

# A review of possible pathways of marine microplastics transport in the ocean<sup>1</sup>

Yanfang Li, Hua Zhang, and Cheng Tang

**Abstract:** Marine microplastics pollution has been a new challenge to marine environmental protection. The research results have shown that microplastics exist everywhere in the ocean. However, understanding of the transport of microplastics in the ocean, including coastal zones, is not clear. This paper provides a holistic overview of the modelling of microplastic transportation. The transport processes are complex, including surface drifting, vertical mixing, beaching, and settling. Besides the dynamic conditions of oceans, the transportation of microplastics is influenced by their physical characteristics, such as size, shape, and density. For buoyant particles, a Lagrange track model is used to simulate the surface drift process, considering current, windage effect, and Stokes drift. It is difficult to observe the vertical mixing process of microplastics because of their small size (<5 mm), therefore the parameters of the vertical mixing process in the model are still less known. Large accumulation of microplastics in sediments may be a result of settlement and entrainment. Also, biofilm formation can increase their density and thus, deposition. Considering sedimentation of microplastics is somewhat different from sediment deposition, some primary parameters (e.g., diffusivity, Stokes-drift, settling rate, biofouling rate) are required in future studies to better understand the transport of marine microplastics.

*Key words:* microplastics, pathways, drift, sedimentation, turbulence mixing.

## 1. Introduction

Marine microplastic pollution is of increasing ecological concern because of its chemical persistence and potential for biological ingestion (Cole et al. 2013; Setälä et al. 2014; Turner and Holmes 2015; Batel et al. 2016; Rochman et al. 2016). Microplastics have been found widely distributed in beaches, sea water, sediments, rivers (Cózar et al. 2014; Woodall et al. 2014; Lots et al. 2017; Schmidt et al. 2017; Vaughan et al. 2017; Yu et al. 2018; J.M. Zhao et al. 2018), and even in polar regions (Eriksson et al. 2013; Lusher et al. 2015; Waller et al. 2017). Recent studies have found a few microplastics in commercial bivalves, fishes, seabirds, and planktonic organisms (Lee et al. 2013; Wright et al. 2013; Lonnstedt and Eklov 2016; Galloway et al. 2017; S.Y. Zhao et al. 2018), which can be a threat to human health and the ecosystem. As a result of their high sorption capacities (Lee et al. 2014), microplastics are also a transport vector for toxic chemicals, such as persistent organic pollutants and heavy

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Y. Li, H. Zhang, and C. Tang. Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China.

**Corresponding author:** Yanfang Li (email: [yfli@yic.ac.cn](mailto:yfli@yic.ac.cn)).

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metals (Bakir et al. 2014; Wang et al. 2016), increasing the potential for these pollutants to enter the food web (Avio et al. 2015).

Marine microplastics have a wide distribution in the world. In coastal regions, land-based sources are considered to be a major contributor to marine plastic debris (Jambeck et al. 2015). For coastal areas, plastics can be directly released to the ocean by mismanaged dumping, or from shipping and recreational activities. Lebreton et al. (2017) estimated that between 1.15 and 2.41 million metric tonnes of plastic waste enters the ocean every year from rivers. Schmidt et al. (2017) revealed that rivers are a major pathway for plastic transport into the sea, which contributes between 80% and 94% of the total plastic load. The near-shore plastic concentrations have a strong correlation with the coastal population (Zhao et al. 2015; Pedrotti et al. 2016; Lots et al. 2017). The highest abundance of microplastic debris has been observed through numerous field surveys in rivers, harbor areas, tourist beaches, as well as nearby industrial areas (e.g., Fok and Cheung 2015; Zhao et al. 2015; Yu et al. 2016, 2018; Auta et al. 2017; Vaughan et al. 2017).

In the ocean, microplastics have a spatial distribution, both in the water column and sea bottom (e.g., Desforges et al. 2014; Woodall et al. 2014). In the Pacific Ocean there are several large areas of surface convergence, which become either natural accumulation or retention areas (Howell et al. 2012). In the North Pacific Ocean, a large calculated mean abundance (334 271 pieces/km<sup>2</sup>) and weight (5114 g/km<sup>2</sup>) of plastic pieces was observed in the eastern garbage patch in 2001 by Moore et al. (2001). Also, a western garbage patch was observed near the Kuroshio Extension by Yamashita and Tanimura (2007). Law et al. (2010) reported high plastic concentration in the western North Atlantic Ocean and Caribbean Sea subtropical convergence (1069–580 000 pieces/km<sup>2</sup>), which was based on the 22 years of ship-survey data from 1986 to 2008. Microplastics also have been found in polar water, sediment, and sea ice (Obbard 2018), and even in Arctic sea ice cores (Obbard et al. 2014).

To better understand the extent and fate of marine microplastics, several studies have been conducted to simulate the microplastic transport considering different processes (e.g., Ballent et al. 2012; Critchell et al. 2015; Critchell and Lambrechts 2016). This paper systematically reviews recent research results about the transport of microplastics in the ocean and links transport pathways and the fate of microplastics in marine environments. The objectives are to understand the underlying dynamics of marine microplastic transportation.

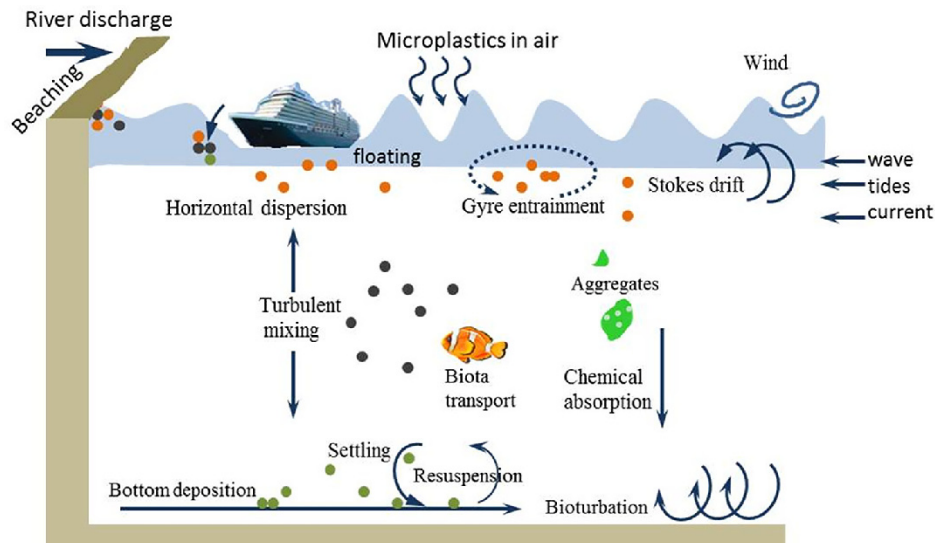
## 2. Microplastic transport pathways

Simulating the transport of microplastics is challenging because the transportation includes physical, chemical, and biological processes (Andrady 2011). Moreover, the physical properties (e.g., size, shape, density, buoyancy) of microplastics, which vary considerably, influence their transport (Ballent et al. 2012, 2013; Kowalski et al. 2016). The density values for microplastics range from <0.05 g cm<sup>-3</sup> for polystyrene foam to 2.1–2.3 g cm<sup>-3</sup> for polytetrafluoroethylene (Chubarenko et al. 2016). The density of microplastics greatly influences their distribution; microplastics with a lower density than seawater either float in the surface layer or are suspended in the water column with neutral density (Kukulka et al. 2012; Isobe et al. 2014), while microplastics with a higher density are concentrated in marine benthic environments (Fig. 1).

### 2.1. Surface drifting

More than half of the produced plastics have a buoyant density, which makes them predominantly float and mix at the surface layer of the oceans (Kukulka et al. 2012). The floating microplastics are transported passively by complex physical flows, resulting in very large variability in surface concentrations even in the heavily sampled western North

Fig. 1. Schematic of the transport pathways of microplastics in the ocean (modified from [Welden and Lusher 2017](#)).



Atlantic ([Law et al. 2010](#)) and eastern North Pacific Oceans ([Moore et al. 2001](#); [Howell et al. 2012](#)).

The transport process of floating plastics in the ocean is primarily determined by dynamic conditions, such as wind forcing and geostrophic circulation. The circulation pattern results in surface accumulation zones that are characterized by convergent particle paths, including plastic debris in subtropical gyres ([Howell et al. 2012](#); [Maximenko et al. 2012](#)). Many scientists have applied the transport models of waterborne materials and particles (oil spills, larvae, sediment) to study the Lagrangian trajectories of microplastics in the surface. [Lebreton et al. \(2012\)](#) used Lagrangian particle tracking model Pol3DD to simulate the floating debris in the world's ocean, which also revealed the high concentration in subtropical gyres. Previous model results have shown that the distribution of microplastics in the ocean can be predicted using Lagrange tracking models considering current, wind-driven current, and horizontal diffusion ([Potemra 2012](#); [Eriksen et al. 2013](#); [Law et al. 2010](#)).

A more subtle influence on the distribution of floating microplastics is that of the wind. Besides wind-driven current, wind waves induced Stokes drift, which can be locally responsible for microplastic transport in shallow coastal waters because of nonlinearity. Onshore transport of drifting microplastics in coastal waters is caused by a combination of surface residual currents, wind, and Stokes drift ([Isobe et al. 2014](#); [Liubartseva et al. 2016](#)). [Iwasaki et al. \(2017\)](#) used a wave model to calculate the Stokes drift and found that the transit time was drastically reduced by considering such drift. These results indicate that Stokes drift plays an important role in coastal microplastic transport.

## 2.2. Transport in the water column

Neutral microplastics float but are suspended in the water column, from sub-surface to deep water. Several studies indicate that a mismatch exists between observed and expected plastic concentrations in surface oceanic waters ([Eriksen et al. 2014](#); [Cózar et al. 2014](#)), which promoted research into the vertical distribution of microplastics within the water column. [Kanhai et al. \(2018\)](#) discovered that there was a vertical distribution of

microplastics in sub-surface waters (8–4369 m) of the Arctic Central Basin, and the highest microplastic abundance was in the mixed layer. [Enders et al. \(2015\)](#) investigated the vertical distribution of plastic and found that the mass of microplastics decreases faster than the abundance. The observation and simulations have confirmed that microplastics are vertically distributed within the upper water column due to wind-induced mixing ([Kukulka et al. 2012](#)). Apart from extrinsic turbulence regimes, the intrinsic characteristics of microplastics, such as size, shape, and particle density, also influence the microplastic vertical distribution through changing the advective velocity ([Ballent et al. 2012](#)).

The vertical distribution of microplastics in a water column is determined by the joint effects of advection transport and turbulent mixing forces. [Enders et al. \(2015\)](#) examined the vertical dispersion of microplastics and found different vertical dispersion results for different sizes of particles; the results showed that larger sized microplastic is much less affected by turbulent mixing. The General Ocean Turbulence Model (GOTM) results revealed that turbulent diffusivity is dependent on the physical properties of microplastics. For example, empirical calculation showed the effect of microplastic shape. Fibrous-shaped microplastics have the lowest velocity, followed by sheets and particles ([Reisser et al. 2015](#)).

### 2.3. Settling

Density difference will influence whether microplastics float in surface waters, are suspended in the water column, become beached in coastal areas, or sink to deep-sea sediment ([Galgani et al. 2015](#)). High-density microplastics are naturally non-buoyant, and usually deposited in sediments from beaches to the deep sea ([Woodall et al. 2014](#); [Zhang 2017](#)).

Microplastic particle properties (e.g., particle density, shape, and size range) are expected to cause different behavior than is observed for natural particles ([Zhang 2017](#); [Kooi et al. 2018](#)). Recent laboratory experiments have been conducted to investigate the characteristics and settling behavior of microplastics with high density ([Chubarenko et al. 2016](#); [Kowalski et al. 2016](#)). [Ballent et al. \(2012\)](#) experimentally tested the settling velocity of microplastic pellets with three different densities (1.06, 1.07, and 1.13 g cm<sup>-3</sup>, greater than the density of seawater). They found that settling velocity varied from 20 to 60 mm/s and increased with higher density in most cases. The laboratory-based studies showed a higher sinking rate of polyamide (1.14 g cm<sup>-3</sup>) than polyvinyl chloride (1.56 g cm<sup>-3</sup>), which indicated that the shape of the polymer particle strongly affects its sinking velocity ([Kowalski et al. 2016](#)). [Sagawa et al. \(2018\)](#) found that the average size of microplastics in bottom sediments was significantly smaller than that of beached particles. [Chubarenko et al. \(2016\)](#) reported that heavy microplastic particles take <18 h to settle through the water column in the central Gotland Basin (250 m), whereas polyethylene fibers spend about 6–8 months in the euphotic zone before sinking as a result of biofouling.

Moreover, microplastics are susceptible to biofouling. Microorganisms can rapidly aggregate on the surface of plastic debris and develop biofilm ([Andrady 2011](#); [Cole et al. 2013](#); [Zhang 2017](#)). [Cózar et al. \(2014\)](#) assumed that biofouling enhances microplastics' densities to such an extent that particles with densities lower than the density of seawater (e.g., polyethylene or polypropylene) can reach densities that match or exceed seawater density leading to slow sinking of the particles. [Morét-Ferguson et al. \(2010\)](#) also found that biofouling increased the density of plastic particles in the western North Atlantic. Additionally, biofilms can reduce the hydrophobicity of plastic particles making them more likely to sink ([Lobelle and Cunliffe 2011](#); [Cózar et al. 2014](#)), which may explain the occurrence of plastic particles that would normally float (e.g., polyethylene and polypropylene) in marine sediments. [Moore et al. \(2001\)](#) reported that subsurface trawls in the North Pacific gyre contained mostly biofilm filament-type plastics.

Finally, incorporation of microplastics into organic aggregates (Zhao et al. 2017; S.Y. Zhao et al. 2018), is another process that can increase sinking rate of low-density particles (Van Cauwenberghe et al. 2013). Based on the laboratory experiments, Long et al. (2015) found that sinking rate of microbeads (2  $\mu\text{m}$  polystyrene, density of  $1.05 \text{ g cm}^{-3}$ ) incorporated into diatom aggregates could reach several hundred metres per day compared to 4 mm per day for freely suspended beads. Additionally, the number of incorporated microbeads varied significantly according to aggregate types. The similar polymer types detected among marine aggregates, seawater, and sediments indicated that aggregates could redistribute microplastics (Woodall et al. 2014; S.Y. Zhao et al. 2018). Therefore, future work should consider biological effects (e.g., biofouling, aggregates incorporate) on the sinking rate of microplastics.

### 3. Concluding remarks

Microplastics may reach remote oceanic regions, benthic sediments, and shorelines as a result of surface currents and bottom water transport. There have been several studies to characterize the physical transport of microplastics, however, further research is still needed to better understand the behavior of microplastics and their sinking rates within the natural environment. The uncertainties involved in microplastic transport that require further study include (i) the role of Stokes drift in controlling the distribution of floating microplastics in the surface; (ii) the shear stress threshold required to separate the two behaviors of suspension and sedimentation for microplastic particles; and (iii) how to evaluate the effects of biofouling and aggregation on the benthic distribution of microplastics, as they can increase the apparent density of microplastics.?

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