



# Plastic After an Extreme Storm: The Typhoon-Induced Response of Micro- and Mesoplastics in Coastal Waters

Ryota Nakajima<sup>1\*</sup>, Toru Miyama<sup>1</sup>, Tomo Kitahashi<sup>1</sup>, Noriyuki Isobe<sup>1</sup>, Yuriko Nagano<sup>1</sup>, Tetsuro Ikuta<sup>1</sup>, Kazumasa Oguri<sup>1,2</sup>, Masashi Tsuchiya<sup>1</sup>, Takao Yoshida<sup>1</sup>, Kunihiro Aoki<sup>1</sup>, Yosaku Maeda<sup>1</sup>, Kiichiro Kawamura<sup>3</sup>, Maki Suzukawa<sup>3</sup>, Takuya Yamauchi<sup>4</sup>, Heather Ritchie<sup>1,5</sup>, Katsunori Fujikura<sup>1</sup> and Akinori Yabuki<sup>1</sup>

<sup>1</sup> Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan, <sup>2</sup> Department of Biology, Nordcee and Danish Center for Hadal Research, University of Southern Denmark, Odense, Denmark, <sup>3</sup> Graduate School of Science and Technology for Innovation, Yamaguchi University, Yamaguchi, Japan, <sup>4</sup> Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto, Japan, <sup>5</sup> RZSS WildGenes, Royal Zoological Society of Scotland, Edinburgh, United Kingdom

## OPEN ACCESS

### Edited by:

Xiaoshan Zhu,  
Tsinghua University, China

### Reviewed by:

Atsuhiko Isobe,  
Kyushu University, Japan  
Muhammad Reza Cordova,  
Indonesian Institute of Sciences,  
Indonesia

### \*Correspondence:

Ryota Nakajima  
nakajimar@jamstec.go.jp

### Specialty section:

This article was submitted to  
Marine Pollution,  
a section of the journal  
Frontiers in Marine Science

**Received:** 01 November 2021

**Accepted:** 01 December 2021

**Published:** 13 January 2022

### Citation:

Nakajima R, Miyama T, Kitahashi T, Isobe N, Nagano Y, Ikuta T, Oguri K, Tsuchiya M, Yoshida T, Aoki K, Maeda Y, Kawamura K, Suzukawa M, Yamauchi T, Ritchie H, Fujikura K and Yabuki A (2022) Plastic After an Extreme Storm: The Typhoon-Induced Response of Micro- and Mesoplastics in Coastal Waters. *Front. Mar. Sci.* 8:806952. doi: 10.3389/fmars.2021.806952

Extreme storms, such as tropical cyclones, are responsible for a significant portion of the plastic debris transported from land to sea yet little is known about the storm response of microplastics and other debris in offshore and open waters. To investigate this, we conducted floating plastic surveys in the center of Sagami Bay, Japan approximately 30 km from the coastline, before and after the passage of a typhoon. The concentrations (number of particles/km<sup>2</sup>) of micro- and mesoplastics were two orders of magnitude higher 1-day after the typhoon than the values recorded pre-typhoon and the mass (g/km<sup>2</sup>) of plastic particles (sum of micro- and mesoplastics) increased 1,300 times immediately after the storm. However, the remarkably high abundance of micro- and mesoplastics found at 1-day after the typhoon returned to the pre-typhoon levels in just 2 days. Model simulations also suggested that during an extreme storm a significant amount of micro- and mesoplastics can be rapidly swept away from coastal to open waters over a short period of time. To better estimate the annual load of plastics from land to sea it is important to consider the increase in leakages of plastic debris into the ocean associated with extreme storm events.

**Keywords:** hurricanes, macroplastics, mesoplastics, microplastics, Sagami Bay, tropical cyclones, typhoon

## INTRODUCTION

Each year, approximately 20 million metric tons of land-based plastic debris makes its way into aquatic systems, including oceans and freshwater networks, and this figure is only likely to rise (Borrelle et al., 2020). Once they end up in the sea, plastic debris eventually accumulates in the marine environment as most plastics are believed to take several hundred years, or even longer, to break down completely (Derraik, 2002; Turner et al., 2020).

One of the main sources of plastic debris that ends up in the sea is mismanaged plastic waste that is leaked directly from shorelines or indirectly through riverine waterways (Lebreton et al., 2017), urban runoff (Weideman et al., 2020), sewage discharge (Browne et al., 2011) and wind dispersal (Schmidt et al., 2017). Particularly, flood events caused by heavy rainfall enhance the movement of plastic debris of land-based origin into the marine environments from multiple source points (Moore et al., 2002; Axelsson and van Sebille, 2017; Kataoka et al., 2019; Nihei et al., 2020). Therefore, extreme weather events that cause strong winds, heavy rainfall, and associated flooding can greatly enhance the leakage of plastic and other debris into the sea (Veerasingam et al., 2016; Gündoğdu et al., 2018; Hitchcock, 2020; Ockelford et al., 2020).

Tropical cyclones, including typhoons and hurricanes, are the most extreme episodic weather events occurring at low- and mid-latitudes. They bring heavy precipitation resulting in increased river flow and terrestrial runoff (Tsuchiya et al., 2015), and when coupled with the powerful winds they generate tropical cyclones can be a significant event that enhances the loading of plastic debris from land to the marine environment (Pelamatti et al., 2019; Wang et al., 2019; Hitchcock, 2020; Lo et al., 2020; Garcés-Ordóñez et al., 2021). For example, a single typhoon can contribute to more than 80% of the annual transport of microplastics that flow in the Edo River in Japan (Kudo et al., 2018). As such, an important focus of recent plastic research has been to establish the role of extreme storm events on plastic pollution and to determine how plastic debris varies in space and time after such events (Wang et al., 2019). Studies of past tropical cyclones have suggested that global warming may lead to increasing intensities of these episodic events (Kunkel et al., 2013; Tu and Chou, 2013) and therefore the impacts of tropical cyclones on the transport of marine debris will also be augmented. Understanding the leakage patterns of marine plastic debris by tropical cyclones and other storm events is essential for determining strategies to mitigate further pollution, especially in regions where there are frequent typhoon or hurricane events.

At present, most studies investigating how microplastics and other debris respond to storm disturbances are based on observing succession patterns by revisiting rivers (Hitchcock, 2020), beaches (Lo et al., 2020), shores (Zhao et al., 2015) or nearshore waters (<10 km) (Gündoğdu et al., 2018; Chen et al., 2019) after storm events. Although these studies provide valuable information on the storm response of microplastics and other debris in rivers, coasts and shallow waters, studies investigating the responses offshore or in open waters are scarce. Debris flowing into the coastal waters through rivers and shores *via* storm events will experience rougher sea conditions, such as higher waves and rapid currents, which may cause; an increase in transportation of debris out to the open waters, debris to be re-deposited into coastlines, or debris to sink to the sea bottom (Kukulka et al., 2012). As a result, the abundance of debris flowing into coastal waters may vary significantly over time after extreme storms. Yet, the true extent of plastic debris that is flowing into coastal waters and offshore through extreme weather events remains unclear.

In September 2019, Typhoon *Faxai*, equivalent to a Category 4 typhoon made landfall near Tokyo, Japan (Suzuki et al., 2020; Tamura et al., 2021). The destructive winds and storm surged with a maximum wind gust speed of 210 km h<sup>-1</sup> which caused landslides, damage to buildings and homes, knocking out power and uprooting trees across central Japan, resulting in 25 billion USD economic loss (Eckstein et al., 2021). However, this typhoon event provided unique research opportunities for estimating the influence of extreme storm events on plastic debris in the marine environment.

Here we present the study of floating micro- and mesoplastics debris in the center of Sagami Bay, some 30 km away from the Japanese coastline, at 3-days before, 1-day after and 3-days the typhoon *Faxai*'s passage. Specifically, our study addressed two key topics regarding typhoon derived debris through observations and model simulations: (1) how much does the concentration of floating plastic debris offshore change before and after a typhoon passage? and (2) where does the debris that is carried from the land to coastal waters by the typhoon go? This will significantly contribute to our understanding of the fate of plastic debris after an extreme storm.

## MATERIALS AND METHODS

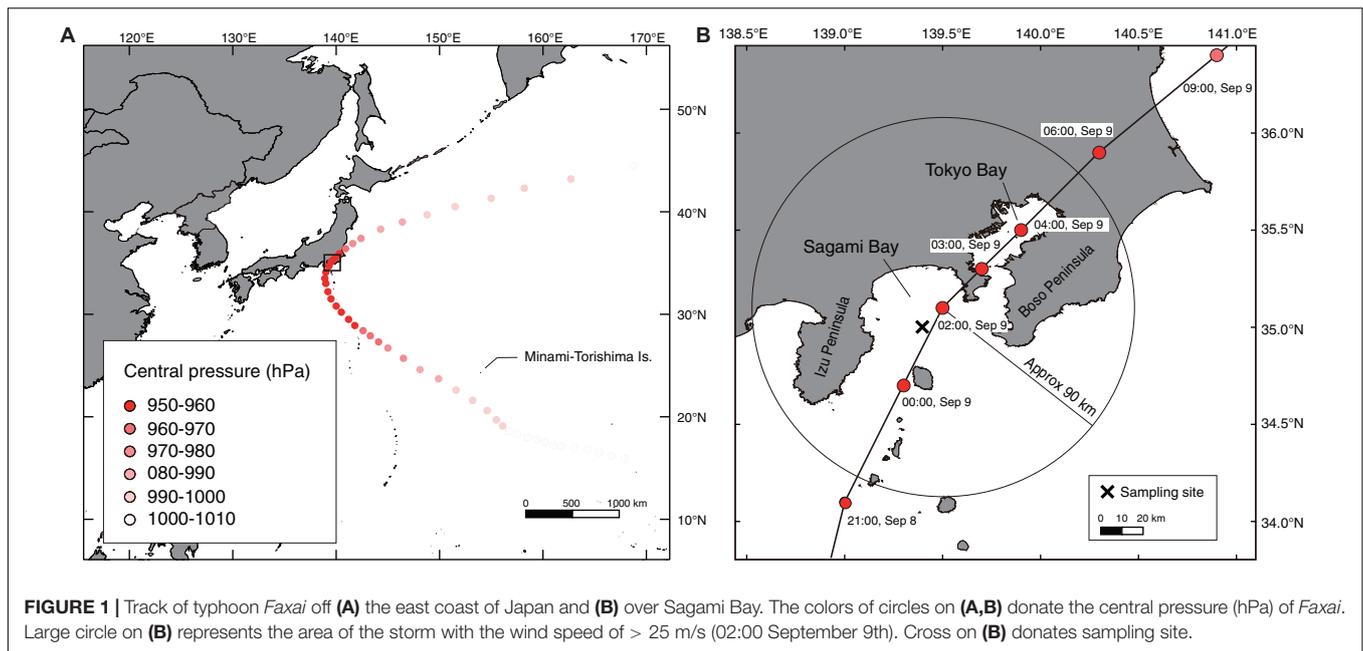
### Typhoon *Faxai*

*Faxai* (T1915) occurred east of the International Dateline presenting as a tropical depression on 2nd September 2019 before being upgraded to a typhoon on 5th September near Minami-Torishima Island as it moved across the Pacific Ocean (Japan Meteorological Agency, 2020; **Figure 1A**). The lowest central pressure of *Faxai* was 955 hPa with maximum sustained winds of 157 km h<sup>-1</sup>. Shortly before 03:00 JST (Japan Standard time, + 9 GMT) on 9th September 2019, *Faxai* passed through Sagami Bay in central Japan with the largest diameter of storm wind determined to be 180 km (**Figure 1B**). The storm caused heavy precipitation with a maximum of 109 mm of rain in 1 h, resulting in urban flooding in Tokyo metropolitan area (Tokyo Regional Headquarters, 2019). This was one of the strongest typhoons to ever hit the region on record (Tamura et al., 2021). After *Faxai* passed through the Tokyo area, it was downgraded to an extra-tropical cyclone on 10th September 2019 off the east coast of Japan.

### Plastic Sampling

Sampling was conducted at a location in the center of Sagami Bay (35°1.25'N; 139°22.65'E) over a water depth of 1,400 m (**Figure 1B**). This site was located near the center of the anticyclonic eddy of the bay (Iwata and Matsuyama, 1989) and thus an accumulation of debris was expected. We conducted sampling 3-days before *Faxai* reached the bay (September 7th), and revisited the same survey site at 1-day after (September 10th) and 3-days after (September 12th) the typhoon passed during a cruise on the R/V *Yokosuka* (YK19-11).

Floating micro- and mesoplastic particles were collected during the day (6:00–13:00) using a neuston net (mesh size, 333- $\mu$ m; mouth opening size, 1.0 m width and 0.75 m height)



**FIGURE 1** | Track of typhoon *Faxai* off (A) the east coast of Japan and (B) over Sagami Bay. The colors of circles on (A,B) donate the central pressure (hPa) of *Faxai*. Large circle on (B) represents the area of the storm with the wind speed of > 25 m/s (02:00 September 9th). Cross on (B) donates sampling site.

equipped with a pre-calibrated flow-meter (Rigo). Prior to towing, the net without cod-end was rinsed from the outside with running seawater in order to remove any contaminants in the net. The neuston net was deployed 4 m from the ship's starboard side using a crane and dragged for 20 min at a speed of 1–2 knots in the upper 0.4 m of the sea surface, where samples were collected in the cod-end of the net (Michida et al., 2019). Triplicate samples were collected at each sampling period by repeating the net towing. Once onboard, the net was thoroughly rinsed from the outside of net with running seawater to concentrate all particles into the cod-end. Samples were then transferred to 450 ml glass jars, fixed with 5% formalin and stored for laboratory analysis. The formalin was filtered before usage applying a 30  $\mu\text{m}$  stainless mesh screen to avoid external contamination.

In addition to the neuston net sampling, floating macroplastic debris was visually counted 3-days before and 1-day after the storm. No visual observation was conducted 3-days after the storm. Three to four researchers were stationed on both the port and starboard side of the ship to observe floating debris for 70–90 min while the ship was running at a speed of 1 knot. All debris > 25 mm within 4 m from the side of the ship was visually counted. The lids of standard plastic bottles (ca. 28 mm in diameter), which were often observed during the observation, were used as a nominal calibration measure during the enumeration of debris > 25 mm.

## Laboratory Analysis

Plastic-fiber free lab coats were worn in the laboratory and work surfaces were pre-cleaned and dust-free prior to working. Sample processing was conducted in a laminar flow cabinet where possible. The neuston net samples were purified using 30%  $\text{H}_2\text{O}_2$  at room temperature for 7 days (Hurley et al., 2018) and then visually inspected using a dissecting stereo microscope (Olympus, SZX16). All potential plastic particles

were sorted out by hand using forceps and transferred to glass multiwell plates with glass lids. Particles were then dried at room temperature for 3 days, photographed with a connected camera (Olympus, DP74) to the microscope, and categorized according to their shape: fragments (mixture of hard fragments and films), line, foam, and pellet (Michida et al., 2019). Length and width of each particle were measured using an image software (Olympus, cellSens Dimension 2.1). Textile microfibers were excluded from the analysis due to the large mesh size of the net and to minimize the inclusion of external contamination. For the samples collected at the 1-day after the storm with many particles, large (>5 mm) or prominent plastic particles were sorted first where possible, then the remaining sample was split (1/8) using a stainless-steel splitter. All potential plastic particles, except for foamed particles, were then sorted from the split samples. As foamed particles were numerous in the split samples these samples were split further (1/8) and all foamed particles were sorted.

Polymer types for each of the sorted plastic-like particles were identified using Fourier Transform Infrared spectroscopy (FT-IR) with a single reflection diamond Attenuated Total Reflection (ATR) (Nicolet iS5, Thermo Fisher Scientific). The samples were positioned onto the ATR crystal and then compressed using the instrument clamp to achieve optical contact, allowing at 4  $\text{cm}^{-1}$  spectral resolution by co-adding 16 scans per sample, and a background in air was collected every 60 min during measurement. Each collected spectrum was compared to multiple spectral database libraries containing both synthetic polymers and non-synthetic materials (Omnic 9, Thermo Fisher Scientific). A hit quality > 60% was used as the threshold for polymer types (Galgani et al., 2013). In total, 1,821 particles were identified as plastic polymers with FT-IR in this study.

Particles identified as plastic were pooled by each net tow sample and transferred to a pre-weighed glass vial, then the

weights of the plastic particles were measured. The plastic particles collected from the neuston nets were characterized into three size-categories: microplastic (<5 mm), mesoplastic (5–25 mm), and macroplastic (>25 mm) based on the lengths of each particle (GESAMP, 2019). After the counting of individual plastic particles in each sample, densities (number of particles per square kilometer) were calculated from the towed distance measured by the flow-meter and the frequency of sample split.

Wooden and plant debris from the neuston net samples were sorted out using forceps prior to the plastic analysis and pooled by net tow sample. These pooled samples were dried for 24 h at 60°C and then weighed. In addition, prominent insects were also counted and sorted out, and identified to family level wherever possible.

## Particle Tracking Simulations After Storm

We conducted particle tracking simulations at the surface of Sagami Bay before and after the typhoon passage using the surface current reproduced from a tide-resolution general circulation model with the horizontal resolution of 1/36 (JCOPE-T DA) (Miyazawa et al., 2021). See **Supplementary Material** for the details of the model configuration. We aligned 100 model particles on the coast of Sagami Bay 2, 7, 9, and 12 h after the storm, and 1 week before the storm to see how many particles could be flushed out of the Sagami Bay across different time scales. We defined the extent of the bay as the inner side of the line connecting the edge of Boso Peninsula and the edge of Izu Peninsula (**Figure 1B**), and the particles which moved out of this line were considered to have been transported out of the bay. Finally, we compared the relative abundance of residual particles in the bay between the different time set ups.

## Statistical Analysis

The difference in the density, mass, and length of microplastics and mesoplastics between different sampling periods (3-days before, and 1- and 3-days after the storm passage) was determined using a one-way ANOVA and differences among means were then analyzed using Tukey-Kramer multiple comparison tests. A difference at  $p < 0.05$  was considered significant.

## RESULTS

### Changes in the Density and Mass of Plastic and Other Debris

At 3-days before the typhoon passed (September 7th), the densities of micro- and mesoplastics were on average ( $\pm$  SD)  $101,762 \pm 13,213$  pieces  $\text{km}^{-2}$  and  $11,340 \pm 7,198$  pieces  $\text{km}^{-2}$ , respectively (**Figures 2A,B**). At 1-day after the typhoon passage (September 10th), the concentrations of micro- and mesoplastics significantly increased by two orders of magnitude ( $p < 0.01$  for both micro- and mesoplastics, Tukey-Kramer), being 226 times and 274 times greater than those at the pre-typhoon period, respectively. Mean concentration of micro- and mesoplastics 1-day after the typhoon passage reached

$23,032,769 \pm 8,372,347$  pieces  $\text{km}^{-2}$  and  $3,104,930 \pm 1,847,652$  pieces  $\text{km}^{-2}$ , respectively. At 3-days after the typhoon passage, the concentration of micro- and mesoplastics significantly ( $p < 0.05$  for both micro- and mesoplastics, Tukey-Kramer) dropped to concentrations similar to pre-typhoon levels (microplastic,  $77,698 \pm 10,863$  pieces  $\text{km}^{-2}$ ; mesoplastics,  $12,143 \pm 10,244$  pieces  $\text{km}^{-2}$ ). There were no significant differences in the density of microplastics ( $p > 0.05$ ) and mesoplastics ( $p > 0.05$ ) between the samples taken pre-typhoon and 3-days after the typhoon passed.

The mass ( $\text{g km}^{-2}$ ) of plastic particles collected by the net (sum of micro- and mesoplastics) showed the same trend as the density data (**Figure 2C**). The mass was on average  $0.070 \pm 0.035$   $\text{kg km}^{-2}$  before the typhoon passage, which significantly ( $p < 0.01$ , Tukey-Kramer) increased 1,309 times immediately after the storm to  $91.6 \pm 30.9$   $\text{kg km}^{-2}$ . Then, it significantly ( $p < 0.01$ , Tukey-Kramer) decreased to the pre-typhoon level at 3-days after the storm ( $0.11 \pm 0.062$   $\text{kg km}^{-2}$ ). There was no significant difference in the mass between pre- and 3-days post typhoon ( $p > 0.05$ , Tukey-Kramer).

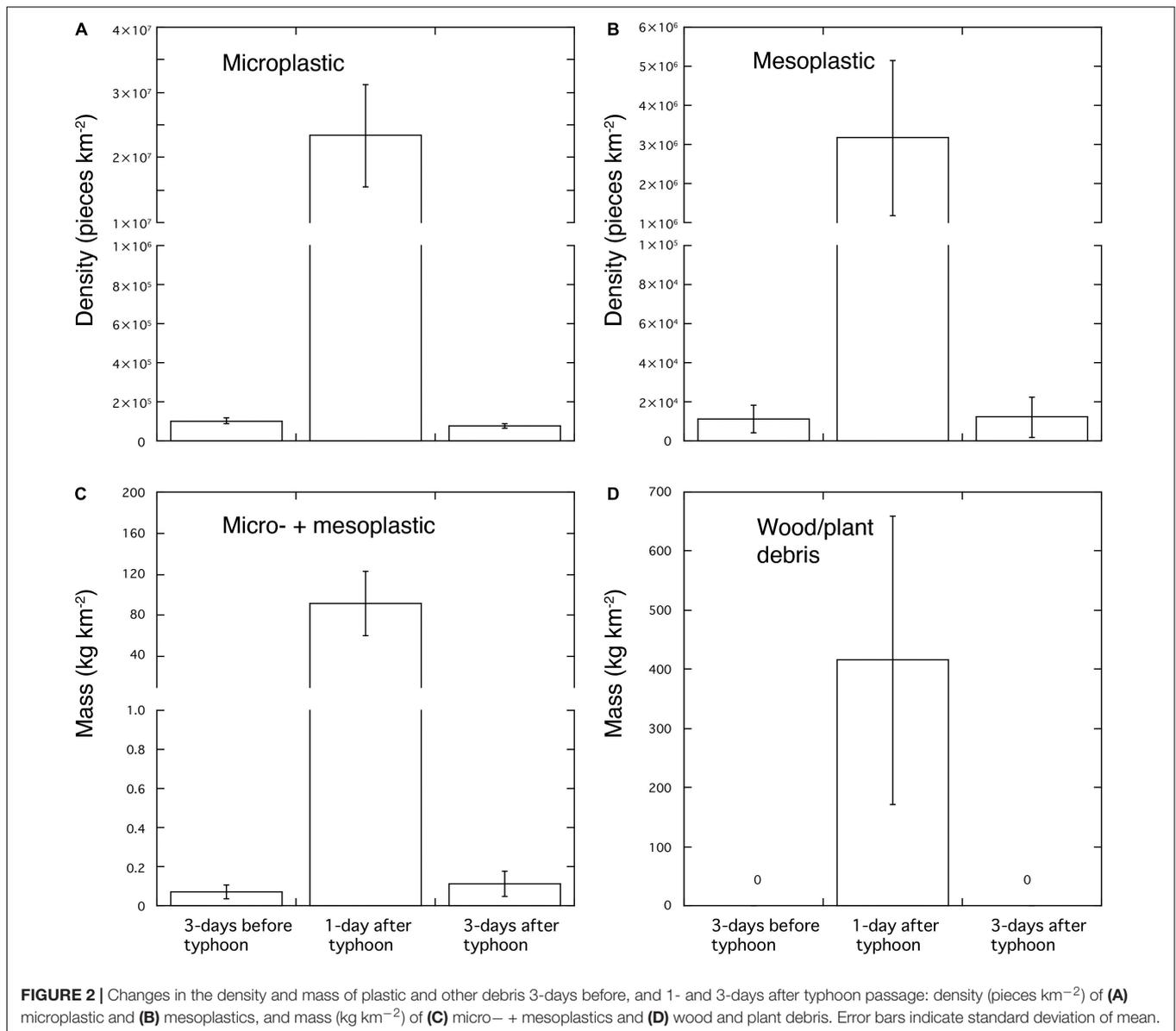
In addition to plastic debris, a markedly large amount of fine wooden debris and plant debris was collected from the net 1-day after typhoon, reaching  $415.3 \pm 243.8$   $\text{kg km}^{-2}$  (**Figure 2D**). Wood and other plant debris were not collected before the typhoon or 3-days after the typhoon. Some insects, including wingless insects such as ants (Formicidae), were also only collected at 1-day after the storm (**Supplementary Figure 1**).

Large plastic debris was also prominent on the sea-surface 1-day after the storm. At 3-days before the typhoon passed, the density of visually counted macroplastic (> 25 mm) ranged from 1,824 to 2,183 pieces  $\text{km}^{-2}$  with a mean of 2004 pieces  $\text{km}^{-2}$  (**Supplementary Figure 2A**). At 1-day after the typhoon passed the mean density was 5.2 times greater than the pre-typhoon period, ranging from 10,092 to 10,698 pieces  $\text{km}^{-2}$  with a mean of 10,392 pieces  $\text{km}^{-2}$ . The mean density of visually counted macroplastic was lower than that obtained from the net sampling at 1-day after the storm ( $29,269 \pm 26,713$  pieces  $\text{km}^{-2}$ ), though no macroplastics were collected by the net 3-days before or 3-days after the typhoon (**Supplementary Figure 2B**).

### Changes in the Polymer Type, Shape and Size of Micro- and Mesoplastics

Polyethylene (PE) and polypropylene (PP) were dominant in microplastics and mesoplastics before the typhoon passed (PE  $59.7 \pm 10.3\%$  and PP  $30.2 \pm 6.3\%$  in microplastics; PE  $80.0 \pm 20.0\%$  and PP  $13.3 \pm 11.5\%$  in mesoplastics) (**Figures 3A,B**). At 1-day after the typhoon, microplastics consisted mostly of polystyrene (PS) ( $76.5 \pm 14.1\%$ ) while mesoplastics were comprised mainly of PE ( $38.4 \pm 24.9\%$ ) and PS ( $37.2 \pm 18.3\%$ ). At 3-days after the storm, PS was still the highest proportion of polymer seen in microplastics ( $63.4 \pm 3.3\%$ ) while mesoplastics were comprised mainly of PE ( $58.3 \pm 52.0\%$ ) and PS ( $33.3 \pm 57.7\%$ ).

The morphological shapes of microplastics and mesoplastics collected before the typhoon passed were predominantly fragments including hard fragments and films ( $93.4 \pm 5.9\%$  in



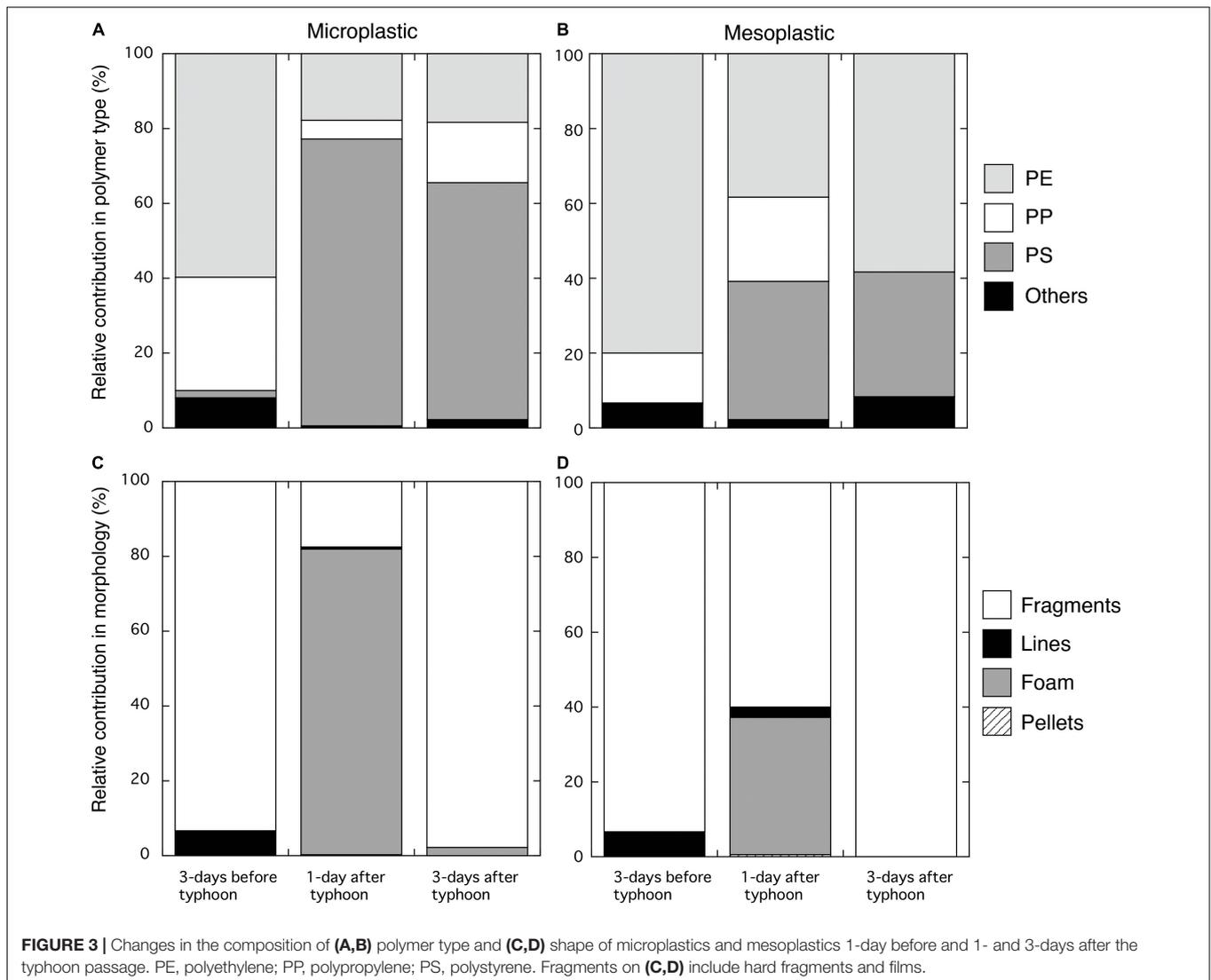
microplastics;  $80.0 \pm 20.0\%$  in mesoplastics) followed by lines ( $6.6 \pm 5.9\%$  in microplastics;  $13.3 \pm 11.5\%$  in mesoplastics) (Figures 3C,D). At 1-day after the typhoon, foamed particles, namely particles of expanded PS (EPS), were dominant in microplastics ( $81.7 \pm 9.9\%$ ). Foamed particles were also an important component in mesoplastics ( $37.1 \pm 17.9\%$ ) 1 day after the storm but the most dominant shapes seen were fragments ( $59.8 \pm 15.1\%$ ). At 3-days after the storm, both microplastics and mesoplastics consisted mostly or entirely of fragments ( $97.8 \pm 3.8$  and  $100.0 \pm 0.0\%$ , respectively).

Boxplots of particle length ( $\mu\text{m}$ ) of microplastics and mesoplastics before and after the typhoon showed a presence of larger particles in microplastics 1-day after the storm (Figure 4). The mean size of microplastic particles at 1-day after the storm was significantly higher ( $p < 0.01$ , Tukey-Kramer) than before and 3-days after the storm, yet no significant difference

was observed between before and 3-days after the storm (Figure 4A). For mesoplastics, no significant difference was found in particle size across the study periods ( $p > 0.05$ , Tukey-Kramer) (Figure 4B).

## Particle-Tracking Simulations

Particle model analysis showed that plastic particles entering the bay immediately after the passage of the typhoon were highly likely to be transported out of the bay to the open ocean. In contrast, plastic particles that entered the bay before the typhoon, or more than 12 h after the passage of the typhoon, were less likely to be transported from the bay to the open ocean (Figure 5, see also movies in Supplementary Material). Most particles released from the coastline at 2 and 7 h after the typhoon passed (i.e., 04:00 and 09:00 September 9th) remained in the bay for the first 24 h ( $>90\%$ ), but only  $< 50\%$  ( $45.7\text{--}49.3\%$ ) continued to persist in the



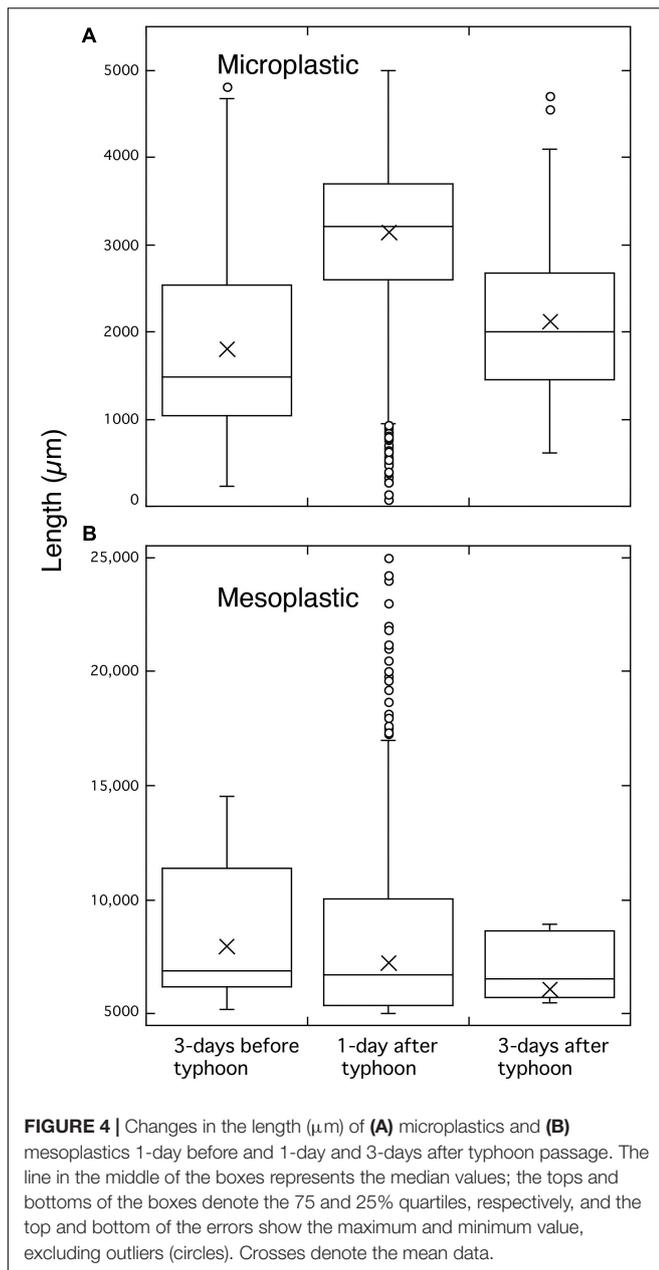
bay after 120 h due to leakage into the open waters (Figure 5). Similarly, particles released 9 h after the typhoon passage (11:00 September 9th) showed persistence of ca. 60% in the bay after 120 h. In contrast, particles released 12 h after the typhoon, or 1 week before the typhoon, showed relatively higher persistence in the bay with 78–82% still residing after 120 h.

## DISCUSSION

Here we provide evidence that extreme weather events are one of the major driving forces responsible for transporting large amounts of plastic debris from the land to the sea. Although earlier studies have documented debris succession patterns before and after storm events in rivers, coasts, and shallow nearshore waters, our results highlight the degree of debris found offshore far from the coast (> 30 km) after an extreme storm event.

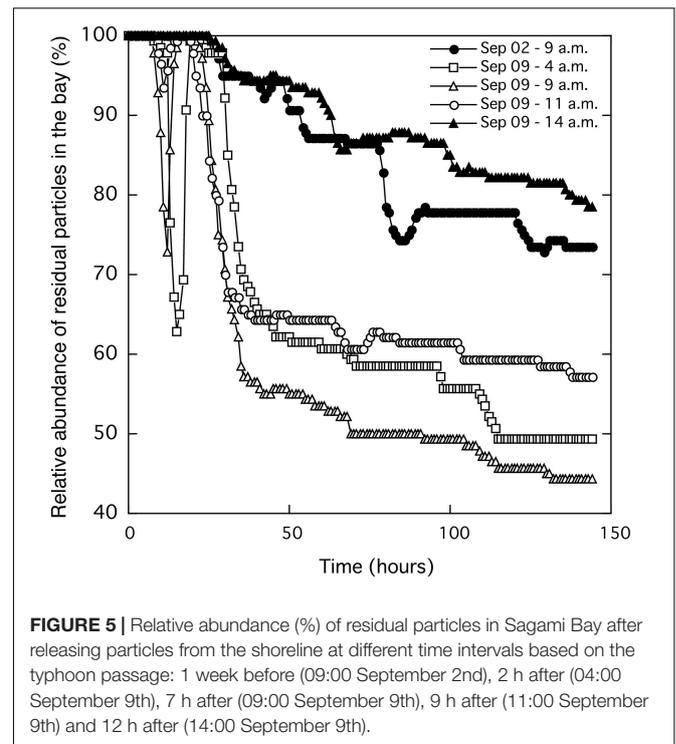
Flood events caused by heavy precipitation enhance the movement of plastic debris of terrestrial origin into the

marine environments from multiple points, of which rivers are considered one of the major pathways (Kudo et al., 2018; Nihei et al., 2020). One typical debris that is abundant in rivers during heavy rainfalls is wooden debris (Doong et al., 2011). Considering the large amount of wooden debris found in this study, as well as the presence of wingless insects (ants), the plastic debris collected 1-day after the storm may be of river-based origin. This hypothesis is further supported by satellite image data taken at 1-day after the storm by Sentinel-2 showing muddy water flowing from the coastlines to the center of Sagami Bay which are occurrences of river runoff (Sentinel, 2019). In addition, the surface chlorophyll data provided by the satellite Shikisai (GCOM-C) showed that the bay at 1-day after the storm the bay experienced very little influx of oceanic seawater that could be a source of microplastics (Japan Aerospace Exploration Agency, 2019). Microplastics on the seafloor can be resuspended after storms that cause sufficient turbulence in the water column (Lattin et al., 2004). However, the study site has a total water depth of 1,400 m making resuspension of plastic debris from



sediments at this depth is unlikely. As such, we can infer that the majority of the debris observed in the center of Sagami Bay after the typhoon most likely originated from river sources.

Although comparatively fewer studies exist on plastic debris before and after tropical cyclones, it is apparent that extreme storms are responsible for a significant portion of the plastic debris transported from land to aquatic ecosystems. Previous investigations examining plastic debris before and after tropical cyclones, and other storm events have revealed that an increase in the abundance of microplastics and macroplastics is typically observed after storms (Table 1). For example, measurements of macroplastic debris densities in Hong Kong beaches during typhoon *Mangkhut* in 2018 showed a 12-fold increase compared



with measurements taken before the typhoon passage (Lo et al., 2020). Similarly, typhoon *Meranti* in 2016 caused a 10 times increase in floating macroplastics in Xiamen Bay, China (Chen et al., 2019). Our results show that macroplastics ( $> 50 \text{ mm}$ ) yielded a 5-fold increase in abundance immediately after the storm, which is comparable to previous studies.

In studies of microplastics, previous investigations revealed that storm events caused 1.1–43.5-fold increase in the density of microplastics from rivers, beaches, estuary and nearshore waters (Table 1). However, in our study, microplastics ( $< 5 \text{ mm}$ ) from offshore sites showed a 280-fold increase in density, which is the highest recorded value to date. Unlike microplastics found in rivers and shores, where microplastics continue to be transited from the land to the sea, the offshore study site is located near the center of an eddy in the bay and, as such, microplastics are likely to be accumulated. This propensity for accumulation at the offshore site compared to rivers and shores may explain the higher enrichment factor in microplastic density seen there. It is interesting to note that the study of the beaches in Hong Kong (Lo et al., 2020) showed a higher enrichment factor in the density of macroplastics than that of microplastics (11.5 vs. 1.8, respectively), which contradicts our offshore results that showed a higher enrichment factor for microplastics. This suggests that smaller plastic particles may be more likely to be transported offshore by storm events. Previous studies showed that microplastics have a much shorter residence time in shore waters than macroplastics so microplastics may be more easily transported to offshore waters *via* backwash waves (Hinata et al., 2017). This may also explain the higher microplastics enrichment factor seen for our offshore site. Additionally, the breakage

**TABLE 1** | Comparative summary of the enrichment factors of macro- and microplastics in several bodies of water after storm events.

Study site	Specific sampling site/distance from shore (km)	Typhoon	Date	Collection method/mesh size	Collection media	Days after storm	Density after storm	Unit	Enrichment factor	Source
<b>Macroplastics</b>										
Hong Kong, China	Beach	Typhoon <i>Mangkhut</i>	16/09/2018	Hand picking	Beach	2–3	0.54	Items/km <sup>2</sup>	11.5	Lo et al., 2020
Xiamen Bay, China	Nearshore/ < 5 km	Typhoon <i>Nepartak</i>	09/07/2016	Net/333 μm	Surface water	1	24 <sup>a</sup>	Items/km <sup>2</sup>	0.4	Chen et al., 2019
		Typhoon <i>Meranti</i>	15/09/2016				312 <sup>a</sup>			
Sagami Bay, Japan	Offshore/30 km	Typhoon <i>Faxai</i>		Visual	Surface water	1		Items/km <sup>2</sup>		Present study
<b>Microplastics</b>										
Saitama, Japan	River	Typhoon <i>Talim</i>	17/09/2017	Net/350 μm	Surface water	1–2	11 billion	Transported items/year	2.9 <sup>b</sup>	Kudo et al., 2018
NSW, Australia	River	Storm	05/10/2019	Bucket/37 μm	Surface waer	0	17,383	Items/m <sup>3</sup>	43.5	Hitchcock, 2020
Hong Kong, China	Beach	Typhoon <i>Mangkhut</i>	16/09/2018	Quadrat	Beach	2–3	335	Items/kg	1.8	Lo et al., 2020
Fuzhou, China	Estuary	Typhoon <i>Soulk</i>	13/07/2013	Pump/333 μm	Surface water	1	1,246	Items/m <sup>3</sup>	1.1	Zhao et al., 2015
Mersin Bay, Turkey	Nearshore/ < 10 km	Storm	Dec 2016–Jan 2017	Net/333 μm	Surface water	3 months	7,699,716	Items/km <sup>2</sup>	14.3	Gündoğdu et al., 2018
California, US	Nearshore/ < 5 km	Storm	12/01/2001	Net/333 μm	Surface water	0	63	Items/m <sup>3</sup>	6.3	Moore et al., 2002
Banderas Bay, Mexico	Nearshore/ < 3 km	Hurrican season		Net/333 μm	Surface water	–	0.044	Items/m <sup>3</sup>	3.4	Pelamatti et al., 2019
Sanggou Bay, China	Neashore/ < 10 km	Typhoon <i>Haitang, Noru</i>	30/07/2017,	Bucket/50 μm	Surface water	3	89,500	Items/m <sup>3</sup>	1.4	Wang et al., 2019
			06/08/2017							
Sagami Bay, Japan	Offshore/30 km	Typhoon <i>Faxai</i>		Grab	Sediment	3	3,035	Items/kg	1.4	
				Net/333 μm	Surface water	1	23,016,841	Items/km <sup>2</sup>	226.2	Present study

<sup>a</sup>Density was obtained from figures. <sup>b</sup>Result from a comparison with the annual cumulative transported microplastics.

of fragile debris by rougher seas could also contribute to the increased number of small plastic particles recorded.

The most significant contributor to the increase in densities of micro- and macroplastics after the typhoon passed was polystyrene foam or expanded PS (EPS) particles. Polystyrene foams are extensively used as disposable take-way food boxes, heat-insulated containers and buoys, where polystyrene foam litter has been widely reported in the Asian-Pacific region (Yamashita and Tanimura, 2007; Kim et al., 2015; Fok et al., 2017). Most EPS particles found in this study were 2–3 mm in length, which largely contributed to the size shift of microplastics toward larger particles. Although the source of the EPS particles is unclear in our study, one possible source could be insulated containers such as the type used for transporting seafood products amongst other things as many EPS insulated containers are made of ca. 1–3 mm diameter of spherical EPS beads bonded together (Subhan, 2006). EPS made containers are fragile and are easily fragmented by external energy releasing small EPS particles (Majanga et al., 2015; Song et al., 2020). High physical energy associated with strong winds and rough ocean waves during typhoons could encourage the breakdown of exposed EPS containers into parts which could be further fragmented into smaller pieces that drift into offshore waters (Lee et al., 2013). As such, it is important to devise measures to prevent EPS containers from leaking into the environment in order to reduce microplastic leakage into the ocean.

The remarkably high abundance of micro- and mesoplastics found 1-day after the typhoon ( $91 \text{ kg/km}^2$ ) returned to the pre-typhoon level in just 2 days ( $0.1 \text{ kg/km}^2$ ). Essentially, ca.  $90 \text{ kg/km}^2$  of plastic particles moved on from the survey site within a few days and it is not immediately clear where they have relocated to. It is unlikely that most plastic particles sank in just 2 days given that the predominant polymers were PP, PE and EPS, which have lower specific gravity than seawater. In fact, it would normally take several months to several years for buoyant plastic debris to move from the surface to the deeper water *via* events such as biofouling (Isobe et al., 2019; Nakajima et al., 2021). As such, the plastic particles may have been pushed back to the shore or swept away from the bay over a relatively short time scale. Our model shows that particles remain in the bay for a relatively longer period when they are not under the influence of a storm (i.e., 1 week before and 12 h after typhoon passage) probably due to the anticyclonic eddy in the Sagami Bay (Iwata and Matsuyama, 1989). On the contrary, half of the particles that moved into the bay right after the typhoon passed were shown to have been swept away from the bay in a few days probably due to the higher outflow from Tokyo Bay, next to Sagami Bay. The higher outflow from the mouth of Tokyo Bay, resulting from the typhoon which rotated counterclockwise and increased water volume in the bay due to increased precipitation (Okada et al., 2011), could have been responsible for the higher leakage of particles from the mouth of the Sagami Bay to the open waters. These results suggest that a significant amount of micro- and mesoplastics can be swept away rapidly from coastal waters to open waters by extreme storms. As such, it is important to consider the enhanced leakages of plastic debris into the ocean associated with extreme storm events to better

estimate the annual plastic load from land to sea. This will be further emphasized in low- and mid-latitudes regions with frequent occurrences of tropical cyclones including typhoons and hurricanes. Notably East and Southeast Asia, the regions with frequent typhoons, account for approximately half of the plastic that ends up in the ocean (Jambeck et al., 2015), which could be upwardly revised considering the effect of typhoons. As the intensity of storm events is expected to increase with a changing climate (Knutson et al., 2010; Kossin et al., 2020), this study highlights the significance of the understanding the leakage patterns of marine plastic debris caused by extreme weather events. This will allow for the development of better strategies to mitigate plastic pollution, especially in regions where there are frequent typhoon or hurricane events.

It is important to note that while the effect of only a single typhoon was analyzed in this study, we believe that this adequately covers the significance of the debris leakage from land to sea. This is evidenced by the highest enrichment factor being recorded as a result of the typhoon *Faxai*. It should also be noted that, unlike rivers or coasts which are relatively easily accessible when typhoons occur, it is difficult to immediately investigate the changes in debris abundances at such an offshore site, some 30 km away from the coastline.

## CONCLUSION

We provide insights into the fate of floating plastic debris transported offshore when a typhoon passed over Sagami Bay, Japan. Our investigation confirms the view that a tremendous amount of waste can be transported from the land to sea by an extreme storm event. This can result in two or three orders of magnitude higher abundance of micro- and macroplastics being recorded immediately after the typhoon compared to the values recorded pre-typhoon. However, the remarkably high abundance of micro- and mesoplastics found 1-day after the typhoon returned to the pre-typhoon levels in just 2 days, because the majority of the debris was swept away from the bay to the open ocean over a short period of time. The annual load of plastic debris being transported from land to sea will be underestimated if episodic storm events are not fully considered. In order to halt the leakage of plastic debris from land to sea, it is important to take measures that consider unexpected natural disasters such as typhoons.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

RN: conceptualization, methodology, formal analysis, investigation, writing—original draft, and visualization. TM:

methodology, formal analysis, and visualization. TK, NI, YN, TI, KO, TYo, YM, KK, MS, TYa, and HR: investigation and writing—review and editing. MT and KF: supervision and writing—review and editing. AY: conceptualization, methodology, investigation, and writing—review and editing. All authors contributed to the article and approved the submitted version.

## FUNDING

This study was partially funded by the New Energy and Industrial Technology Development Organization (NEDO) project (JPNP18016) to RN, NI, YN and JSPS KAKENHI grant (19H04262) awarded to RN.

## REFERENCES

- Axelsson, C., and van Sebille, E. (2017). Prevention through policy: urban macroplastic leakages to the marine environment during extreme rainfall events. *Mar. Pollut. Bull.* 124, 211–227. doi: 10.1016/j.marpolbul.2017.07.024
- Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., et al. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* 369, 1515–1518. doi: 10.1126/science.aba3656
- Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., et al. (2011). Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ. Sci. Technol.* 45, 9175–9179. doi: 10.1021/es201811s
- Chen, H., Wang, S., Guo, H., Lin, H., Zhang, Y., Long, Z., et al. (2019). Study of marine debris around a tourist city in East China: implication for waste management. *Sci. Total Environ.* 676, 278–289. doi: 10.1016/j.scitotenv.2019.04.335
- Derraik, J. G. B. (2002). The pollution of the marine environment by plastic debris: a review. *Mar. Pollut. Bull.* 44, 842–852. doi: 10.1016/s0025-326x(02)00220-5
- Doong, D.-J., Chuang, H.-C., Shieh, C.-L., and Hu, J.-H. (2011). Quantity, distribution, and impacts of coastal driftwood triggered by a typhoon. *Mar. Pollut. Bull.* 62, 1446–1454. doi: 10.1016/j.marpolbul.2011.04.021
- Eckstein, D., Künzel, V., and Schäfer, L. (2021). *Global Climate Risk Index 2021. Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000–2019*. Berlin: Germanwatch e.V.
- Fok, L., Cheung, P. K., Tang, G., and Li, W. C. (2017). Size distribution of stranded small plastic debris on the coast of Guangdong, South China. *Environ. Pollut.* 220, 407–412. doi: 10.1016/j.envpol.2016.09.079
- Galgani, F., Hanke, G., Werner, S., Oosterbaan, L., Nilsson, P., Fleet, D., et al. (2013). *Guidance on Monitoring of Marine Litter in European Seas*. Luxembourg: Publications Office of the European Union, doi: 10.2788/99475
- Garcés-Ordóñez, O., Saldarriaga-Vélez, J. F., and Espinosa-Díaz, L. F. (2021). Marine litter pollution in mangrove forests from Providencia and Santa Catalina islands, after Hurricane IOTA path in the Colombian Caribbean. *Mar. Pollut. Bull.* 168:112471. doi: 10.1016/j.marpolbul.2021.112471
- GESAMP (2019). *Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean—GESAMP*. Reports and Studies No. 99. Nairobi: United Nations Environment Programme, 130.
- Gündoğdu, S., Çevik, C., Ayat, B., Aydoğan, B., and Karaca, S. (2018). How microplastics quantities increase with flood events? An example from Mersin Bay NE Levantine coast of Turkey. *Environ. Pollut.* 239, 342–350. doi: 10.1016/j.envpol.2018.04.042
- Hinata, H., Mori, K., Ohno, K., Miyao, Y., and Kataoka, T. (2017). An estimation of the average residence times and onshore-offshore diffusivities of beached microplastics based on the population decay of tagged meso-and macrolitter. *Mar. Pollut. Bull.* 122, 17–26. doi: 10.1016/j.marpolbul.2017.05.012
- Hitchcock, J. N. (2020). Storm events as key moments of microplastic contamination in aquatic ecosystems. *Sci. Total Environ.* 734:139436. doi: 10.1016/j.scitotenv.2020.139436
- Hurley, R. R., Lusher, A. L., Olsen, M., and Nizzetto, L. (2018). Validation of a method for extracting microplastics from complex, organic-rich,

## ACKNOWLEDGMENTS

We thank the captain and the crew of R/V *Yokosuka* for their efforts to make the sampling possible, and Tomoko Morotomi, Rie Matsui and Nozomi Noha for their help in sample analysis. We also thank M. Morioka, Nippon Marine Enterprises, Ltd. for her technical help during the cruise.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.806952/full#supplementary-material>

- environmental matrices. *Environ. Sci. Technol.* 52, 7409–7417. doi: 10.1021/acs.est.8b01517
- Isobe, A., Iwasaki, S., Uchida, K., and Tokai, T. (2019). Abundance of non-conservative microplastics in the upper ocean from 1957 to 2066. *Nat. Commun.* 10:417. doi: 10.1038/s41467-019-08316-9
- Iwata, S., and Matsuyama, M. (1989). Surface circulation in Sagami bay: the response to variations of the Kuroshio axis. *J. Oceanogr.* 45, 310–320.
- Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352
- Japan Aerospace Exploration Agency (2019). *Shikisai GCOM-C Surface Chlorophyll*. Available online at: [https://www.eorc.jaxa.jp/JASMES/SGLI\\_NRT/data/CHLA/2019/09/10/GC1SG1\\_201909100120004900\\_L2MG\\_IWPRQ\\_2000\\_CHLA\\_11.png](https://www.eorc.jaxa.jp/JASMES/SGLI_NRT/data/CHLA/2019/09/10/GC1SG1_201909100120004900_L2MG_IWPRQ_2000_CHLA_11.png) (accessed November 27, 2021).
- Japan Meteorological Agency (2020). *Annual Report on the Activities of the RSMC Tokyo-Typhoon Center 2019*. Available online at: <https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/AnnualReport/2019/Text/Text2019.pdf> (accessed November 27, 2021).
- Kataoka, T., Nihei, Y., Kudou, K., and Hinata, H. (2019). Assessment of the sources and inflow processes of microplastics in the river environments of Japan. *Environ. Pollut.* 244, 958–965. doi: 10.1016/j.envpol.2018.10.111
- Kim, I.-S., Chae, D.-H., Kim, S.-K., Choi, S., and Woo, S.-B. (2015). Factors influencing the spatial variation of microplastics on high-tidal coastal beaches in Korea. *Arch. Environ. Contam. Toxicol.* 69, 299–309. doi: 10.1007/s00244-015-0155-6
- Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., et al. (2010). Tropical cyclones and climate change. *Nat. Geosci.* 3, 157–163.
- Kossin, J. P., Knapp, K. R., Olander, T. L., and Velden, C. S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. *Proc. Natl. Acad. Sci. U.S.A.* 117, 11975–11980.
- Kudo, K., Kataoka, T., Nihei, Y., and Kitaura, F. (2018). Estimation of temporal variations and annual flux of microplastics in rivers under- and high-flow conditions. *J. Jpn. Soc. Civ. Eng. Ser. B1 (Hydraul. Eng.)* 74, 529–534.
- Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D. W., and Law, K. L. (2012). The effect of wind mixing on the vertical distribution of buoyant plastic debris. *Geophys. Res. Lett.* 39:L07601.
- Kunkel, K. E., Karl, T. R., Brooks, H., Kossin, J., Lawrimore, J. H., Arndt, D., et al. (2013). Monitoring and understanding trends in extreme storms: state of knowledge. *Bull. Am. Meteorol. Soc.* 94, 499–514.
- Lattin, G. L., Moore, C. J., Zellers, A. F., Moore, S. L., and Weisberg, S. B. (2004). A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. *Mar. Pollut. Bull.* 49, 291–294. doi: 10.1016/j.marpolbul.2004.01.020
- Lebreton, L. C. M., Van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.* 8:15611.
- Lee, J., Hong, S., Song, Y. K., Hong, S. H., Jang, Y. C., Jang, M., et al. (2013). Relationships among the abundances of plastic debris in different size classes

- on beaches in South Korea. *Mar. Pollut. Bull.* 77, 349–354. doi: 10.1016/j.marpolbul.2013.08.013
- Lo, H.-S., Lee, Y.-K., Po, B. H.-K., Wong, L.-C., Xu, X., Wong, C.-F., et al. (2020). Impacts of Typhoon Mangkhut in 2018 on the deposition of marine debris and microplastics on beaches in Hong Kong. *Sci. Total Environ.* 716:137172. doi: 10.1016/j.scitotenv.2020.137172
- Majanga, B. D., Fujieda, S., Nishi, R., and Hosotani, K. (2015). Marine debris distribution, variation and pattern/seasonal changes along the coast and on sea surface of the Kagoshima Bay. *J. Jpn. Soc. Civ. Eng. Ser. B3 (Ocean Eng.)*, 71, 1\_503–1\_508.
- Michida, Y., Chavanich, S., Cabañas, A. C., Haggmann, P., Hinata, H., Isobe, A., et al. (2019). *Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods*. Tokyo: Ministry of the Environment Japan.
- Miyazawa, Y., Varlamov, S. M., Miyama, T., Kurihara, Y., Murakami, H., and Kachi, M. (2021). A nowcast/forecast system for Japan's coasts using daily assimilation of remote sensing and *in situ* data. *Remote Sens.* 13:2431. doi: 10.3390/rs13132431
- Moore, C. J., Moore, S. L., Weisberg, S. B., Lattin, G. L., and Zellers, A. F. (2002). A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. *Mar. Pollut. Bull.* 44, 1035–1038. doi: 10.1016/s0025-326x(02)00150-9
- Nakajima, R., Tsuchiya, M., Yabuki, A., Masuda, S., Kitahashi, T., Nagano, Y., et al. (2021). Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the North West Pacific. *Mar. Pollut. Bull.* 166:112188. doi: 10.1016/j.marpolbul.2021.112188
- Nihei, Y., Yoshida, T., Kataoka, T., and Ogata, R. (2020). High-resolution mapping of Japanese microplastic and macroplastic emissions from the land into the sea. *Water* 12:951.
- Ockelford, A., Cundy, A., and Ebdon, J. E. (2020). Storm response of fluvial sedimentary microplastics. *Sci. Rep.* 10:1865. doi: 10.1038/s41598-020-58765-2
- Okada, T., Nakayama, K., Takao, T., and Furukawa, K. (2011). Influence of freshwater input and bay reclamation on long-term changes in seawater residence times in Tokyo Bay, Japan. *Hydrol. Process.* 25, 2694–2702. doi: 10.1002/hyp.8010
- Pelamatti, T., Fonseca-Ponce, I. A., Rios-Mendoza, L. M., Stewart, J. D., Marín-Enriquez, E., Marmolejo-Rodríguez, A. J., et al. (2019). Seasonal variation in the abundance of marine plastic debris in Banderas Bay, Mexico. *Mar. Pollut. Bull.* 145, 604–610. doi: 10.1016/j.marpolbul.2019.06.062
- Schmidt, C., Krauth, T., and Wagner, S. (2017). Export of plastic debris by rivers into the sea. *Environ. Sci. Technol.* 51, 12246–12253. doi: 10.1021/acs.est.7b02368
- Sentinel (2019). *Sentinel-1 L2C True Color*. Available online at: <https://apps.sentinel-hub.com/eo-browser/?zoom=10&lat=35.10755&lng=139.34647&themeId=DEFAULT-THEME&visualizationUrl=https%3A%2F%2Fservices.sentinel-hub.com%2Fogc%2Fwms%2F42924c6c-257a-4d04-9b8e-36387513a99c&datasetId=S2L1C&fromTime=2019-09-10T00%3A00%3A00> (accessed November 27, 2021).
- Song, Y. K., Hong, S. H., Eo, S., Han, G. M., and Shim, W. J. (2020). Rapid production of micro-and nanoplastics by fragmentation of expanded polystyrene exposed to sunlight. *Environ. Sci. Technol.* 54, 11191–11200. doi: 10.1021/acs.est.0c02288
- Subhan, T. F. L. (2006). Lightweight high strength concrete with expanded polystyrene beads. *Mektek* 8, 9–15.
- Suzuki, T., Tajima, Y., Watanabe, M., Tsuruta, N., Takagi, H., Takabatake, T., et al. (2020). Post-event survey of locally concentrated disaster due to 2019 Typhoon Faxai along the western shore of Tokyo Bay, Japan. *Coast. Eng. J.* 62, 146–158. doi: 10.1080/21664250.2020.1738620
- Tamura, H., Kawaguchi, K., Iwamoto, T., and Fujiki, T. (2021). Coastal destruction and unusual wave spectra induced by Typhoon Faxai in 2019. *Coast. Eng. J.* 63, 92–105. doi: 10.1080/21664250.2021.1877944
- Tokyo Regional Headquarters. (2019). *Preliminary Weather Report of Typhoon Faxai 2019*. Tokyo: Tokyo Regional Headquarters.
- Tsuchiya, K., Kuwahara, V. S., Hamasaki, K., Tada, Y., Ichikawa, T., Yoshiki, T., et al. (2015). Typhoon-induced response of phytoplankton and bacteria in temperate coastal waters. *Estuar. Coast. Shelf Sci.* 167, 458–465. doi: 10.1016/j.ecss.2015.10.026
- Tu, J.-Y., and Chou, C. (2013). Changes in precipitation frequency and intensity in the vicinity of Taiwan: typhoon versus non-typhoon events. *Environ. Res. Lett.* 8:14023.
- Turner, A., Arnold, R., and Williams, T. (2020). Weathering and persistence of plastic in the marine environment: lessons from LEGO. *Environ. Pollut.* 262:114299. doi: 10.1016/j.envpol.2020.114299
- Veerasingam, S., Saha, M., Suneel, V., Vethamony, P., Rodrigues, A. C., Bhattacharyya, S., et al. (2016). Characteristics, seasonal distribution and surface degradation features of microplastic pellets along the Goa coast, India. *Chemosphere* 159, 496–505. doi: 10.1016/j.chemosphere.2016.06.056
- Wang, J., Lu, L., Wang, M., Jiang, T., Liu, X., and Ru, S. (2019). Typhoons increase the abundance of microplastics in the marine environment and cultured organisms: a case study in Sanggou Bay, China. *Sci. Total Environ.* 667, 1–8. doi: 10.1016/j.scitotenv.2019.02.367
- Weideman, E. A., Perold, V., Arnold, G., and Ryan, P. G. (2020). Quantifying changes in litter loads in urban stormwater run-off from Cape Town, South Africa, over the last two decades. *Sci. Total Environ.* 724:138310. doi: 10.1016/j.scitotenv.2020.138310
- Yamashita, R., and Tanimura, A. (2007). Floating plastic in the Kuroshio current area, western North Pacific Ocean. *Mar. Pollut. Bull.* 4, 485–488. doi: 10.1016/j.marpolbul.2006.11.012
- Zhao, S., Zhu, L., and Li, D. (2015). Microplastic in three urban estuaries, China. *Environ. Pollut.* 206, 597–604. doi: 10.1016/j.envpol.2015.08.027

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher's Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Nakajima, Miyama, Kitahashi, Isobe, Nagano, Ikuta, Oguri, Tsuchiya, Yoshida, Aoki, Maeda, Kawamura, Suzukawa, Yamauchi, Ritchie, Fujikura and Yabuki. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.