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Coastal ocean dynamics reduce the export of microplastics to the open ocean

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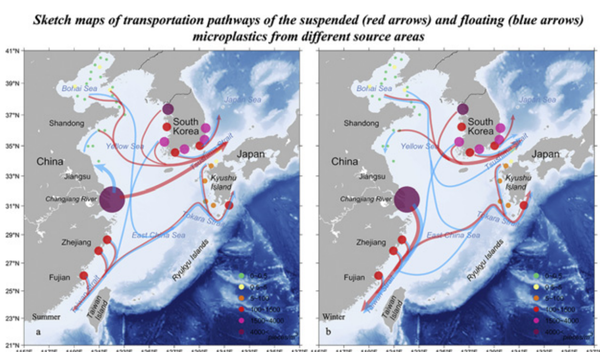
HIGHLIGHTS

- Tidal dynamics play a significant role in the microplastic transport in coastal oceans.
- Only a small fraction of the microplastics from China enter the Pacific Ocean.
- The Tsushima, Tokara, Taiwan Straits are identified as main delivery channels.

GRAPHICAL ABSTRACT



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ABSTRACT

Huge amounts of plastic waste are dumped into the ocean every year, forming large Garbage Patches. Countless microplastics, originating from fragmentation, weathering of larger objects or primary sources, pose a widespread ecological risk. In this study, the dispersion of suspended and floating microplastic particles in the East China Seas (ECSs) and adjacent seas was investigated via a coupled numerical model that included a Lagrangian particle tracking module. The role of tidal dynamics was considered in transporting the microplastic particles in the ECSs and adjacent seas. The results highlighted significant differences between the transport of suspended and floating microplastic particles. Although microplastic particles originating from different source areas followed different pathways, the Taiwan Strait, the Tokara Strait and the Tsushima Strait were identified as the major delivery channels. Of these, the Taiwan Strait played the most important role in the export of near-surface floating microplastic particles from the ECSs. The results showed that only a small fraction of the microplastic particles produced from the coastal waters of China (~18%) and Korea (~14%) entered the Pacific Ocean. However, nearly all of the microplastic particles originating from the west and south coasts of Kyushu Island entered the Pacific Ocean.

1. Introduction

Nearly 348 million tons of plastic are produced worldwide annually (Plastics Europe, 2018) resulting in serious environmental issues in

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various ecosystems. It is estimated that between 4.8 and 12.7 million tons of plastic waste entered the ocean in 2010, and this continues to increase dramatically (Jambeck et al., 2015). Huge quantities of plastic waste have been carried by ocean currents and accumulated within subtropical gyres, forming the five major Garbage Patches (Law et al., 2010, 2014; Cózar et al., 2014; Eriksen et al., 2013, 2014). The fragmentation of microplastics from weathering, or primary sources, present a potential threat and a non-negligible ecological risk to marine ecosystems (Green et al., 2016; Rochman et al., 2016). Plastic pollution affects ecosystems through ingestion and entanglement of marine fauna, ranging from zooplankton to large predators (Gregory, 2009; Tanaka et al., 2013). In recent years many studies have been conducted to investigate the physical and chemical characteristics (Hidalgo-Ruz et al., 2012), distribution (Cózar et al., 2014; Lebreton et al., 2018; Song et al., 2018), fate (Carr et al., 2016; Duis and Coors, 2016), transport (Lebreton et al., 2012, 2018; Lebreton and Borrero, 2013; Desforges et al., 2014; Isobe et al., 2014, 2019), and toxicological effects (Von Moos et al., 2012; Lu et al., 2016) of microplastics due to their significant influence on the environment.

The wide variation in physical characteristics (e.g., density, size, shape, buoyancy) (H. Zhang, 2017), as well as complex dynamics and biological processes including sinking, deposition, resuspension, fragmentation, degradation, and biofouling (Fazey and Ryan, 2016; Kowalski et al., 2016; Kaiser et al., 2017; Kooi et al., 2017; Song et al., 2017; H. Zhang, 2017; Alimi et al., 2018), make the numerical simulation of microplastic transport challenging. The transport of microplastics in estuaries and coastal areas is critical in determining the migration of microplastics from land to the open ocean. However, many previous studies focused on microplastic transport in the open ocean, without investigating coastal and estuarine transport processes (Lebreton et al., 2012, 2018; Lebreton and Borrero, 2013; Cózar et al., 2014; Eriksen et al., 2014; Iwasaki et al., 2017; Isobe et al., 2019). Some studies have been conducted in the Japan Sea (Yoon et al., 2010), the Nazaré Canyon (Ballent et al., 2013), the southern North Sea (Neumann et al., 2014), the Mediterranean basin (Mansui et al., 2015), and Jervis Bay (Jalón-Rojas et al., 2019), showing complex microplastic movements. Nevertheless, significant uncertainties remain and further research is needed to understand the transport of plastic debris in marginal seas. While boundary currents (e.g. Gulf Stream and Kuroshio) along continental shelves play a significant role in the transport of terrestrial material to the open ocean (H. Zhang, 2017), the lack of knowledge on the coastal transport of microplastics may lead to a false estimation of the amount of microplastics and the time taken to reach the open ocean from the land.

The areas surrounding the East China Seas (ECSs, including the East China Sea (ECS), Yellow Sea, and Bohai Sea) are considered to be one of the largest emitters of microplastics in the world (Jambeck et al., 2015). Meanwhile, the ECSs are also known as areas where ocean dynamic processes are complex and physical mechanisms are poorly understood. Observational data are constantly being collected in this region, which has led to recent progresses on ocean dynamic processes and exchange mechanisms between coastal waters and the open ocean (H. Wu et al., 2014; T. Wu and H. Wu, 2018). In this study, an elaborate coupled numerical model, including a Lagrangian particle tracking module, was used to investigate the transport of microplastics in the ECSs and its adjacent areas. This study emphasized the influence of coastal ocean dynamics (e.g. currents, tides, turbulence, and wind drift) on the transport of suspended and floating microplastics. Details of the numerical model, microplastic data sources, and experiment settings are provided in Section 2. In Section 3, the effects of tidal dynamics and suspended and floating microplastic transport pathways are described, while Section 4 discusses the main delivery pathways for microplastics from the coastal areas of China, Korea and Japan and the conclusion of the study is presented.

2. Data and methods

2.1. Study area

The ECSs are marginal seas of the western Pacific Ocean, which are surrounded by the Ryukyu Islands, the Kyushu Island, the Korean Peninsula and the Asian continent (see Fig. 1). This region exhibits complex tides and currents (Guan, 1994) and is one of the most active monsoon areas in the world. Northerly winds prevail in winter, while southerly winds dominate in summer. The Kuroshio, the western boundary current in the western North Pacific, flows northward along the east coast of Taiwan towards the southeastern coast of the Japanese archipelago (Mizuno and White, 1983). The Taiwan Warm Current is another important current originating from both the Taiwan Strait and northeast of Taiwan Island as a result of the Kuroshio intrusion (Zhu et al., 2004; Chen and Sheu, 2006), which then flows northeastward along the 50-m isobath off the Zhejiang and Fujian (Zhe-Min) coast. The Tsushima Warm Current, which originates from both branches of the Kuroshio and the Taiwan Warm Current, flows into the Japan Sea (Isobe, 1999). The Yellow Sea Warm Current is a branch of the Tsushima Warm Current which flows northward along the Yellow Sea Trough and then bypasses the Liaodong Peninsula to enter the Bohai Sea (Guan and Mao, 1982; Guan, 1994).

In addition, coastal currents with a strong seasonal variability also exist, such as the Yellow Sea Coastal Current and the Korean Coastal Current with surface water flowing southward in winter and northward in summer (Xia et al., 2006). Similarly, the Zhe-Min Coastal Current flows southward along the Zhe-Min coast in winter, and the majority of this current turns northward in summer (Beardsley et al., 1985; H. Wu et al., 2013; T. Wu and H. Wu, 2018). As the largest river in the northwest Pacific region, the Changjiang River substantially influences dynamics in the ECSs, with the extensive Changjiang River plume flowing offshore towards Jeju Island in summer and southward along the Zhe-Min coast in winter (Mao et al., 1963; Beardsley et al., 1985; H. Wu et al., 2014). A third and minor branch of the Changjiang River plume propagates northward along the coast of Jiangsu (H. Wu et al., 2014).

2.2. Numerical model

Many previous studies have used modeled current data to drive the emission of microplastic particles, such as the HYbrid Coordinate Ocean Model (HYCOM, Lebreton et al., 2012, 2018; Lebreton and Borrero, 2013; Eriksen et al., 2014; Isobe et al., 2019), Japan Sea Forecasting System of RIAM (OOPS, Yoon et al., 2010), 3D operational circulation model of the Federal Maritime and Hydrographic Agency of Germany (BSHcmod, Neumann et al., 2014), Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM, Critchell et al., 2015), Adriatic Forecasting System (AFS, Liubartseva et al., 2016), and the Regional Ocean Modelling System (ROMS, Pereiro et al., 2019). However, in these models tidal forcing was not included or discussed explicitly, which yielded large differences when compared with real coastal ocean dynamics (H. Wu et al., 2011). Therefore, a well-validated model (H. Wu et al., 2011, 2014, 2018; Wu, 2015) including tidal dynamics was used in this study. This model originates from ECOM-si (Blumberg, 1994), which introduces the third order, oscillation-free advection scheme HSIMT (H. Wu and Zhu, 2010). In addition, a Lagrangian particle tracking module was coupled to the model, which simulated the movements of ocean plastics (Lebreton et al., 2012). The ECOM-si model provides the fundamental physical basis for the Lagrangian particle tracking module under the combined effects of wind, tides, and shelf circulation.

The model domain covers the entire Bohai Sea, Yellow Sea and ECS, as well as parts of the Pacific Ocean and the Japan Sea (see H. Wu et al., 2011). The open boundary is roughly parallel to the Ryukyu Islands. In the horizontal dimension, 367 × 319 cell indices are included in the grid mesh whose resolution is several hundred meters inside the

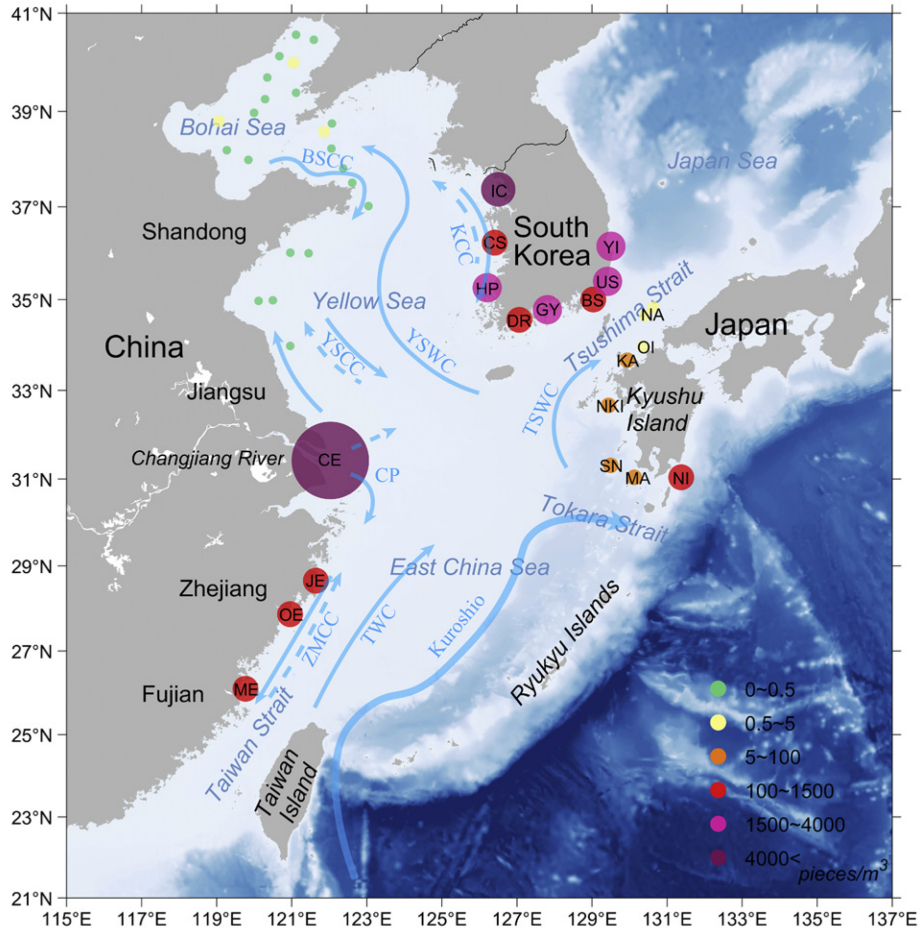

Fig. 1. Schematic map of Bohai Sea (BH), Yellow Sea (YS), East China Sea (ECS) and adjacent seas. Dots represent microplastic sources and associated concentrations (pieces/m^3, in color). The meanings of the abbreviations are as follows: Changjiang River Estuary (CE), Minjiang River Estuary (ME), Oujiang River Estuary (OE), Jiaojiang River Estuary (JE), Incheon (IC), Cheonsu (CS), Hampyeong (HP), Deungnyang (DR), Gwangyang (GY), Busan (BS), Ulsan (US), Yeongil (YI), Nagasaki (NKI), Shimokoshikicho Nagahama (SN), Karatsu (KA), Makurazaki (MA), Oshima Island (OI), Nagato (NA), Nishinoomote (NI). Solid arrows indicate the Taiwan Warm Current (TWC), Tsushima Warm Current (TSWC), Cheju Warm Current (CWC), Yellow Sea Warm Current (YSWC), Yellow Sea Coastal Current (YSCC), Changjiang River plume (CP), Zhejiang and Fujian Coastal Current (ZMCC), Bohai Sea Coastal Current (BSCC), Korean Coastal Current (KCC). The dashed arrows represent the summer states of the KCC, ZMCC, CP, and YSCC.

Changjiang River mouth, 2–3 km outside the river mouth, ~ 3 km in the Yellow Sea and ECS, and ~10 km in the Japan Sea and Kuroshio region. In the vertical dimension, the model includes 20 non-uniform sigma layers that are refined near the surface.

The forcing at the open boundary is driven by shelf currents and tidal currents. The shelf currents, temperature and salinity at the boundary, and initial conditions were extracted from the Simple Ocean Data Assimilation (SODA) dataset. Sea surface momentum and heat flux were calculated from climatological monthly mean data via a bulk formula (Ahsan and Blumberg, 1999). The data were provided by the European Center for Medium-Range Weather Forecasts (ECMWF), and include wind speed, air temperature, air pressure, cloud cover, and dew point temperature at a spatial resolution of 0.125° × 0.125°. The climatological monthly mean Changjiang River discharge data from the Datong station were provided by the Changjiang Water Resource Commission.

Given the complexity of microplastic transport processes, poorly understood sub-processes such as biological interactions are ignored and the simulations focus on the influence of ocean dynamic processes (e.g., currents, tides, turbulence, wind drift) on the movement of microplastics suspended in the water column (Isobe et al., 2014) or floating in the surface layer (Cózar et al., 2014). The surface transport of microplastics is affected by many aspects like currents, turbulent mixing, or Ekman transport (H. Zhang, 2017) and the required hydrodynamic fields are provided by the hydrodynamics model. Here, the velocity of the floating particles ($\overrightarrow{U_f}$) is determined following H. Zhang (2017):

$$\overrightarrow{U_f} = \overrightarrow{U_c} + \overrightarrow{U_r} + \overrightarrow{U_w} \tag{1}$$

where $\overrightarrow{U_c}$ is the surface horizontal advection velocity simulated by the model, and $\overrightarrow{U_r}$ is a random walk representing horizontal turbulent mixing, defined as follows:

$$\overrightarrow{U_r} = \delta\sqrt{2\overrightarrow{K_h}/\Delta t} \tag{2}$$

where δ is a random number (here $\delta \in (-1\ ,\ \ 1)$), $\overrightarrow{K_h}$ is the horizontal eddy viscosity that represents the scale of turbulence and Δt is the time step. $\overrightarrow{U_w}$ is the floating microplastic velocity directly caused by the wind, whose linear approximation is as follows:

$$\overrightarrow{U_w} = D_w \overrightarrow{V_w} \tag{3}$$

where D_w is the wind drift coefficient (here $D_w = 0.03$, a widely recognized rule of thumb, e.g. Csanady, 1982), and $\overrightarrow{V_w}$ is the sea surface wind vector. The wave-induced Stokes drift is implicitly considered, as it is difficult to separate it from direct wind drift (Kubota, 1994; Liubartseva et al., 2016). Hence, the wind drift coefficient is proposed, which combines the movement by Stokes drift into the wind drift process for simplification, to represent the drag force of the wind (Critchell et al., 2015; Chubarenko et al., 2016).

Similarly, the velocity of the suspended particles ($\overrightarrow{U_s}$) is given as:

$$\overrightarrow{U_s} = \overrightarrow{U_v} + \overrightarrow{U_r} \tag{4}$$

where $\overrightarrow{U_v}$ is the current velocity and all vectors in (4) are three-dimensional.

To estimate the main microplastic transport pathway, the simulation domain is divided into 0.5° × 0.5° grid cells. The proportion of times that microplastic particles emerge in every grid cell is calculated after release. The main microplastic transport pathway is then defined as the track line, which connects the grids with higher proportions of emerging microplastic particles. In addition, the flux and transit time of microplastic particles passing through the strait was calculated, excluding those particles crossing the strait before being pushed back again by currents or wind. Similarly, if one microplastic particle statistically passed through two straits, it would only be considered as having passed through the latter one. When the amount of microplastic particles passing through the strait from a source reached a stable state, that moment was recorded as the final transit time. The average time taken for microplastic particles to pass through the straits were also calculated.

2.3. Microplastic data and data input

The distributions of microplastic concentrations in the entire east Asian marginal sea area, including the Yellow Sea, Bohai Sea, ECS and the Japan Sea (Fig. 1), were obtained from existing studies listed in Table 1. Areas without data are not necessarily free of microplastic pollution, but no observations had been made or reported for these areas. In addition, the available data were limited as a result of collection methods with various mesh size or sampling collecting method. Therefore, the quantification in this study was made in terms of percentage of released particles, rather than absolute values of microplastic volume or weight. The mesh size used for the different works cited in Table 1 varied from 20 μm to 500 μm (the smaller the mesh size, the more microplastics collected), and the sampling methods included trawl net and water pump. The microplastic concentration in the Changjiang River Estuary and at Incheon were extremely high, which may be due to the highly developed economies in these areas, contributing to increased environmental issues (Jambeck et al., 2015). In China, the microplastic concentration along the southeastern coast was distinctly higher than that along the coastal areas of the Shandong peninsula and the Bohai Sea. The microplastic concentration was higher along the South Korea coastal areas. The coastal areas off the Kyushu Island had a low concentration of microplastics.

Table 1
Microplastic data sources.

Location	Concentration (particles/m^3)	Mesh size (μm)	Reference
Changjiang River Estuary (CE)	4137	32	Zhao et al., 2014
Jiaojiang River Estuary (JE)	956	333	Zhao et al., 2015
Oujiang River Estuary (OE)	680	333	Zhao et al., 2015
Minjiang River Estuary (ME)	1171	333	Zhao et al., 2015
Yellow Sea (YS)	0.13	500	Sun et al., 2018
Bohai Sea (BH)	0.33	330	W. Zhang et al., 2017
Incheon (IC)	4064	20	Song et al., 2018
Cheonsu (CS)	784	20	Song et al., 2018
Hampyeong (HP)	1548	20	Song et al., 2018
Deungnyang (DR)	1146	20	Song et al., 2018
Gwangyang (GY)	2362	20	Song et al., 2018
Busan (BS)	1000	20	Song et al., 2018
Ulsan (US)	1764	20	Song et al., 2018
Yeongil (YI)	1688	20	Song et al., 2018
Japan	3.7	350	Isobe et al., 2015

In areas with high microplastic concentrations (>500 particles/m^3), the number of released particles equaled the value of the microplastic concentration. To avoid statistical errors, a scaled approach was used to define the number of released particles for low microplastic concentration areas. Specifically, the number of released particles was set to 1000 times the microplastic concentration for the Yellow Sea and Bohai Sea, and 50 times for the areas off the Japan coast. In total, 33,533 particles were released from 42 microplastic sources of various concentrations in the coastal areas of China, Korea, and Japan in winter and summer.

2.4. Numerical experiment settings

Three numerical experiments were conducted in this study. In Experiment 1, the movement of suspended particles was simulated under climatological conditions without tides and with a random walk. Experiment 2 simulated the movement of suspended particles under climatological conditions with tides and a random walk, with all other settings being the same as those in Experiment 1. In Experiment 3, the model simulated the movement of floating particles by adding the wind drag effect, with all other settings being the same as those in Experiment 2. The climatological monthly means of the atmospheric fields were obtained by averaging the 20 year value of each meteorological parameter for each Julian day. All microplastic particles were released together in the second year of the simulation, and then simulated for another four years. When the particle continuously stayed on a dry grid point, it was considered as beached on the coast.

3. Results

3.1. The role of tide in the numerical model

Tides in the ECSs are mainly caused by tidal waves propagating from the Pacific Ocean, and become intricate under the influence of the complex topography and coastline. The M_2 constituent is the dominant component of the tides in this area. Many previous studies using the HYCOM, or similar model data products, ignored the effect of tides (Lebreton et al., 2012, 2018; Lebreton and Borrero, 2013; Eriksen et al., 2014; Isobe et al., 2019). While this approach is reasonable in the open ocean, in marginal seas like the ECSs and adjacent seas, tidal dynamics play a substantial role even in sub-tidal circulation, and neglecting tidal dynamics could lead to dramatic errors (H. Wu et al., 2011). The comparison of Experiment 1 and Experiment 2 aimed to demonstrate the effects of tide in determining particle transport.

The microplastic particles originating in the Changjiang River Estuary were released in winter and summer, and their trajectories showed distinctive movements with and without tides (Fig. 2). Out of all the microplastic particles released from the Changjiang River Estuary in summer, ~70% left the ECSs and ~63% entered the Japan Sea through the Tsushima Strait in Experiment 2 (with tides), whereas almost all of the microplastic particles left the ECSs and ~90% entered the Japan Sea in Experiment 1 (without tides). This suggested that the amount of microplastic particles leaving the ECSs in summer could be overestimated if the tidal effect was not considered. Although no large difference could be seen in the monthly mean current fields with or without tides, the microplastic pathway and residence time showed significant

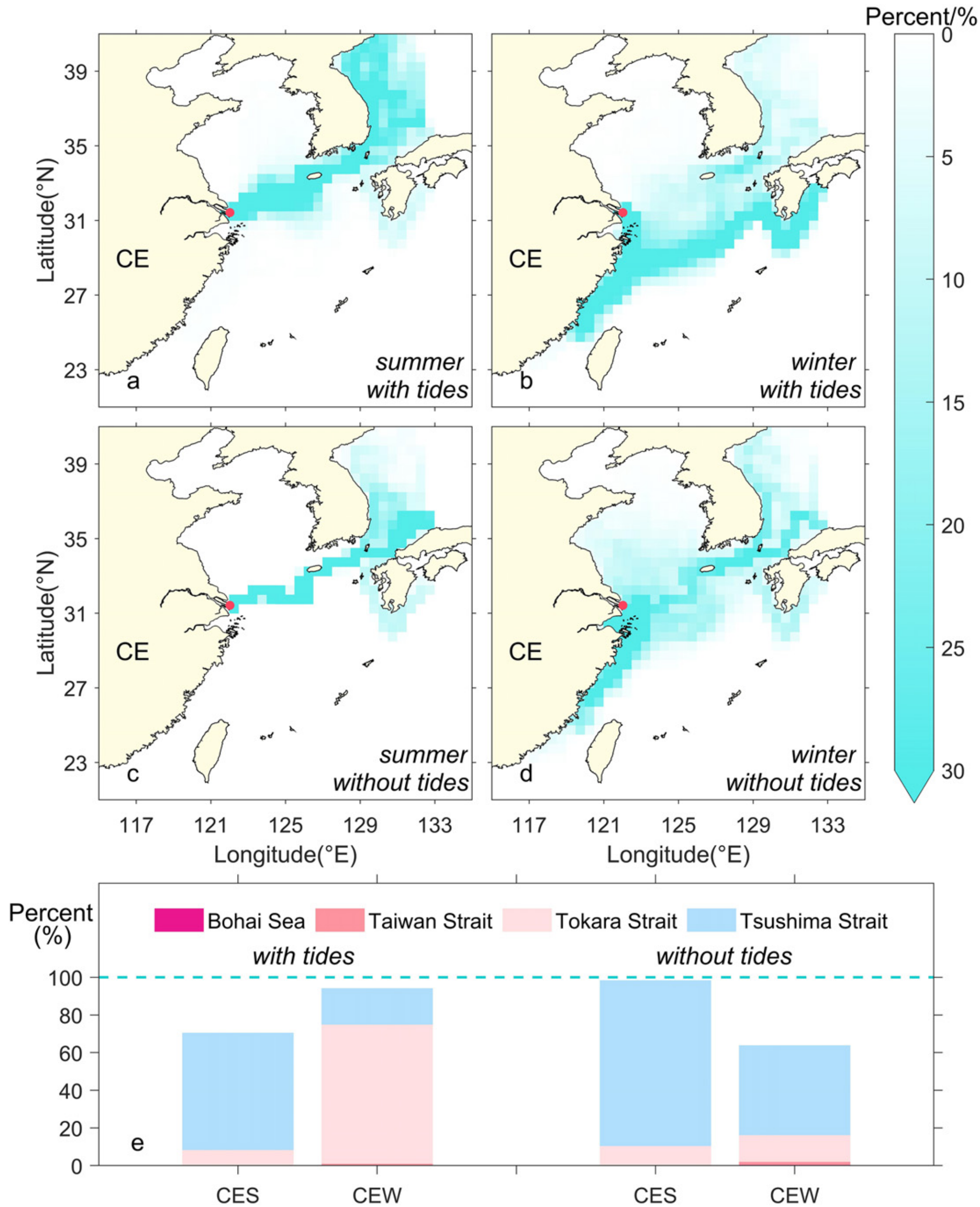

Fig. 2. Differences in typical microplastic sources (the Changjiang River Estuary, CE), and transport pathways of particles released in different seasons and the percentages that pass through different straits with and without tides. Identification of the main transport path was carried out by calculating the proportion of times that particles appear in each grid cell.

changes (Fig. 3). The pathway of particles released in summer (Fig. 3a, b) and winter (Fig. 3c, d) with and without tides exhibited large discrepancies between the two simulations. These differences were more obvious in winter, when particles moved along the coast in Experiment 1, whereas Experiment 2 saw the particles first moving towards the south along the Zhe-Min coast before heading to the northeast and passing through the Tsushima Strait. In addition, some microplastic particles were randomly selected to show the temporal differences with and without tides. Without tides, it only took about 1 month for the particles released in summer to travel from the Changjiang River Estuary to the Tsushima Strait, which was significantly shorter than the simulation including tides. This difference could be attributed to the oscillatory motion induced by the tidal current, which often moves particles from the main stream of the mean current. Particles accumulated in the Yellow Sea due to the combined effect of tidal currents and seasonally varying circulations.

Hence, tidal dynamics played a significant role in the transport of microplastic particles in the ECSs and adjacent seas. Not only did tidal dynamics affect the amount of microplastic particles leaving this region, but also it impacted transport pathways and transport times. Tidal dynamics substantially extended the time needed for microplastics to leave the ECSs. Therefore, in the following sections, the analyses of all results were based on the simulations including tidal effects.

3.2. Microplastic particle transport from different sources

As shown in Figs. 4 and 5, microplastic particles from 16 distinct sources were selected to illustrate the transport of microplastic particles.

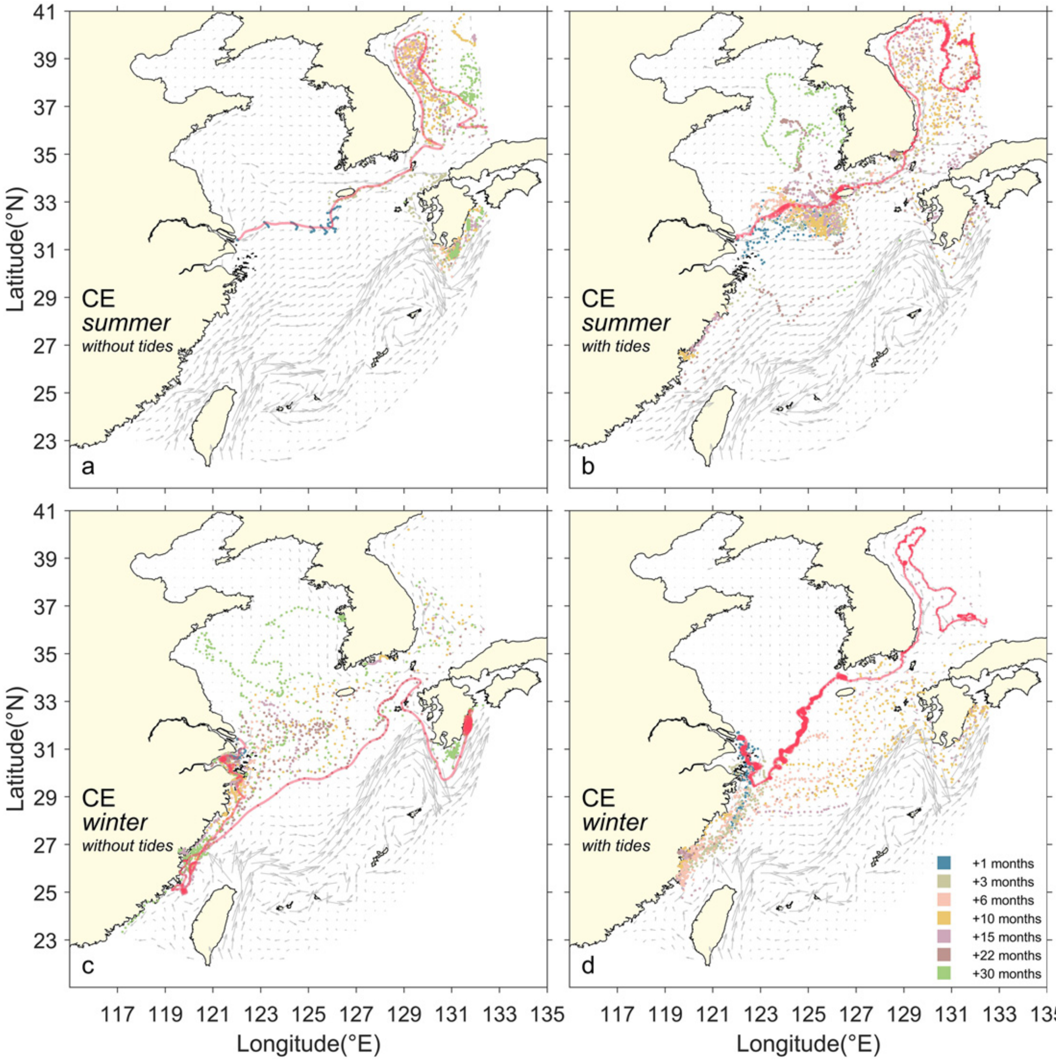

Fig. 3. Transportation pattern of suspended microplastic particles from the Changjiang River Estuary (CE) with (b, d) and without (a, c) tides. The grey arrows represent monthly mean currents in summer (a, b) and winter (c, d), with and without tides. The red line represents the same particle transportation pathway under different conditions.

3.2.1. Suspended particle transport (experiment 2)

Microplastic particles originating from the Chinese coastal areas mainly followed three distinct pathways to the north and south of the Changjiang River. The transport of microplastic particles released from the Changjiang River Estuary was complicated by the various topographic and dynamic conditions, and showed strong seasonality (Fig. 4W1; S1). In particular, microplastic particles released during winter were affected by the Changjiang River plume and Zhe-Min Coastal Current which propagate towards the south along the Zhe-Min coast. After arriving north of the Taiwan Strait (about three months after their release, Fig. 7c), the particles became stagnant due to the blocking effect of the northward Taiwan Strait Current (Guan and Fang, 2006). About four months after their release, some particles joined in the Taiwan Warm Current and moved further northeastward, while others were transported to the beach and remained there. The rest of the particles flowed back to the northeast with the Zhe-Min Coastal Current after it reversed to a northeastward direction (i.e. summer pattern). Most of the microplastic particles (~74%) passed through the Tokara Strait and entered the Pacific Ocean under the influence of the Kuroshio current approximately 7 months after their release (Figs. 6a, 7b). About 20% of the microplastics left the ECSs and entered the Japan Sea through the Tsushima Strait under the influence of the Taiwan Warm Current and Tsushima Warm Current approximately nine months after their release (Figs. 6a, 7a). A small proportion of the particles were affected by the summertime Changjiang River plume and the Yellow Sea Warm Current, entering the Yellow Sea. However, the situation for the particles released in summer was totally different. Over 60% of the microplastics flowed northeastward and entered the Japan Sea through the Tsushima Strait approximately three months after their release, following the summertime Changjiang River plume (Figs. 4S1, 7a–c). These microplastics can hardly reach the Pacific Ocean gyres because the Japan Sea is largely a closed marginal sea. Only a small proportion of microplastic particles (~8%) left the ECSs to join the Kuroshio flowing southwest of Kyushu Island (Figs. 6a, 7b).

Particles released in winter in the Jiaojiang River Estuary, Oujiang River Estuary, and Minjiang River Estuary were transported southward to some extent (Fig. 4W2–4; S2–4), and most of them (70% ~ 80%) joined the Kuroshio and left the ECSs through the Tokara Strait approximately 7 months after release. A small proportion (15% - 20%) passed through the Tsushima Strait approximately 10 months after release. Very few suspended microplastic particles passed through the Taiwan Strait (Fig. 7c). If released in the summer, suspended microplastic particles from these rivers took a longer time to reach the Tokara Strait (9–-13 months), because the particles first moved north under the

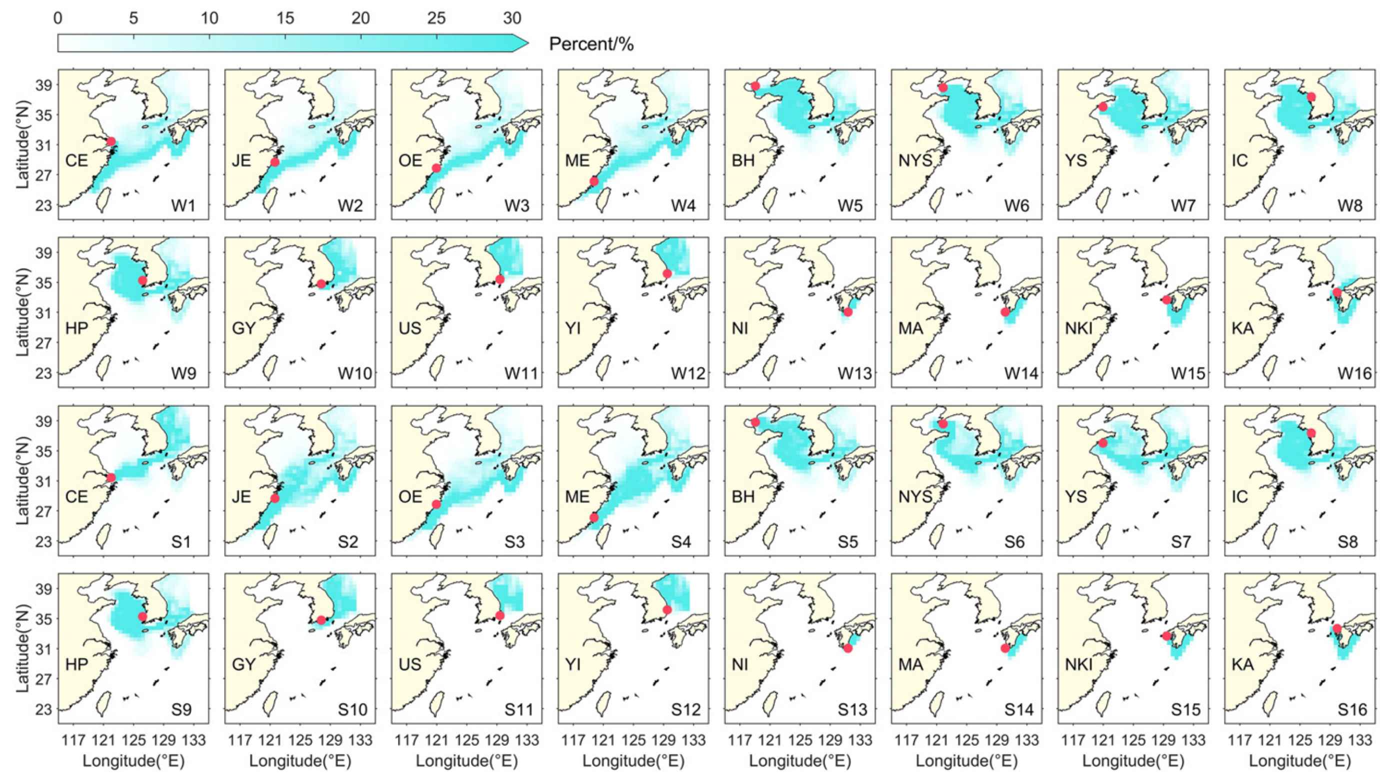

Fig. 4. Sixteen suspended microplastic transport pathways released from different places in summer (S) and winter (W). Red dots represent the origin of the microplastic particles. Identification of the main transport path was carried out by calculating the proportion of times that particles appear in each grid cell.

summertime circulation and monsoon, before moving back southward and joining the Kuroshio after the change in season. About 55% (Figs. 6a, 7b) of the particles released in the summer passed through the Tokara Strait, while ~30% (Fig. 6a) were affected by the Tsushima Warm Current and passed through the Tsushima Strait.

The movements of microplastic particles released in the Bohai Sea and Yellow Sea were very similar, entering the Yellow Sea and then passing through the Jeju Strait and the Tsushima Strait. Regardless of being released in the summer or winter, about 60% of the particles passed through the Tsushima Strait. Some particles (~18%) were affected by the Kuroshio to the west of the Kyushu Island and moved southward along the coast, finally entering the Pacific Ocean through the Tokara Strait ~17 months after release (Fig. 6a). The remaining particles became beached on the shore or remained in the Bohai Sea and Yellow Sea.

Microplastic particles released from Incheon and Hampyeong on the western coast of Korea showed a similar transport mechanism to those released from the Bohai Sea and Yellow Sea, under the influence of the Yellow Sea current system (Fig. 4W8–12; S8–12). When released in both winter and summer, the particles were transported to the south along the western coast of Korea under the Korean Coastal Current. The difference was that if released in summer, they would arrive at the Tsushima Strait faster (~13 months in summer and ~19 months in winter). Overall, 65–75% of the microplastic particles crossed the Jeju Strait, moving eastward. Among them, ~55% passed through the Tsushima Strait and entered the Japan Sea, while ~15% turned southward to the west of Kyushu and then passed through the Tokara Strait (Fig. 6a). Therefore, only about 15% of the microplastic particles released from the western Korean coast entered the Pacific Ocean. Particles released in the southern and eastern coasts of Korea mainly entered the Japan Sea (Fig. 6a). Suspended microplastic particles released from the coastal areas of Japan were transported through the Tsushima Strait and the Tokara Strait, depending on their release location (Fig. 6a).

Therefore, suspended microplastic particles released in the Bohai Sea, Yellow Sea, the Korean coastal areas, and the coastal regions of Kyushu north of Fukuoka, tended to pass through the Tsushima Strait and enter the Japan Sea. In contrast, particles released along the southeastern coastal areas of China and the coast to the south of Fukuoka tended to enter the Pacific through the Tokara Strait. Microplastic particles released in the Changjiang River Estuary had transport pathways that varied with the season. The microplastic particles released in summer mainly passed through the Tsushima Strait and entered the Japan Sea, whereas the particles released in winter tended to pass through the Tokara Strait. The average times needed for particles released from coastal areas of ECSs to pass through the Tsushima Strait, the Tokara Strait, and the Taiwan Strait were about 15, 14, and 8 months, respectively.

3.2.2. Floating microplastics (experiment 3)

The microplastic particles floating at the surface exhibited distinct transport patterns compared to the suspended particles (Fig. 5). For floating microplastic particles, the Taiwan Strait became the major exit channel, as opposed to the Tokara and Tsushima straits (Figs. 4, 5). Specifically, about 33% of the microplastic particles released in winter passed directly through the Taiwan Strait within 1 month of their release (Fig. 7f). Some of the remaining particles joined the Kuroshio flow through offshore transport, and others landed on the shore similar to the suspended microplastic particles. Some the particles returned to the northeast after the monsoon reversed from a northerly to a southerly direction. About 10% of the particles moved to the northeast and passed through the Tsushima Strait under the effects of the Changjiang River plume, the Taiwan Warm Current and the summer monsoon (about 9 months after release), while the remaining ~25% passed through the Tokara Strait under the influence of the Kuroshio approximately 10 months after release. Most of the floating microplastic particles released in summer quickly moved to the northern coastal areas of

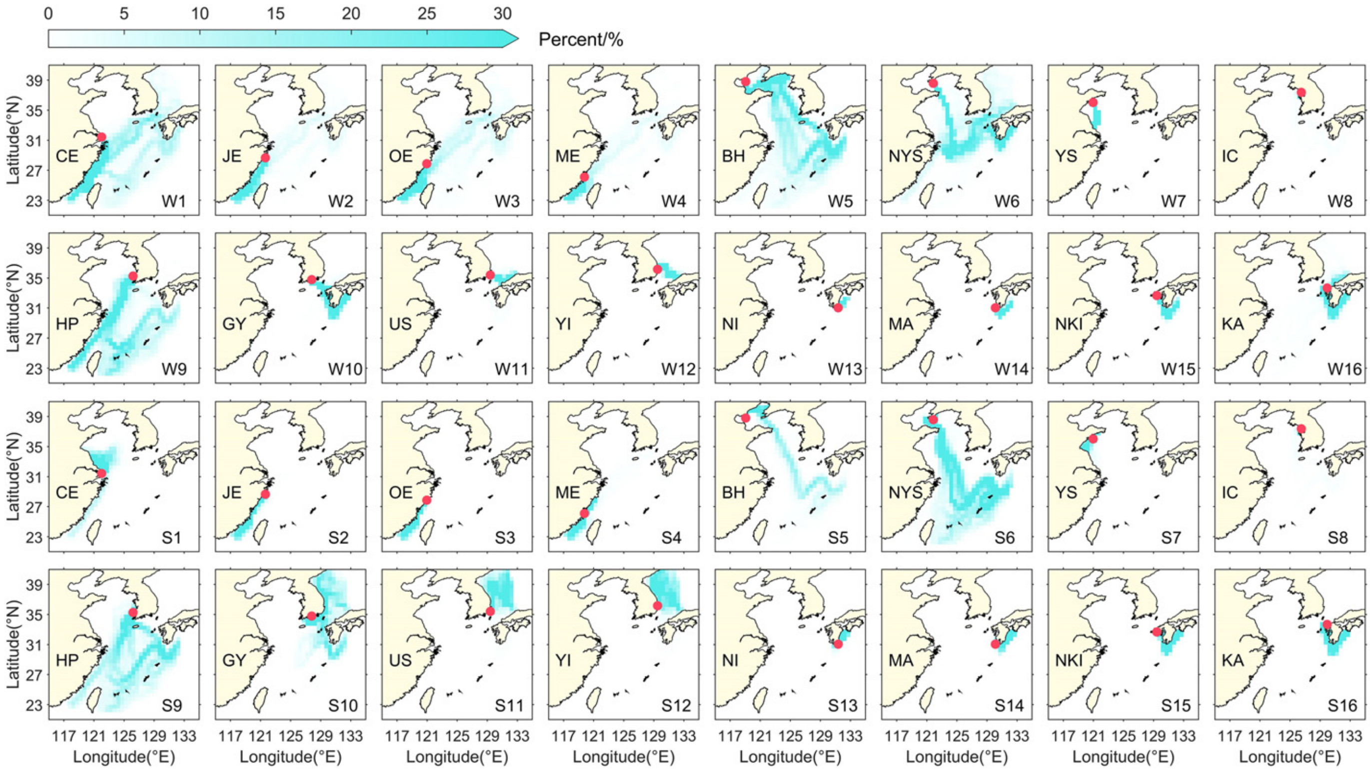

Fig. 5. Sixteen floating microplastic transport pathways released from different places in summer (S) and winter (W). Red dots represent the origin of the microplastic particles. Identification of the main transport path was carried out by calculating the proportion of times that particles appear in each grid cell.

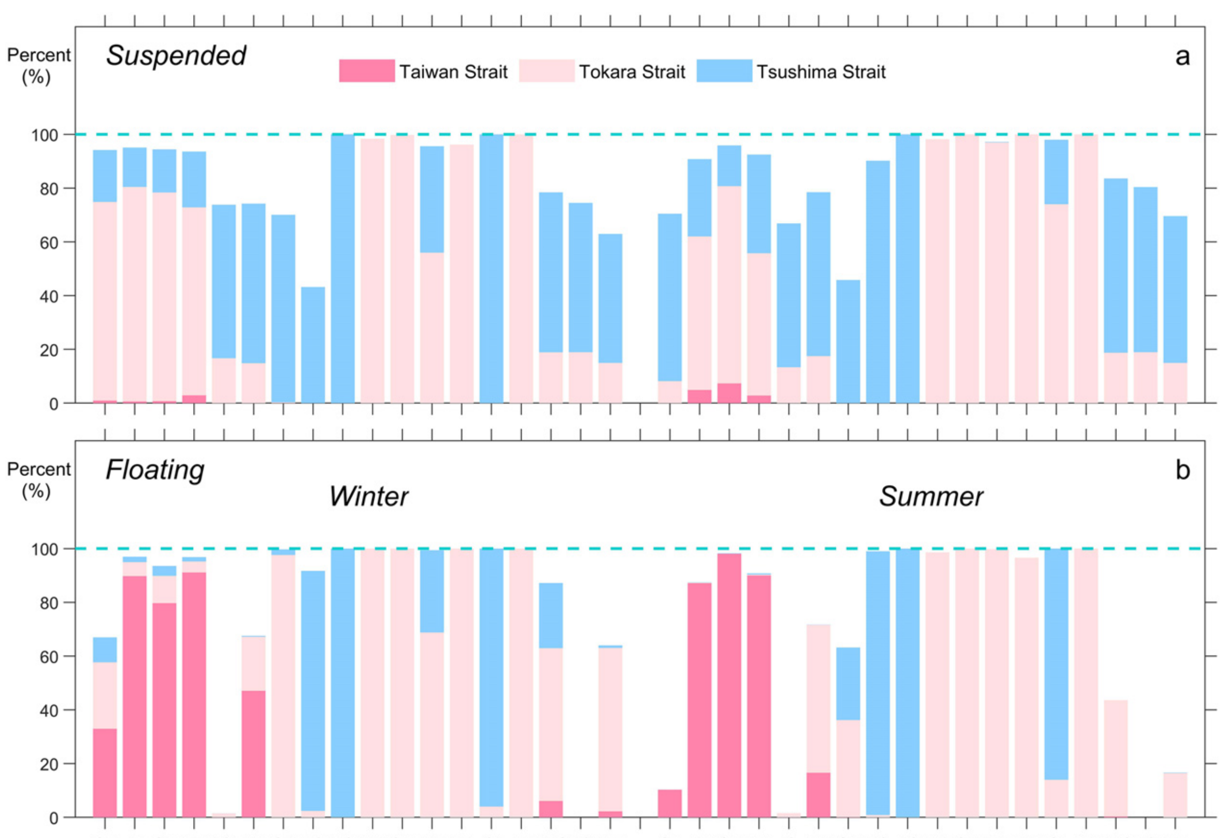

Fig. 6. The percentage of suspended (a) and floating (b) microplastic particles passing through different straits that were released in summer and winter, respectively.

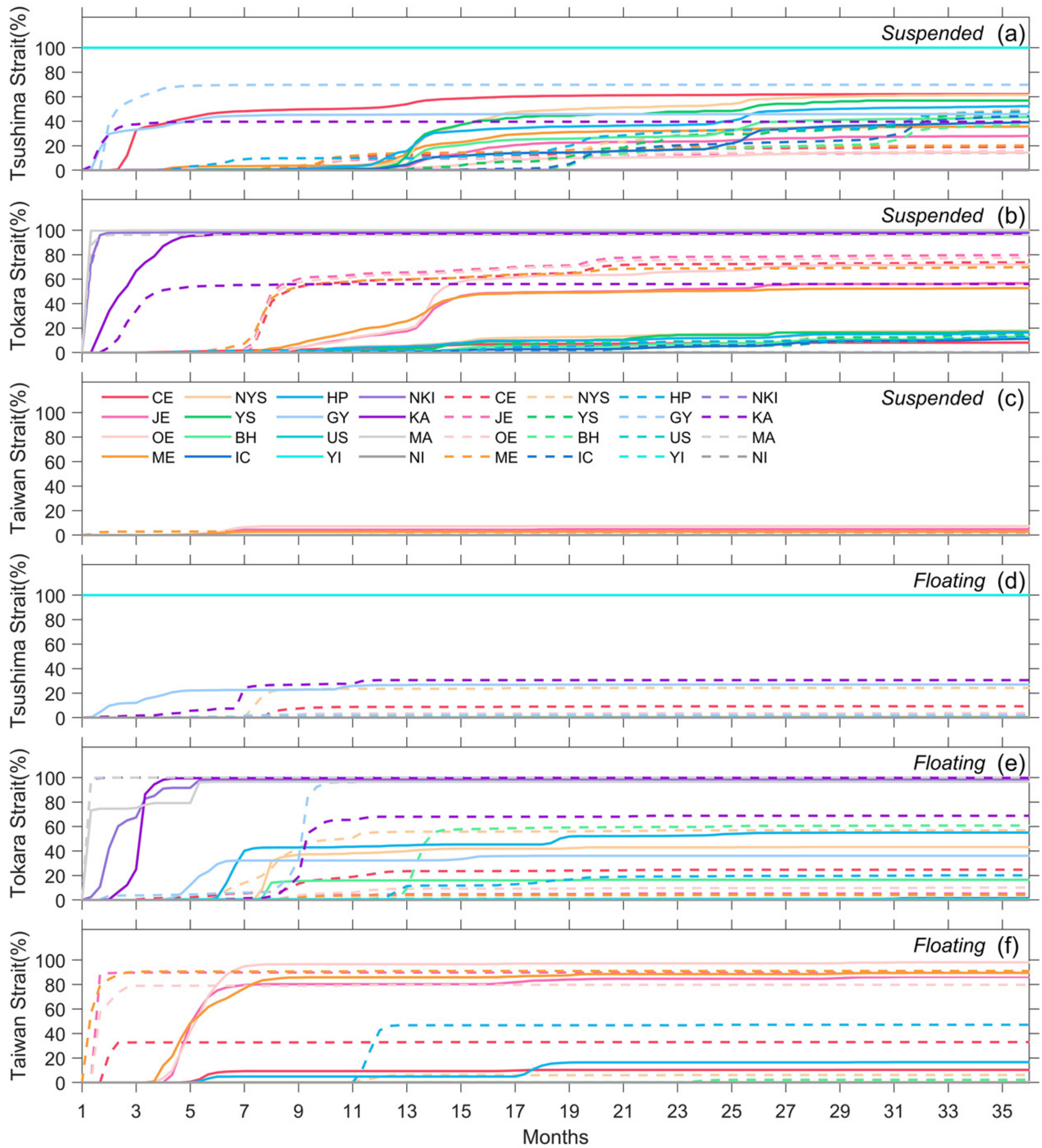

Fig. 7. Percentages of suspended (a, b, c) and floating (d, e, f) microplastics passing through the Tsushima Strait (a, d), the Tokara Strait (b, e), and the Taiwan Strait (c, f). Solid lines represent those released in summer while dotted lines represent those released in winter.

Jiangsu under the influence of the summer monsoon (Fig. 5S1). Approximately 10% of the particles left the ECSs through the Taiwan Strait after the monsoon change. In comparison to the ~70% and ~95% of suspended microplastic particles that left the ECSs after being released in summer and winter, only ~10% and ~67% of the floating microplastics left the ECSs in these seasons, respectively (Fig. 6b).

Nearly 90% of the floating microplastic particles released from the Jiaojiang River Estuary, Oujiang River Estuary, and Minjiang River Estuary left the ECSs through the Taiwan Strait regardless they were released in winter or summer (Fig. 5W2–4; S2–4). When released in winter, the particles passed through the Taiwan Strait much faster (approximately 1 month) than those released in summer (3–5 months), under the effects of wind drag. Microplastic particles released from the Bohai Sea and the North Yellow Sea (Fig. 5W5–7; S5–7) were affected by the winter monsoon and moved directly southward to the Kuroshio current and the Taiwan Warm Current. The Tokara Strait became the main conveying channel. About 43% and 57% of the microplastic particles from the North Yellow Sea released in summer and winter passed through the Tokara Strait, respectively (Fig. 6b). Noticeably, nearly all of the microplastic particles from the southwestern Yellow Sea landed on the shore regardless of the release season.

All of the microplastic particles released from Incheon on the western coast of Korea were pushed towards the shore. Whereas large amounts of the microplastic particles released from Hampyeong in winter were transported over a long distance to the Zhe-Min coast under the influence of the winter monsoon, which generally took ~12 months, and half of them passed through the Taiwan Strait (Fig. 7f). The rest joined the Kuroshio via cross-shelf exchanges (Wang and Oey, 2016) and finally left the ECSs through the Tokara Strait. The summer pattern was different, with only a small proportion of particles (~17%) being transported to the Zhe-Min coast passing through the Taiwan Strait approximately 6 months after release (Fig. 7f). Others crossed the Jeju Strait and moved southward along the west coast of Kyushu, or were transported southward and joined the Kuroshio to the northwest of Taiwan Island, and finally entered the Pacific through the Tokara Strait approximately 6 months after release. In addition, particles released from the southern coast of Korea (for example Gwangyang), were largely affected by the winter monsoon, and mostly passed through the Tokara Strait. The floating microplastic particles released from the east coast of Korea (for example Ulsan, Yeongil) remained in the Japan Sea, while those released from Japanese coastal areas followed the same transport pathways as the suspended particles.

In general, large differences existed between the fates of the floating and suspended microplastic particles. The floating microplastic particles were more directly influenced by the wind, which played a more crucial role in the surface layer. The floating particles released in the southeastern coastal areas of China tended to pass through the Taiwan Strait and leave the ECSs under the influence of northerly winds during the winter monsoon. Floating microplastic particles released in the Bohai Sea, Yellow Sea, the southeastern coastal areas of Korea, and the coast to the north of Fukuoka tended to pass through the Tsushima Strait before entering the Japan Sea. Floating microplastic particles from the western and southwestern coastal areas of Korea and the coast to the south of Fukuoka likely entered the Pacific Ocean through the Tokara Strait. As for the floating microplastic particles released in the Changjiang River Estuary, the Taiwan Strait became the main delivery channel regardless of the release season, and only ~25% and ~10% of the particles released in winter passed through the Tokara Strait and the Tsushima Strait, respectively. It took on average 9, 7, and 11 months for floating microplastics to pass through the Tsushima Strait, the Tokara Strait and the Taiwan Strait, respectively.

3.3. Fate of total microplastic particles from different regions

According to previous studies, around 60% of plastic waste is buoyant (Andrady, 2011). Using this proportion, the simulated floating and suspended microplastics through each strait in this study were combined to form total microplastics. For this purpose, a supplementary experiment was conducted where the same amount of microplastic particles were continuously released in every month over the year. It should be noted that there are uncertainties regarding this proportion, since sinking or decaying processes were not considered, and microplastic concentrations actually vary across 12 months. However, based on the microplastic concentrations from the literature (i.e. Fig. 1) and the simulated transports, it is possible to give a first glance estimation on the overall fate of microplastics from different regions. The proportion of total microplastic export relative to its source was determined as:

$$P = (T_s \times 40\% + T_f \times 60\%)/T_t \tag{5}$$

where T_s is the amount of suspended microplastic particles leaving the ECS or entering the Pacific Ocean from each source, T_f is that of floating particles, T_t is that of the total amount from each source. The results are shown in Fig. 8.

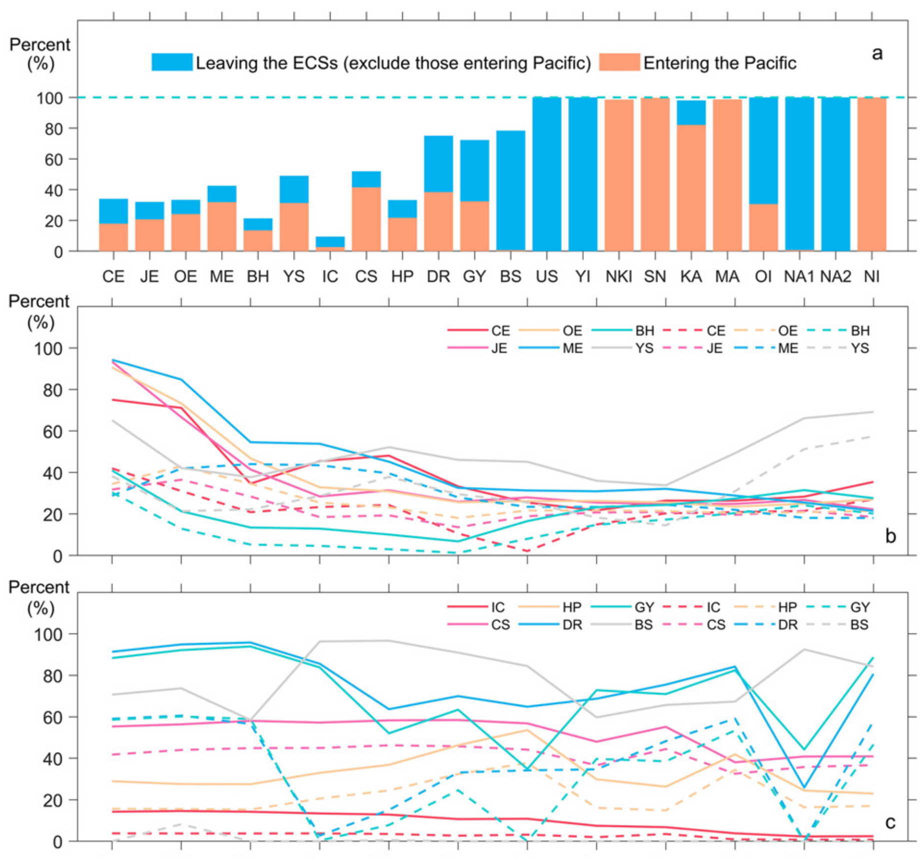

Fig. 8. (a) Percentages of microplastics leaving the ECSs (whole bars) and entering the Pacific (orange bars). (b) Percentages of microplastics released in different months from the coastal areas of China leaving the ECSs (solid line) and entering the Pacific (dotted line). (c) Percentages of microplastics released in different months from the coastal areas of Korea leaving the ECSs (solid line) and entering the Pacific (dotted line).

Annually ~36% of particles from the Jiaojiang River Estuary, Oujiang River Estuary, and Minjiang River Estuary left the ECSs, but only ~25% entered the Pacific Ocean through the Tokara Strait. Meanwhile, a large amount (~66%) of microplastic particles from the Changjiang River Estuary remained in the ECSs as they were beached on the coasts, and only ~18% of the particles entered the Pacific Ocean through the Tokara Strait. Particles from the Bohai Sea mainly (~80%) stayed in the ECSs due to beaching. Overall, more particles released in winter from the coastal areas of China left the ECSs or entered the Pacific Ocean. About 90% particles released in winter from the Jiaojiang River Estuary, Oujiang River Estuary, and Minjiang River Estuary left the ECSs, while the proportion decreased to ~25% for particles released in the summer.

The major source of microplastics in the coastal waters of China is the Changjiang River Estuary, due to its great discharge. Particles from the Jiaojiang River Estuary, Oujiang River Estuary, and Minjiang River Estuary were smaller than those from the Changjiang River Estuary, but their contribution can be weighted based on their river discharges. Microplastic particles from the Bohai Sea and the Yellow Sea were not considered in the total estimation due to their low concentration (Fig. 1). The proportion of particles from the coastal areas of China leaving the ECSs varied from ~75% if released in winter, to ~22% if released in summer, and those entering the Pacific Ocean varied from ~42% if released in winter, to ~3% if released in summer, respectively. Therefore, annually ~34% and ~18% of particles leave the ECSs and enter the Pacific Ocean, respectively.

For microplastic particles from the coastal areas of Korea and Japan, the contributions of different sources were simply weighted by their concentrations, as the sampling sites were evenly distributed. >70% of the particles released along the coastal areas of Korea left the ECSs, with the exception of those released in western coastal areas (~10% in Incheon, ~30% in Gwangyang, and ~50% in Cheonsu). In addition, >30% of the microplastic particles released from the southwestern coastal areas of Korea (except those released in Hampyeong) entered the Pacific Ocean through the Tokara Strait. Almost all of the particles released from the coastal areas of Japan left the ECSs, with most of those released south of Fukuoka joining the Pacific Ocean via the Tokara Strait.

Therefore, of the extensive amounts of microplastic particles released from the coastal areas of China, >80% stayed in the ECSs or entered the Japan Sea, rather than entering the Pacific Ocean. Similarly, only ~14% of the particles released from the coastal areas of Korea entered the Pacific Ocean via the Tokara Strait, whereas nearly all particles released from the coastal areas of Japan south of Fukuoka entered the open ocean.

4. Discussion and conclusion

The Tsushima Strait, the Tokara Strait and the Taiwan Strait were identified as the main delivery channels for microplastics released from the coastal areas of China, Korea and Japan. Suspended microplastic particles were more affected by current systems, while floating microplastic particles were more affected by wind. Transport pathways of microplastics from different source areas are summarized in the graphical abstract.

Generally, suspended microplastics released in the Bohai Sea, the Yellow Sea, the Korean coastal areas, and the coast to the north of Fukuoka tended to pass through the Tsushima Strait and entered the Japan Sea, while those released in the coastal areas southeast of China and the coast to the south of Fukuoka tended to enter the Pacific Ocean through the Tokara Strait. Seasonal variations also played a role as suspended microplastics released from the Changjiang River Estuary tended to enter the Japan Sea through the Tsushima Strait in summer and entered the Pacific Ocean through the Tokara Strait in winter.

The floating microplastics released along the southeastern coastal areas of China (including the Changjiang River Estuary) tended to leave the ECSs through the Taiwan Strait, while those released in the Bohai Sea, the Yellow Sea, the southeastern coastal areas of Korea, and the coast to the north of Fukuoka were more likely to enter the Japan Sea through the Tsushima Strait. Floating microplastic particles released from the western and southwestern coastal areas of Korea and the coast to the south of Fukuoka tended to enter the Pacific Ocean through the Tokara Strait. The results of our experiments highlighted the very large discrepancy between microplastic export from coastal areas and export to the open ocean. Although huge amounts of microplastic particles were released from the coastal areas of China and Korea, annually only ~18% and ~14% of these entered the Pacific Ocean, respectively.

Coastal areas with their complex hydrodynamic structures, and interactions with tides, river plumes and currents, play a significant role in microplastic transport from the coasts to the open ocean. This was demonstrated by the results of the simulations in the current study, and it is suggested that key coastal dynamic processes should be thoroughly investigated in future research on microplastic transport. It is inaccurate to use the global no-tides model data to simulate microplastic transport in coastal areas or the export of terrestrial microplastics to the open oceans.

In this study, the transport of suspended and floating microplastics was investigated in coastal areas during different seasons using climatological input data. Several simulation conditions have yet to be improved, starting with obtaining a better prior knowledge of the sample data based on which experiments were run. In the current study, the sample data was limited in terms of temporal and geographical resolution. The sample collection methods differed and the mesh sizes were different, which precludes accurate knowledge of the amount and type of microplastic particles transported. In view of this, the quantification in this study was made in terms of the percentage of released particles from each source, rather than the absolute values of microplastic volume or weight. Several processes were ignored in the current study, such as sinking, deposition, re-suspension, fragmentation, degradation and biofouling, etc. Should all of these processes be considered in the model, the value of terrestrial microplastic export to the open oceans might become lower. Moreover, a larger simulation area may enable a more complete assessment of microplastic transport from coastal areas to the open oceans.

Declaration of competing interest

The authors certify that they have no financial and personal relationships with other people or organizations that can inappropriately influence their work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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