Are smaller microplastics missing?

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Abstract

The size distribution of marine microplastics (< 5 mm) provides a fundamental data source for understanding the dispersal, break down, and biotic impacts of the microplastics in the ocean. The observed size distribution generally shows, from large to small sizes, a gradual increase followed by a rapid decrease. This decrease has led to the hypothesis that the smallest fragments are selectively removed by sinking or biological uptake. Here we propose a new model of size distribution without any removal of material from the system. The model uses an analogy with black-body radiation and the resultant size distribution is analogous to Planck’s law. In this model, the original large plastic piece is broken into smaller pieces once by the application of “energy” or work by waves or other processes, under two assumptions, one that fragmentation into smaller pieces requires larger energy and the other that the probability distribution of the “energy” follows the Boltzmann distribution. Our formula well reproduces ob-
served size distributions over wide size ranges from micro- (<5 mm) to mesoplastics (>5 mm). According to this model, the smallest fragments are fewer because large “energy” required to produce such small fragments occurs more rarely.

Introduction

A large fraction of the estimated billion tonnes of plastic waste that goes into the ocean is found in a fragmented form, “microplastics”, with sizes of less than 5 mm through photodegradation and weathering processes. Those microplastics spread globally, potentially acting as a transport vector of chemical pollutants and causing physical and chemical damages on marine organism. Recent drift simulations of microplastics calibrated against observed abundance of microplastics have produced global or semi-global maps of estimated microplastics abundance and concentration near the sea surface. These simulations will be further used to assess the biological impacts of microplastics.

Such simulations generally assume the size distribution of microplastics and their results would depend on the assumption because sedimentation and biological uptake can depend on size. Interestingly, the number of small pieces rapidly decreases toward smaller sizes in most observations (Fig. S2). This feature is puzzling because the number of plastic pieces is expected to increase toward smaller sizes if the pieces keep broken down into smaller and smaller pieces (progressive fragmentation). For example, Cózar et al. indicates that a type of progressive fragmentation leads to a cube law toward smaller sizes. The observed decrease at smaller sizes has generally been hypothesized to be due to selective
sinking to depths or to selective ingestion by marine organisms\textsuperscript{19–21,23}.

The fracture mechanisms of marine plastics, however, are not well known. The power law is often invoked to explain observed size distributions of plastics. It tends to fit well observed size distributions at larger sizes\textsuperscript{20}. The power law can be derived, for example, from collision cascade among objects, as often applied to the fragmentation of asteroids\textsuperscript{24–26}, which does not include any decrease toward smaller sizes unless or until other processes than fragmentation start to dominate. Somewhat different fragmentation processes lead to a log-normal distribution\textsuperscript{27–29}, which has been applied to the fragmentation of sand grains, mastication, and the fracturing of thin glass rods\textsuperscript{30–32}, but not to oceanic microplastics to our knowledge. The log-normal distribution has a peak skewed toward smaller sizes and is similar to observed size distributions of fragments at smaller sizes but tends to deviate from observed distribution at larger sizes, where the power law tends to fit better\textsuperscript{20}. To the best of our knowledge, only the Weibull distribution\textsuperscript{33,34} is similar to observed size distributions across the microplastics and mesoplastics ranges, at least in Cózar et al.’s study\textsuperscript{20}. The Weibull distribution as applied to the size distributions of various types of particles is largely empirical but with an interpretation as resulting from the branching tree of cracks\textsuperscript{34}.

In this paper, we propose a new model where “energy” needed to break down the plastic pieces acts as a constraint. We assume that the probability of the “energy” obeys the Boltzmann distribution. The statistics of fragmentation is then analogous to that of the black body radiation and the resultant size distribution is analogous to the Planck distribution. As
we shall see, even though there is no sink in the model (there are no “missing” plastic pieces),
this size distribution has a peak skewed toward small sizes and the smaller plastic pieces
beyond the peak are much scarcer.

Results

Fracture model. We offer the following physical model only as an illustration of physical
processes that may be involved. We do not claim that the following are exactly the underlying
processes that lead to the observed size distribution.

The model assumes that the original plastic piece is a square plate with a size of $L \times L$
and a uniform thickness of $\Delta h$. This plate is broken into $n \times n$ equal-sized cells (Fig. 1a). We
define the size of each broken piece to be $\lambda \equiv L/n$; we also define an associated “wavenumber”
$\nu \equiv \lambda^{-1} = n/L$ for convenience. The number of the fragments of this particular size is given
by $n^2$ multiplied by the number of the original plates.

The fragmentation is assumed to be caused by some mechanical force and the required
“crush energy” is assumed to be proportional to the total length of the fractures. This
assumption may be justified by equating the crash energy to the surface energy of the newly
created surfaces (Fig. 1b). Because the total area of the new surfaces is proportional to the
total length of the contact boundaries for a plate (Fig. 1a) and because the surface energy is
proportional to the area of the new surfaces$^{35}$, the crush energy is proportional to the total
length of the fracture, which is $2L(n - 1) \approx 2Ln$ for a large $n$ (Fig. 1a). The crush energy
Figure 1: a. Schematic representation of our fracture model. An idealized plastic plate with a size of $L \times L$ and a thickness of $\Delta h$ is broken into $n \times n$ equal-sized pieces. We define the size of the small pieces to be $\lambda \equiv L/n$ (top). The total length of the contact boundaries (red lines) is obviously $l \equiv 2(n - 1)L$ (middle). We sum up energy needed to break $j$ plates into $\lambda$-sized pieces and denote it as $\varepsilon$ (bottom). b. Schematic representation of breakage. Energy needed to break up the plate is proportional to the cross-sectional area of the contact boundary and hence to the length of the fracture. c. Upper, size distributions expected from (5) for different values of $\gamma^*$ under a fixed $A (= 1.0)$. The dashed curve connects the peaks of the size distributions. Lower, a log-log plot of the same distribution for $\gamma^* = 0.4$ and $A = 1.0$ (solid curve). The dashed line denotes the power law $A\gamma^*/\lambda^3$, which the size-distribution curve asymptotes to for large $\lambda$. 
for a plate can therefore be written as \( b \nu \) with a constant \( b \equiv 2L^2 \Delta h \phi \), where \( \phi \) is a uniform surface energy density, and hence the crush energy for \( j \) plates as

\[
\varepsilon \equiv j b \nu. 
\]

(1)

To produce smaller pieces requires larger energy, which ultimately limits the number of small fragments as shall be seen below. This is the most significant new element of our model.

We next assume that the Boltzmann distribution governs the occurrence probability of crush energy:

\[
p(\varepsilon) \propto e^{-\varepsilon / \gamma}.
\]

(2)

The factor \( \gamma \) may be regarded as a representative energy level of the environment since the expected value of the energy is \( \langle \varepsilon \rangle = \int \varepsilon e^{-\varepsilon / \gamma} d\varepsilon / \int e^{-\varepsilon / \gamma} d\varepsilon = \gamma \). According to this formula, a crush event with a large energy value is less frequent, consistent with common expectation. In statistical mechanics, the Boltzmann distribution describes the probability of energy in an equilibrated heat bath\(^{36}\), where \( \gamma \) is temperature times the Boltzmann constant (Supplementary Fig. S1). This is the analogy to the “environment” for microplastics.

From (1), the expected value of the crush energy as a function of \( \nu \) is

\[
\langle \varepsilon \rangle_\nu = \sum_{j=0}^{\infty} j b \nu p(j b \nu) = b \nu \langle j \rangle_\nu,
\]

and from (2),

\[
\langle j \rangle_\nu = \frac{\sum_{j=0}^{\infty} j e^{-j b \nu / \gamma}}{\sum_{j=0}^{\infty} e^{-j b \nu / \gamma}} = \frac{1}{e^{b \nu / \gamma} - 1},
\]

(3)
which is the expected value of the number of fractured plates for each \( n \). This formula is called the Bose distribution\(^{37} \). Since the number of the fragments of a particular size is \( n^2/j \) (Fig. 1a, bottom) and \( n = L \nu \) by definition (Fig. 1a, top), the expected number of fragments is \( P(\nu) \propto n^2(j)_\nu \propto \nu^2(j)_\nu \) and therefore,

\[
P(\nu) d\nu = Av^2 \frac{1}{e^{b^v/\nu} - 1} d\nu, \tag{4}
\]
or converting from \( \nu \) to \( \lambda \), we have the size spectrum

\[
S(\lambda) d\lambda = A \frac{1}{\lambda^4 e^{b/\nu} - 1} d\lambda, \tag{5}
\]
where \( A \) is an arbitrary positive constant. These equations provide the size distribution of the plastic fragments. They can describe the number of fragments per unit volume of seawater, the number per unit area of the sea, or the raw number of fragments by adjusting the dimension of \( A \).

This size distribution has a shape skewed to smaller sizes similarly to the observed size distribution of the microplastics, as shown in Fig. 1c. For a fixed \( A \), the size distribution is controlled by \( \gamma \) and \( b \). The factor \( b \) depends on the plastic material and the size of the original plate. The increase of \( \gamma \) and the decrease of \( b \), however, have the same effect on controlling the size distribution and hence we introduce a new parameter \( \gamma^* \equiv \gamma/b \). This parameter measures the strength of the mean environmental energy against the strength of the plastic material. As this parameter increases, the size at which the maximum of the size distribution occurs decreases like \( \gamma^{* -1} \) and the corresponding maximum value increases like \( \gamma^{* 4} \). Furthermore, in the large size limit, i.e., \( \lambda \gamma^* \gg 1 \), this size distribution asymptotes to
$S(\lambda) d\lambda \sim A \gamma^* / \lambda^3 d\lambda$ (Fig. 1c), consistent with the cube power law observed in the mesoplastic range. In addition, the total abundance of the fragments for $\lambda < \Lambda \leq L$ is also regulated by $\gamma^*$:

$$N \equiv \int_0^\Lambda S(\lambda) d\lambda \approx \int_0^\infty S(\lambda) d\lambda = \sigma A \gamma^* 3,$$

$$M \equiv \int_0^\Lambda \rho \Delta h \lambda^2 S(\lambda) d\lambda = \rho \Delta h A \gamma^* \ln(1 - e^{-1/\gamma^*}) \approx \rho \Delta h A \gamma^* \ln(\gamma^* \lambda), \quad (6)$$

where $\sigma \equiv 2.404$ (Supplementary Note 1) and $\rho$ is the plastic density. Both of the above approximations are for $\gamma^* \Lambda \gg 1$. See Supplementary Note 1 for details. As $\gamma^*$ increases, the total number of plastic pieces increases and this increase is mainly in the form of smaller fragments (Fig. 1c). The total mass increases with $\gamma^*$ like $\gamma^* \ln(\gamma^* \Lambda)$. In both cases, the amount of the plastic fragments that enters the ocean increases with the mean environmental energy.

The constant $A$ is determined by two processes. One is the production of the fragments: a large value of $A$ corresponds to a higher frequency of crush events under a fixed $\gamma^*$. The other is the dilution of the fragments: only a fraction of the plastic fragments originally produced at a coast is collected in an observation because of dispersion due to turbulent oceanic flow. We will fit our model (5) to an observed size spectrum by adjusting $A$ and $\gamma^*$.

Eq. 4 or 5 is formally analogous to Planck’s formula for black body radiation (Supplementary Note 2). Here we discuss the analogy between the fragmentation of plastics and the photoelectric effect. This effect explains the emission of an electron from an atom when the atom is hit by a photon with energy $h \nu$, where $h$ is the Planck constant, larger than
the energy to attract the electron to the atom. In our model, likewise, the idealized plate is fractured when the work (energy), $h\nu$, done by the mechanical force is beyond the surface energy bonding the cells of the plate. Further, the number of fractured plates is analogous to the number of photons and its expected value is given by the Bose distribution (Eq. 3) both for plastics and for photons.

**Application to observed data.** We begin by comparing the present theory with the observed size distribution obtained by Isobe et al. This size distribution is based on the collection of plastic fragments sampled around Japan (Fig. 2a); this is the largest collection with the highest size resolution to date. For a precise comparison, we have converted the original size histogram into spectral density. Details are shown in Methods.

Theoretical curve is fitted to the observed size spectrum by adjusting the parameters $A$ and $\gamma^*$ by a least-squares method over $\lambda < 5$ mm. The theoretical curve fits the observed size distribution well over the whole microplastic range (Fig. 2b) and also in the 5 to 10 mm range (not shown). For a comparison, we also plot a lognormal distribution, $LN(a, \mu, \sigma^2)$, where the parameters $a$, $\mu$, and $\sigma^2$ are determined by the same least-squares method. The lognormal distribution is not much different from our model in this size range.

Our model also agrees well with the observed size distributions in the Western-Pacific transoceanic section and the Seto Inland Sea (Figs. 2c and d). The number of plastic pieces per unit volume of sea water (vertical axis) is roughly 10–100 times smaller here than in the area surrounding Japan, which is reflected in the smaller values of $A$. Also, the peak is
Figure 2: a. Schematic map of observation stations in Isobe et al\cite{isobe1981, isobe1981b, isobe1981c}. See their original papers for the detailed locations. b–d. Theoretical and observed size spectral densities of microplastics in the area surrounding Japan, along a Western-Pacific transoceanic section, and in the Seto Inland Sea. The black bars display the observed size spectral density (left axis), and gray bars are the original histogram (right axis) taken from Isobe et al. In the range $\lambda < 5$ mm, the black and gray rectangles perfectly coincide. See “Observed data in Isobe et al” in the Method section. The blue and orange curves denote our model and the lognormal distribution, respectively. The parameter $A$ is dimensionless ($\times 10^{-9}$) in this case. The green dashed curve in e denotes the empirical curve $\beta\lambda e^{-\alpha\lambda}$ of Isobe et al\cite{isobe1981}. 
located at a smaller size in the Seto Inland Sea than in the other two regions; this shift is reflected in a larger value of $\gamma^*$. The lognormal distribution is somewhat more different from our model in these two regions (Figs. 2c and d) than in the area surrounding Japan (Fig. 2b). The empirical fitting curve used in Isobe et al. has a large error (Fig. 2c).

We next compare our model with another set of observations summarized by Cózar et al. (Fig. 3a) based on samples collected in the accumulation zones (“garbage patches”) over the globe, where microplastics originating from coastal areas tend to converge by ocean currents. Cózar et al.’s method of sampling plastic fragments is similar to Isobe et al.’s (See Methods) but their size distributions include more size bins in the mesoplastic range than Isobe et al.’s. Our model generally reproduces well the observed size distributions although it somewhat underestimates for $\lambda < 0.5$ mm in the South Atlantic Ocean and in the mesoplastic range in the South Atlantic and North Pacific Oceans (Fig. 3b). Importantly, the model reproduces the cube power law toward the mesoplastic range (Blue curve in Fig. 3d) as found by Cózar et al. The theoretical curve is not particularly good in the smallest size range, but this discrepancy reduces when the South Atlantic Ocean is excluded (gray curve and symbols). If the plastic pieces sampled in the South Atlantic came from different regions with a wide variety of $\gamma^*$ values, this discrepancy may be explained (Supplementary Fig. S3 and S4). In contrast, the lognormal distribution does not follow the cube power law in the large size range (orange curve in Fig. 3d) and this discrepancy exists also in the case without the South Atlantic data (not shown).
Figure 3: **a.** Schematic map of observation stations in Cózar et al. See the original paper for the detailed locations. **b.** Theoretical (curves) and observed (symbols) size spectral density of all samples for each accumulation zone. The observed data are same as those in their Fig. S6, except that the values are expressed as a spectral density (see Methods). **c.** Expected wave energy levels at source regions (rectangles) and $\gamma^*$ (dots) for accumulation zones. The accumulation zones are denoted by abbreviations such as SI for South Indian Ocean. The red dashed rectangle shows the wave energy level for the North Pacific Ocean in the case where the contribution from China is removed. See Methods for details. **d.** Sum of the size spectral densities plotted in **b** over the basins for observation (black dots) and our model (blue curve). The orange curve and black dashed line denote lognormal distribution and a cube power law, respectively. The observed data and cube power law line are the same as those in Cózar et al’s Fig. S10. The gray dots and curve are the same as the black dots and blue curve, respectively, except that the South Atlantic data is excluded for the sizes less than 30 mm (the digitizer does not recognize the small spectral values above 30 mm for the South Atlantic data in Cózar et al’s figure).
The fitting of our model to observations gives a geographical distribution of $\gamma^*$. The $\gamma^*$ value for Cózar et al’s observation is largest in the Pacific Oceans, smallest in the North Atlantic, and inbetween elsewhere (Fig. 3c). Given that the plastics are likely to be fragmented on beaches possibly by ocean waves\textsuperscript{4}, the value of $\gamma^*$ would represent wave energy on beaches where plastic waste is littered or comes ashore before fragmented there and washed away into the ocean as micro- or mesoplastics. A scenario-based numerical experiment (See Methods) suggests that the coastal area located along the western boundary of each basin is likely the major source region for the plastics in each accumulation zone, except that a large fraction of the plastics in the South Indian Ocean comes from South East Asia\textsuperscript{40}. Compared with a map of categorized wave energy levels along the world coastlines\textsuperscript{42}, the wave energy level in the potential source regions for a basin (Table 1) appears correlated with the $\gamma^*$ value for the accumulation zone of the basin in the emission scenario considering impervious area of land (Fig. 3c; the results for the other scenario are found in Table 1 and Supplementary Fig. S5). The only exception is the North Pacific: the North Pacific accumulation zone has a large $\gamma^*$ value in spite of the relatively small wave energy level in the South China Sea, likely the major source region for the North Pacific. In fact, a large fraction of the plastic emission from the East China Sea is likely to come ashore on the southern coast of Japan\textsuperscript{40}, where the wave energy level is large (Table 1). If the majority of plastic waste is fragmented there, therefore, the large $\gamma^*$ value for the North Pacific may be explained (Fig. 3c).

The interpretation of $\gamma^*$ for Isobe et al’s observations is less straightforward because the source region is less clear. The relatively low value of $\gamma^*$ for the area surrounding
Japan (Fig. 2b and Supplementary Table S1) may be due to the low wave energy in the East China Sea, which may be the source region of the microplastics\textsuperscript{40}. In contrast, there are clearly multiple source regions contributing to the Western Pacific transoceanic section and it is possible that the distribution is a superposition of distributions with different $\gamma^*$ values (Supplementary Fig. S3). It is interesting that the Seto Inland Sea has a very large $\gamma^*$ (Fig. 2d and Supplementary Table S1), which may be due to some local conditions or to the conditions of some remote locations where the microplastics originate. It is indeed possible that some microplastics in this region originate from the Philippine Sea, where wave energy is large\textsuperscript{42}, as previous studies indicate that some waters from the Philippine Sea are transported into the Seto Inland Sea through the western boundary current\textsuperscript{43–45}.

**Discussion**

In summary, we derive a theoretical size distribution of micro- and meso-plastics using a statistical mechanical approach. It assumes that larger “energy” is required to break down the original plastic piece into smaller fragments and that this energy follows the Boltzmann distribution. This model well reproduces observed size distributions from the micro- to meso-plastics. In particular, it naturally explains the rapid decrease toward smaller sizes without invoking a removal of smaller fragments.

The power law, which the literature often invokes to explain size distributions, is usually ascribed to some progressive fragmentation processes. Such processes may also result in a
decrease at small sizes if a limitation of energy is introduced as it is to our model. When the observed spectrum drops at smaller sizes, the lognormal distribution is also often invoked and contrasted to the power law in the literature. Quantitatively, the lognormal distribution does not much differ from our model spectrum (Figs. 2 and 3). Distributions which were compared to the lognormal distribution in the literature may be explained by similar mechanisms to our model.

The above explanation of the reduced abundance at small sizes does not necessarily contradict the possibility of deep intrusion of smaller microplastics. Consistent with deep intrusion, Reisser et al.’s observation shows that the size distribution shifts toward smaller sizes with depth. It is, however, not clear, how significant or how universal this tendency is. There is an observation that the size distribution of microplastics in a bottom sediment is similar to that at the sea surface, both with a rapid decrease toward smaller sizes. Our model assumes that the size distribution is basically determined before the fragments are released to the ocean and the other processes that modify the size distribution, such as deep intrusion, are secondary.

As pointed out above, Cózar et al.’s South Atlantic size distribution deviates from our theoretical curve more than the other size distributions in the same dataset. Supplementary Note 3 considers theoretical size distributions that would result if the sample is a mixture of plastic pieces originating from various source regions with different values of $\gamma^*$, assuming that each source contributes the same number of plastic fragments for simplicity. The resultant
superposition deviates from the single-source size distribution in a similar way that Cózar et al’s South Atlantic size distribution deviates from the single-source theoretical distribution (Supplementary Fig. S3). Interestingly, the value of $1/\gamma^*$ that best fits the mixture is close to the average of $1/\gamma^*$ values of the origins in this simple example (See Size distribution in Supplementary Note 3).

Similarly, a mixture of plastic fragments produced in various conditions may need to be considered for interpreting the observed total plastic mass. Isobe et al\textsuperscript{8} show that the total mass of the plastics for sizes below 5 mm is about 0.3 mg m\textsuperscript{-3} for their samples in the Western-Pacific transoceanic surveys assuming that $\rho = 1000$ kg m\textsuperscript{-3}. To obtain this value from our $M$ formula (6) with the optimal values of $A$ and $\gamma^*$ for their dataset and with $\Lambda = 5$ mm, we arrive at a value $\Delta h \approx 1$ mm. Obviously this value of $\Delta h$ is too large for the fragmentation model presented in this study because fragments smaller than $\Delta h$ cannot be produced by the two-dimensional fragmentation of a plate with a thickness of $\Delta h$. This problem may be resolved if the value of $\Delta h$ obtained like this is in fact an average of the various thicknesses of the original plastic plates (See Total mass in Supplementary Note 3).

To our knowledge, oceanic observations miss plastic particles smaller than a few hundred micrometers because of the mesh sizes of the nets used to capture microplastics\textsuperscript{8,19–21}. On the other hand, smaller microplastics are observed on beaches\textsuperscript{22,48}. Interestingly, the size distribution of the microplastics on Korean beaches in Eo et al\textsuperscript{22} has a shape similar to those from ocean observations but has a peak at about 0.1 mm. We try fitting our model to their
data. Our model tends to overestimate in the sizes slightly larger than the peak size (Supplementary Fig. S6, solid cyan curve) but this error largely disappears if our formula (Eq. 5) is multiplied by $\lambda^{-1}$ (Supplementary Fig. S6, dashed cyan curve), a form that results when the original plastic piece is a block rather than a plate and the fragmentation is three-dimensional, suggesting a potential direction to take when our model is extended to smaller sizes.

The present fracture model may open paths toward developing sophisticated numerical simulations for predicting the production and dispersion of the microplastics. There have been numerical simulations to evaluate the spreading microplastics in the ocean\textsuperscript{6–9, 49}. In such simulations, virtual parcels representing a mass of plastic pieces are released in source regions and advected by ocean currents. The amount of plastics released has to be either assumed or calibrated so that the resultant mass distribution agrees with observations. Our size distribution model could be used to estimate the initial mass of plastics released from beaches to the ocean by parameterizing $\gamma^*$ at the beaches as a function of weather conditions such as winds and waves, and determining the initial value of $A$ as a function of $\gamma^*$ and the amount of plastic waste dumped there.

Methods

**Observed data in Isobe et al.** The observed size distributions in Isobe et al. are from surveys around Japan\textsuperscript{21}, in a western Pacific transoceanic section\textsuperscript{8}, and in Seto Inland Sea\textsuperscript{19} (Fig. 2a). The first set of samples is from 56 stations around Japan during the period of July 17 through September 2, 2014\textsuperscript{21}. The second is a transoceanic survey at 38 stations across a meridional
transect from the Southern Ocean to Japan during 2016; the stations in Southern Ocean and the other ones were occupied from January 30 to February 4 and from February 12 to March 2, respectively. The third dataset is collected at 15 stations in the Seto Inland Sea of Japan in May–September from 2010 to 2012.

For all surveys, neuston nets with mouth, length, and mesh sizes of 0.75 × 0.75 m², 3 m, 0.35 mm, respectively, were used to sample small plastic fragments. The nets were towed near the sea surface around each station for 20 min at a constant speed of 2–3 knots (1–1.5 m/s). The numbers of fragments are counted for each size bin with a bin width of 0.1 mm for microplastics and 1 mm for mesoplastics (defined to be >5 mm) between 5 and 10 mm, except for the surveys in the Seto Inland Sea, in which the bin width becomes wider beyond the size of 4 mm. The size of a fragment is defined by the longest length of its irregular shape. The concentration of the fragments (pieces per unit volume of sea water) within each size bin were calculated by dividing the number of fragments by the water volume measured by the flow meter at each sampling station. This concentration binned according to size is the observational data used in the present study. To obtain the numbers, we have digitized the plots of Isobe et al’s using WebPlotDigitizer version 4.3 (https://automeris.io/WebPlotDigitizer/). The original size distributions in the Seto Inland Sea are presented separately for four different areas, but they are averaged in the present study.

Supplementary Figure S2a replots one of these size distributions as an example. As stated above, the bin width is not uniform: for this particular data, \( \Delta \lambda = 0.1 \) mm for \( \lambda < 5 \) mm,
\[ \Delta \lambda = 1 \text{ mm for } 5 \text{ mm} < \lambda < 10 \text{ mm}, \text{ and } \Delta \lambda = 10 \text{ mm for } \lambda > 10 \text{ mm}. \] This is the reason that the concentration jumps up beyond \( \lambda > 5 \text{ mm} \). For comparison with theories, we introduce a “size spectral density” \( n_i \) (Supplementary Fig. S2b) such that

\[ \Delta \lambda_{i} n_{i} = N_{i}, \tag{7} \]

where \( \Delta \lambda_{i} \) is the width of the \( i \)-th bin and \( N_{i} \) is Isobe et al.'s value for the bin. By this definition, each rectangular area of the spectral plot is proportional to the number of plastic fragments within the bin. The spectral density is less sensitive to the bin widths, and in the limit of \( \Delta \lambda \to 0 \), it converges to a continuous size spectrum \( S(\lambda) \) such that \( \int_{\lambda_{a}}^{\lambda_{b}} d\lambda S(\lambda) \) is the number of fragments between \( \lambda_{a} \) and \( \lambda_{b} \). All of Isobe et al.’s size distributions are converted to size spectral densities in the present study.

**Observed data in Cózar et al.** The plastic samples summarized in Cózar et al\textsuperscript{20} were collected in the accumulation zones\textsuperscript{41} around the world (Fig. 3a) from December 2010 to July 2011. Their method of sampling was the same as that of Isobe et al.’s studies, except for the different mesh size (0.2 mm) and mouth area (1 \( \times \) 0.5 m\(^2\)) of the neuston net and the different towing durations (10–15 min). The collected plastic fragments are classified into bins whose widths increase exponentially (like \( \Delta \lambda_{k} = c10^{0.1k} \) mm, where \( k \) is the bin number) for 0.2 mm < \( \lambda \) < 100 mm.

Cózar et al summed the number of plastic pieces over each accumulation zone without dividing the number by the volume of the sampled sea water (Fig. S6 in their paper). Their data are digitized and converted to spectral densities in the same way as described above for
Isobe et al’s data. Sizes larger than 40 mm in the tail of the distribution have had to be omitted because the numbers are so small there that the data points are too close to the horizontal axis of the plots for the digitizer to resolve. This limitation does not significantly influence the curve fitting because the fitting result is most highly sensitive to the values of the size spectral density around the peak size. The present study has also digitized Cózar et al’s Fig. S10b to create a logarithmic plot of the sum of the size distributions for all the observed accumulation zones (Fig. 3d).

**Wave energy in source region.** We use the Lebrenton et al’s plastic dispersal simulation result\(^4\) to identify the source regions of the plastic fragments sampled in the Cózar et al’s accumulation zones. Lebrenton et al’s numerical simulation provides the dispersion of virtual particles representing a set of plastic fragments originating from land following the sea-surface currents reproduced by an oceanic circulation modelling system HYCOM/NCODA\(^5\). The particles are released at coastal locations on the basis of two scenarios, the amount of released particles determined as a function of impervious surface area (ISA-based scenario) and of coastal population density (PD-based scenario), respectively. The former is intended to reflect contributions from major rivers and the latter from large cities. Contribution in percentage of each emission region to the amount of the plastics in the accumulation zones are summarized in Table 1 from Lebrenton et al’s supplementary data. For example, the plastic emission from Australia accounts for about 9.5% of the amount of plastics found in the South Pacific accumulation zone for the ISA scenario.

Next, we estimate wave energy at each emission region from the 6-grade wave energy
level along the global coastlines provided by Fairley et al\textsuperscript{42}. Each of Lebrenton et al’s emission
regions for each emission scenario consists of multiple emission points (their supplementary
figures S2–S7). We select the point with the largest emission within the region, look up
Fairley et al’s figure to determine the wave energy level of the point, and assign the energy
level to the region. If there are multiple points with similarly large energy levels, we assign
the average energy level to the region. These energy levels are summarized in the “Energy
Level” column of Table 1; the left and right subcolumns are for the ISA and PD senarios,
respectively. Some of the energy level values are missing in the table because the selected
emission points are not covered in Fairley et al’s map. Finally, the expected wave energy level
that the plastics found in the accumulation zone experienced for each scenario is calculated
by the contribution-weighted average $\sum_i E_i f_i / \sum_i f_i$, where $E_i$ and $f_i$ denote the wave energy
level and the contribution of the $i$-th source region, respectively. For the North Pacific, we
calculate the expected wave energy level without contribution from China, assuming that
plastic wastes from China go to the North Pacific accumulation zone via Japan. The resultant
expected wave energy level for each accumulation zone is shown in Fig. S5.

Data availability

The observed data were obtained by digitizing the published original figures with Web-
PlotDigitizer version 4.3 (https://automeris.io/WebPlotDigitizer/). All data are
available from the authors on reasonable request.
Table 1: Expected wave energy levels (based on Fairley et al.’s map) at source regions and plastic emissions (percentage) that contribute to the five major oceanic accumulation zones based on the two terrestrial release scenarios (ISA scenario and PD scenario) from Lebrenton et al. The categorization of the source regions is from Lebrenton et al’s supplementary material. The values for the ISA and PD scenarios are indicated in the left and right sub-columns of each column, respectively. See the method section for the details.

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Expected wave energy level

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Without China

Expected wave energy level (Ave.)

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Without China
References


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**Author contributions**

K.A. and R.F. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

**Additional information**

**Competing interests**

The authors declare no competing interests.