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# Medium-Term Oceanic Transport of River-Derived Microplastics in the South China Sea Analyzed with a Particle Tracking Model

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**Abstract**. Plastic waste is currently one of the biggest global environmental issues. To gain the comprehensive understanding of oceanic microplastic contamination as a key global environmental problem, Lagrangian particle tracking experiments were conducted to evaluate the transport of microplastics (MPs) derived from the four major rivers that have been known to discharge large amounts of plastic waste into the South China Sea (SCS). We carried out two types of experiments using a pre-computed 3D current climatological oceanic model: (1) 2D tracking of MP particles placed at the surface to represent positively buoyant (light) MPs, and (2) fully 3D tracking of neutrally buoyant MP particles that are passively transported by ambient current. The seasonally varying monsoons in the SCS were found to provoke strong seasonal variability in the river-derived MP transport. It was found that a large number of MPs, especially from south China, are transported to the East China Sea in the seasons when the southwesterly monsoon prevails. Moreover, the difference in the density of MPs substantially affects their oceanic transport patterns. The buoyant MPs accumulated near the surface tend to be transported toward nearshore areas by wind-driven Ekman currents.

**Keywords:** Microplastics; Lagrangian Particle Tracking Model; The South China Sea; Monsoons.

## 1. Introduction

In recent years, the problem of marine plastic pollution has been widely recognized as one of the biggest global environmental issues. Microplastics (MPs), which are plastic fragments degraded and miniaturized to less than 5 mm in diameter, enter the ocean from the land and drift for a long time because of their lesser density than seawater. Marine organisms may be harmed by ingesting MPs [1]. Hence, MPs may have negative effects on the marine ecosystem in the future. It is estimated that 4.8–12.7 million tons of plastic wastes enter the ocean annually from 192 coastal countries [2]. In particular, rivers with catchments in densely populated areas in Asian countries have the highest discharge of plastic waste [3]. For example, the Pearl River (China), the Pasig River (Philippines), and the Mekong River (Vietnam), which have their river mouths in the South China Sea (SCS), annually discharge 110,000, 39,000, and 23,000 tons of plastic waste into the ocean, respectively [3]. Nevertheless, the oceanic transport processes of MPs from these rivers have not yet been fully studied.

MPs have different rising and settling velocities depending on their size and shape [4]. A large proportion of MPs exist within 1 m from the surface, and MPs with diameters of approximately 1 mm are dominant in the open ocean [5]. MPs with a diameter of 1 mm or more could appear in the surface

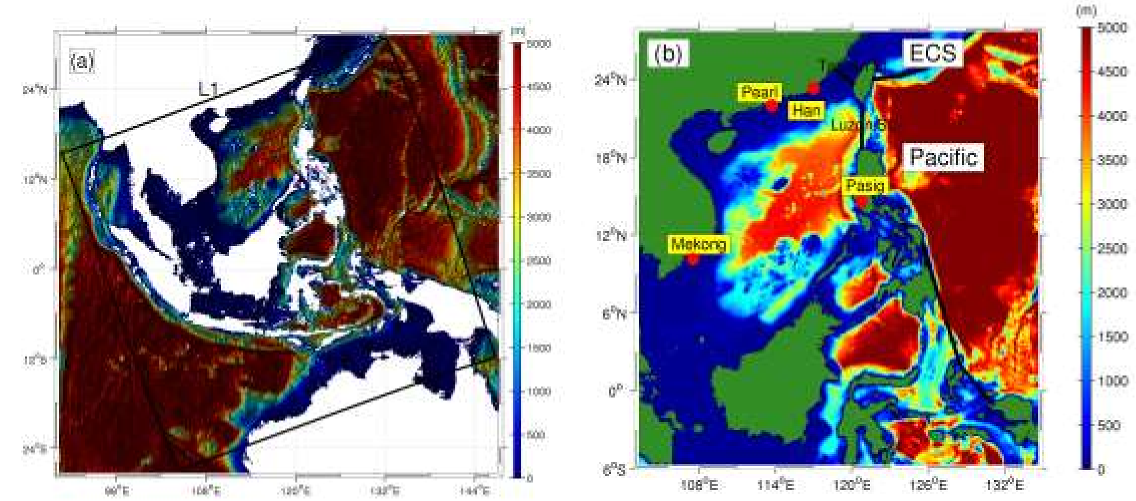


**Figure 1.** Left: Study area around the South China Sea. Right: Locations of the four MP release patches located around the major river mouths of Pearl, Han (China), Mekong (Vietnam), and Pasig (Philippines) rivers. Black lines in the right panel represent the borders to separate the East China Sea and the Pacific Ocean from the South China Sea. Colors show the bathymetry in meter.

layer due to vertical turbulent mixing, even though they have mostly disappeared from the surface layer. In contrast, smaller MPs (approximately 10–100 μm) are unlikely to return to the surface layer once they have disappeared from there and can be found anywhere in the oceanic water column because they are less buoyant than larger MPs [6]. Thus, it is important to understand the transport processes of MPs not only drifting the surface layer, but also being passively transported by currents in the interior ocean where observations of MPs have not yet been abundant.

In this study, we aimed to evaluate the oceanic transport and dispersal of two types of MPs, viz. positively buoyant (light) and neutrally buoyant (passive) MPs in the SCS derived from four major rivers, Pearl (China), Han (China), Mekong (Vietnam), and Pasig (Philippines) rivers, which have been known to discharge a large amount of plastic waste into the SCS [3], using a regional ocean circulation model and an offline Lagrangian particle tracking model. We investigated the horizontal transport patterns of MPs in and around the SCS and evaluated the rate of MPs originating from the SCS that flowed out to the surrounding seas. Based on the modeled outcomes, we further discuss the possible impacts of high MP concentrations on MP pollution in East Asian seas, and the differences in transport patterns of MPs of two different weight densities.

## 2. HYCOM-ROMS Downscaling Climatological Model

We analyzed the three-dimensional oceanic transport of MPs using the HYCOM-ROMS climatological model designed for the SCS and adjacent seas. This model is based on the Regional Oceanic Modeling System (ROMS), with the lateral boundary conditions imposed by HYCOM+NCODA, which is a global ocean reanalysis product with 3D-VAR data assimilation. Other numerical conditions are described in a previous study [7]. In this study, we focused on the transport of MPs in the normal-year condition. Therefore, boundary and forcing conditions were averaged daily over seven years to exclude interannual variability such as influences from typhoons, El Niño, and La Niña to reflect the climatological conditions of the SCS.

## 3. Three-dimensional Offline Lagrangian Particle Tracking Model

We exploited an offline 3D Lagrangian particle tracking model originally developed by Carr *et al*. (2008) [8], which was run with ROMS model outputs [9]. We carried out two types of experiments

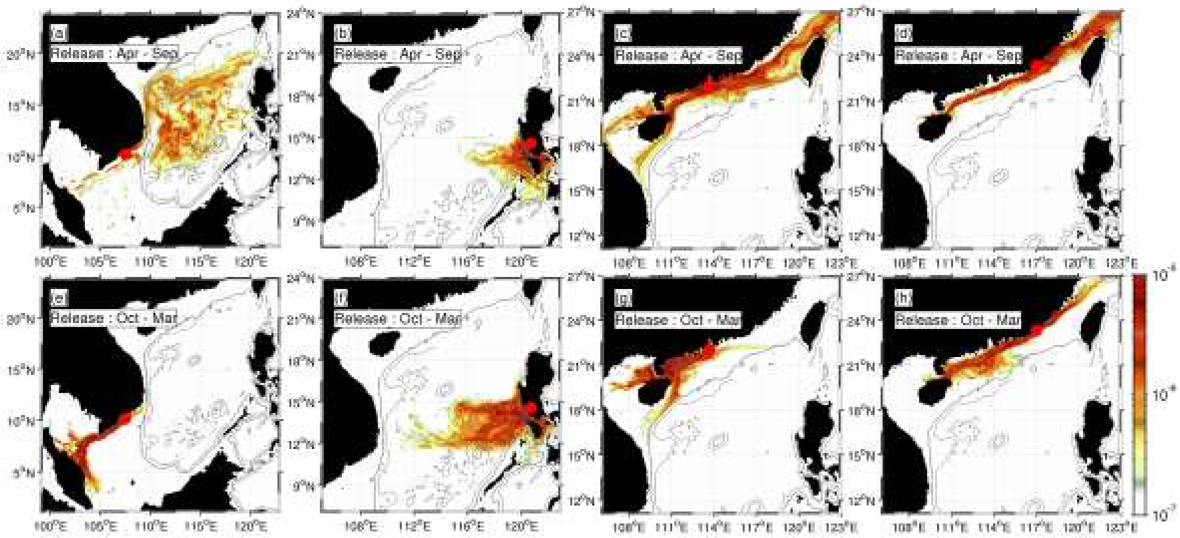


**Figure 2.** Lagrangian PDFs of the released MPs on the advection time of 100 days. The results for the surface 2D and passive 3D models are averaged. (a)-(d): MPs released from April to September. (e)-(h): MPs released from October to March. (a) and (e): MPs released from Mekong River, (b) and (f): MPs released from Pasig River, (c) and (g): MPs released from Pearl River, (d) and (h): MPs released from Han River.

using the pre- computed 3D current climatological oceanic model: (1) 2D tracking of MP particles placed at the surface to represent positively buoyant (light) MPs, because a large proportion of MPs exist within 1 m from the surface [5] and (2) full 3D tracking of neutrally buoyant MP particles that are passively transported by ambient flow to represent nano-sized plastics [10] and MPs that lose buoyancy due to biofouling [11]. More than 400 particles were released twice a day for one year into the climatological model field from each circular release patch with a radius of 25 km, located around the river mouths. In total, more than 1.2 million particles were released and tracked in this study. To quantify the dispersal of Lagrangian particles released from source patches, we calculated Lagrangian probability density functions (PDFs) using the particle tracking model results, following the methodology described by Mitarai *et al*. (2009) [9]. In this study, the beaching of MPs was considered, in which once the particle was judged as beached, the tracking was terminated and the particle stopped at the position.

## 4. Medium-Term Horizontal Transport of River-Derived Microplastics in the South China Sea

**Figure 2** shows the two-dimensional distributions of the Lagrangian PDFs of the particle displacement from the four rivers in the SCS at an advection time of 100 days after each release. The MPs released from the Mekong River from April to September were noticeably transported northeastward (**Fig. 2a**). On the other hand, the MPs released from October to March were conversely transported southwestward to reach the Malay Peninsula (**Fig. 2e**). The MPs released from the Pearl River and Han River were dispersed over the continental shelf, showing prominent seasonality in dispersal patterns (**Fig. 2c, d, g, and h**). If MPs released from April to September, they are transported northeastward to pass through the Taiwan Strait and then reach the East China Sea. In contrast, the MPs released during the period of the northeasterly monsoon in winter are transported southwestward. Such seasonal patterns in MP dispersal are well explained by wind-generated circulation induced by seasonally varying monsoons in this region. In the central part of the SCS, strong northeasterly winds blow normally from October to March, whereas relatively weaker southwesterly winds blow from April to September. The oceanic flow field in the SCS is known to be predominantly composed of monsoon-

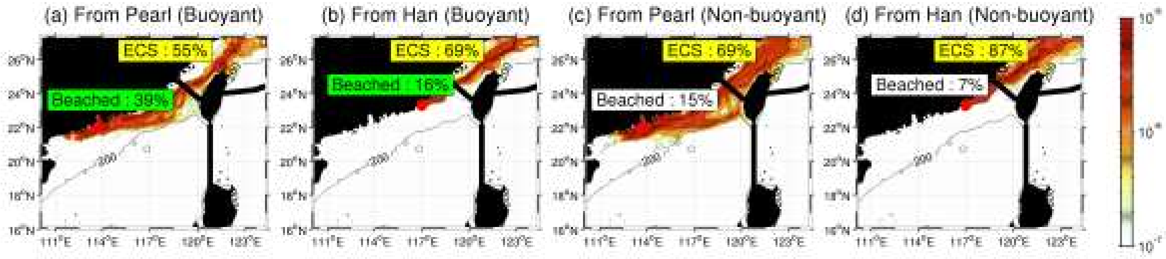


**Figure 3**. One-hundred and twenty days-averaged Lagrangian PDFs of the MPs derived from Pearl and Han Rivers released from April to June. The indicated figures in "%" are the fraction of MPs that are transported to the East China Sea and are beached. (a) Buoyant MPs from Pearl River, (b) buoyant MPs from Han River, (c) non-buoyant MPs from Pearl River, and (d) non-buoyant MPs from Han River.

induced wind-generated circulating gyres [12]. In winter, the mean surface currents form a cyclonic gyre in the northern part of the SCS by the northeasterly coastal monsoon, which induces an elevated sea surface height near the shore, leading to the southward current off the Vietnam coast and the southeastward current off the southern China coast as part of the intensified western boundary current. In turn, in summer, the western boundary current is reversed by the southerly to southwesterly monsoon to generate northeastward currents off the southern China coast as a part of the SCS Warm Current directed to the Taiwan Strait [12]. The transport of MPs in the SCS is obviously affected by this seasonally varying circulation system.

There are seasonal differences in the transport distance of MPs released from the Pasig River. During the northeasterly monsoon in winter, the southwestward transport is enhanced and the particles are widely dispersed in the central part of the SCS (**Fig. 2f**). Thus, in the SCS, MP transport is characterized by distinctive seasonality influenced by the prevailing monsoon over the sea. The MPs originating from the four major rivers are mostly transported over a wide area in the SCS, while outflowing to surrounding seas to a certain extent under normal year conditions.

## 5. Transported Fraction of MPs from Southern China Coasts to the East China Sea

The East China Sea is reported to be one of the seas most contaminated by MPs worldwide [13]. However, oceanic transport processes of MPs from particular sources, such as major rivers, have not yet been fully studied. In this study, we have quantified the rate of MPs originating from the SCS that flowed out to the surrounding seas, and then discussed the possible impact of the MP from the SCS on the distribution of MPs in the seas around Japan. In the previous section, we observed that a significant fraction of the MPs released from the Pearl River and Han River were transported to the East China Sea if MPs were released from spring to summer, as shown in **Figure 2**. **Figure 3** shows the Lagrangian PDFs of the MPs released from the Han and Pearl Rivers from April to June (in spring), averaged for 120 days of advection time. The use of percentages in each panel with the label "ECS" indicates the rates of MPs that are transported through the Taiwan Strait to the East China Sea. Apparently, most of the MPs derived from these two rivers are transported to the East China Sea, where 69% (buoyant) and 87% (non-buoyant) of the MPs derived from the Han River and 55% (buoyant) and 69% (non-buoyant) of the MPs from the Pearl River passed through the Taiwan Strait and transported to the East China Sea. These MPs are presumed to be transported further northeastward by the Taiwan Warm Current, which is the prevailing northeastward current occurring around the Taiwan Strait in summer [15]. Therefore, this result suggests that MPs from southern China coasts, including those from the Han and Peal rivers, are potential predominant sources of MP pollution observed in the seas in East Asia [13].

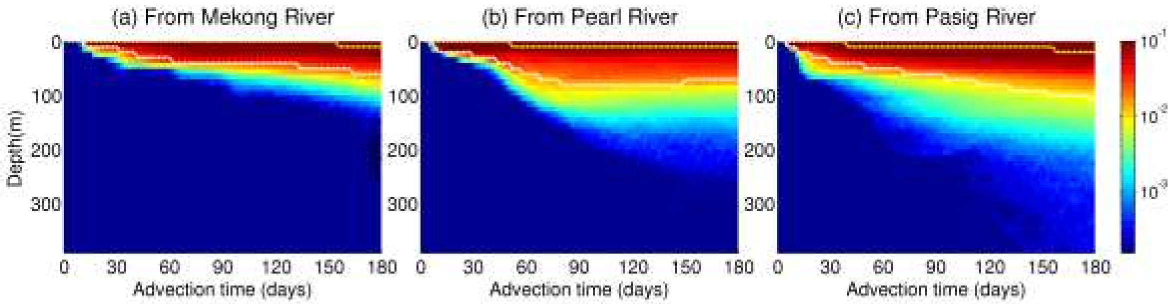


**Figure 4.** Hovmöller diagrams of the vertical distribution of Lagrangian PDFs of the MPs on each advection time until 180 days for the non-buoyant MPs released from (a) Mekong River, (b) Pearl River, and (c) Pasig River. Note that the PDFs are averaged over the entire study area. Yellow and white dotted lines show the corresponding 50 and 95 percentiles.

## 6. Medium-Term Vertical Transport of River-Derived Microplastics in the South China Sea

MPs change their density due to biofouling and fragmentation [4, 11] under the influence of vertical mixing dominated in the surface boundary layer [14] and vertical advective transport. MPs have been observed in the ocean at depths ranging from several hundred meters to several thousand meters [16]. To accurately estimate MP pollution below the surface layer, it is necessary to computationally simulate the MP transport by 3D circulation models that can represent oceanic currents three-dimensionally from the surface to the bottom, which is generally difficult to observe *in situ*.

**Figure 4** shows the vertical distribution of the area-averaged Lagrangian PDFs for each advection time for non-buoyant MPs, that is, neutrally buoyant particles that are transported passively to ambient currents. Although the non-buoyant MPs are mostly suspended in the surface layer within a depth of 10 m from the surface, some particles are affected by vertical mixing and advection to be diluted vertically as the advection time progresses. After approximately half a year of advection time in the ocean, approximately 50% of the particles are transported to depths of several tens of meters, and approximately 5% of MPs are transported to depths of approximately 100 m or deeper. These MPs may contribute to MP pollution in the middle and lower layers of the SCS. Thus, non-buoyant MPs that disappear from the surface layer but do not return to the surface layer again [6] are transported to the deep ocean, and may contribute to subsurface MP pollution observed down to a depth of several hundred meters depth of a wide area of the SCS.

## 7. Differences in Transport Patterns due to Two Different Weight Densities of MPs

**Figure 3** shows the Lagrangian PDFs of the MPs released from the Pearl and Han rivers in spring averaged over 120 days of advection time after each release. The rate of beached MP particles over 120 days is also shown. The difference between buoyant and non-buoyant MPs in the horizontal transport patterns is not apparent. The mean direction of the MP transport is in the same direction as that of the northeastward current in southern China, regardless of buoyancy. However, the beaching rate was significantly different, in which the rate of the non-buoyant MPs was lower than that of the buoyant MPs. Because of the difference in the weight density of the MPs, the buoyant MPs are confined in the surface layer, while the non-buoyant MPs can spread over a wider depth range (**Figure 4**). In the surface layer, the intensive southwestward wind blowing in the southern China coastal areas promotes the onshore Ekman flow to be approximately perpendicular to the continent. Thus, the buoyant MPs in the surface layer are transported to the coastal area due to wind-induced currents that are largely influenced by the northerly to north-easterly monsoon (**Figure 5a**), leading to more beached MPs. In contrast, the direction of the subsurface currents at a depth of 5 m is rather in the along-shelf direction with a much weaker velocity (**Figure 5b**). Hence, the non-buoyant MPs distributed widely in the vertical direction (**Figure 4**) are affected by subsurface currents, which do not promote onshore transport and thus less

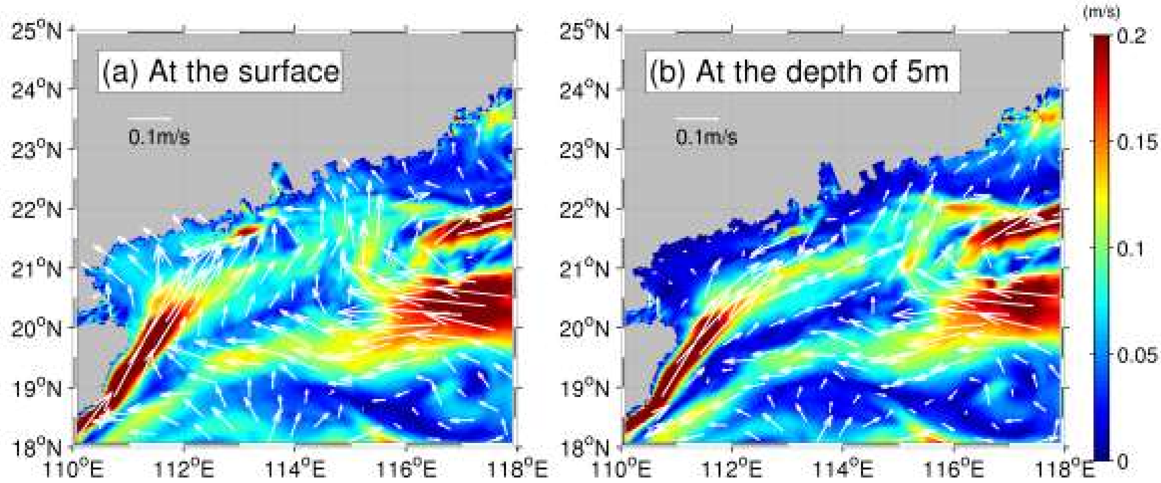


**Figure 5**. Monthly averaged (April) horizontal velocity vectors (white arrows) on their own magnitude (color) at the surface (a) and at the depth of 5 m from the surface (b).

beaching occurs. This result suggests that the buoyancy of the MP particles alters their mean vertical positions, resulting in being driven by different horizontal current velocities and directions in the spiraled Ekman boundary layer.

## 8. Conclusion

We conducted particle tracking experiments to evaluate the oceanic transport and dispersal of two types of microplastics (buoyant and non-buoyant) in the SCS derived from four major rivers, Pearl, Han (China), Mekong (Vietnam), and Pasig (Philippines) rivers, which have been known to discharge a large amount of plastic waste into the SCS. In the SCS, it was confirmed that the transport pattern of MPs is influenced by the wind-driven circulation system induced by the prevailing monsoon in the area under normal conditions. In particular, MPs released from the southern coasts of China have a large proportion of discharge into the East China Sea across the Taiwan Strait, indicating that they may be one of the major sources of MP pollution observed in the seas around Japan. Although approximately half of the non-buoyant MPs are found within a depth of 10 m from the surface, the remaining MPs are transported down to 10–100 m from the surface. Thus, non-buoyant MPs can affect pollution from the surface to depths of approximately 100 m. The buoyant MPs drifting on the continental shelf originating from southern China tend to be pushed toward the shore by northward wind-induced currents more pronouncedly than the non-buoyant MPs, which, in contrast, diffuse to deeper layers due to vertical mixing and vertical advection. This result suggests that differences in the weight density of the river-derived MPs affect their beaching processes and thus plastic pollution on beaches.

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