Marine Pollution Bulletin xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

In situ estimates of horizontal turbulent diffusivity at the sea surface for oil transport simulation

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ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 4 October 2016
Accepted 10 October 2016
Available online xxxx

Keywords:
In situ estimates
Horizontal diffusivity
Sagami Bay
Oil transport simulation

ABSTRACT

Despite many previous in situ estimates of horizontal diffusivity below the sea surface, horizontal diffusivity at the sea surface, which is a parameter required in the prediction of oil diffusion, has not been formulated. This study conducted in situ estimations to quantify horizontal diffusivity at the sea surface. To measure the horizontal diffusivity at and below the sea surface, clusters of thin sponge rubbers (simulating spilled oil), together with drifting buoys, were deployed on successive occasions in Sagami Bay, Japan. The experimental results revealed that horizontal diffusivity was larger at the sea surface than below. Based on the results, a procedure for estimating horizontal diffusivity at the sea surface was introduced to predict the diffusion of spilled oil, which was verified using numerical simulations. The simulation results showed good agreement with observations, suggesting the procedure is appropriate for the estimation of horizontal diffusivity at the sea surface.

1. Introduction

Serious oil spill incidents from tankers have reduced in both number and quantity since peaking in the 1970s, but they do still occur (Musk, 2012). For example, the Prestige oil tanker spill occurred off the Iberian Peninsula in 2002, and the Hebei Spirit oil tanker spill happened off the western coast of Korea in 2007. In addition to tanker-related spillages, oil spill incidents involving other types of ship have been of concern in recent years. Given that the recent upsizing of cargo vessels means that some now carry about 10,000 kL of fuel, similar to some oil tankers, and that many double-hulled oil tankers are now over 20 years old, the risk of a serious large-scale oil spill incident is increasing.

To prepare for large-scale oil spill incidents, the Ministry of Land, Infrastructure, Transport, and Tourism in Japan has deployed three oil recovery vessels that can reach any of the waters surrounding Japan within 48 h. Reliable forecasting of spilled oil is necessary for a coordinated response plan for oil recovery by the oil recovery vessels. Therefore, an oil transport simulation model based on a Lagrangian oil particle model has been developed (Matsuzaki and Fujita, 2014).

The three major factors that affect the transport of oil on the sea surface are formulated in this model, i.e., tidal-current-, ocean-current-, and wind-driven advection, mechanical spreading, and turbulent diffusion. Turbulent diffusion of oil is calculated using a random walk technique in this model, as in many other oil transport simulations (e.g., Proctor et al., 1994, Varlamov et al., 1999, Chao et al., 2003, Sotillo et al., 2008, Wang et al., 2008, Guo and Wang, 2009). In the random walk technique, horizontal diffusivity is given as a numerical coefficient, which has exclusive influence on the results of the simulation. According to the ASCE task Committee on Modeling of Oil Spills of the Water Resources Engineering Division (1996), the value of horizontal diffusivity varies within the range of 1–100 m^2/s; thus, the simulated oil diffusion area also varies by a magnitude of the order of 10^2. Other previous studies have not indicated how best to estimate the horizontal diffusivity of oil.

Many in situ estimates of horizontal diffusivity have been conducted in the ocean using passive tracer and drifting buoy experiments. For example, Okubo (1971) conducted in situ estimates using dye and described the diffusion characteristics at sea. Yanagi and Higuchi (1982) also conducted experiments using 50 wooden floats that were 60 cm square with a resistance board situated 1 m beneath the water surface. LaCasce and Bower (2000) computed horizontal diffusivity based on experiments using subsurface floats. The length of their drifting buoys was about 1.5 m, and they measured the mean ocean current vertically. Michida et al. (2009) conducted experiments using GPS-tracked surface drifters with a drogue at depths of 1, 6, 11, and 16 m beneath the water surface. Ohlmann et al. (2012) also conducted experiments using a GPS-tracked surface drifter with a drogue 1 m below the water surface. Nencioli et al. (2013) conducted experiments using GPS-tracked subsurface drifters tethered to a holey-sock drogue centered at a depth of 15 m.

In many previous studies, passive tracers such as dyes and drifting buoys have been positioned in the upper mixed layer, not at the sea surface, meaning the computed values were of subsurface horizontal

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http://dx.doi.org/10.1016/j.marpolbul.2016.10.026

diffusivity. However, external factors such as waves or wind-induced currents are considered to affect horizontal diffusivity at sea and therefore, surface horizontal diffusivity should be greater than that underwater. Michida et al. (2009) stated, "it is natural that the horizontal diffusivity has dependence on the depth of the sea," but they did not prove this assertion quantitatively. Given that the value of horizontal diffusivity at the sea surface is required for reasonable simulation of the turbulent diffusion of oil, drifting objects that are more appropriate should be employed for in situ estimations of surface horizontal diffusivity.

To measure only turbulent diffusion at the sea surface, drift objects for in situ estimations should have the same drift characteristics as an oil slick, which is strongly affected by wind. Therefore, in our previous work, in situ estimations using pseudo oil objects were conducted in the mouth of Tokyo Bay to formulate an expression for surface horizontal diffusivity (Matsuzaki and Fujita, 2013), and hindcast simulations of an oil spill incident off the western coast of Korea were conducted using this formulation (Matsuzaki and Fujita, 2014).

Based on the above two previous works, this study conducted in situ estimates using two types of cluster of GPS receiver: tracked sea surface drifters made of thin sponge rubber and subsurface drifters, to compare the horizontal diffusivity at and below the sea surface. A formulation for surface horizontal diffusivity was derived and applied to our numerical simulation model. Hindcast simulations of an oil spill incident off the western coast of Korea coast (e.g., International Tanker Owners Pollution Federation Ltd., ITOPF, 2008) were conducted to discuss the applicability of this formulation.

2. Materials and methods

2.1. In situ estimates

The in situ estimates were conducted in Sagami Bay, Japan (see Fig. 1). The drifting oil was represented by pseudo oil objects made of sponge rubber sheet (INOAC EPDM Type, Part number E-4388, Hardness 20 ± 5, Density 150 kg/m^3). To estimate horizontal diffusivity at the sea surface for the simulation of oil diffusion, the drift characteristics of the pseudo oil objects must be the same as a real oil slick, and they must move with the water surface primarily under the effect of wind-driven currents. Thus, to ensure the pseudo oil object had the appropriate wind coefficient, we conducted drift experiments in a wind channel tank in a previous study (Matsuzaki and Fujita, 2013). The pseudo oil object used in this study was 1 m in diameter and 10-mm thick (see Fig. 2). Wind-driven speed of spilled oil is estimated to be 3% of the wind speed 10 m above the sea surface (e.g., ASCE Task Committee on Modeling of Oil Spills of the Water Resources Engineering Division, 1996). Thus, the drift factor of the pseudo oil object was set at 3% of the wind speed. The measured scale of horizontal diffusivity is dependent on the size of the pseudo oil object; thus, we paid particular attention to ensure that small eddies (scale: <1 m) were averaged by the size of the pseudo oil object. A small GPS logger (model number: WBT-202, dimensions: 64 × 40 × 17 mm, weight: 55 g, accuracy CEP (Circular Error Probability): 2.0 m (SBAS) / 2.5 m (stand-alone), Wintec Co. Ltd., Taiwan) was attached to each pseudo oil object.

Drifting buoys (Fig. 2) were also used to obtain estimates of the underwater horizontal diffusivity. These buoys used the same type of GPS logger, and their drogue was set 1.5 m below the water surface to measure underwater turbulence. The cylindrical-shaped buoy was 89 mm in diameter and 40 cm long. The size of cross-shaped drogue was 91 × 45 cm.

In each experimental case, the pseudo oil objects were followed by a research vessel, which recorded local wind and current, and the GPS loggers recorded the position of each pseudo oil object and drifting buoy. The wind speed and direction data, recorded every second and averaged over 10-min intervals, were measured on the research vessel using an anemometer (Model number: WindSonic PGWS-100, Gill Instruments Ltd., UK) positioned 4 m above the sea surface. Current speed and direction profiles from 1.5 to 41.0 m below the sea surface were measured using an Acoustic Doppler Current Profiler (Model number: Sentinel ADCP 1200 kHz, Teledyne RD Instruments, USA) installed on the research vessel. The measurement data were averaged over 10-min intervals. The directions of the wind and sea currents were corrected for the vessel's movement using a GPS compass (model number: V100, Hemisphere GNSS, USA).

Table 1 shows the experimental conditions. The experiments, conducted between December 2013 and January 2014, comprised seven deployments of the pseudo oil objects and four deployments of the drifting buoys, with drift times varying between 2.3 and 5.3 h. For safety reasons, the experiments were conducted only under calm conditions, i.e., wind speed <10 m/s.

The values of horizontal diffusivity K_H of the pseudo oil objects and the drifting buoys were calculated every 10-min at 1-h intervals based on the temporal variation in horizontal dispersion of the objects or buoys following Okubo (1971):

$$K_H = \frac{1}{2}\frac{\partial \sigma^2}{\partial t} \tag{1}$$

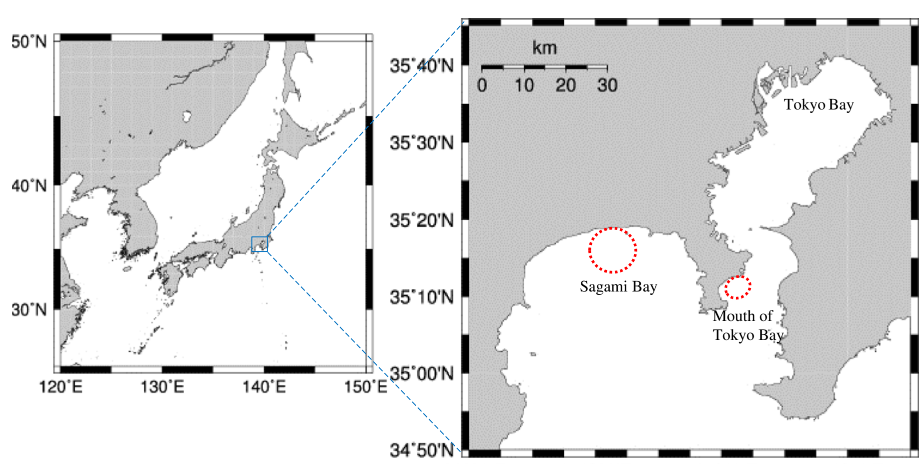

Fig. 1. Study area showing location where in situ estimates were performed in Sagami Bay, Japan. The in situ estimates conducted at the mouth of Tokyo Bay in Yokosuka were part of a previous study (Matsuzaki and Fujita, 2013).