Marine Pollution Bulletin 135 (2018) 569–580

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

# On the transport and modeling of dispersed oil under ice

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ARTICLE INFO

*Keywords:*
Oil spill model
Ice-water boundary layer
Random walk
Eddy diffusivity

ABSTRACT

Theoretical arguments and numerical investigations were conducted to understand the transport of oil droplets under ice. It was found that the boundary layer (BL) in the water under ice produces a downward velocity that reaches up to 0.2% of horizontal current speed, and is, in general, larger than the rise velocity of 70 μm oil droplets. The eddy diffusivity was found to increase with depth and to decrease gradually afterward. Neglecting the gradient of eddy diffusivity when conducting Lagrangian transport of oil droplets would result in an unphysical spatial distribution. When the downward velocity of water was neglected, oil accumulated at the water-ice interface regardless of the attachment efficiency. The lift force was found to scrape off droplets of the ice, especially for droplets ≤ 70 μm. These findings suggest that previous oil spill simulations may have overestimated the number of small droplets (≤70 μm) at the water-ice interface.

## 1. Introduction

As shipping in ice-prone environments increases (Yumashev et al. 2017), the risk from oil spills grows. In response, major renewed efforts have emerged in the last decade for understanding and modeling the behavior of oil spills on the water surface in ice or in ice-infested water (Dickins et al. 2008, Lee et al. 2011, Li et al. 2016, Wilkinson et al. 2017). Recent reviews (Afenyo et al. 2016; French-McCay et al. 2017) pointed out there is little information on the modeling of oil spills in ice in comparison to oil spills in open water. Some general guidelines have emerged, such as oil transport is practically unaffected by ice areal coverage when the coverage is < 30% and become greatly impacted by it when the ice coverage is > 70% (Reed et al. 1999; Li et al. 2016; French-McCay et al. 2017). As pointed out in the comprehensive review of Afenyo et al. (2016), the movement of oil droplets in the water column under ice is limited to the equations of entrainment developed by Delvigne and Sweeney (1988) and Mackay et al. (1980). These are empirical equations that are expedient but do not account directly for the hydrodynamics. In addition, they require the presence of waves, which could be negligible under ice due to the dampening effects of ice (Afenyo et al. 2016). Therefore, a research gap emerges which is the transport of oil droplets under ice under small waves or even in the absence of waves, which is the focus of this manuscript. But droplets in the water column could result from an underwater blowout (Zhao et al. 2015; Gros et al. 2017), or they could result from surface spills, especially if chemical dispersant are used (NRC 2005; Chapman et al. 2007). We attempt herein to address salient features of oil droplet transport under ice, providing modeling approaches that better capture the physics of the problem.

The transport of oil droplets in the water column has been commonly modeled using a Lagrangian random walk approach, where each droplet size is tracked individually as it travels in the water column (Reed et al. 1995; McCay 2003; Paris et al. 2012). In three dimensions, the general equations for the Lagrangian transport of oil droplets in the water column are (Hunter et al. 1993; LaBolle et al. 1996):

$$\mathrm{X}(t+\Delta t) = X(t) + U.\,\Delta t + \frac{\partial D_x}{\partial x}\Delta t + R\sqrt{2.\,\Delta t.\,D_x} \tag{1a}$$

$$\mathrm{Y}(t+\Delta t) = Y(t) + V.\,\Delta t + \frac{\partial D_y}{\partial y}\Delta t + R\sqrt{2.\,\Delta t.\,D_y} \tag{1b}$$

$$\mathrm{Z}(t+\Delta t) = Z(t) + (W+W_b).\,\Delta t + \frac{\partial D_Z}{\partial z}\Delta t + R\sqrt{2.\,\Delta t.\,D_Z} \tag{1c}$$

where $X(t)$ and $Y(t)$ are the horizontal coordinates of the oil droplet at time t, and $Z(t)$ is its vertical coordinate at time $t$; $\Delta t$ is the time increment; $U$ and $V$ represent the horizontal water velocities in the x and y directions, respectively, and W represents the vertical water velocity (i.e., in the $z$ direction); $D_x$, $D_y$, and $D_Z$ are the turbulent diffusion

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https://doi.org/10.1016/j.marpolbul.2018.07.046
Received 7 April 2018; Received in revised form 9 July 2018; Accepted 17 July 2018
0025-326X/ 

coefficients (also known as eddy diffusivity) in the $x$, $y$, and $z$ direction, respectively; $W_b$ is the Stokes rise velocity; and $R$ is a normal Gaussian random number (mean of zero and variance of 1.0). The second terms on the RHS of Eqs. (1a), (1b), and (1c) represent the displacement due to water currents in the x and y direction (Eqs. (1a) and (1b)) and due to water currents plus buoyancy (due to $W_b$) in the $z$ direction (Eq. (1c)); the third terms in Eqs. (1a), (1b), and (1c) represent transport due to the variation of the diffusion coefficient over space; and the last terms on the RHS in Eqs. (1a), (1b), and (1c) represents random transport due to turbulence at scales below the scale at which the water velocity is obtained.

Sea currents needed for Eqs. (1a), (1b), and (1c) are commonly obtained from hydrodynamic models, such as the US Navy software NCOM (Navy Coastal Ocean Model, https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/navoceano-ncom-glb) and the HYCOM (Hybrid Coordinate Ocean Model, https://www.hycom.org). The usage of these models for oil spill modeling maybe found in recent works (MacFadyen et al. 2011; Paris et al. 2012; Boufadel et al. 2014). As the hydrodynamic models provide the water velocity at given locations, interpolation is commonly used to obtain the water speed at the location of the oil droplet of interest.

The diffusion coefficients in Eqs. (1a), (1b), and (1c) represent transport below the spatial and temporal scales at which the water velocity is obtained. Thus, if the velocity is obtained at increments of 10 km (in the horizontal), the horizontal transport below this scale would be simulated using diffusion coefficients. Also, although the diffusion coefficient increases with the size of the plume (Okubo 1971), current approaches take it as constant, probably due to the uncertainty in estimating it, which is resulting from two non-exclusive reasons: 1) Oil forms windrows due to Langmuir cells and fronts (D'Asaro et al. 2018), and thus behaves differently from the zero-buoyancy tracers used by Okubo (1971), 2) Depending on the time scale of interest (e.g., days), the release may not be considered as emanating from a "point" or occurring over a "short duration" which would invalidate the assumptions made by Okubo (1971). Nevertheless, the Okubo expressions provide guidelines to modelers.

The horizontal diffusion coefficients based on oil spill modeling (above the kilometer scale) has been found to vary from 1 $m^2/s$ to up to tens of $m^2/s$ (Chao et al. 2001; Paris et al. 2012; Boufadel et al. 2014). The vertical diffusion coefficient was found to be much smaller, due to the fact that horizontal flow is much larger than vertical flow and due to stratification in oceans; it was found to vary from $10^{-6}$ to $10^{-2}$ $m^2/s$ (Elliott and Wallace 1989; Reed et al. 1995; French-McCay et al. 2008). In the laboratory, the distinction between horizontal and vertical tends to disappear, as noted in a recent work (Gopalan et al. 2008) where they reported values of the diffusion coefficient on the order of 1.0 to $8 \cdot 10^{-4}$ $m^2/s$ based on the transport of oil droplets in a laboratory isotropic chamber (dimensions $< 1.0\,m^3$). A brief review on the values of the horizontal and vertical diffusion coefficients is presented by Geng et al. (2016).

A complete solution of Eqs. (1a), (1b), and (1c) requires also determining the boundary conditions of the domain, namely the bottom and top of the domain. A reflective condition is sometimes used as follows: if the numerical scheme causes a droplet to be, for example, 5 cm above the water-ice interface, the scheme reflects it so that it is 5 cm below the interface. The justification for such an approach is to ensure that the statistical distribution of the random number $R$ in Eqs. (1a), (1b), and (1c) are conserved. However, we believe that such an approach is not physical, as there is no physical mechanism for the reflection (or the bouncing of particles). Rather, as the droplet approaches the water-ice boundary, its diffusivity decreases, and it is more reasonable to place the droplet at the boundary if the scheme resulted in the droplet crossing the boundary. This would result in a truncated probability distribution and thus the statistics is not conserved, but we believe the physics of the problem requires such as truncated distribution.

What complicates droplet transport at the water-ice interface is the fact that the ice is porous, and some oil droplets would attach to it. However, the attachment efficiency is not known, and it is reasonable to consider that it depends on the hydrodynamics at the interface. For example, it is expected that a large horizontal velocity would cause the oil to avoid the ice due to a mechanism known as lift (Saffman 1965), a topic that would be addressed in the Discussion section.

When considering large-scale transport (kilometers), simplifications are made to Eqs. (1a), (1b), and (1c) based on four commonly used assumptions are: 1) The horizontal velocities $U$ and $V$ obtained from large-scale models are assumed constant over depth intervals of 10 m or more; 2) The vertical velocity $W$ is taken as zero; 3) The vertical eddy diffusivity is assumed to be uniform within down to 20 m depth, and 4) the gradient of eddy diffusivity is neglected in the transport equation. These assumptions were observed in applications of the oil spill models SIMAP (French-McCay 2003, 2004) and OSCAR (Reed et al. 1999), and, for example, in the work of Paris et al. (2012). Making these assumptions might be justified depending on the applications of interest, and thus, we are not questioning the quality of the findings of these works. We are rather merely providing examples of major works making these assumptions. We provide herein theoretical arguments addressing these assumptions focusing on experimental data (laboratory or field) and the physics.

## 2. Hydrodynamics at the water-ice interface

At the ice-water interface, the horizontal water velocity is equal to that of ice velocity, which is due to the so-called no-slip velocity (Afenyo et al. 2016). Thus, for shore-fast ice (or land ice), the water velocity is zero at the ice-water interface, and in the case of packed-ice (i.e., free flowing ice), the water velocity at the ice-water interface is equal to the velocity of the ice block. Thus, what really matters is the relative ice-water velocity. For this reason, we will consider a coordinate system fixed to the ice so that the ice velocity is neglected and water is moving underneath it at its relative velocity.

At the water-ice interface, a boundary layer (BL) forms (Roach et al.

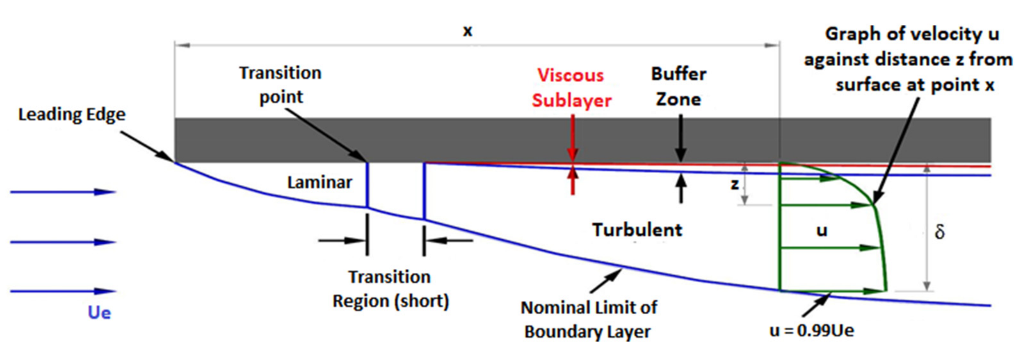


**Fig. 1.** Boundary layer formed when water passes under smooth ice. The velocity $U_e$ is the current velocity away from ice.