking wave phase lifetime ($\tau$), influences the agitated area fraction ($A_{\text{mix}}$) as well as the time between two successive breaking waves ($T_{\text{bw}}$). Through $A_{\text{mix}}$, the volume entrained per unit time is affected. A change in $T_{\text{bw}}$ affects the droplet sizes that can remain suspended for longer than a breaking wave period. The chosen parameterization for the breaking wave free fall height ($H_{\text{pl}}$) affects the MassMedianDiameter of the entrained droplets and thereby affects the amount of small stable droplets.

In order to investigate the impact of these chosen values/relationships for ($\tau$ and $H_{\text{pl}}$) on the model results, an additional set of model runs is performed. The inputs span a full factorial with three settings for both parameters; $\tau$ is varied from 0.5, 1, and 1.5, and the calculated breaking wave free fall height ($H_{\text{pl}}$) is multiplied by a factor ($F_{H_{\text{pl}}}$) 0.5, 1, or 1.5. These calculations were performed on six of the original input combinations; the medium viscosity oil type, in three wind speeds and two dispersant conditions. (The results are given in supporting information).

Of course, changing either $\tau$ or $H_{\text{pl}}$ with a factor of 2–3 will affect the modeling outcome. However, comparable changes in wind speed and interfacial tension have a larger influence on the dispersibility factor than the variation of $\tau$ or $H_{\text{pl}}$ (supporting information). Therefore, we conclude that the model outcome depends mostly on variation in the input parameters applied, and is to a far lesser extent influenced by the exaggerated variation of the chosen fixed parameters.

### 4. Conclusions and Future Perspectives

The proposed model is capable of simulating the oil slick elongation and transport over time. This phenomenon has been observed at sea, but cannot be perceived in any other type of bench scale or wave tank testing. As the main goal of dispersant application is to reduce impacts of the surface oil, understanding and predicting oil slick elongation and transport over time is crucial in assessing the net effect of dispersant application.

Our simulation results illustrate how the expected benefit of dispersants in reducing slick surface expression greatly depends on environmental and initial spill conditions, and is predictable via the dispersibility factor. Future research should aim at quantifying and validating full slick surface expression in 3-D, also taking into account mass loss by other weathering and spreading processes as well as variability of weather conditions.

### Notation

- $A_{\text{mix}}$: area fraction agitated, $s^{-1}$.
- $d$: Droplet diameter, m.
- $d_{\text{lim}}$: limiting diameter: largest diameter that is suspended for $T_{\text{bw}}$, m.
- $F_{p}(D)$: $Pr(d_{\text{low}} < d < d_{\text{up}})$; cumulative probability density within the drop size class D.
- $g$: gravitational acceleration, $m s^{-2}$.
- $H_{\text{bw}}$: breaking wave height, m.
- $h_{\text{oil}}$: oil layer thickness, m.
- $h_{\text{oil}0}$: initial oil layer thickness, m.
- $H_{\text{sig}}$: significant wave height, m.
- $l_{0}$: initial oil slick length, m.
- $\text{MMD}$: mass median diameter, m.
- $Q_{\text{entr}}$: entrainment rate, $m^3 m^{-2} s^{-1}$.
- $T_{\text{bw}}$: breaking wave period (time between two “mixing incidents” in one location), s.
- $U_{\text{stokes}}$: Stokes-induced velocity, m $s^{-1}$.
- $U_{\text{wind}}$: wind-induced velocity, m $s^{-1}$.
- $U_{\text{relz}}$: relative velocity of a droplet at depth $z$ compared to the surface slick, m $s^{-1}$.
- $U_{\text{slick}}$: slick speed, m $s^{-1}$.
- $U_{\text{water}}$: wind speed (at 10 m above water level), m $s^{-1}$.
This research was made possible in part by a grant from The Gulf of Mexico Research Initiative, and in part by the Wageningen UR, IPOP TriplePSea innovation program (KB-14–007). Data are publicly available through the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) at https://data.gulfresearchinitiative.org (doc.id:7266/NYSQ8KFT). The data set in this repository contains the individual model outputs as well as the R script to run the calculation.

**References**


