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Fate of microplastics and mesoplastics carried by surface currents and wind waves: A numerical model approach in the Sea of Japan

Shinsuke Iwasaki[a,*], Atsuhiko Isobe[a], Shin'ichiro Kako[b], Keiichi Uchida[c], Tadashi Tokai[c]

[a] Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-Koen, Kasuga 816-8580, Japan
[b] Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan
[c] Tokyo University of Marine Science and Technology, 4-5-7 Konan, Minato-ku, Tokyo 108-8477, Japan

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A B S T R A C T

A numerical model was established to reproduce the oceanic transport processes of microplastics and mesoplastics in the Sea of Japan. A particle tracking model, where surface ocean currents were given by a combination of a reanalysis ocean current product and Stokes drift computed separately by a wave model, simulated particle movement. The model results corresponded with the field survey. Modeled results indicated the micro- and mesoplastics are moved northeastward by the Tsushima Current. Subsequently, Stokes drift selectively moves mesoplastics during winter toward the Japanese coast, resulting in increased contributions of mesoplastics south of 39°N. Additionally, Stokes drift also transports micro- and mesoplastics out to the sea area south of the subpolar front where the northeastward Tsushima Current carries them into the open ocean via the Tsugaru and Soya straits. Average transit time of modeled particles in the Sea of Japan is drastically reduced when including Stokes drift in the model.

1. Introduction

Plastic waste accounts for about 70% of marine debris. Because of exposure to ultraviolet radiation and mechanical erosion, it is gradually degraded into small plastic fragments that can be categorized by size as macroplastics (greater than a few centimeters), mesoplastics (> 5.0 mm), microplastics (< 5.0 mm), and nanoplastics (less than a few micrometers) (Gregory, 1996; Andrady, 2011; Cole et al., 2011). Small plastic fragments, called "primary microplastics" by Cole et al. (2011), are also used in the manufacturing of cosmetics and cleaning products and in air blasting (Gregory, 1996; Andrady, 2011). The term "small plastic fragments" is used hereafter to refer to all fragments smaller than mesoplastics. Of note, microplastics smaller than 1.0 mm are of similar size to food organisms such as zooplankton and thus, they might be ingested by a wide range of marine organisms (e.g., Browne et al., 2008; Boerger et al., 2010; Murray and Cowie, 2011; Cole et al., 2015; Desforges et al., 2015). Current knowledge of the ecological impact of microplastics is poor. However, the true scale of their damage might materialize in the future because they never completely disappear from the environment, and because the abundance of microplastics will increase gradually unless the discharge of plastic waste ceases.

To predict the potential influence of marine plastic pollution it is critical to elucidate the sources, fate, and accumulation zones of small plastic fragments, where the harm to marine organisms might be most severe. However, few studies on the transport processes of buoyant small plastic fragments have considered the motion in the turbid uppermost layer of the ocean. The combination of a particle tracking model (PTM) and surface ocean currents provided by ocean reanalysis products or satellite observations is inadequate for simulating the movement of small plastic fragments, although such combinations have been used widely in reproducing the oceanic transport of relatively large marine debris (e.g., Kubota, 1994; Maximenko et al., 2012; Kako et al., 2014). Difficulty arises from the fact that pelagic small plastic fragments are composed mostly of polyethylene or polypropylene, which are less dense than seawater (Isobe et al., 2014); thus, they move within the uppermost layer (depth: < 5 m) of the water column (Reisser et al., 2015). Isobe et al. (2014) suggested that small plastic fragments are carried partly by the mass transport (Stokes drift) generated in the uppermost layer in response to wind waves, as well as by ocean currents that extend into deeper layers. However, the effects of Stokes drift are not incorporated in either the ocean reanalysis products used widely by the oceanographic community (e.g., Usui et al., 2006; Chassignet et al., 2007; Miyazawa et al., 2009; Hirose et al.,

* Corresponding author.
E-mail addresses: iwasaki@riam.kyushu-u.ac.jp (S. Iwasaki), aisobe@riam.kyushu-u.ac.jp (A. Isobe), kako@oce.kagoshima-u.ac.jp (S. Kako), kuchida@kaiyodai.ac.jp (K. Uchida), tokai@kaiyodai.ac.jp (T. Tokai).

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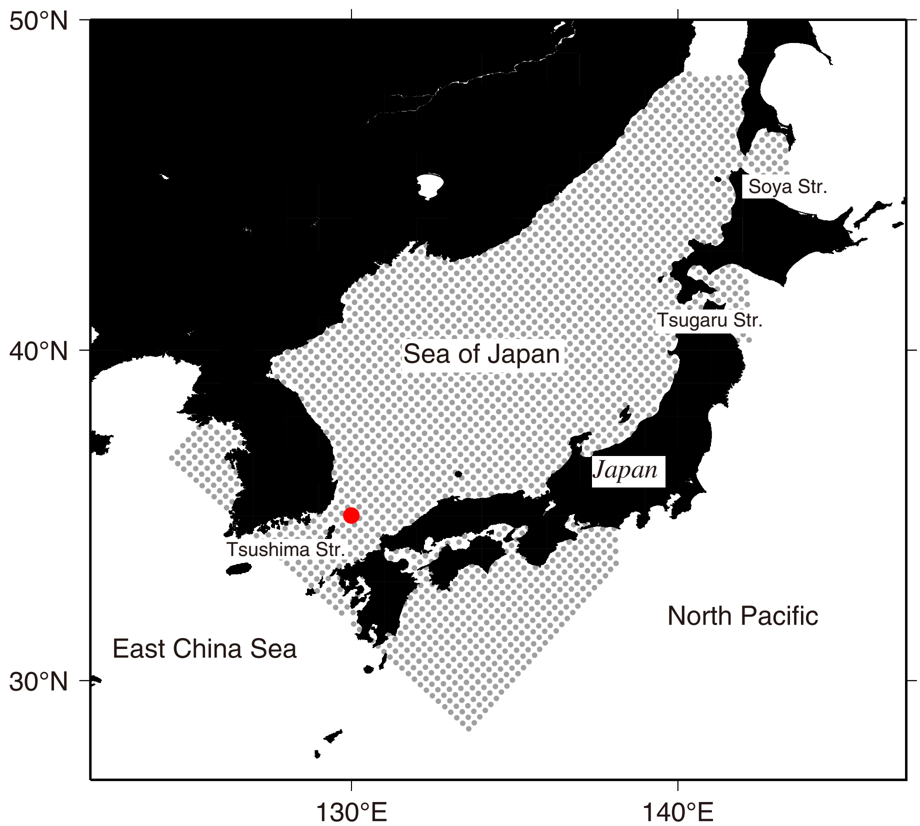

Fig. 1. Model domain of the PTM experiments (stippled). Red dot indicates the release position of the modeled particles in the Tsushima Strait. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2013) or the satellite-derived ocean currents deduced by geostrophy (e.g., Bonjean and Lagerloef, 2002; Willis and Fu, 2008).

The objective of the present study was to establish a numerical model that could reproduce the transport processes of small plastic fragments in the ocean. Currently, small plastic fragments are widespread throughout the world's oceans (Cózar et al., 2014; Eriksen et al., 2014; Isobe et al., 2014; Zhao et al., 2014; Enders et al., 2015; Isobe et al., 2015; Isobe et al., 2017). In particular, the East Asian seas around Japan are regarded as a “hot spot” of microplastics because their total particle count is estimated at 1,720,000 pieces km^{-2}, which is 16 times greater than the North Pacific and 27 times greater than the average of the world's oceans (Isobe et al., 2015). Thus, the Sea of Japan (Fig. 1) was chosen as the domain for the present numerical modeling because Isobe et al. (2015) surveyed areas within this ocean, and their data were used for the model validation in this study. This study had two advantages in addressing the numerical simulation of the distribution of small plastic fragments. The first was the use of a three-dimensional PTM in which the modeled particles were carried by a combination of the surface ocean currents provided by ocean reanalysis data and the Stokes drift computed separately in a wave model driven by satellite-derived winds. In addition to marine plastic pollution research, the transport process of small plastic fragments is an interesting topic in physical oceanography because transport systems within the highly turbid uppermost layer of the ocean are poorly understood. The second advantage was that the modeled results obtained in the present study were validated using data acquired during intensive mesoplastics and microplastics field surveys around Japan in 2014 and 2015. The incorporation of Stokes drift into the PTM was justified by comparison of the observed and modeled distributions of small plastic fragments. In addition, the comparison established the limitations of the presented model in reproducing the transport behavior of small plastic fragments.

2. Method

2.1. Modeled Stokes drift and surface ocean currents

The University of Miami wave model version 1.0.1 (UMWM) (Donelan et al., 2012; http://yyy.rsmas.miami.edu/groups/umwm/) was used to compute the Stokes drift over the model domain (20°–55°N, 115°–150°E) with 0.25° horizontal resolution. The UMWM resolves 37 wave frequencies from 0.0313–2.000 Hz with 32 directional bins. The wave model was driven by daily wind data acquired by the Advanced Scatterometer (ASCAT) (Kako et al., 2011; http://mepl1.riam.kyushu-u.ac.jp/~kako/ASCAT/NetCDF/) with 0.25° resolution in both latitude and longitude. The ETOPO1 (http://www.ngdc.noaa.gov/mgg/global/global.html) was used to provide the bottom topography and coastlines. The Stokes drift velocity ($\boldsymbol{U_{St}}$) in the UMWM is computed as follows:

$$\boldsymbol{U_{St}} = \int_0^{2\pi}\int_0^{\infty} \omega k^2 \frac{cosh\,[2k\,(d+z)]}{2sinh^2\,kd} F\,(k,\theta)\,dkd\theta, \tag{1}$$

where ω, k, θ, and $F(k,\theta)$ are the angular frequency, wave number, wave direction measured counterclockwise from east, and wavenumber variance spectrum, respectively, all of which are computed in the UMWM. The direction of Stokes drift is identical to θ. In addition, d and z represent the finite ocean depth and vertical position measured upward from the sea surface ($z = 0$), respectively. The computation was conducted for the period January 1 through December 31, 2014. The significant wave heights and Stokes drift were both saved once daily (00:00 UTC) during the computation period. The Stokes drift was dumped at 1-m vertical intervals from depths of 0 to 5 m.

The horizontal velocities computed by the Data assimilation Research of the East Asian Marine System (DREAMS; Hirose et al., 2013) in the uppermost layer (defined as depths > 4 m in Hirose et al.