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Effects of rainfall on oil droplet size and the dispersion of spilled oil with application to Douglas Channel, British Columbia, Canada

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ABSTRACT

Raindrops falling on the sea surface produce turbulence. The present study examined the influence of rain-induced turbulence on oil droplet size and dispersion of oil spills in Douglas Channel in British Columbia, Canada using hourly atmospheric data in 2011–2013. We examined three types of oils: a light oil (Cold Lake Diluent - CLD), and two heavy oils (Cold Lake Blend - CLB and Access Western Blend - AWB). We found that the turbulent energy dissipation rate produced by rainfalls is comparable to what is produced by wind-induced wave breaking in our study area. With the use of chemical dispersants, our results indicate that a heavy rainfall (rain rate > 20 mm h^{-1}) can produce the maximum droplet size of 300 μm for light oil and 1000 μm for heavy oils, and it can disperse the light oil with fraction of 22–45% and the heavy oils of 8–13%, respectively. Heavy rainfalls could be a factor for the fate of oil spills in Douglas Channel, especially for a spill of light oil and the use of chemical dispersants.

1. Introduction

Oil spills at sea generally take the form of a thin layer of oil on the sea surface. The thin layer is better known as an oil slick (Tkalick and Chan, 2002). Advective and dispersive processes break up the slick into smaller patches and, eventually, small droplets (Delvigne and Sweeney, 1988). In near shore and coastal waters, wave breaking is a well-known process that contributes to disaggregation of oil slicks (Li and Garrett, 1998; Tkalick and Chan, 2002; Li et al., 2007; Zeinstra-Helfrich et al., 2015). As reported by Delvigne and Sweeney (1988), in addition to breaking waves, several other hydrodynamic processes, such as wind stress, tidal currents, and non-breaking waves, also contribute to the breakup of oil slicks.

When raindrops fall on the sea surface, they transfer kinetic energy from the air to the sea (Zappa et al., 2009). Small raindrops that have a weak vertical impact velocity are insufficient to overcome the surface tension of the sea surface water; therefore, the freshwater will accumulate on the sea surface. Larger raindrops with higher fall velocity are able to penetrate into the ocean with little or no splashing (Prosperetti and Oğuz, 1993; Soloviev and Lukas, 2006). The raindrop penetration distorts the sea surface layer and produces turbulence mixing. The intensity and depth of the mixing mainly depends on the raindrop size and the vertical impact velocity (Houk and Green, 1976). According to previous studies, large raindrops with a radius of 1–3 mm, even in quite small numbers, are able to generate noticeable turbulence intensity with a depth of 100–300 times of the raindrop radius (Green and Houk, 1979). For example, Zappa et al. (2009) reported that a heavy rain event with a rate of 30–60 mm h^{-1} significantly enhanced the gas exchange between the air and the ocean. In their study, the instantaneous turbulent energy dissipation rate is comparable to, or even higher than, that caused by typical breaking waves. In addition, the presence of wind accelerates raindrops and thus increases the horizontal shear when the raindrops reach the sea surface. Caldwell and Elliott (1971) pointed out that a rain event of several centimeters per hour could create shear stress on the sea surface comparable to that caused by wind speed, which can be as high as 10–20 m s^{-1}. Moreover, raindrops falling through the boundary layer of the wind profile are able to enhance the wind-induced stress by 10–15% with a rain rate of 30 mm per hour (Caldwell and Elliott, 1972).

Many studies have investigated the effects of the rain-induced turbulent mixing on physical and biological processes in the surface layer of the ocean. Green and Houk (1979) observed that organic surface films composed of original hexadecanol could quickly be dispersed within 5 min by a rain event with a drop size of 2–6 mm and a fall rate of 30–40 mm h^{-1}. Rainfall was also found to effectively increase the gas exchange between air and sea (Ho et al., 2000; Takagaki and Komori, 2007; Zappa et al., 2009). However, few studies, except

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Murphy et al. (2015), who investigated the splash and oily marine aerosol production by raindrops impacting oil slicks, examine the role of rainfalls on the disaggregation of an oil slick, which we focus on in the present paper.

The layout of this paper is as follows. First, we describe the rainfall and wind conditions in our study area, followed by models of turbulence energy dissipation rates due to rain falls and wind-induced wave breaking, and the relationships of the maximum oil-droplet sizes with the dissipation rate. Using the models, we then examine the contributions of rainfall and wave breaking to the maximum size of oil-droplet and the dispersion rate with air forcing data.

2. Study site

Our study area is Douglas Channel, a major fjord system on the northern coast of British Columbia, Canada (Fig. 1). The Northern Gateway Pipeline Project proposed by Northern Gateway Pipelines Inc. involves building a twin pipeline system to transport petroleum products from the province of Alberta to a marine terminal at Kitimat, which is located at the head of Douglas Channel (Emerson, 2010). The maritime shipping routes of the project would pass through the Douglas Channel fjord system, which is environmentally sensitive to oil spills.

The onshore flow of Pacific airstreams dominates the climate of this region, and large amounts of precipitation (mostly in the form of rain) fall whenever a Pacific cyclone approaches (Hare and Thomas, 1979; Fissel et al., 2010). In this region, the rainfall rate is high, and the annual-average precipitation from 1966–2002, at the Kitimat weather station (Fig. 1), was 2734 mm. The observed monthly maximum at the time (in October) was 965 mm (Fissel et al., 2010). At Hartley Bay (Fig. 1), the observed data (1973–1996) showed that the annual-average precipitation amount was 4492 mm and the maximum monthly rainfall was 1242 mm (Fissel et al., 2010). The precipitation was 3 times higher than the global annual-average precipitation amount of 912 mm (Huffman et al., 1997).

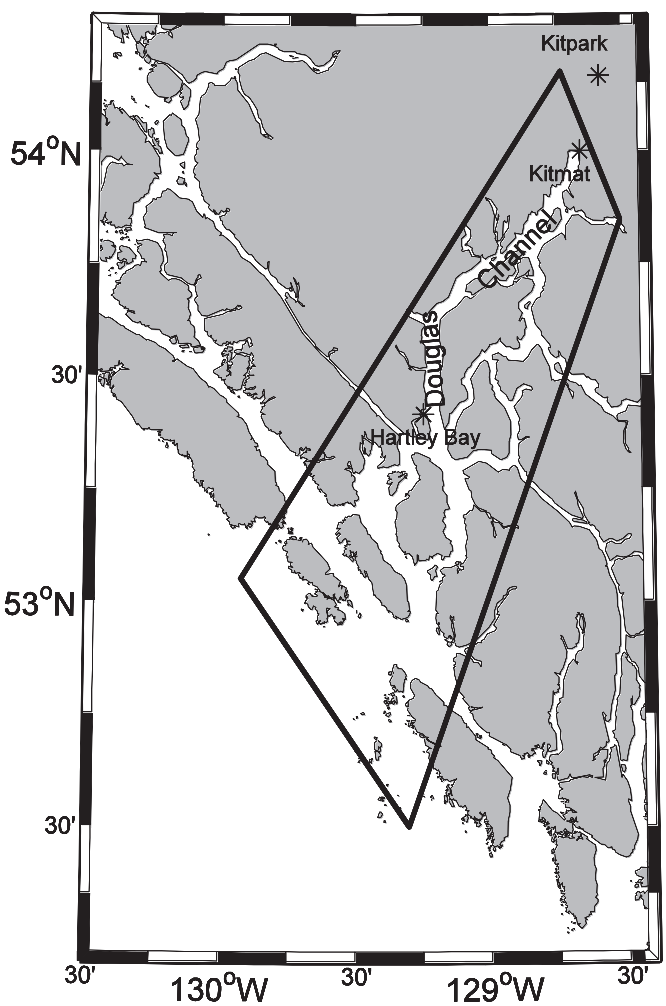

Fig. 1. Study domain. The box indicates the area where rain data are analyzed.

The wind speeds in this region, however, are considerably lower than those on the open coast of the northeastern Pacific. Using historical wind data from 1996–2005, Fissel et al. (2010) reported that the maximum wind speed was only 11.1 m s^{-1} near Kitimat. The precipitation rate usually peaks in the fall (October–December), whereas the strongest wind speeds typically occur in winter (January–March). The difference in the timing of the intense wind and rainfall would make it possible for rainfall to have an important role in the breakup of oil slicks in this area.

3. Methods and materials

3.1. Turbulent energy dissipation rate under rainfall

To describe the vertical distribution of the turbulent energy dissipation rate under wind-driven breaking waves in the upper ocean layer, Craig and Banner (1994, hereafter CB94) developed a parameterization model based on the Mellor-Yamada turbulence closure model (Mellor and Yamada, 1982). The turbulence closure model is associated with the surface diffusion boundary conditions for wave breaking. In CB94, the energy dissipation rate decays with inverse depth to the power of 3.4,

$$\varepsilon_b = 2.4(\alpha_{CB} u_*^3) z_0^{2.4} (z_0 + z)^{-3.4} \tag{1}$$

where $\varepsilon_b$is the turbulent energy dissipation rate due to wave breaking (unit: $m^2\ s^{-3}$); $\alpha_{CB}$is the wave breaking factor (a dimensionless constant with a default value of 100); z_0 is the surface roughness (unit: m); and z is depth below the sea surface (positive downward, unit: m). The wind-induced surface friction velocity u_*(unit: m s^{-1}) is estimated using $u_* = \sqrt{\tau_w/\rho_w}$, where $\tau_w$is the wind-induced shear stress, given as:

$$\tau_w = \rho_a C_d U_{10}^2 \tag{2}$$

in which $\rho_a$is the air density ($\rho_a = 1.25$ kg m^{-3}); $C_d$is the drag coefficient; and $U_{10}$is the wind speed (m s^{-1}) at 10 m above the sea surface. In this study, the value of $C_d$as a function of wind speed is obtained from Smith (1988).

Recently, the turbulence model presented in CB94 was modified by Zappa et al. (2009, hereafter Z09). The modification simulated the vertical distribution of the turbulent energy dissipation rate due to rainfall by replacing the energy flux due to breaking waves with the kinetic energy flux (KEF, unit: J $m^{-2}\ s^{-1}$) caused by raindrops. The modified form of the model equation reads:

$$\varepsilon_v = 2.4\left(\frac{KEF}{\rho_w}\right) z_0^{2.4} (z_0 + z)^{-3.4} \tag{3}$$

where $\varepsilon_v$is the rain-induced turbulent energy dissipation, and ρ_w is the sea water density. Following Z09, the KEF can be estimated from:

$$KEF = \frac{\rho_r}{2}\frac{\pi}{6}\int_0^{D_{\max}} v^3 \cdot D^3 \cdot N(D) \cdot dD \tag{4}$$

where $\rho_r$is the water density of rain ($\rho_r = 1000$ kg m^{-3}); D is the diameter of the raindrops with a unit of m; $D_{\max}$is the maximum diameter of the raindrops ($D_{\max} = 0.006$ m according to Villermaux and Bossa (2009)); $v$is the terminal velocity of rain drops at the sea surface in