Trajectory mapping of microplastics originating from the Seto Inland Sea, Japan

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Abstract. Knowledge of microplastic trajectories is useful for a variety of fields ranging from science to commerce. In this research, microplastic trajectories in the upper water column in each season were simulated using Python-based OceanParcels. The simulation domain covers Japan and its surrounding waters. HYCOM current data were used as input for the simulation. The simulation results show that in boreal winter and spring, the trajectory of microplastics tends to move toward the Pacific Ocean. Meanwhile, in summer and fall, the microplastic trajectory tends to move northward in the waters around Japan. The distribution of microplastics reaches various areas in Japanese waters with the northernmost area reached being Akita Prefecture. Meanwhile, the southernmost area reached is the islands in Kagoshima Prefecture which are close to the Okinawa Islands.
Key Words: marine plastic debris, microplastics transport, ocean modelling, Python.

Introduction. The quantity of microplastics in the water column has continued to increase since 1950 and if the rate of microplastic emissions continues to increase, it is estimated that there will be 2,652,700 tons of microplastics at sea level by 2050 (Ritchie et al 2018; Lebreton et al 2019). The existence of microplastics has a negative impact on both marine ecosystems and humans. Microplastics have been found in the water column, seabed, and sea ice (Van Cauwenberghe et al 2013; Martin et al 2017; Everaert et al 2018; Bergmann et al 2019; Lebreton et al 2019). Its wide distribution has resulted in microplastics being found in marine organisms, whether nekton or filter feeders (Wang et al 2020; Cverenkárová et al 2021). The discovery of microplastics in consumption fish is one way for microplastics to enter the human body (Thiele et al 2021).

The Seto Inland Sea (SIS), which is encompassed by three of Japan's primary islands, namely Honshû, Kyûsû, and Shikoku, constitutes a distinctive and ecologically significant marine ecosystem (Yoneda et al 2022). As per the Japanese Territorial Sea Law, the SIS spans an area of 19,700 km^2 from its western to eastern boundaries, with an average depth of 38 m, and a maximum depth of 105 m (Ministry of Agriculture Forestry and Fisheries of Japan 1977). Over the course of its existence, the SIS has played a pivotal role in sustaining fisheries, particularly in the cultivation of oysters and various fish species (Isono et al 2020; Yoneda et al 2022). Notably, the SIS serves as a crucial fishing ground for Japanese anchovy (*Engraulis japonicus*), and comprehending the underlying factors that contribute to their reproductive success is imperative for the implementation of sustainable fisheries management practices (Yoneda et al 2022).

One area where extensive modeling has been conducted is the Sea of Japan, where researchers have investigated the path and accumulation of microplastics over seasonal and annual periods (Iwasaki et al 2017; Kaandorp et al 2021; Nakano & Arakawa 2022). However, microplastic modeling efforts have also been undertaken in other water areas across Japan, which have both inland and aquatic sources of microplastics (Iwasaki et al 2017; Kataoka et al 2019; Nakao et al 2020). Recent studies have placed greater emphasis on the development of microplastic models that improve the accuracy of dispersion estimation, fate, and transport of microplastics (Kooi & Koelmans 2019; Aoki & Furue 2021; Kaandorp et al 2021).

Previous studies have primarily concentrated on examining the grain size distribution and destiny of microplastics in specific geographical areas. However, there remains a dearth of research specifically investigating the distribution of microplastics originating from SIS, and the existing studies are confined to a relatively limited scope. The primary objective of this research endeavor is to ascertain the dispersion patterns of microplastics originating from SIS across Japanese waters. Gaining a comprehensive understanding of the distribution of microplastics is of utmost significance for the fisheries sector, as it serves as a crucial material for analyzing diverse facets such as the impact on seafood safety, ecological ramifications, bioaccumulation, environmental monitoring, regulatory compliance, consumer awareness, and market demand. Furthermore, this study can serve as a comparative reference for different methods within the same domain.

Material and Method

Description of the study sites. The simulated geographical area encompasses latitudes 28-55°N and longitudes 120-160°E, encompassing various bodies of water such as the SIS, Sea of Japan, a small portion of the Yellow Sea, East China Sea, Sea of Okhotsk, and the Pacific Ocean (see Figure 1). The selection of this specific domain is motivated by the desire to optimize resource allocation, as it excludes the waters in southern Japan that are not relevant to the study. This decision is informed by previous research conducted by Iwasaki et al (2017), which demonstrated that microplastic particles tend to move towards the northeast region of the Sea of Japan. The three points depicted in Figure 1 (with corresponding coordinates and locations provided in Table 1) serve as the initial release points for the simulated microplastic particles. These points were deliberately chosen due to their strategic location, as they are situated in the water bodies connecting the SIS with its surrounding areas, known to be contaminated with microplastics (Isobe 2016; Iwasaki et al 2017).

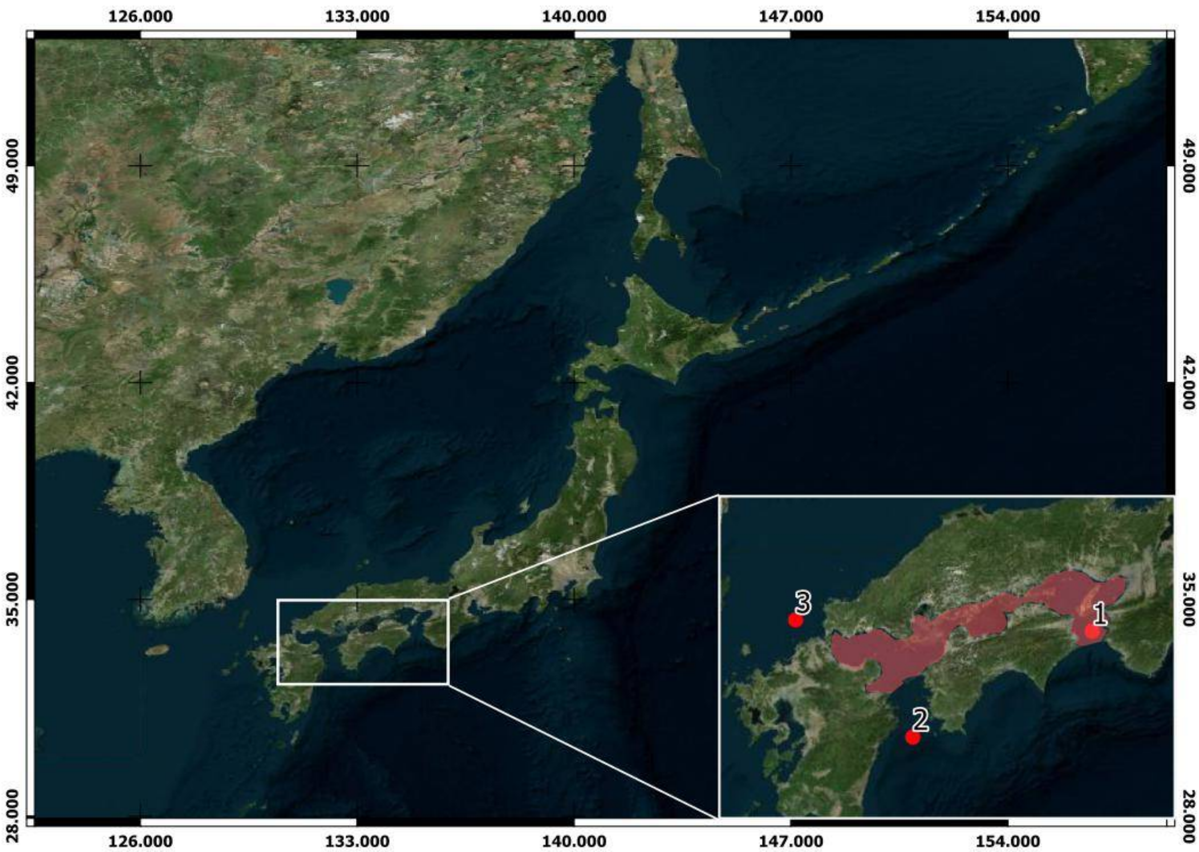

Figure 1. Simulation domain (the area highlighted in red is the SIS).

Table 1

Initial point

Station	Coordinates	Location
1	34,0188°N, 134,9193°E	Kii Strait
2	32,6888°N, 132,2232°E	Bungo Strait
3	34,1580°N, 130,4621°E	Kanmon Strait

Simulation duration. The simulation period spans one year, commencing on 1 December 2021 and concluding on 30 November 2022. This timeframe is partitioned into four distinct seasons, namely boreal winter (December-February, 90 days), spring (March-May, 92 days), summer (June-August, 92 days), and autumn (September-November, 91 days). The decision to adopt a one-year simulation duration was motivated by the need to investigate the seasonality patterns in the study area. This approach enabled a comprehensive analysis of the study, facilitating direct comparisons of the differences and/or similarities across each season.

Datasets. The present study employs data from the HYBRID COORDINATE OCEAN MODEL (HYCOM) Consortium as the primary input for the simulation. Specifically, the GOFS 3.1: 41-layer HYCOM + NCODA Global 1/12° Analysis (NRL) database is utilized. The current velocity variables, namely Eastward Water Velocity (representing current speed on the X axis) and Northward Water Velocity (representing current speed on the Y axis), are incorporated in the analysis. The integration of these two variables enables the determination of the speed and direction of the ocean current in the simulation domain.

Statistical analysis. The validation of HYCOM data relies on the utilization of in-situ ocean current data obtained from the Japan Oceanographic Data Center. To assess the accuracy of the statistical model's predicted values against the actual values, all data underwent testing through the calculation of the Root Mean Square Error (RMSE). In order to obtain a more comprehensive evaluation, the RMSE values were normalized, enabling a more informed determination of the quality of a given RMSE value.

Parcels. Parcels, an acronym for Probably A Really Computationally Efficient Lagrangian Simulator, is a program based on the Python programming language. It comprises Python classes and methods that facilitate the creation of particle tracking simulations in aquatic environments (Lange & van Sebille 2017). Parcels is designed to operate at the petascale, which denotes a computing system capable of performing at least 10^{15} floating point operations per second, thereby enabling rapid and efficient computation. The particle type selected for the study was JITParticle, as it aligns with the research objectives and offers superior computational efficiency compared to ScipyParticle. The particle settings employed involved the release of 80 particles every 24 hours from the same initial point at a depth of 0 m, utilizing freeslip interpolation.

Results. The validation of HYCOM current speed data against observation data yielded a RMSE value of 0.160477856 for *U current* speed and 0.14959648 for *V current* speed. A RMSE value below 0.30 is considered favorable, indicating a close match between the model data and observational data. Based on these results, it can be inferred that the model data is suitable for utilization as input in simulations.

The Parcels simulation data is organized and stored in a two-dimensional array, with dimensions corresponding to traj (trajectory) and obs (observation). The traj dimension represents the number of particles involved in the simulation, while the obs dimension provides information about the trajectory of each particle over time. The trajectory of each particle is essentially recorded as a time series, encompassing data such as longitude, latitude, and time as the particle traverses the ocean.

The number of particles in each season (Table 2) exhibits variation due to differences in simulation time. Spring and summer demonstrate the highest particle count and observations, specifically 22,320 particles with 2,209 observations, while boreal winter exhibits the lowest count with 21,840 particles and 2,161 observations. Spring and summer share identical dimension values as their simulation times are the same.

Table 2

Dimensions in every season

Season	*Traj*	*Obs*
Boreal winter	21.840	2.161
Spring	22.320	2.209
Summer	22.320	2.209
Fall	22.080	2.185

During boreal winter (Figure 2), microplastics move eastward towards the Pacific Ocean and southwest towards the Okinawa islands. Accumulation of microplastics is observed in the region between 130° and 140°E. This distribution pattern suggests that the Kuroshio current is stronger compared to other currents.

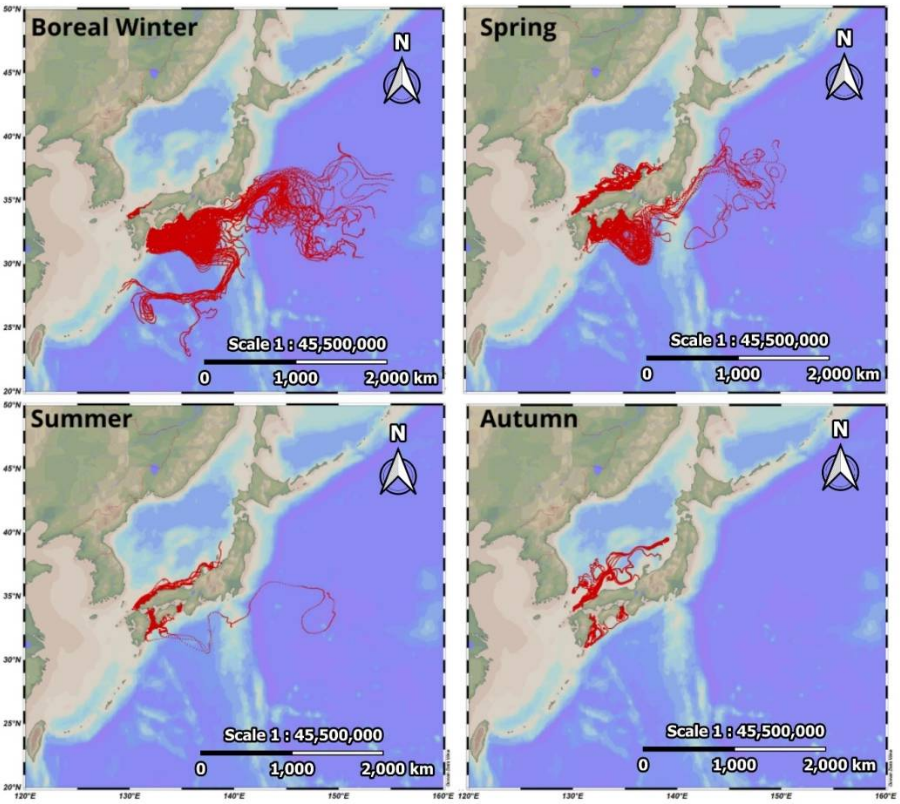

Figure 2. Pathways of microplastics per season.

Similarly, in spring, microplastics accumulate significantly in the region between 130° and 140°E, as the direction and strength of the currents during this season tend to resemble those of boreal winter. However, in this season, the distribution of microplastics is also observed to spread in the Sea of Japan, extending up to 38°N. This indicates a strengthening of the Tsushima Current during this period.

In summer, the distribution of microplastics predominantly moves northward, evident from the movement of microplastics from the Bungo Strait to the Kanmori Strait. Nevertheless, three microplastic paths are carried by the Kurishio current, leading them to end up in the Pacific Ocean. The trajectory of microplastics during this season extending up to 39°N.

In contrast to boreal winter, the distribution of microplastics in autumn displays widespread movement in the Sea of Japan and no distribution in the Pacific Ocean region.

Microplastics reach a latitude of 39.7°N in the Sea of Japan, representing the highest latitude among the simulations conducted for each season.

Discussion

Trajectories in boreal winter. The convergence of multiple oceanographic parameters, including wind-generated currents, Ekman currents, geostrophic currents, and Stokes drift, leads to a combined eastward and southwesterly water movement. Consequently, microplastics are transported from their initial location towards the Kanmori Strait, where they accumulate.

In the Sea of Japan (Figure 3), microplastics undergo an eastward trajectory, passing through Yamaguchi Prefecture until they ultimately reach the city of Oda in Shimane Prefecture (35°N, 132.5°E) at the conclusion of the simulation. This simulation aligns with the findings of Kabir et al (2022), who observed the presence of microplastics in the Yamaguchi Prefecture area, albeit at a moderate level compared to other regions worldwide. The primary forms of microplastics detected were large fragments and high-density particles composed of various polymers such as polyvinyl chloride, polyethylene, and polypropylene (Kabir et al 2022). Although the specific sources of microplastics in the Yamaguchi Prefecture area were not identified in their study, this simulation can serve as a reference for understanding the potential sources of microplastics in the region based on the sea-based transportation scheme.

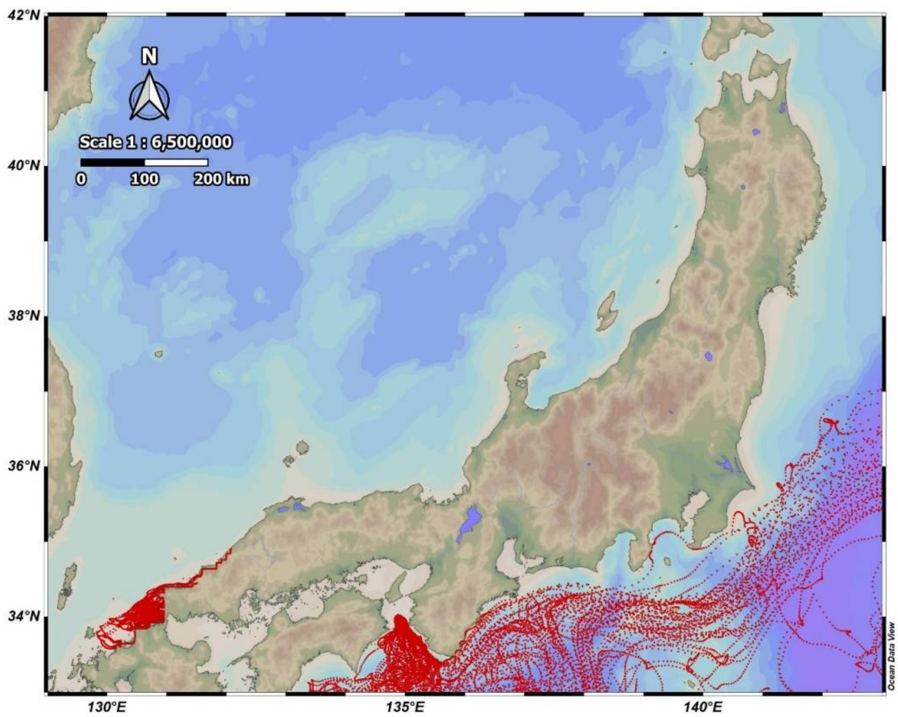

Figure 3. Distribution of microplastics in the Sea of Japan in boreal winter.

The distribution of microplastics originating from the Bungo Strait and Kii Strait exhibits a bifurcation pattern, as depicted in Figure 2. These microplastics are observed to disperse in two main directions: eastward towards the Pacific Ocean, propelled by the Kuroshio Current, and southward towards the Okinawa Islands, carried by the Kuroshio Countercurrent. It is worth noting that microplastics transported by the Kuroshio Current have a higher likelihood of encountering substantial diatom biofouling due to the Kuroshio Current's association with a highly productive current. However, it is important to acknowledge that this assertion is solely based on theoretical findings derived from modeling outcomes (Fischer et al 2022).

The Tokai region, situated within the coordinates of 34-36° N and 136-140° E, represents one of the areas traversed by microplastics transported by the Kuroshio

Current. Surface water samples collected from this region indicate the presence of 1,000-5900 particles m^{-1}, with polyethylene and polypropylene being the predominant types of microplastics detected (Xu et al 2022). In contrast, investigations conducted in the Kagoshima region and the Okinawa Islands (located in the upper left section of the black rectangle in Figure 4) reveal the presence of microplastics composed of polyethylene, polypropylene, and polystyrene (Sharma et al 2023).

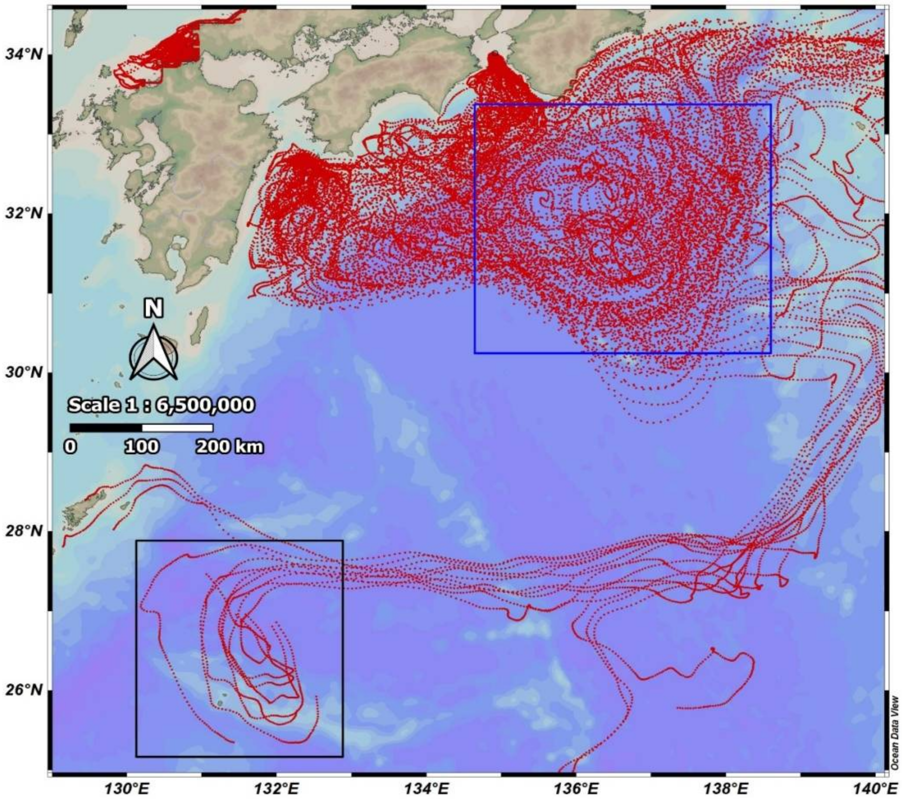

Figure 4. Microplastics on Eddies in the Pacific Ocean in the boreal winter.

There is a discernible distinction in the dispersion pattern of microplastics during the boreal winter compared to other seasons. Specifically, microplastics tend to accumulate within eddies located in two specific regions, namely the vicinity of the Tokai region (as indicated by the blue square in Figure 4) and near Kagoshima (as denoted by the black square in Figure 4). Eddies, which are formed as a result of variations in temperature, topography, and typhoons, play a significant role in influencing the distribution and aggregation of microplastics (Nakajima et al 2022). If microplastics persist within these circular currents, they will gradually amass and form what can be referred to as a "shadow island".

Trajectories in spring. In contrast to the distribution of microplastics during the boreal winter, the distribution of microplastics during the spring season exhibits a wider spatial extent in the Sea of Japan, extending as far as Niigata Prefecture, which is situated 850 km to the east of the initial point (Figure 5). The findings from the simulation of microplastic distribution in the Sea of Japan during the spring season are consistent with those reported by Iwasaki et al (2017) during the same season. The distribution pattern of microplastics in the region extending from the Kanmori Strait to Shimane Prefecture, and the subsequent splitting of the microplastic track by Okinoshima Island (36° N, 133° E), exhibits similarities between the simulation results and the research conducted by Iwasaki et al (2017). However, a notable difference arises in the endpoint of the microplastic trajectory. In the research simulation, the microplastics reach Niigata Prefecture, whereas in Iwasaki et al's study, the endpoint is Akita Prefecture, which is in close proximity to Hokkaido. This discrepancy can be attributed to the disparity in simulation durations employed in the two studies.

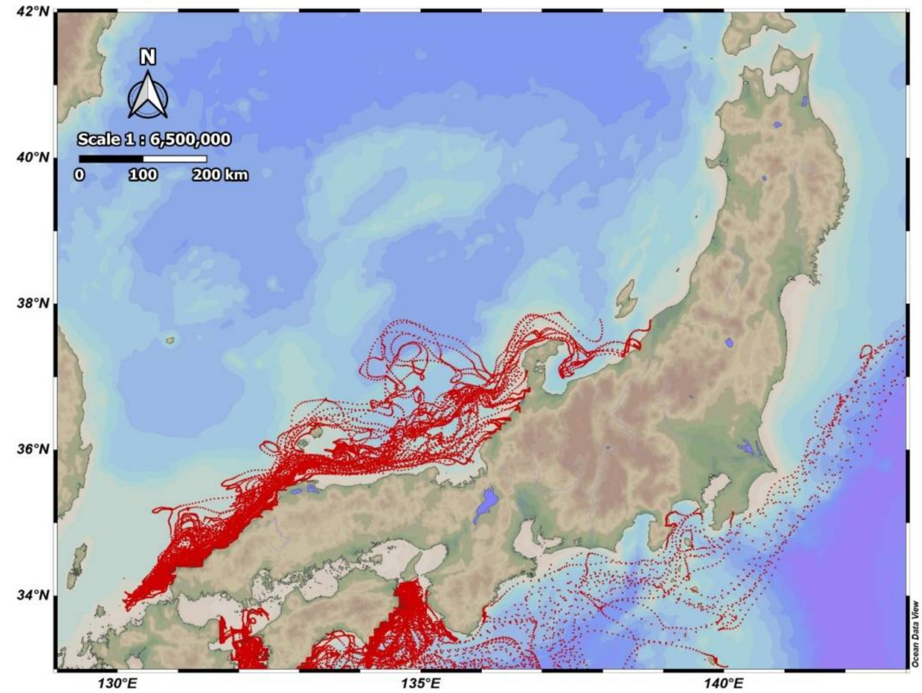

Figure 5. Distribution of microplastics in the Sea of Japan in spring.

A distinct variation in the distribution of microplastics is observed around the SIS during the spring season (Figure 6) and the boreal winter. In the spring, certain microplastics enter the SIS through the Bungo Strait and ultimately accumulate in Matsuyama Prefecture (33.5° N, 132.5° E) and Oita Prefecture (33.5° N, 131.5° E). Furthermore, during this season, microplastics are also trapped within an eddy, similar to the situation in the boreal winter. However, in the spring season, only one eddy is present (Figure 6). Notably, there is no movement of microplastics towards the southwest of the initial point, as microplastics originating from the Bungo Strait tend to move northward.

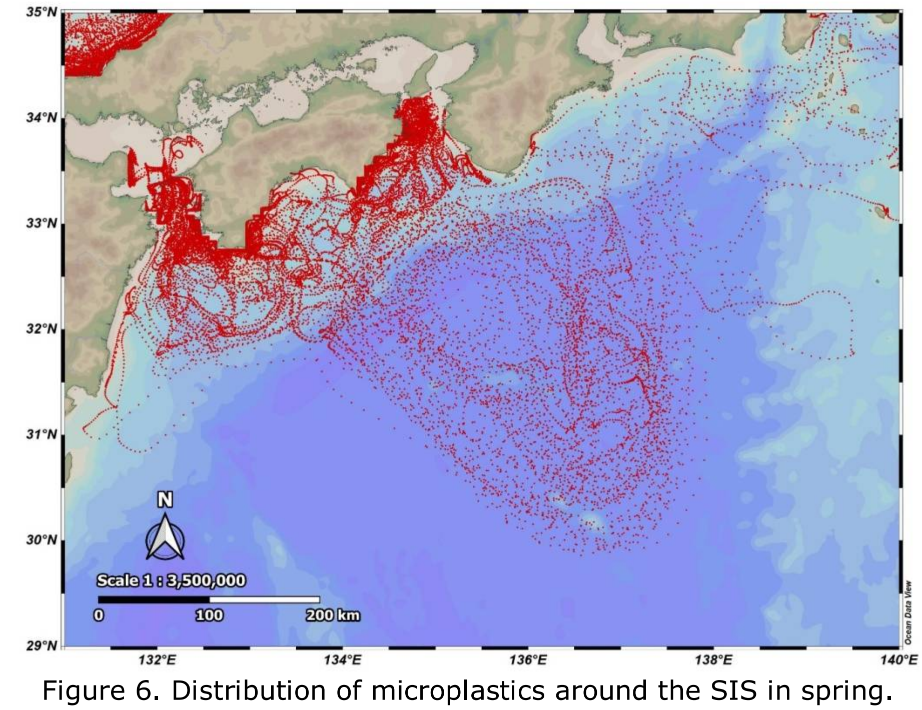

Figure 6. Distribution of microplastics around the SIS in spring.

Trajectories in summer. The spatial distribution of microplastics in the Sea of Japan during the summer season exhibits similarities to that observed in the spring season.

However, in the summer, the proximity between the distribution of microplastics and the coastline is closer compared to the spring season (Figure 7). Similar to the spring season, microplastic particles originating from the Bungo Strait tend to migrate northwards towards the SIS, albeit with a wider coverage area. Notably, during the summer season, microplastics have been observed to disperse as far as Hiroshima Bay (34° N, 132.5° E), Yamaguchi Prefecture (34° N, 131.75° E), and Oita Prefecture (33.7° N, 131.5° E) (Figure 8). Conversely, in the Kii Strait, the distribution pattern remains consistent with that observed in the spring season, with microplastics accumulating in the Naruto Strait.

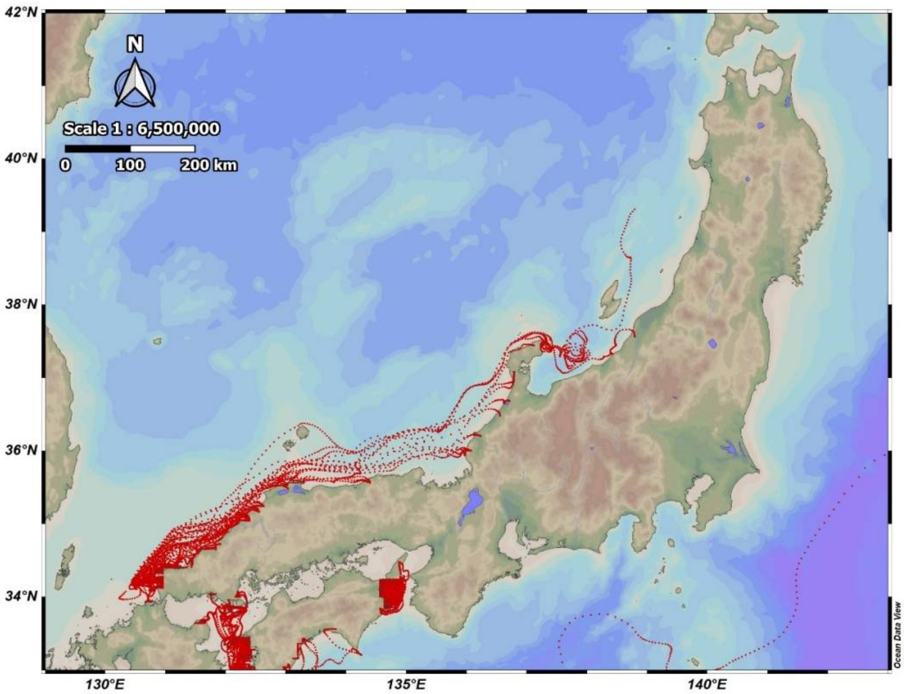

Figure 7. Distribution of microplastics in the Sea of Japan in summer.

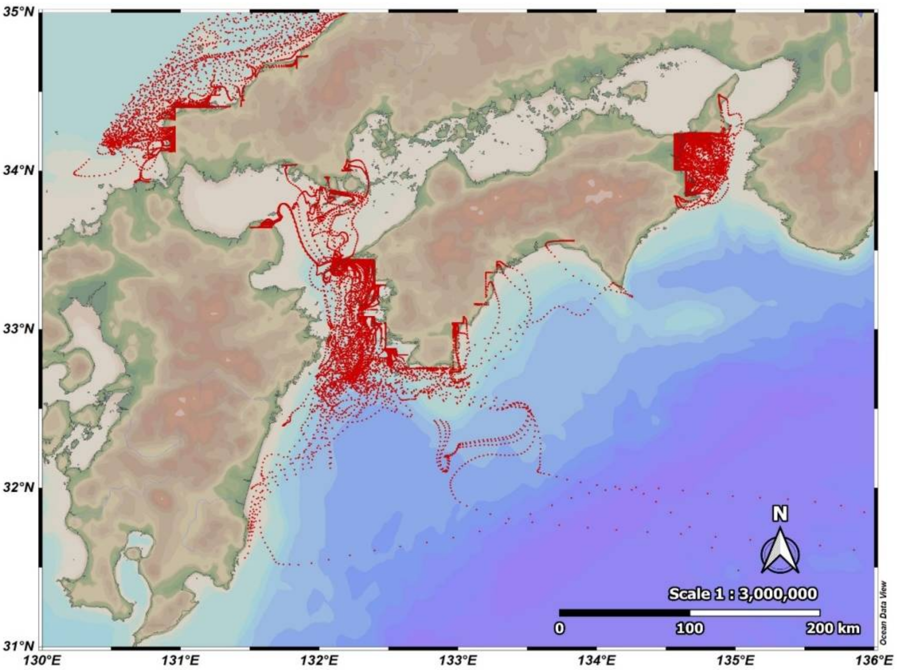

Figure 8. Distribution of microplastics around the SIS in summer.

Trajectories in autumn. The autumn season exhibits the most extensive distribution of microplastics in the Sea of Japan, surpassing other seasons in terms of reach, particularly extending towards Akita Prefecture (40° N, 139° E) and approaching South Korea (Figure

9). The distribution of microplastics during this season is attributed to the Tsushima current, which divides into two branches within the Sea of Japan. One branch moves along the coastline, while the other branch moves towards the open sea.

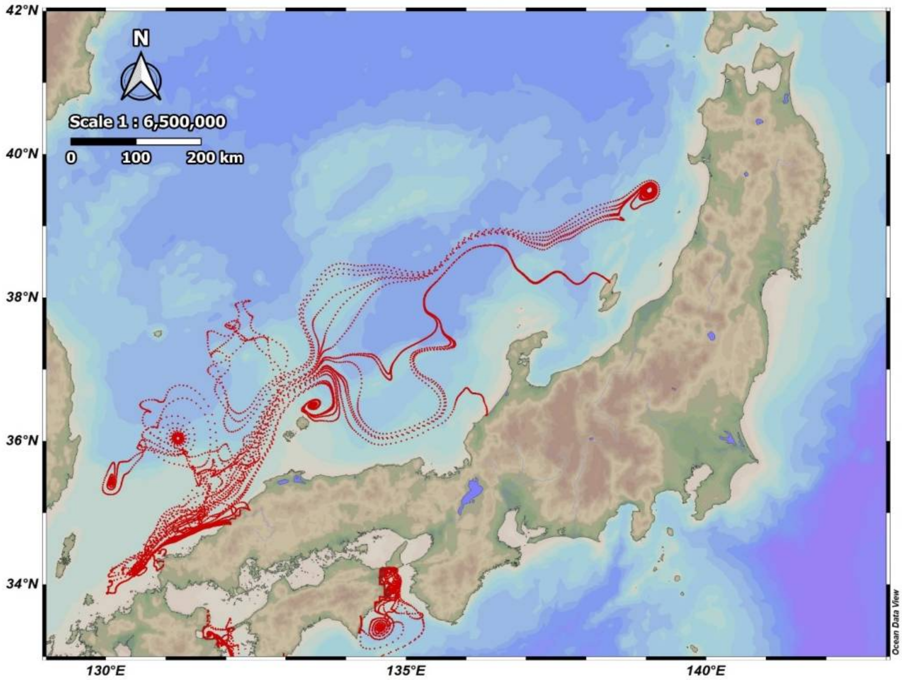

Figure 9. Distribution of microplastics in the Sea of Japan in autumn.

The movement of microplastic particles towards the open sea initiates from point 36° N, 133° E, as the Tsushima current's speed in this region is 0.2 m s^{-1} faster compared to the current near the shoreline. Additionally, the spread of microplastics is influenced by the occurrence of a typhoon passing over Japan during the autumn of 2022 (NOAA 2022). The accumulation of microplastics in eddies generated by typhoons in the waters of southern Japan is observed from October 11 to October 21, 2022 (Figure 10). In the Sea of Japan (Figure 9), microplastic accumulation in these eddies is also observed, but the duration of initial accumulation is longer, starting on October 16 and lasting until November 11, 2022.

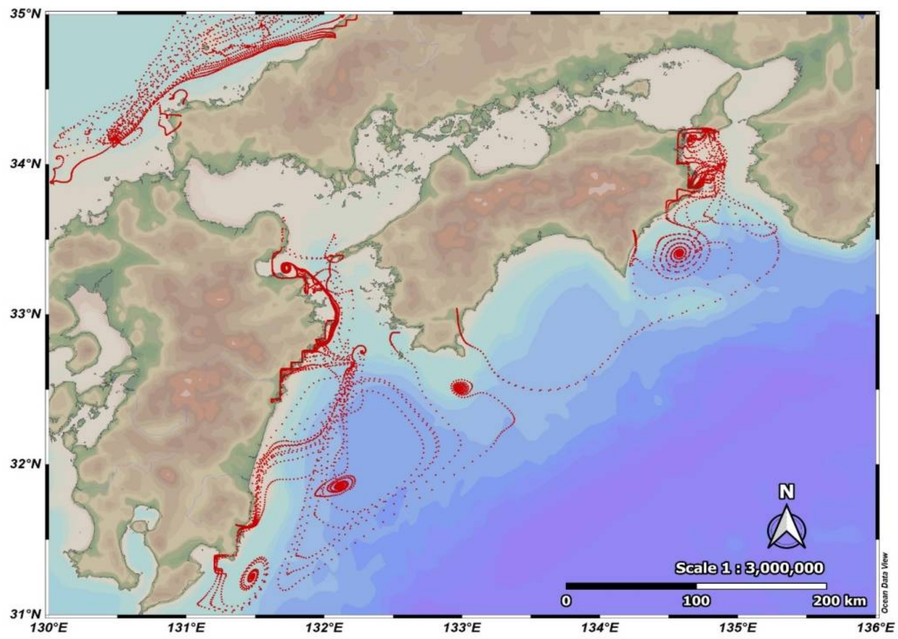

Figure 10. Distribution of microplastics around the SIS in autumn.

Model limitation. The omission of fragmentation processes and vertical particle movement in modelling deep water areas can be attributed to computational simplification efforts, primarily due to the extensive spatial coverage of the study area and the relatively low occurrence of microplastic particles reaching the deep sea (Bigdeli et al 2022).

Conclusions. The distribution patterns of microplastics originating from the SIS exhibit seasonal variations. During the boreal winter, microplastics tend to disperse towards the Pacific Ocean, with minimal distribution observed in the Sea of Japan. A similar distribution pattern is observed in spring, although a greater proportion of microplastics is found in the Sea of Japan compared to the winter season. The altered direction of ocean currents in spring leads to a northward trend in microplastic distribution, with a higher concentration observed in the Sea of Japan compared to both spring and winter. It is worth noting that there are three distinct routes through which microplastics migrate to the Pacific Ocean. Additionally, the autumn season is influenced by a natural phenomenon, namely typhoons, which significantly impact the distribution of microplastics. Typhoons generate eddies in the Sea of Japan and the southern waters of Japan, creating favourable conditions for the accumulation of microplastics in these regions.

Acknowledgements. We thank Japan Oceanographic Data Center for the in-situ data used in this study. Funding for the development of HYCOM has been provided by the National Ocean Partnership Program and the Office of Naval Research. Data assimilative products using HYCOM are funded by the U.S. Navy. Computer time was made available by the DoD High Performance Computing Modernization Program. The output is publicly available at https://hycom.org.

Conflict of interest. The authors declare that there is no conflict of interest.

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Received: 11 October 2023. Accepted: 31 October 2023. Published online: 12 December 2023.
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How to cite this article:
Yuniarti MS., Faid G. M., Subiyanto, Ismail M. R., 2023 Trajectory mapping of microplastics originating from the Seto Inland Sea, Japan. AACL Bioflux 16(6):3138-3149.