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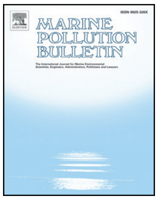

Oil droplets transport due to irregular waves: Development of large-scale spreading coefficients

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ABSTRACT

The movement of oil droplets due to waves and buoyancy was investigated by assuming an irregular sea state following a JONSWAP spectrum and four buoyancy values. A technique known as Wheeler stretching was used to model the movement of particles under the moving water surface. In each simulation, 500 particles were released and were tracked for a real time of 4.0 h. A Monte Carlo approach was used to obtain ensemble properties. It was found that small eddy diffusivities that decrease rapidly with depth generated the largest horizontal spreading of the plume. It was also found that large eddy diffusivities that decrease slowly with depth generated the smallest horizontal spreading coefficient of the plume. The increase in buoyancy resulted in a decrease in the horizontal spreading coefficient, which suggests that two-dimensional (horizontal) models that predict the transport of surface oil could be overestimating the spreading of oil.

1. Introduction

Waves play an important role in the transport and fate of oil spills (Sobey and Barker, 1997; Korotenko et al., 2000; Wang et al., 2005). The water velocity engendered by waves causes the shearing of the oil slick and its breakup into droplets, the smaller of which sink deeper into the water column. Understanding the effects of waves on slicks at sea has been hampered by logistical difficulty, as it is not possible to have sufficient measurements to have a predictive relation between the sea state and the oil droplet distribution in the water column. This has led to extensive wave tank studies where such relations were sought and developed (Coulaloglou and Tavlarides, 1977; Millies and Mewes, 1999; Pohorecki et al., 2001). Regardless of the success of these relations at the field scale, there are very few works that explored the effect of waves on the transport and spreading of oil droplets at sea. The vast majority of works (and the current practice) computes the bulk transport of oil based on wind direction and speed, and predicts the spreading using empirical coefficients based on the experience of the operator (ASCE Task Committee, 1996; Boufadel et al., 2014). However, there is no assurance that such values could be used at another location or even at the same location under different sea states.

Elliot et al. (1986) briefly addressed the direct effect of waves on transport. Another one Walter and Blanch (1986) used a depth averaged formulation to account for transport due to waves. Boufadel et al. (2006) and (2007) investigated the effects of regular waves on dispersed oil. They explained, among other, the "comet" shape of spills based on the droplet sizes and the Stokes drift; as the large droplet stay closer to the surface, they get entrained forward by the Stokes drift, which is maximum at the surface. The smaller droplets, thus, trail behind, giving the appearance of a comet. The current work expands on the previous work by considering irregular waves, which is more realistic. This also requires using different numerical techniques for tracking the water surface and for obtaining the velocity at the water surface. In particular, velocity values in irregular waves cannot be referred to the Mean Water Level (MWL), as the MWL is an ensemble-engendered quantity, and the water surface could be much higher or much lower than the MWL.

We assume the sea to be well represented by the empirical spectrum JONSWAP (Hasselmann et al., 1973), and particle tracking techniques was adopted within a Monte Carlo framework. We focus on analyzing the role of the turbulent diffusion in the mixed layer in affecting the spatial distribution of the oil droplets. We also treat the oil as consisting of a large number of identical particles, and we consider situations where they are buoyant.

The layout of this paper is as follows: first the fundamentals of droplet transport at sea and justification of the choice of the JONSWAP spectrum are presented. Then the details of numerical implementation are given such as the range of frequency of the JONSWAP spectrum and the cases investigated in this paper by varying buoyancy velocity and

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eddy diffusivity. Finally, the simulation results are presented to address the roles of diffusivity and buoyancy in oil transport.

2. Methodology

2.1. JONSWAP wave spectrum

The sea state can be defined in a variety of ways. For example, one may use the Beaufort scale (Singleton, 2008) that describes the sea state based on qualitative terms. It is an empirical yet expedient scale. A more quantitative means is the wave magnitude Fourier spectrum (Phillips, 1985), which is essentially a plot of wave height as function of the corresponding wave period or wave length. The earliest work on the spectrum was reported in the seminal work of O.M. Philips (see in Phillips, 1985), who surmised that the spectrum becomes "saturated" at high wave frequency or high wave numbers. Pierson and Moskowitz (1964) produced the now called the P-M spectrum. They postulated that given enough time (roughly 10,000 wave periods), a steady wind would come to an equilibrium with waves, defining a "fully developed" sea. To obtain their spectrum of a fully developed sea, they used accelerometers on British weather ships in the North Atlantic. Experiments conducted later in the North Sea (in German Bight) led Hasselmann et al. (1973) to develop a fetch-limited and time-variant spectrum known as the JONSWAP spectrum, rejecting the idea of a "fully developed sea". Though the Bight concerned is only about 20 m deep, the JONSWAP is termed a deep water spectrum because the wavelengths used for measurement were relatively small. Another spectrum, the TMA spectrum was proposed by Bouws et al. (1985) building on the work by Kitaigordskii et al. (1975). The TMA spectrum is a modified version of the JONSWAP spectrum, albeit for water of finite depth. The advantage of the JONSWAP spectrum is that it represents a young sea state, and is thus more common than the "fully developed" sea (Holthuijsen, 2007). The expression for the JONSWAP spectrum is:

$$E(f) = (2\pi)^{-4}\alpha g^2 f^{-5} \exp\left[\frac{-5}{4}\left(\frac{f}{f_m}\right)^{-4}\right]\Gamma(f), \tag{1}$$

where f is the frequency (inverse of wave period), $\Gamma(f)$ is the JONSWAP-peak enhancement function given as:

$$\Gamma(f) = 3.3^{\exp\left[\frac{-\left(1-\frac{f}{f_m}\right)^2}{2\sigma^2}\right]}, \tag{2}$$

where $\sigma = 0.07$ for $f \le f_m$ and $\sigma = 0.09$ for $f > f_m$, g is the acceleration due to gravity and the parameter f_m is the peak frequency given as:

$$f_m = 3.5\tilde{X}^{-0.33}, \tag{3}$$

where $\tilde{X}$ is the modified fetch parameter given as:

$$\tilde{X} = \frac{gX}{U_{10}^2}, \tag{4}$$

where X is the fetch (m) and U_{10} is the wind velocity (m/s) at 10 m above the sea surface.

The parameter α is the traditional Philip's constant (1961) but now evaluated as a function of the modified fetch parameter:

$$\alpha = 0.076\tilde{X}^{-0.22}, \tag{5}$$

note that the JONSWAP spectrum reduces to the Li et al. (2008) spectrum when γ is equal to 1.0. As the upper cutoff of the JONSWAP spectrum is 1.0 Hz (thus the wave period $T = \frac{1}{f}$ is larger than 1.0 s), it represents only gravity waves, and does not extent into capillary waves whose period is usually less than 0.25 s (Dean and Dalrymple, 1984).

It is important to note that the spectrum is based on the linear wave theory, also known as first-order theory (Dean and Dalrymple, 1984). This is understandable as using higher order theories makes the superposition of more than a few waves extremely complicated (Sharma and Dean, 1981).

Once a spectrum is found, all the hydrodynamic properties could be defined based on it. In particular, the wave amplitude a_i for a given frequency f_i (or wave period $T_i = \frac{1}{f_i}$) could be obtained simply as:

$$a_i = \sqrt{2E(f_i)\Delta f}, \tag{6}$$

where Δf is the frequency increment.

Using the linear theory, the expression for the water free surface, η, for a set of 'n' waves is:

$$\eta = \sum_{i=1}^{n} a_i \cos(k_i x - \omega_i t + \phi_i), \tag{7}$$

where $\omega_i = 2\pi f_i$ is the radian frequency, $k_i = \frac{2\pi}{l_i}$ is the wave number, l_i is the wave length, and ϕ_i is the (random) phase angle. Eq. (7) indicates that the elevation $z = 0$ represents the Mean Water Level (MWL), which coincides with the Still Water Level (SWL) in deep sea. But the MWL is a theoretical line, and when the water surface (water line in 2D vertical) is above it, one cannot obtain the water velocity between the MWL and the water surface. Boufadel et al. (2006) and (2007) used a second-order Taylor expansion from the MWL to obtain the velocity between the MWL and the water surface above it. The approach was attempted herein but did not lead to correct results, because in irregular seas, the water surface could be much higher than the MWL and it could remain there for a long time. Therefore, extrapolating for large distances (above the MWL) and for long durations lead to numerical errors. For this reason, we used the concept known as Wheeler stretching (Wheeler, 1969).

In the Wheeler stretching method, when the water surface, η, is above the MWL the water kinematics is computed by "stretching" the MWL to the instantaneous water line. The Wheeler stretching gave good agreement with laboratory experiments and has comparable results to the computationally intensive kinematic boundary condition fit method (Forristall, 1985).

Applying Wheeler stretching, for each given wave 'i' the velocity expressions takes the form:

$$u_i = a_i \omega_i e^{k_{in}(z-\eta)} \cos(k_{ni} x - \omega_i t + \varphi_i), \tag{8a}$$

$$w_i = a_i \omega_i e^{k_{ni}(z-\eta)} \sin(k_i x - \omega_i t + \varphi_i). \tag{8b}$$

Note that "z" is negative below the MWL. Thus, the velocity components at any (x, z) location are given by the superposition of the corresponding components due to individual waves as given by Eq. (8a) and Eq. (8b). Thus, one obtains:

$$u_{\text{wave}} = \sum_i u_i \tag{9a}$$

$$w_{\text{wave}} = \sum_i w_i. \tag{9b}$$

2.2. Net water transport

A water "particle" at sea (i.e., a small water mass) exhibits a net forward motion known as the Stokes drift (after its discoverer Stokes who first derived a theoretical description for this drift in 1847, Dean and

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