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Global simulations of marine plastic transport show plastic trapping in coastal zones

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Abstract

Global coastlines potentially contain significant amounts of plastic debris, with harmful implications for marine and coastal ecosystems, fisheries and tourism. However, the global amount, distribution and origin of plastic debris on beaches and in coastal waters is currently unknown. Here we analyze beaching and resuspension scenarios using a Lagrangian particle transport model. Throughout the first 5 years after entering the ocean, the model indicates that at least 77% of positively buoyant marine plastic debris (PBMPD) released from land-based sources is either beached or floating in coastal waters, assuming no further plastic removal from beaches or the ocean surface. The highest concentrations of beached PBMPD are found in Southeast Asia, caused by high plastic inputs from land and limited offshore transport, although the absolute concentrations are generally overestimates compared to field measurements. The modeled distribution on a global scale is only weakly influenced by local variations in resuspension rates due to coastal geomorphology. Furthermore, there are striking differences regarding the origin of the beached plastic debris. In some exclusive economic zones (EEZ), such as the Indonesian Archipelago, plastic originates almost entirely from within the EEZ while in other EEZs, particularly remote islands, almost all beached plastic debris arrives from remote sources. Our results highlight coastlines and coastal waters as important reservoirs of marine plastic debris and limited transport of PBMPD between the coastal zone and the open ocean.

1. Introduction

Marine plastic debris is found in almost all marine habitats, specifically on coastlines worldwide [1]. Coastal ecosystems can be particularly sensitive to plastic pollution [2], and plastic debris on beaches can reduce the economic value of a beach by up to 97% [3]. Furthermore, while an estimated 1.15–12.7 million tons of plastic enter the ocean per year [4–6], the amount of positively buoyant marine plastic debris (PBMPD) found floating at the ocean surface is estimated to be significantly lower [7–10]. Some of the plastic entering the ocean likely immediately sinks, as 34.5% of all plastics produced between 1950

and 2015 were made of neutrally or negatively buoyant polymers [11, 12], yet a significant amount of PBMPD is still unaccounted for. A large fraction of this missing PBMPD is potentially distributed on coastlines [12–14], with local concentrations varying between 0 and 647 kg km^{-1} [15, 16]. However, given the scarcity of measurements relative to the length of coastlines, limited insight into local temporal and spatial fluctuations in beached PBMPD concentrations and the lack of a standardized sampling methodology, it is currently not possible to estimate the total amount of beached plastic debris from field measurements alone, or to describe the global pattern of beached plastic [1].

Using a simple box model, Lebreton *et al* [12] suggest that 66.8% of PBMPD released into the ocean since 1950 is stored on coastlines, however assuming a very high beaching probability and a resuspension probability below the observed range [17]. More complex global Lagrangian simulations of PBMPD have either not included beaching at all [18, 19] or use simple best guess implementations without considering resuspension [20–22]. Most of these studies have focused on plastic debris in the open ocean [9, 18], and do not report how global estimates of the amount and distribution of beached plastic vary with different beaching and resuspension parametrizations.

Here we present a series of idealized beaching experiments, using a Lagrangian particle tracking model with beaching and resuspension parameterizations. We estimate upper and lower bounds for the fraction of positively buoyant terrestrial plastic debris in coastal waters, on beaches and in the open ocean within the first years of release into the marine environment. Additionally, we describe the global relative distribution of beached plastic debris, and we analyze the relative amount of plastic with local versus remote origin.

2. Methods

2.1. Ocean surface current data

For the 2005–2015 global surface currents, we use the HYCOM + NCODA Global 1/12° surface current reanalysis [23] and the surface Stokes drift estimates from the WaveWatch III hindcast dataset [24, 25]. The HYCOM + NCODA Global 1/12° reanalysis [23] has a temporal resolution of 3 h and a equatorial spatial resolution of 1/12° ($\approx$9.3 km). The HYCOM + NCODA Global 1/12° reanalysis does not incorporate Stokes drift, which has been shown to play an important role in shoreward surface transport [18]. Therefore, we add surface Stokes drift estimates from the WaveWatch III hindcast dataset [24, 25], which has a temporal resolution of 3 h and a spatial resolution of 1/2°. Comparison of Stokes drift estimates from the WaveWatch III dataset with *in situ* measurements from drifters have shown high correlations [26, 27], where root mean square errors have been on orders of centimeters per second [26]. Unless otherwise mentioned, simulations discussed in this paper have been done with surface currents obtained by the sum of the HYCOM currents and Stokes drift, as has been done in earlier modeling studies [10, 28, 29]. Not including Stokes drift reduces the amount of PBMPD that beaches by 6%–7% (supplementary figure 3 (available online at stacks.iop.org/ERL/16/064053/mmedia)) and reduces the trapping of PBMPD near the coast (supplementary figure 4). Stokes drift is thus an important component of the ocean circulation to consider in global PBMPD transport and beaching modeling.

PBMPD floating at the surface can be exposed to winds, with the strength of this effect depending on the size of the object that is exposed to winds above the ocean surface [30]. However, for the open ocean, the best model performance for modeling PBMPD is without including a separate windage term [10]. Furthermore, windage and Stokes drift are shown to be similar on a global scale [18]. Given that we include Stokes drift, we therefore do not consider an additional term for windage.

2.2. Lagrangian transport

We use Parcels [31, 32] to model plastic as virtual particles which are advected using surface ocean flow field data. A change in the position $\vec{x}$ of a particle is calculated according to:

$$\vec{x}(t + \Delta t) = \vec{x}(t) + \int_{t}^{t+\Delta t} \vec{v}(\vec{x}(\tau), \tau) d\tau + R \sqrt{\frac{2 \, dt \, K_h}{r}}, \qquad (1)$$

where $\vec{v}(\vec{x}(t), t)$ is the surface flow velocity at the particle location $\vec{x}(t)$ at time t, $R \in [-1, 1]$ is a random process representing subgrid motion with a mean of zero and variance $r = 1/3$, dt is the integration timestep, and K_h is the horizontal diffusion coefficient. The seed value of the random number generator does not influence the amount of beached plastic (supplementary figure 3). Equation (1) is integrated with a 4th order Runge–Kutta scheme with an integration timestep of $dt = 10$ min, and particle positions are saved every 24 h. We take $K_h = 10$ m^2 s^{-1} [29, 33] to parameterize sub-grid processes.

2.3. Plastic emissions into the ocean

We use a terrestrial plastic input estimate based on the low end estimates of [4], where 15% of mismanaged plastic from the population living within 50 km of the coast enters the ocean. To obtain high-resolution estimates we multiply the country-specific mismanaged waste estimates with population densities [34] for 2010. This results in estimates of total mismanaged plastic for all cells on the HYCOM grid (supplementary figure 2). Polypropylene, polyethylene and polystyrene constitute 54% of primary plastic production in 2010 [11], and we assume that this fraction is indicative of how much mismanaged plastic is initially buoyant. We acknowledge that this 54% is a rough estimate, as it assumes that mismanaged plastic inputs have the same composition as global plastic production, whereas it has also been reported that heavier polymers can float with sufficient trapped air bubbles [35] and light polymers have been found submerged [36]. This leads to a total buoyant plastic input of 2.16×10^6 tons in 2010 (71.70% Asia, 4.39% North America, 3.94% South America, 2.16% Europe, 17.36% Africa and 0.45% Oceania).

The release of the virtual particles is scaled according to the estimate of buoyant plastic entering the ocean, where each particle represents up to 5.4 tons of buoyant plastic. To save computational resources we neglect sources smaller than 0.06 tons per year per grid cell, which represent 0.007% of the total input. In each run particles are released every 31 d during the first year of the simulation starting in 2010 (628,236 particles in total) and advected for 5 years. Starting the simulation in 2005 barely affects the amount of beached plastic (supplementary figure 3). We refer to this input scenario as the Jambeck input.

To test the model sensitivity to the plastic input, we calculate one simulation using a low end estimate of plastic waste entering the ocean from rivers [5]. Again assuming 54% of plastic entering the ocean is initially buoyant, we have an input of 6.21×10^5 tons for 2010 (87.04% Asia, 0.78% North America, 4.58% South America, 0.13% Europe, 7.45% Africa, 0.02% Oceania). Due to the smaller total input, no sources were neglected. We refer to this input scenario as the Lebreton input.

Particles are released in the shore-adjacent ocean cell nearest to the total mismanaged plastic cell in question. Since it is unlikely that real plastic always enters the ocean at exactly the same location, at the first time step particles are distributed randomly throughout the shore-adjacent ocean cell prior to the start of advection by the ocean currents.

2.4. Beaching parametrizations

2.4.1. Stochastic beaching and resuspension

Many processes are hypothesized to influence the amount of beached plastic on coastlines, such wind direction and speed, coast angle, aspect and morphology, local runoff, the proximity to urban centers and the degree of human usage of the beach [1, 36–42]. Many of these factors have some limited predictive power in statistical models that attempt to explain patterns of beached plastic [38, 39]. However, it is unclear from these studies whether these factors influence beaching, resuspension or both. They can also partially cancel each other out as they might work in opposite directions and in general it is unclear how these factors should be parameterized. We therefore decided to implement the simplest model possible, where we assume that on a global average, the main drivers of plastic beaching are the surface currents and the location of plastic input.

To account for the uncertainty of the ocean current data in land-adjacent ocean cells, we parametrize beaching as a stochastic process in the coastal zone, within which we consider the currents unreliable. For any given time step, we calculate the beaching probability p_B as:

$$p_b = \begin{cases} \text{if } d \leqslant D, \ p_B = 1 - \exp(-dt/\lambda_B) \\ \text{if } d > D, \ p_B = 0, \end{cases} \quad (2)$$

where d is the distance of particle to the nearest coastal cell, D is a predefined distance to the shore within which beaching can occur, dt is the integration timestep and λ_B is the characteristic timescale of plastic beaching. Beaching is therefore only possible within a beaching zone set by D. To account for the fact that global-scale ocean current datasets are inaccurate in ocean cells adjacent to land (referred to henceforth as coastal cells), we set D such that all coastal cells are fully contained within the beaching zone, resulting in a beaching zone of 10 km.

The probability of beaching is set by the beaching timescale λ_B, where λ_B is the number of days that a particle must spend within the beaching zone such that there is a 63.2% chance that the particle has beached. There is no experimental study to base the value of λ_B on, nor how it might vary for different types of plastic debris, so we selected a range of possibilities to investigate the sensitivity. For the sensitivity analysis we take $\lambda_B \in [1, 2, 5, 10, 26, 35, 100]$ days. Given the mean current speed in the coastal cells in the HYCOM dataset, $\lambda_B = 1$ day is the time a particle would require to travel 10 km in a straight line, representing a lower bound for the beaching probability. In the Mediterranean, analysis of GPS trajectories of drifter buoys suggests $\lambda_B = 76$ days [43], and an inverse modeling study suggests $\lambda_B = 26$ d for plastic debris [43]. We consider $\lambda_B = 100$ d to represent scenarios in which particles have very low beaching probabilities. A wooden drifter experiment in the North Sea found 46.88% of drifters beached within 91 d, traveling geodesic distances between 452 and 559 km [44]. Given that the drifters crossed the North Sea in this time and therefore spent time outside of the coastal zone, this suggests that λ_B is less than 100 d. However, we acknowledge that the values for λ_B remain a major source of uncertainty. Furthermore, unless specifically mentioned we parameterize beaching (and also resuspension) rates as global constants.

Particle resuspension is also implemented stochastically, where the resuspension probability p_R of a beached particle is defined as:

$$p_R = 1 - \exp(-dt/\lambda_R), \quad (3)$$

where dt is the time step and λ_R is the characteristic timescale of plastic resuspension. Hinata *et al* [17] has experimentally studied the resuspension timescale of plastic objects with different sizes and found $\lambda_R = 69$–273 d. For our sensitivity analysis we take $\lambda_R \in [69, 171, 273]$ d. When a particle beaches, we save its last floating position, and when a particle resuspends it continues its trajectory from this position.

2.4.2. Coast-dependent resuspension

There have been a number of studies that have tried to explain the pattern of beached plastic using

statistical models that among others factors take geomorphology into account [38, 39]. However, it is unclear whether plastic beaching, resuspension or both are affected by geomorphology, and the influence of geomorphology likely differs for different types of plastic debris [45]. We are not aware of any studies investigating how geomorphology affects beaching probabilities. However, the dependence of resuspension probabilities on beach types have been studied with regard to the resuspension of oil [46]. Oil resuspension rates for sandy and rocky shores were found to be 24 and 18 h, respectively, and while these timescales are much shorter than the resuspension timescales for plastic [17], we use the ratio of the timescales of different coast types as a starting point for a sensitivity analysis.

For coastal geomorphology, we use data from Luijendijk *et al* [47] to determine the relative amount of sandy coastline s of each model cell of the HYCOM grid, where $s = 0$ indicates a completely not-sandy coastline while $s = 1$ indicates a completely sandy coastline (supplementary figure 1). Note that 'not sandy' covers multiple shore geomorphologies, such as rocky shores, cliffs and shorelines covered by vegetation such as mangrove forests. The resuspension timescale is determined by:

$$\lambda_R = \begin{cases} \text{3:4 Dependence} \rightarrow \lambda_R = 69 \times (0.75 + 0.25 \times s) \\ \text{1:4 Dependence} \rightarrow \lambda_R = 69 \times (0.25 + 0.75 \times s), \end{cases}$$
$$(4)$$

where with 3:4 Dependence we use the resuspension timescale coastline dependence for oil [46], whereas with 1:4 Dependence there a stronger dependence on the coastline type to check the sensitivity. In both cases we use $\lambda_{RT, s=1} = 69$ d.

There is currently little knowledge about how resuspension timescales vary with the coastline type and the classification of coastlines as sandy and not-sandy is overly simplistic, as coastlines such as rocky beaches, cliffs and mangroves are now considered equivalent. However, to our knowledge there have not been any studies that consider how plastic resuspension might depend on coastal geomorphology, and therefore we consider these runs as a first exploration of the potential role of coastal geomorphology on the global beached plastic budget and distribution.

2.5. Model concentration units

Model concentrations are computed by binning beached particle masses onto the same grid as the HYCOM reanalysis data, and then dividing the total beached mass in each cell by the length of model coastline (sum of cell edges shared with land cells) for that cell. This is because the beached plastic is not distributed homogeneously over the entire cell, but is instead concentrated on the shoreline interface between land and water, such as beaches. Since there is no global dataset of beach area, concentrations are

instead reported as the amount of plastic per length of model coastline (kg km^{-1}), which is commonly used for reporting field measurements (see table 1). However, due to the coarse resolution of the HYCOM grid, the length of the model coastline is an approximation of the true coastline length for a given cell.
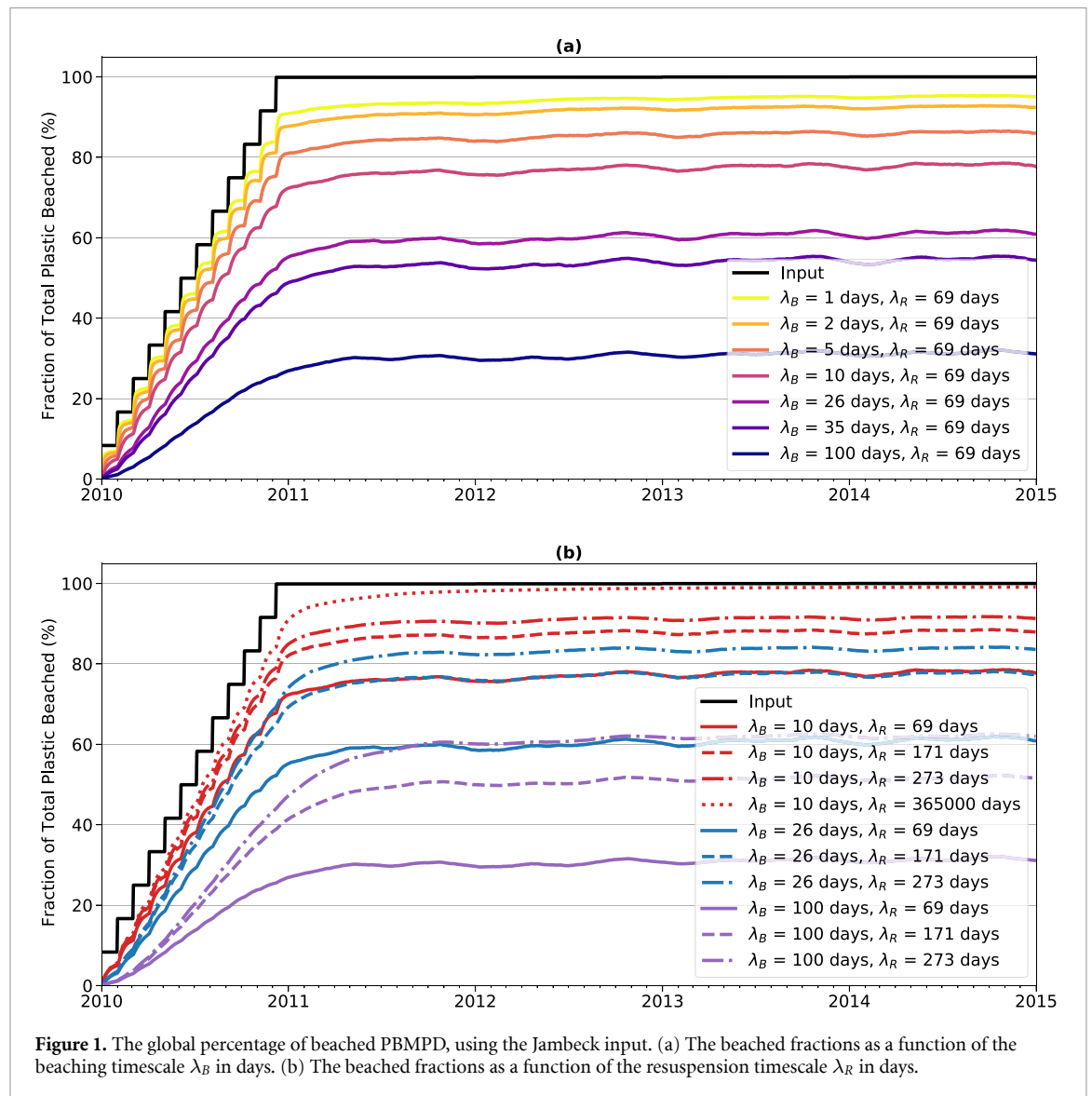
3. Results

3.1. Global beached plastic budget

A systematic test of the effect of different beaching and resuspension probabilities on the global plastic budget is shown in figure 1. In all scenarios, the model reaches an equilibrium between the beaching and resuspension fluxes after the initial release within less than two years. At the end of our 5 years of simulations, between 31% and 95% of PBMPD is beached depending on parameter values. High beaching probabilities combined with small resuspension probabilities lead to a large amount of plastic stored on beaches and vice versa. With the Jambeck input, and assuming 54% of the input is buoyant, this corresponds to 0.72–2.06 × 10^6 tons of beached PBMPD originating from plastic debris released in 2010 alone.

Rather than being a function of the absolute values of λ_B and λ_R, our model shows that the average beached fraction is dependent on the ratio λ_B/λ_R (figure 2(a)). At very low ratios, i.e. high beaching but low resuspension probabilities, up to 99% of PBMPD is beached in the 5th year of the simulations. As the ratio increases, the beached fraction decreases to 31%. However, at least 77% of the PBMPD remains within 10 km of the model coastline in all scenarios (figure 2(a)) and only a small fraction escapes to the open ocean. Multiple studies report decreasing concentrations of floating PBMPD with increasing distance from shore, which is commonly attributed to PBMPD being removed from the ocean surface over time [35, 48–50]. However, such trends could also be partially due to PBMPD remaining trapped near-shore by the surface ocean currents.

While PBMPD can leave and return to the coastal zone, a large portion of PBMPD never travels far from the coastline (figure 2(b)). Over 25% of PBMPD mass never travels beyond 50 km from the nearest coastline even with the lowest beaching probability (supplementary table 1). The likelihood for plastic to leave the coastal zone is not uniform worldwide, as PBMPD that enters the ocean from island sources or from sources close to energetic boundary currents is more likely to travel further from shore (figure 2(c)). However, there are long stretches of coastline where most plastic remains near shore, as the median of the maximum distances from shore reached by particles released from those coastlines is less than 20 km offshore.

Figure 1. The global percentage of beached PBMPD, using the Jambeck input. (a) The beached fractions as a function of the beaching timescale λ_B in days. (b) The beached fractions as a function of the resuspension timescale λ_R in days.
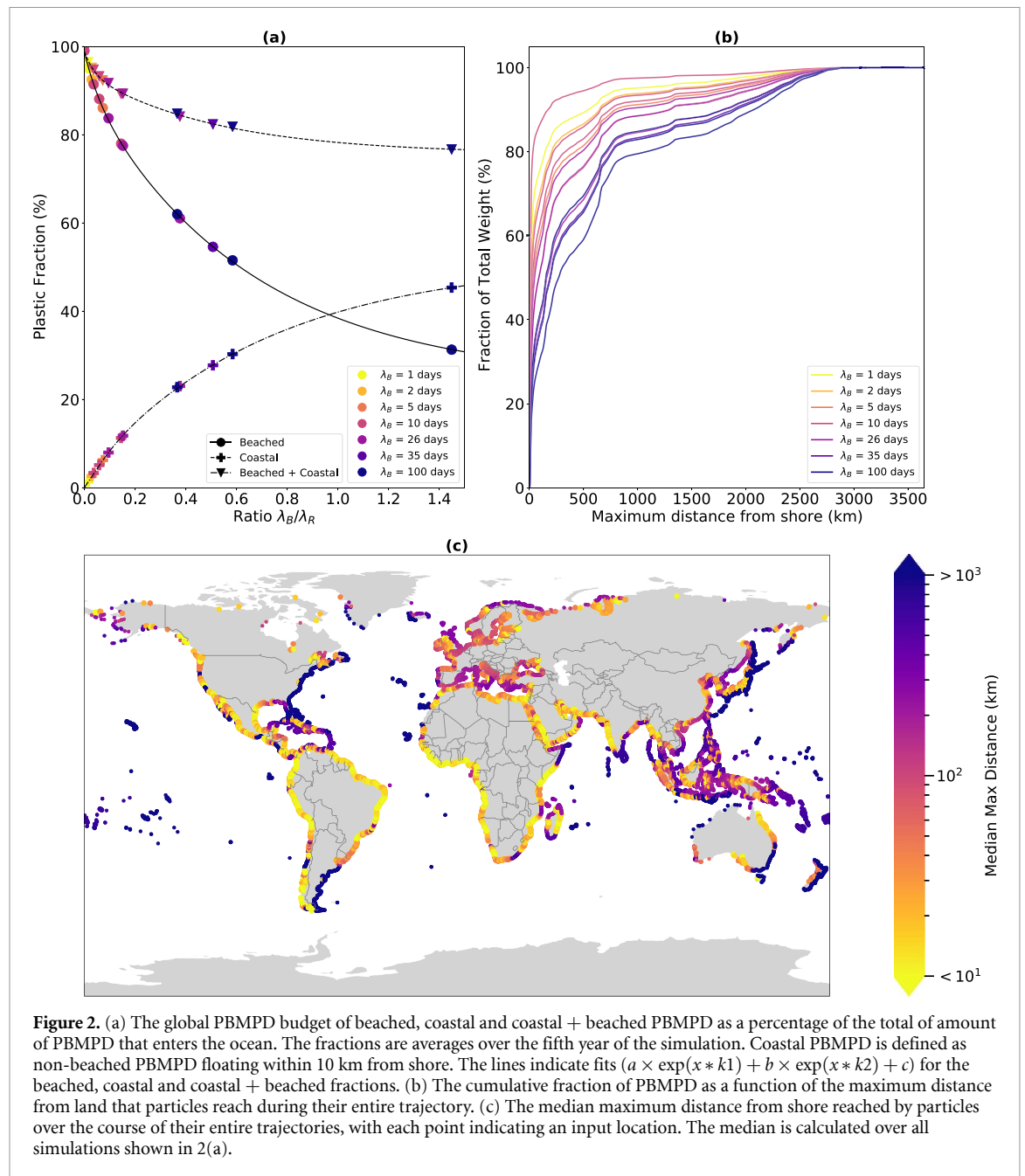
3.2. Global beached plastic distribution

Across all simulations, the highest beached PBMPD concentrations are found near regions with the largest PBMPD sources. These include areas such as Southeast Asia and the Mediterranean Sea (figure 3(a)), and have concentrations up to 10^6 kg km^{-1}. The lowest concentrations are in areas with low population densities, such as polar regions, the Chilean coastline and parts of the Australian coast. No PBMPD reaches the Antarctic mainland in any of our simulations. This is largely in line with measurements of plastic in Antarctica, which have been very low both on beaches [15] and afloat [51]. The lack of PBMPD in Antarctica is due to a lack of terrestrial input sources and the Antarctic Circumpolar Current blocking transport of PBMPD to Antarctic coastlines.

The global pattern of beached plastic is fairly robust towards the choice of beaching and resuspension probabilities (supplementary figure 5) but strongly depends on the plastic input distribution. With the Lebreton input, the relative global fraction

of PBMPD that is beached over the last year of simulation is 3% higher in comparison to using the Jambeck input (supplementary figure 3). However, absolute beached PBMPD concentrations are significantly lower, and a larger fraction of beached PBMPD is concentrated in Southeast Asia (figure 3(b)), reflecting higher inputs in this region. Therefore, detailed knowledge of the distribution and size of marine plastic debris sources are essential for understanding the global distribution of beached PBMPD.

While the overall distribution of beached plastic is largely shaped by the plastic input scenario, the ocean currents can play an important local role for beached PBMPD concentrations. For example, while higher beaching probabilities lead to higher global beached fractions, certain coastlines exhibit lower beached concentrations, such as Kenya, the Indian west coast and Libya (supplementary figure 5). More beached PBMPD globally results in less PBMPD afloat, and therefore reduced transport of PBMPD by the ocean currents to these areas.

Figure 2. (a) The global PBMPD budget of beached, coastal and coastal + beached PBMPD as a percentage of the total of amount of PBMPD that enters the ocean. The fractions are averages over the fifth year of the simulation. Coastal PBMPD is defined as non-beached PBMPD floating within 10 km from shore. The lines indicate fits ($a \times \exp(x * k1) + b \times \exp(x * k2) + c$) for the beached, coastal and coastal + beached fractions. (b) The cumulative fraction of PBMPD as a function of the maximum distance from land that particles reach during their entire trajectory. (c) The median maximum distance from shore reached by particles over the course of their entire trajectories, with each point indicating an input location. The median is calculated over all simulations shown in 2(a).
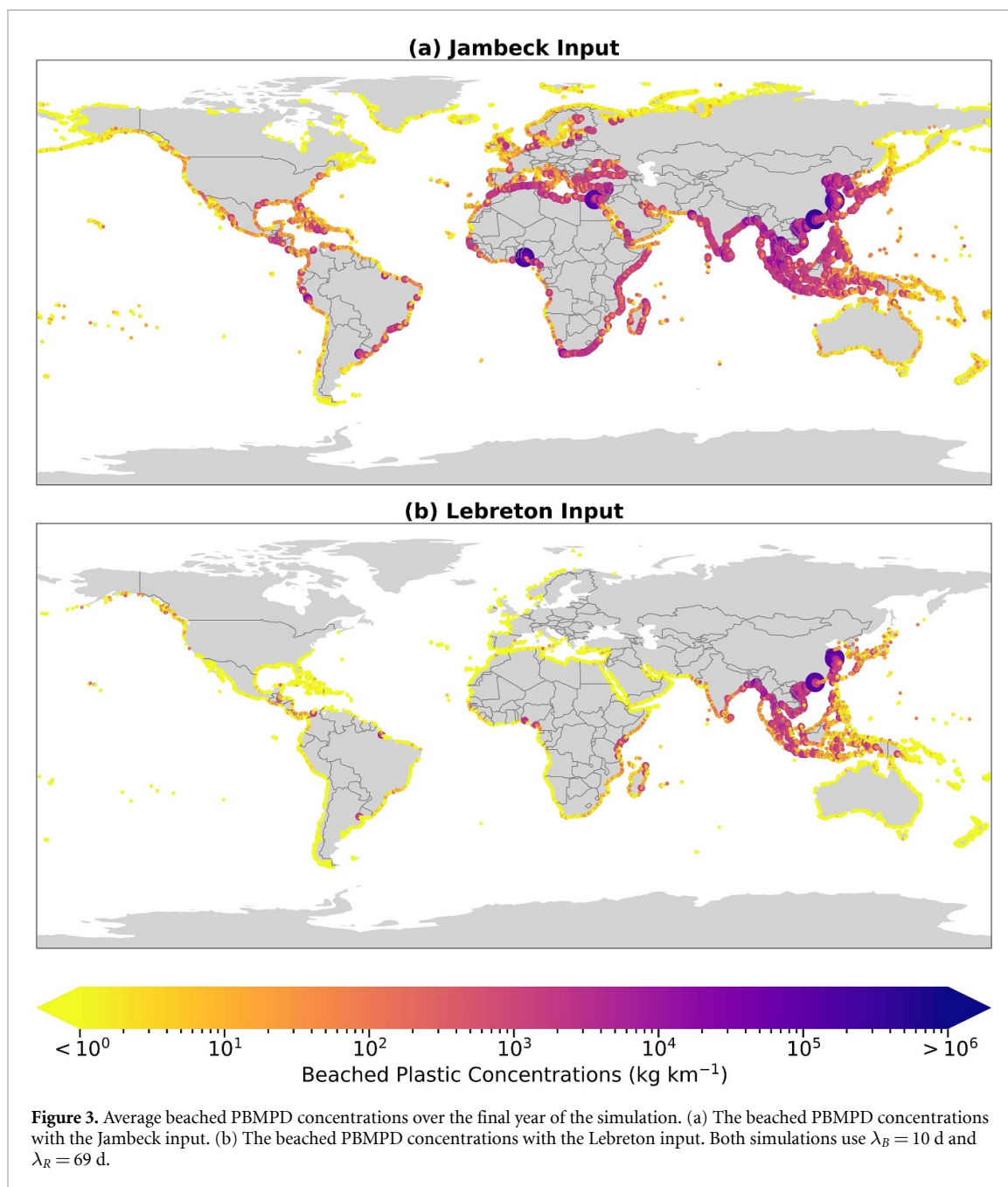
3.3. Local versus remote origin of beached plastic debris

On a global average, 48.5% of beached PBMPD within all exclusive economic zones (EEZ, [52]) is local, in that it originates from a source within the EEZ. However, the local fraction of beached PBMPD is highly variable (figure 4). Generally, the local fraction for island EEZs is relatively low, matching recent reports for individual islands in various oceans [36, 53–55]. This is likely since their location in the open ocean exposes them to floating PBMPD originating from a wide range of EEZ's, while at the same time, PBMPD originating from an island EEZ itself is less likely to beach locally than on a mainland shore due to the comparatively small coastline of islands on which beaching can occur. In the field the fraction from local sources is further reduced due

to the contribution of maritime sources [36, 54, 55], which are not included in this model.

Higher local fractions of beached PBMPD are due to a combination of factors. Large local inputs generally lead to a higher local fractions, as a large fraction of PBMPD beaches close to its initial input. Examples of such EEZ's include China, Indonesia and Brazil. In addition, the ocean currents can play a critical role (see also figure 2(c)). Eastern Africa has relatively low local beached fractions, partly due to receiving high amounts of PBMPD from Indonesia transported by the Indian Ocean South Equatorial Current (matching observations by Ryan [56]). Meanwhile, coastlines such as the Russian Arctic and Chilean mainland have high local fractions despite low local inputs, since the prevailing local currents do not carry much PBMPD from other regions.

Figure 3. Average beached PBMPD concentrations over the final year of the simulation. (a) The beached PBMPD concentrations with the Jambeck input. (b) The beached PBMPD concentrations with the Lebreton input. Both simulations use $\lambda_B = 10$ d and $\lambda_R = 69$ d.
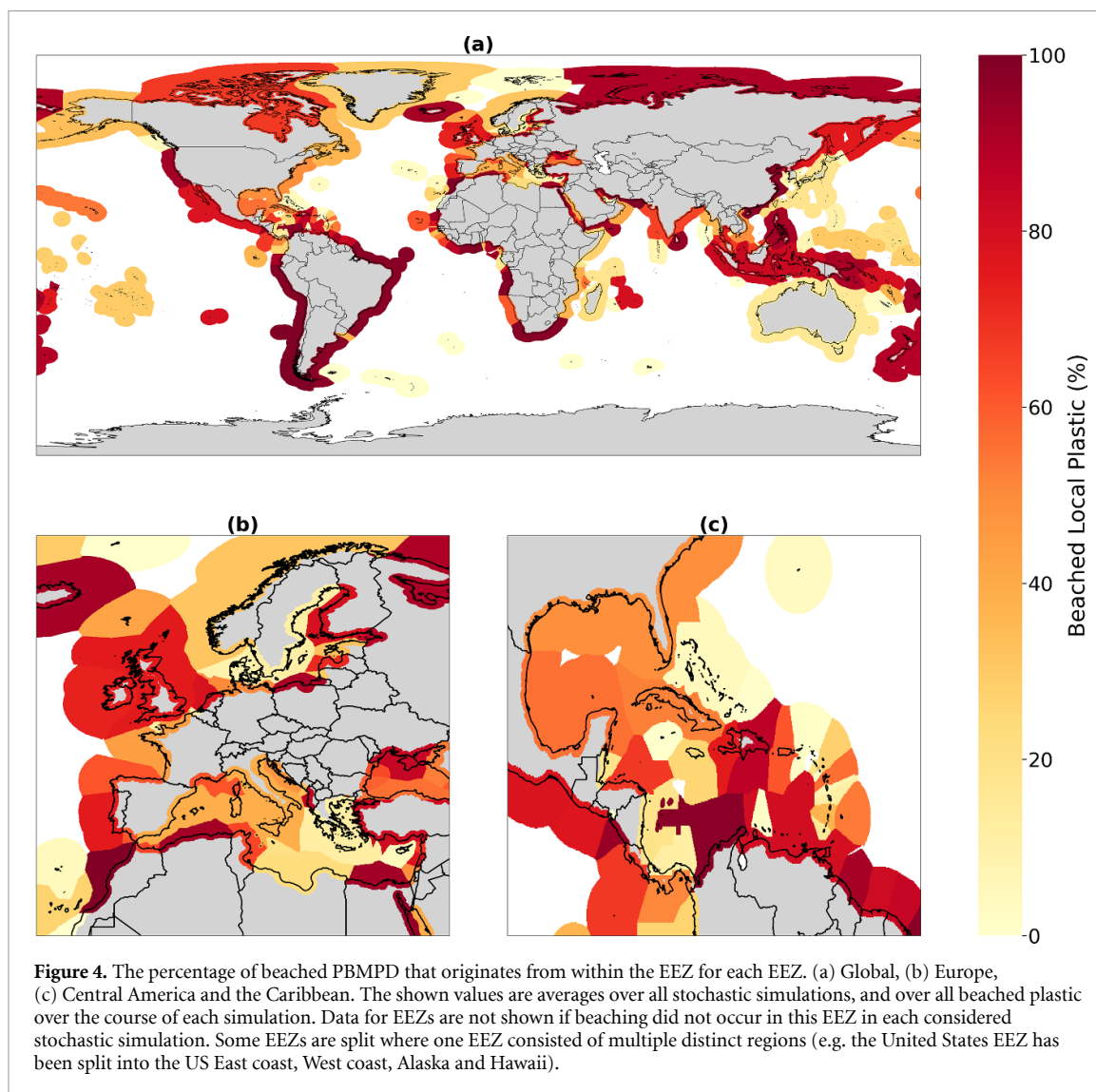
However, our local beached fraction estimates are only based on PBMPD that enters the ocean and subsequently beaches. Coastlines can also contain debris that is littered onto the coastline directly and never enters the ocean, and plastic debris that originates from maritime sources. Furthermore, ocean surface plastic removal processes such as sinking can further reduce the non-local fraction, but it is uncertain how large an effect this would have. As such, our estimates are only approximations of the actual local fraction of beached PBMPD.

4. Discussion

A systematic evaluation of our model based on a large number of field observations is currently impossible due to the lack of a standardized measurement methodology of beached plastic [1], which prevents comparisons of plastic debris concentrations reported by different studies. Beached plastic concentrations are reported either as counts or masses, per unit area or unit length of coastline, and considering different debris sizes. Furthermore, our parameterizations do not account for beach cleanups, which are known to occur at many study sites (table 1). Additionally our simulations represent idealized scenarios: there is only one year of input; we do not consider loss processes such as sinking, ingestion, or burial in sediment [70]; maritime sources of PBMPD and beach littering are not considered.

Nevertheless, we compare the modeled relative distribution of beached plastic with studies that

Figure 4. The percentage of beached PBMPD that originates from within the EEZ for each EEZ. (a) Global, (b) Europe, (c) Central America and the Caribbean. The shown values are averages over all stochastic simulations, and over all beached plastic over the course of each simulation. Data for EEZs are not shown if beaching did not occur in this EEZ in each considered stochastic simulation. Some EEZs are split where one EEZ consisted of multiple distinct regions (e.g. the United States EEZ has been split into the US East coast, West coast, Alaska and Hawaii).

measured beached plastic concentrations with a standardized method over multiple study sites. The modeled beached PBMPD distribution for South Africa closely resembles the distribution from field measurements [39], likewise our model captures the very low concentrations found on the Australian Northwestern coast [38]. However, the model appears to over-predict the amount of beached plastic on the Northeastern Australian coastline, potentially due an overestimated input of plastic from Polynesian islands. In the United States, the concentration ratio between the Northern Pacific coast and the Southern California Bight is approximately equal to the ratio reported in Ribic *et al* [62], but the relative amount of beached plastic in Hawaii is underestimated (table 1). PBMPD from maritime sources is often an important contributor of beached plastic on remote shores and islands [1, 55], and the lack of maritime sources in the input scenarios might partially account for this discrepancy. The overall relative similarity of the measured and modeled distribution is encouraging and indicates that we may have captured the dominant

drivers of beaching on a continental scale. However, these studies only allow comparisons of the relative patterns, as the model units ($kg\,km^{-1}$) do not match the field measurement concentrations. Compared to studies that do report concentrations in terms of mass, the model generally overestimates field concentrations by a factor of 5–560 (table 1). This either indicates that substantial losses of beached and floating plastic occur on short timescales that our model does not account for (such as burial within sediments [55, 71], sinking [35, 72, 73] and beach cleanups [74, 75]), and/or that the input estimates are too high. The sites where beached concentrations are underestimated (both in absolute and relative terms) are all islands, which could be due to neglecting maritime sources in the model.

Our results depend strongly on the representation of the ocean currents, the accuracy of the plastic input estimate, the beaching/resuspension parameterizations and the relative importance of processes that are not included. HYCOM has been shown to represent circulation patterns well in various parts

Table 1. A comparison of measurements of plastic debris with model simulations. The average, minimum and maximum model outputs are calculated over all stochastic simulations with the Jambeck input. Studies that do not report the occurrence of beach cleanups are indicated by a hyphen.

Study	Location	Concentration (items km^{-1})	Cleanup	Model mean [min max] (kg km^{-1})
Barnes and Milner [58][a,b]	Iceland	40	—	3.28 [0.72 8.98]
	Faeroe Islands	210	—	6.41 [0.04 30.58]
	La Gomera, Canary Islands	1910	—	69.58 [0.55 178.99]
	Ascension	3400	—	0.45 [0.00 6.14]
	Falkland Islands	430	—	2.49 [0.68 7.68]
	Dominica	1500	—	124.54 [0.00 918.14]
Pieper *et al* [37][a]	Faial, Azores	4610	Regular during summer, none during the study period	93.59 [0.00 285.74]
Ryan [59][a]	Tristan da Cunha	240	—	16.31 [0.00 100.53]
	Gough Island	100	—	9.12 [0.00 96.57]
Otley and Ingham [60][a]	Falkland Islands	370	—	2.49 [0.68 7.68]
Convey *et al* [15]	Candlemas Island	31	None	0.00 [0.00 0.00]
	Saunders Island	50	None	0.00 [0.00 0.00]
	Adelaide Island	0	None	0.00 [0.00 0.00]
Ribic *et al* [61][b]	Northeast US Atlantic Coast	102	—	12.46 [1.96 43.55]
	Middle US Atlantic Coast	429	—	106.09 [5.86 397.56]
	Southeast US Atlantic Coast	83	—	220.50 [64.85 683.85]
Ribic *et al* [62][b]	Northern US Pacific Coast	56	Not regularly	56.65 [35.00 116.03]
	Southern California Bight	139	Not regularly	160.80 [43.92 623.58]
	Hawaii	134	Not regularly	33.24 [4.90 120.65]

Study	Location	Concentration (kg km^{-1})	Cleanup	Model mean [min max] (kg km^{-1})
Corbin and Singh [63]	Dominica	8	—	124.54 [0.00 918.14]
	St. Lucia	3	—	110.18 [0.00 550.12]
Debrot *et al* [16]	Bonaire	647	—	53.26 [0.00 285.57]
Debrot *et al* [40]	Curaçao	506	Occasionally	43.12 [0.00 362.68]
Claereboudt [64]	Northern Oman	15	Occur, but frequency not specified	86.43 [10.08 449.02]
Ali and Shams [65]	Clifton Beach, Karachi, Pakistan	11	Periodically, but frequency not specified	4718.88 [167.62 55 688.46]
Hong *et al* [66]	South Korea	262	Not regularly	970.65 [263.95 1611.52]
Pervez *et al* [67]	Shilaoren Beach, Qingdao, China	5	Daily	2721.28 [327.44 13 124.59]
Pervez *et al* [68]	No. 1 Bathing Beach, Qingdao, China	73	Daily	2721.28 [327.44 13 124.59]
Madzena and Lasiak [69]	Transkei Coast, South Africa	47	Not regularly	1383.42 [111.45 5084.47]

Study	Location	Total Plastic (metric tons)	Cleanup	Model mean [min max] (kg km^{-1})
Lavers and Bond [55]	Henderson Island	17.6	Never	0.08 [0.00 0.49]

[a] Concentrations as reported in Monteira *et al* [57].

[b] Total of marine debris, not solely plastic.

of the world [76–78]. However, HYCOM does not account for Stokes drift, which plays an important role in shoreward surface transport [18]. In line with earlier modeling studies [10, 28, 29], we take the sum of the HYCOM currents and Stokes drift from the WaveWatch III reanalysis [24, 25], and we consider this the best available representation of global scale circulation. Nevertheless, we acknowledge that

trajectory modeling is more accurate in the open ocean than on the coastal shelf, where we also miss the effects of tidal currents [79–81].

With an estimated global beached fraction of 31%–95%, we show that the beached amount of plastic is a lot less constrained than suggested in Lebreton *et al* [12], whose simple 6-box model predicted that 69% of plastic that has entered the ocean since 1950 is found beached. In this box model, the authors assumed a 97% annual beaching rate of coastal PBMPD (equivalent to $\lambda_B = 104$ d), which is at the upper end of our tested range of plausible λ_B values (1–100 d), and they tuned their resuspension rate to match the global amount of floating PBMPD, resulting in a 1% annual resuspension rate of beached plastic (equivalent to $\lambda_R = 36\,317$ d) that is much slower than what is indicated by field experiments (69–273 d, [17]). In addition, the box model of Lebreton *et al* [12] assumes uniform off-shore transport, while we show that transport varies strongly in different regions (figure 2(c)).

We mostly use the Jambeck input scenario for our model [4]. There have been a number of estimates for plastic inputs into the ocean [4–6, 82], but it is unclear which are most accurate. Furthermore, all alternative estimates also neglect contributions from maritime sources and primary microplastics. There are indications that the amount of plastic entering the ocean is lower than estimated in the Jambeck input [83, 84] and given how strongly the modeled global distribution of PBMPD is influenced by the input scenario, it is crucial to get better estimates of plastic debris input sources, both terrestrial and maritime.

The model assumes that there are no PBMPD loss processes, or at least that they do not play a significant role during the first 5 years. For example, we assume PBMPD remains at the ocean surface, but processes such as biofouling can cause the density of PBMPD to increase until it starts to sink [85]. PBMPD can also be removed through ingestion by wildlife [86]. Experiments with tethered PBMPD biofouling show sinking of cm-sized plastic sheets after 17–66 d underneath a floating dock [85], but it is unclear how this translates to sinking rates for free floating PBMPD for different sizes, shape and regions. PBMPD has been found at the surface up to 50 years after its estimated production date [10], and while this PBMPD might not have floated at the ocean surface over this entire time period, it does suggest biofouling requires more than 66 d to sink PBMPD in the open ocean. Given these uncertainties, sinking was not included as PBMPD removal process in this study. Plastic ingestion has been found to occur with a wide range of species [87], but it is unclear how much total plastic has been ingested and at what rate this occurs. We also assume beached PBMPD remains available for resuspension indefinitely, but PBMPD can be transported towards the backshore [88] or be buried [1]. As a

consequence, the beached PBMPD budgets are upper estimates given that PBMPD is unable to exit the cycle of beaching and resuspension in our model.

Finally, we assume globally uniform beaching and resuspension probabilities. Exploratory tests with shore type dependent resuspension affects the global budget and distribution of beached plastic only minimally (supplementary figures 6 and 7), even when applying substantial differences in resuspension probability. These results indicate that on a global scale, local variations in resuspension probability driven by factors such as wind direction or coastal geomorphology play only a minor role. Nevertheless, more research is needed to understand how both beaching and resuspension are influenced by geomorphology and climatological factors, particularly on local to regional scales.

5. Conclusion

Our results indicate that part of the discrepancy between current plastic input estimates and estimates of floating plastic debris in the open ocean is due to high amounts of beached and coastal PBMPD. We have also identified coastlines where PBMPD is much more likely to reach the open ocean, such as the Eastern United States, Eastern Japan and Indonesia. Here, cleanups would be particularly effective in intercepting PBMPD before it escapes to the open ocean. However, more work needs to be done investigating the behavior of PBMPD in coastal waters, specifically the role of wind, waves, tides, and coastal morphology in PBMPD transport, beaching and resuspension. This would be strongly aided by standardized beached PBMPD field measurements, allowing comparisons of PBMPD concentrations at different measurement sites. Furthermore, future studies ought to consider the influence of maritime sources on beached PBMPD, as this study only considers terrestrial inputs.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Author's contribution

Development of the beaching and resuspension parametrizations was done by V O, C E J, and C L, with input from M J H. The manuscript was written by V O and C L, with extensive input from C E J, M J H and E v S. Everyone contributed to the study design and discussion of the analysis, with V O carrying out the analysis.

Conflict of interests

The authors declare no competing interests.

Code availability

The code for the Lagrangian simulations is available at: https://github.com/VictorOnink/Modeling-Global-Plastic-Beaching.

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