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Laboratory experiments related to marine plastic pollution: a review of past work and future directions

Expériences de laboratoire en lien avec la pollution plastique océanique : une revue des travaux passés et directions futures

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Abstract. Plastic pollution is a very active research topic for a wide variety of scientific disciplines. While existing reviews of plastic pollution in the ocean cover the topic from different disciplinary and interdisciplinary viewpoints, this review addresses the contributions from laboratory experiments towards the geophysical processes important in marine plastic pollution research. We review the laboratory research on the transport, transformations, and origin and fate of marine plastic pollution with recommendations for future research.

Résumé. La pollution plastique mondiale est un sujet d'étude très actif pour de nombreuses communautés des sciences géophysiques. Un certain nombre de revues bibliographiques ont déjà abordé la pollution plastique des océans selon différents points de vue, avec des perspectives ciblées ou bien interdisciplinaires. Nous passons ici en revue les contributions récentes d'études expérimentales en laboratoire abordant certains aspects spécifiques de la pollution plastique marine. Plus précisément, nous avons considéré tous les processus basés sur la physique pour décrire l'origine, le devenir et le transport des particules plastiques dans les océans.

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Keywords. plastic pollution, ocean dynamics, laboratory approaches.
Mots-clés. pollution plastique, dynamique océanique, expérience de laboratoire.
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1. General considerations

1.1. *Overview*

Oceanic plastic pollution, also called marine plastic litter, is a global challenge for society and the actions to monitor, assess, or prevent its impacts have been identified in the Sustainable Development Goals by the United Nations Organization (#14 "Life below water") [1]. Marine litter in general encompasses materials other than plastic (i.e., glass, ceramics, metal, wood), but plastic pollution is the dominant fraction [2]. Marine plastic pollution research is currently focused on improving understanding and modelling tools of transport processes, fluxes, origin and the final fate of the global plastic odyssey [3].

A consensus is emerging on the physical oceanography of *floating* plastics, as summarized in a recent review [4] and illustrated in Figure 1. The dynamics of floating plastic is intricately coupled to many geophysical flows covering all spatiotemporal scales, from basin-scale long-lived gyres to wind- and wave-driven transport at the local scale. This is due to the persistence of plastic particles, which also span a wide size range from large debris ($O(1)$ m) to microplastics of $O(1)$ mm, and smaller. The large-scale open ocean flows (process A in Figure 1), which are driven by a balance between surface winds and geostrophy, are responsible for the main accumulation zones of plastic pollution, often referred to as the "7^{th} continent" or "garbage patch".

Plastics also enter the deep marine environment due to *settling* or *accumulation* processes as illustrated in Figure 2. The physical oceanography of deep sea plastics is less known, but field observations have provided clues to relate it to many geophysical processes related to the thermo-haline circulation and submarine sediments dynamics [5].

1.2. *Mass budget*

Assessing the mass budget of marine plastics sea is still a debated point, however it is an important milestone in order to close the gap between production and the global inventory of marine plastics. Estimates for marine plastic litter entering the oceans are based on population density and waste management, suggesting that between 4.8 and 12.7 million tonnes of plastic debris per year enter the ocean [7]. Considering the cumulative effects, including the accumulation of uncertainties over the years, it is estimated that the oceans would have accumulated between 75 to 200 million tonnes by 2015 [1]. We can assess these figures with the values obtained from modelling and observations for the three main vertical regions of the oceans: surface waters, ocean bottom, and the water column.

The most recent estimates for the mass of floating marine plastic are 0.13 between 3.8 million tonnes [8], compared to previous estimates that were lower with larger uncertainties, in the range 0.14 to 236 thousands of tonnes [9–11]. The first estimates of plastics in the deep sea sediments span from 3 million tonnes [12] and 170 million tonnes [13], but these are based on field samples covering only a few percent of the seafloor. Within the water column, microplastics particles smaller than 0.5 mm have been found throughout the oceans, with estimates for the global ocean in the range between 11.6 and 21.1 million tonnes [14].

Recently, the most complete global model gave a consistent view of the plastic cycle in the ocean, based on data assimilation and 3D transport models [15]. After re-evaluating sources and plastic concentrations from all the various marine reservoirs and sinks, the model based on

different scenarios for various sizes of particles gives coherent values for the mass budget to be adequately described without evoking a "missing" plastic sink. While this is an encouraging step forward in the global plastic mass budget, it is worth noting that this model (and in models in general) only account for macro-plastics (larger than 200 mm), meso-plastics (5 – 200 mm), and large micro-plastics (1 – 5 mm). Small micro-plastics (1 – 1000 μm) and nano-plastic (less than 1 μm) are not considered, which have a smaller contribution to the overall mass budget, but are of great importance in terms of eco-toxicological effects [1]. These size classifications, although slightly unusual for describing particle motion in oceanic environments, is a common approach in plastic pollution research.

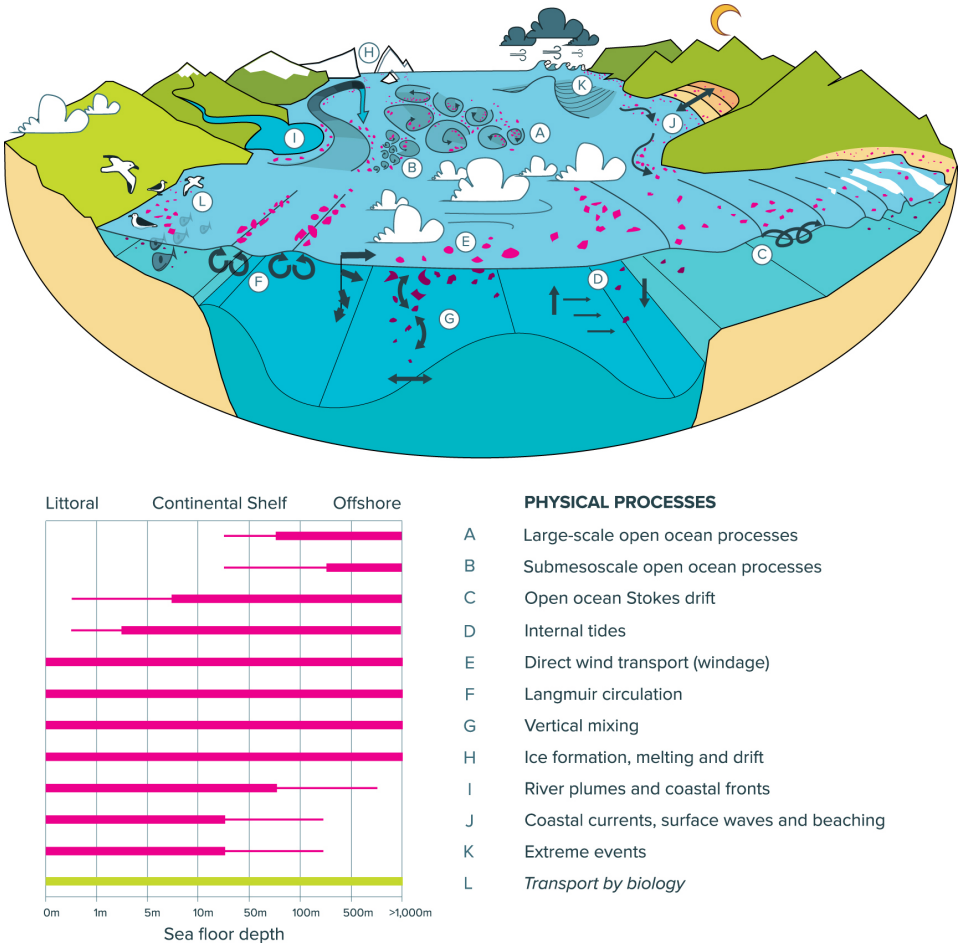

Figure 1. Schematic from [4] of the physical processes that affect plastic transport in the ocean (top panel). The table identifies the regions in which different processes are important (bottom panel). Thick pink lines indicate the process is amongst the most important in that region while thin pink lines indicate the process is of secondary importance. Transport by organisms is represented with a green line since it is not a physical process.

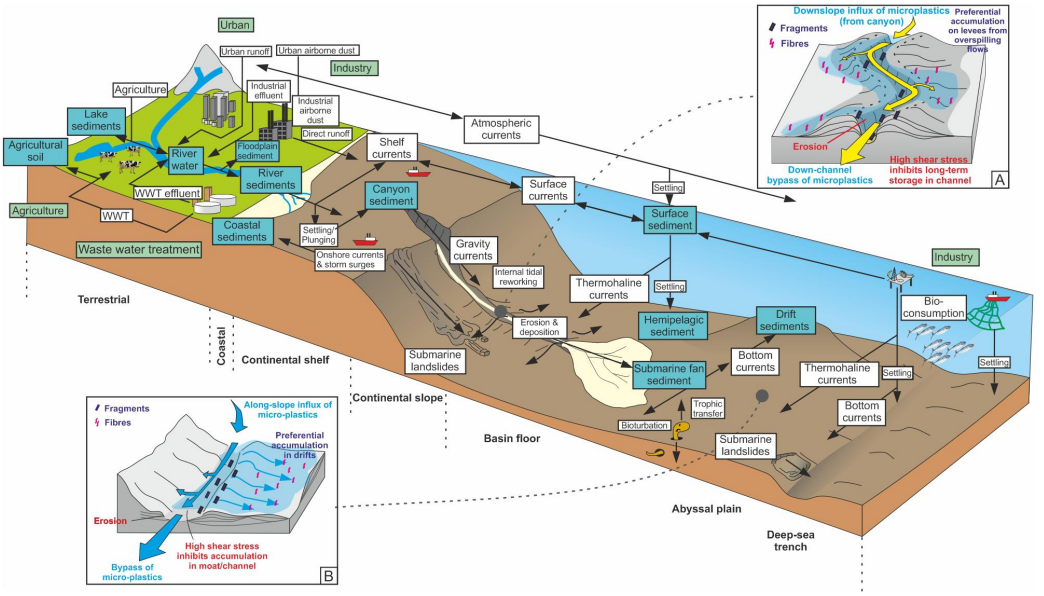

Figure 2. Microplastic sources, fluxes, and sinks from [5] modified and extended to the marine environment from [6]. Green boxes represent primary sources, blue boxes represent temporary and permanent sinks, white boxes represent transport mechanisms with arrows representing fluxes. Insets show the potential distribution and fluxes in (A) a channel-levee system and (B) a bottom current moat and drift system. WWT refers to waste water treatment plants.

1.3. *Scope and key parameters*

For marine plastics throughout the oceans, a far better understanding of transport processes and fate is required to properly assess the overall plastic mass budget. The Physics and Mechanics research communities can provide this improved understanding by adequately parameterizing all the relevant processes in the plastic cycle. Ultimately, this will allow modelling approaches to improve their ability to predict plastic pollution distributions, a key tool for political and public actions [1].

In this review, we are focused on reviewing research that seeks to parameterize geophysical processes using laboratory experiments. We address transport processes in § 2 (separated into horizontal and vertical transport, including processes B,C,E,G and J in Figure 1), transformation processes in § 3 (e.g., biofouling, fragmentation, and aggregation), and origin and fate processes in § 4 (exchanges of plastics in the ocean with benthic sediments, coastlines). In addition to reviewing existing research, we attempt to anticipate where future breakthroughs are likely or required. Terrestrial and atmospheric plastic pollution [16], although related to marine plastic pollution, are out-of-scope of this review.

Other recent reviews have also addressed the importance of physics-based research for plastic pollution. These include a focus on solute and particle transport on nearshore and shelf processes [17], plastic dynamics in coastal [18] and estuarine [19] environments, and a survey on fluid dynamical challenges related to plastic pollution [20]. We recommend the interested reader to consult these reviews alongside ours in order to benefit from complementary points-of-view, particularly on the description of the physical properties of plastic particles in the oceans, and on the role of tidal flows.

Table 1. Dimensional (resp. non-dimensional) in black (resp. color) physical parameters describing the fluid and plastic particles.

Symbol	Definition / Name	Typical values (when relevant)
ρ_i	particle (subscript p) or fluid (subscript f) density	$\rho_p \in [0.8, 2.3]$ g/cm^3, $\rho_f \in [1.00, 1.03]$ g/cm^3
ν	kinematic viscosity of the fluid	$\sim 10^{-6}$ m^2/s (20°C)
ℓ_p	characteristic length of the particle	[~ 1 μm, ~ 1 m]
ϕ_p	porosity of the particle	[0, 1[(solid VS highly porous)
E	Young modulus of the particle	~ 1 GPa
$\lambda = \ell_{p,\max}/\ell_{p,\min}$	aspect ratio of the particle	$\lambda \ll 1$ (fragments), $\lambda = O(1)$ (beads), $\lambda \gg 1$ (fibers)
$G_M(x,y,z)/\ell_{p,max}$	non-dimensional center of mass of the particle	$[-0.5, 0.5]$
δ_R/ℓ_p	non-dimensional roughness of the particle	$< 10^{-8}$ (smooth pellets) up to 10^{-1} (fragments)
Φ_v	volumetric concentration	$\Phi_v < 0.01$
D_{10}, D_{50}, D_{90}	sizes related to percentiles (10%, 50%, and 90%) of the particles size cumulative distribution.	

Table 2. Dimensional (resp. non-dimensional) in black (resp. color) dynamic parameters describing the properties of the fluid-plastic coupling. An * indicates a general definition, with a more precise definition dependent on the specifics of the problem.

Symbol	Definition / Name	Sections where it appears
ℓ_f	characteristic length scale of the flow*	§ 2–4
τ_f	characteristic timescale of the flow*	§ 2–4
τ_p	relaxation time scale of the particle*	§ 2–4
U	slip velocity of the particle relative to flow*	§ 2–4
K_h, K_v	horizontal and vertical eddy diffusivities*	§ 2
$\gamma = \rho_p/\rho_f$	density ratio	§ 2–4
$\mathrm{Re} = U\ell_p/\nu$	Reynolds number	§ 2.1, § 2.2
$\mathrm{Ga} = \left((\gamma-1)g\ell_p^3\right)^{1/2}/\nu$	Galileo number	§ 2.2
$\mathrm{Sz} = \ell_p/\ell_f$	Size number, the ratio of particle-to-fluid length scales	§ 2.1, § 2.2, § 3.2
$\mathrm{St} = \tau_p/\tau_f$	Stokes number	§ 2.1, § 2.2
$\mathrm{Sd} = \tau_w/\left(\left(\rho_p-\rho_f\right)g\ell_p\right)$	Shields number (with τ_w the wall-shear-stress)	§ 4.1
$\mathrm{Sv} = U_s/U_f$	settling/rising number (also known as Dean/Rouse number)	§ 2.2, § 4.2
$\mathrm{Sc}_t = \nu_t/K_{v\text{ or }h}$	turbulent Schmidt number (with ν_t the eddy viscosity)*	§ 2.2

The properties of plastic particles are a rich set since they have range of complex various shapes, cover a large range of length scales, and density values usually near the one of water although they are not neutrally buoyant. The coupling of marine plastics with the fluid motion covers a large range of different scenarios, from tracers for very small plastic particles to inertial, floating and/or settling particles. Additionally, plastic at sea is subject to physical, biological, and chemical transformations of its physical and mechanical properties. Given this large range of possibilities, we list the important parameters related to physics-based modelling of marine plastic pollution at the outset. Table 1 lists the dimensional and non-dimensional parameters that describes the physical properties of marine plastic pollution, and Table 2 lists the dynamical parameters associated with the transport, transformation and fate of plastic pollution in a fluid. The typical values indicated in Table 1 are extracted from previous review papers focusing on the description of plastic particles as pollutants [18,21] or sediments [22]. Extra parameters could be considered, such as a shape descriptor or a class for angularity for instance, but that are not uniquely defined hence we did not included them for simplicity. Along the manuscript, plastic pollution is described either as solid particles, for instance as a new class of sediment [23] as discussed in § 4.1, but also as a dispersed phase estimating its concentration for continuous modelling (in § 2.2 for instance), often used for eco-toxicological concerns or global approaches.

Finally, it shall be noted that achieving similarity with respect to the non-dimensional parameters presented before, in the context of marine plastic litter, is apparently easier than with natural sediments. Indeed, the density ratio γ being close to 1, it can be easily adjusted to match the other parameters such as the Reynolds/Galileo number or Schields number. The scaling of the particles dynamics with respect to the flow is not the only constraint for laboratory approaches, the appropriate scaling of the geophysical flows of interest remains.

2. Transport

To date, there have been two broad approaches to describe plastic transport in geophysical flows. The first one focuses on horizontal distribution of plastics in the two-dimensional surface flows of the oceans, usually considering only the large scale features. The second approach describes the vertical transport of plastic, and predicts concentration profiles based on a flux equilibrium formalized by an advection-diffusion equation. In this section, we briefly review these two approaches using two complementary descriptions of particle transport in fluids, i.e. the Lagrangian vs. Eulerian formalisms. Examples of laboratory experiments designed to improve the reliability of plastic transport modelling are also discussed.

2.1. *Horizontal transport*

The study of horizontal transport of plastics was initially carried out to determine where plastics end up after being released into the environment. The aim was to highlight areas of accumulation on the ocean surface (assuming that the majority of plastics float on the ocean/sea surface). These models are called ocean global circulation models (OGCMs), and combine Eulerian and Lagrangian approaches. In these models, plastics are modeled as tracers whose transport is computed using a stochastic differential equation [24]. More precisely, their trajectory as a function of time, $\mathbf{X}(t)$, is obtained from information on the Eulerian velocity field of the fluid, $\mathbf{v}(\mathbf{x},\tau)$, as

$$\mathbf{X}(t+\Delta t) = \mathbf{X}(t) + \int_t^{t+\Delta t} \left[\mathbf{v}(\mathbf{x},\tau) + \mathbf{v}_{\text{subgrid}}(\mathbf{x},\tau)\right] d\tau. \tag{1}$$

The velocity field $\mathbf{v}_{\text{subgrid}}(\mathbf{x},\tau)$ is used to describe the physics at the subgrid-scale of OGCMs, which can correspond to local processes such as submesoscale eddies, wind or wave-induced

Stokes drift [25]. When this subgrid modelling is neglected compared to large-scale open ocean flows (process A in Figure 1), OGCMs are still successful in identifying the continuous accumulation zones of plastic pollution, often referred to as the "7$^{\text{th}}$ continent" or "garbage patch" [11]. But, there are a number of pathways that lead to non-homogeneous plastics surface concentrations [26,27]. In practice, $\mathbf{v}_{\text{subgrid}}(\mathbf{x},\tau)$ encompasses all unresolved physics, including stochastic terms to model particle dispersion [24].

In this framework, plastic particle properties such as density, size, deformability, porosity are usually ignored. To address this, approaches for computing inertial plastic particle motion based on the 'Maxey–Riley–Gatignol' modelling framework coupled to geophysical flows have attempted to include the unresolved physics as explicitly computed forces acting on the particles [28]; this in order to include the influence of relevant parameters such as the Stokes and particle Reynolds number. Laboratory experiments in a controlled environment are also dedicated to the study of the impact of the various aspects mentioned above (particle and flow properties) on particle transport with the aim of providing more realistic modelling in OGCMs. The paragraphs below discuss various aspects related to this aim.

Wave-induced transport by Stokes drift (U_{SD})

The Stokes drift is the difference between the wave-averaged velocity of the particle (Lagrangian point of view) and the mean Eulerian fluid velocity in a stationary reference frame [29,30]. Laboratory measurement of Stokes drift as predicted from irrotational wave theory in a closed laboratory wave tank has been the source of much confusion due to the presence of mean Eulerian currents and viscous boundary layers that are specific to each laboratory setup [30]. Laboratory confirmation of the classical Stokes drift theory was finally provided by van den Bremer et al. [31] (see also [32]), who showed good agreement between theoretical predictions based on irrotational wave theory and laboratory experiments using transient wave groups. The difficulties and subtleties involved in confirming the classical Stokes drift demonstrate that laboratory data of horizontal plastic transport due to Stokes drift should be interpreted with care. For regular (or harmonic) wave forcing, the Eulerian-mean flows must be either explicitly measured or indirectly inferred from measurements of the drift of small floating particles. Alternatively, transient waves or wave groups may also be used to understand how the drift of plastic particles differs from that of ideal tracers. Laboratory experiments have been carried out to study the influence of the plastic properties on their horizontal drift in wave flume experiments. The open questions tackled are related to the different behaviors of plastics with various sizes, shapes, and buoyancy.

The wave-induced transport of plastic particles under harmonic wave forcing has been studied in a large-scale facility [33]. It must be noted that such configurations are weakly influenced by the rigid flat bottom, with intermediate water depths ($0.3 < kh < 3$, with h the water depth and k the wave number) [33]. The authors considered spherical particles with diameters up to 1.4 % of the wavelength, i.e. small particles. However, the authors played with the particle buoyancy through the particle to fluid ratio, γ, to compare the transport of negatively (> 1) and positively (< 1) buoyant particles. For information, the Stokes number St, which compares the characteristic response time of the transported species to changes in the surrounding fluid velocity with the wave angular frequency, is about 10^{-2} in this study. Therefore, the particles are assumed to be weakly inertial although the particle density differs from that of the fluid by around 30 %. As the particle Reynolds number is also used to characterize particle dynamics, we additionally provide its range in this study: $100 < \text{Re} < 3000$. In the context of plastic pollution, these particles can be used as models for meso-plastics.

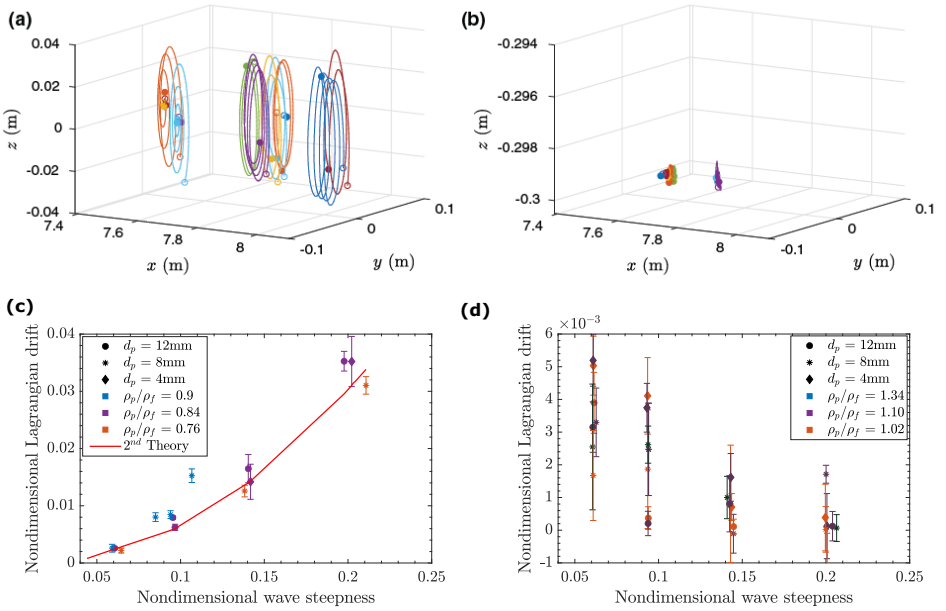

Figure 3. Examples of Lagrangian trajectories for (a) buoyant and (b) non-buoyant particles. Note the different z scales. Nondimensional Lagrangian drift measured over different steepness for (c) buoyant and (d) non-buoyant particles with varying size and densities. Solid line represents the theoretical second order solution. Results from [33].

The wave characterization was performed thanks to resistance-type wave gauges placed in a mobile frame to ensure a large spatial resolution of the wave field without any particles. Particle trajectories, over a large field of view (around 0.3×1 m^2), were measured using a Particle Tracking Velocimetry system involving two cameras. Examples of trajectories for buoyant (resp. non-buoyant) particles are shown on Figure 3 (a) (reps. Figure 3 (b)). First, the trajectories of non-buoyant particles are shorter than the ones of buoyant particles which exhibit orbital motion. However, depending on the wave height and wavelength ratio, the non-buoyant particles can move faster than in conditions presented in Figure 3 (b). Second, the authors showed that buoyant particles with different sizes and densities have a positive (shoreward) drift which increases when the wave steepness increases (Figure 3 (c)), the latter being defined as Ak with A the wave amplitude.

This increase is well predicted by classical second-order Stokes drift theory (solid line in Figure 3 (c)). Furthermore, particle size and density appear to have no influence on the Lagrangian drift of buoyant particles as long as the particle size does not exceed 1.5 % of the wavelength (Sz $\ll$ 1), which is in agreement with [34]. Finally, for non-buoyant particles staying near the flume bottom, a positive Lagrangian drift is also observed (Figure 3 (d)). However, this is one order of magnitude less than the Lagrangian drift of buoyant particles, meaning that the particles move essentially with the bottom orbital velocity. A reduction in drift with particle size and density is also suggested, although the uncertainty in the experimental data is too high to identify it with certainty. More interestingly, the Lagrangian drift of non-buoyant particles decreases when the wave steepness increases. These observations are in opposition with previous studies [35] and cannot be predicted by a single drift formulation. The authors explained this due to a larger influence of bottom orbital velocity in their experiments. Therefore, in this case, a modified

"Maxey–Riley–Gatignol" formulation is needed.

Recently, similar laboratory experiments [36] than previously described have investigated the influence of the size and shape under deep-water-wave conditions ($kh > 3$), extending the results presented for spherical plastic particles with $Sz \ll 1$. Spheres and anisotropic objects ($\lambda \neq 1$) such as discs, bottle caps, plates or net fragments are considered, with Sz varying between 0.003 and 0.2. The authors have summarized their observations by defining an amplification factor for the Stokes drift of a finite-size object compared to the one for an infinitely small one. The discs have shown the strongest amplification of the drift, increasing by $5-6\%$ for a relative increase of size of 1%, while spheres experienced an increase of 3% for the same increase of size. Results for spheres have shown reasonable agreement with numerical/theoretical predictions [34]. An increase in Stokes drift has also been predicted due to the rise in particle buoyancy (related to the enhancement of particle size). In the numerical study, the authors also mention an influence of the ratio of particle to fluid density, γ. This could not be validated experimentally, however, due to the wide dispersion of γ in the experimental measurements.

In conclusion, the main parameters that control the horizontal wave-induced transport (Stokes drift) are the ratio of particle to fluid density γ, the wave steepness Ak and the non-dimensional water depth kh, in good agreement with theoretical predictions. This drift can be enhanced for particles having at least one dimension not too small compared to the wavelength of the wave (Sz > 0.1); the amplification due to size effects being stronger for anisotropic particles than spheres, although the influence of λ has not been quantified. The results are valid for a large range of values for the Reynolds number (10 < Re < 3000), and small values of the Stokes number (St < 0.01). It should be noted that wave-induced transport is only involved in the transport of meso (and larger) plastics. Smaller plastics (microplastics typically smaller than 10 cm), due to their low buoyancy, are easily suspended in the water column and are more subject to vertical transport (see § 2.2). Consequently, as Isobe et al. [37] suggest, the larger plastics, due to net shoreward drift, remain in the coastal region, while the smaller ones, depending on their vertical position, move seaward. Large objects are also sensitive to wind-induced drift, which is discussed in the next paragraph.

Transport due to winds and currents

The influence of wind forcing at the air-water interface on the transport of plastic particles relates to the more general problem of the relative importance of water currents and winds in determining the drift of floating objects [38]. This well-known phenomenon has been thoroughly investigated recently [38] to provide a complete description of the wind factor $(U-U_w)/U_a$, which compares the drift velocity of an object U (with respect to the current velocity U_w) to the near-surface wind velocity U_a. The dominant forces at play are the inertial drag in the fluid and the air, and inertia. Various limits can be considered depending on the density of the object with respect to water, γ, and on its aspect ratio λ. Slender bodies (membrane-like), with $\lambda > 10^4$, are all drifting in a similar manner whatever γ with a wind factor being approximately 0.03. This value is due to the dominant influence of the 'skin' drag (both in air and in water) in the drag forces, hence the wind factor is nearly equal to $\sqrt{\rho_a/\rho_f}$ in this case, with ρ_a the air density. For objects with moderate values of the aspect ratio, typically $\lambda \leq 10^2$, the wind factor is controlled by the comparison of the form drag in air and water, which is related to the position of the waterline. Hence, depending on γ, its value is in the range 0.015 (for iceberg) to 0.08 (for cork).

The results in [38] have been obtained experimentally for a large range of the parameters. Additional data from mangroves to iceberg observations have validated the theoretical results for objects smaller than $\ell_p \sim 1$ km, the limit at which the influence of the Coriolis force must also be considered in the forces at play. For most object commonly found floating in the oceans, the wind factor remains very small, between 0.02 and 0.04.

Other unresolved processes

When modelling the horizontal transport of floating plastic litter using eq. (1), other "coherent" flow features would require similar laboratory interest to discriminate the specificity of plastic models with respect to the transport of other more commonly studied objects (plankton, pollution, etc.). One can mention specifically the meso-scale eddies [26], the Langmuir cells [39], or thermal fronts [40], that have been specifically identified to influence local surface concentration estimates of plastic. In general, the velocity $\mathbf{v}(\mathbf{x},\tau)$ does not include sub-surface phenomena influencing surface dynamics [41]. Neverthelss, this "near-surface" physics is of importance for proper modelling. Van der Mheen et al [42] showed, based on field measurements, that the horizontal distribution of drogued drifters (15 m below the surface) and undrogued drifters (at the surface) can differ. In particular, they showed a high concentration in the western part of the Indian Ocean, while undrogued drifters are more dispersed.

Finally, another challenging aspect is the rich nature of open-ocean wave climate. Wave packets for instance have been studied to refine classic modeling for more realistic scenarios [31]. However, validation from laboratory experiments remains uncertain. Stokes drift due to random waves forcing is often considered more simply modelled as a diffusive process [30], hence this approach relates to the other processes described hereafter. Others contributions involving more complex (open-ocean wave climate) and turbulent features can be modeled by a diffusion process, typically using a diffusion tensor $\mathbf{K_h}$, or by modifying eq. (1) into a "Fokker–Planck" equation. In its simplest form, the stochastic horizontal transport can be modeled by a white-noise of constant value amplitude added to the trajectory described in eq. (1) [24]. No specific laboratory experiments have investigated the particular case of plastic particles evolving in two-dimensional turbulence, although they appear to be well-suited tools for some pioneer work on Lagrangian transport in "chaotic" flows [43].

2.2. *Vertical transport*

The study of vertical transport was first initiated to understand the depth concentration profile, $n_p(z)$, of plastic collected at the sea surface. Knowledge of the depth concentration profile makes it possible to (i) correct surface sampling by eliminating the influence of meteorological conditions during sampling, and (ii) reduce the proportion of plastic missing from the environment [14,44]. Vertical transport of plastics is described by a balance between a buoyant flux and a turbulent one. From the mass conservation equation (see [45–47] for calculation details), this balance can be written as the advection-diffusion equation

$$\frac{\partial n_p(t,z)}{\partial t} + W_p \frac{\partial n_p(t,z)}{\partial z} - \frac{\partial}{\partial z}\left[K_z(z)\frac{\partial n_p(t,z)}{\partial z}\right] = 0, \tag{2}$$

where W_p is the plastics rise velocity and K_z is the vertical eddy diffusivity. On the one hand, the depth concentration profile depends on particle shape, density and size via W_p, as recently demonstrated by field measurements [48]. On the other hand, this transport depends on the features of the turbulence, through the eddy diffusivity (numerical study of [49]). Therefore W_p and K_z have to be chosen carefully. Note that we generally consider a stationary problem, meaning that $n_p(t,z)$ is taken as $n_p(z)$, the first term is thus removed in eq. (2).

This 1D modelling was formulated first by Kukulka et al. [50] in the context of plastic pollution, by analogy with air pollution [51], oceanography (temperature and salinity profiles) [52] and sediment transport [47,53]. The main difference between atmospheric/oceanic applications and plastic/sediment transport applications is the inertia of the species transported. This is characterized by the Stokes number St, which compares the characteristic response time of the transported species to changes in the surrounding fluid velocity with the dissipative time scale

of the flow. In atmospheric/oceanic applications, the transport of tracers is modeled (St $\ll 1$), whereas in the case of sediments or plastics transport, particles are in general no longer tracers (St > 1).

In the context of plastics pollution, the Stokes number falls in an intermediate regime not classically studied in particle dynamics field. In addition, we have to consider a combined effect of both finite size (with respect to the Kolmogorov scale) and buoyancy. If we can consider to first order that the density of plastics is close to the density of water, leading to $\gamma \sim 1$, it was shown that the behavior of particles with slightly positive buoyancy differs greatly from that of tracers and from that of particles with slightly negative buoyancy, even for particles size close to the Kolmogorov scale and therefore for particles with small and intermediate St [54]. As previously mentioned in the literature [55,56], the use of St based on the Kolmogorov scale is not the only relevant parameter to describe the vertical transport of floating particles such as plastics: γ must also be taken into account. Therefore, plastics transport opens up a new range of parameters for predicting both W_p and K_z.

Vertical settling/rising speed

Firstly, to predict vertical transport (and deduce the depth concentration profile), studies to date have used the rise velocity of an isolated particle in a fluid at rest to set W_p [57]. In recent years, a considerable effort has been made to provide an estimate of the rise velocity of an isolated particle in a quiescent fluid, based on real plastics [58,59] or on regular shapes based on plastic sizes [60]. Based on the classic balance between buoyancy and drag forces, the relevant parameters to set W_p for a given plastic are γ, ℓ_p, Re (or Ga) and a shape factor. The influence of non-homogeneous density distribution, leading to a center of mass not collocated with the center of buoyancy, on the settling dynamics has been recently investigated for spheres [61], cylinders ($1 < \lambda < 4$) [62] or fibers ($\lambda \gg 1$) [63], leading to a moderate changes in the settling/rising speed induced by changes in the wake dynamics, for high enough values of the Galileo/Reynolds numbers (Ga/Re).

As a remark, the volume fraction of plastics in the ocean is very diluted (few pieces/m^3, [58]) and therefore modulations of W_p due to collective effects observed at high volume fractions [64,65] are not expected. However, even for low volume fractions, experiments and direct numerical simulations on particles denser than the surrounding fluid have shown that turbulence modulates the vertical velocity of the particles [66,67]. When turbulence intensity is high (i.e. Sv < 1), W_p is greater than the particle velocity in a quiescent fluid and it evolves linearly with characteristic velocity of the flow, U_f [66,67]. However, when U_f is less than W_p (i.e. Sv > 1), W_p becomes less than the velocity in a quiescent fluid [66,67]. Again for dense particles, this effect is sharpen as γ decreases and approaches 1 [68]. In addition, the vertical velocity modulation was also observed in wavy flows. For spherical particles, the flow increases W_p relative to the particle velocity in a quiescent fluid, this effect being all the more evident the larger the particles [69]. To date, to the author's knowledge, there is no model for predicting W_p in turbulent flow for plastics (and also finite size and/or inertial particles), W_p is generally considered to be the velocity in a fluid at rest.

Free-surface turbulence

Secondly, to model the vertical dynamics of plastics, the eddy diffusivity is required. K_z is the capacity of turbulence to transport particles. It depends on the properties of the particles and the turbulence. Due to technical limitations in (i) simulating finite sizes and buoyant particles in geophysical flows and/or (ii) tracking large quantities of particles in geophysical flows in time and space, eddy diffusivity for plastic litter has never been measured directly, at least to the author's

knowledge. One possibility is to reproduced similar approaches proposed for other transported quantities in geophysical flows (sediment, plankton, etc.), and to approximate it as

$$K_z(z) = \frac{\nu_t(z)}{Sc_t}, \tag{3}$$

with $\nu_t(z)$ the vertical profile of the eddy viscosity, and Sc_t the turbulent Schmidt number. While eddy viscosity is determined using classical turbulent models such as $k-\epsilon$ or $k-\omega$, the turbulent Schmidt number is still debated, with values ranging from 0.1 to 7 [70–72]. To date, there is no law to predict its value according to particle size, concentration and the nature of the flow [70,72,73]. Therefore, it must be determined from laboratory experiments for each flow configuration and particle type. In the context of plastic pollution, the aim is to reproduce both the vertical characteristics of turbulence (anisotropy and inhomogeneity) and the properties of particles (finite size and buoyancy).

We describe below one of the laboratory experiments carried out to study vertical particle transport induced by wind and waves in the context of plastic pollution [71].

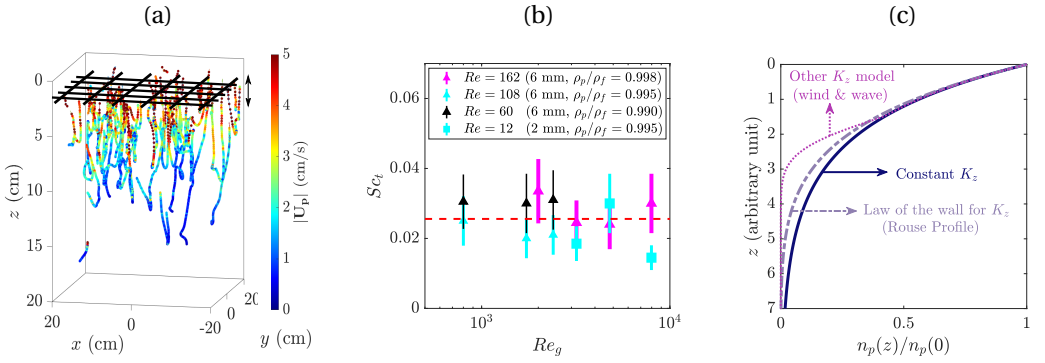

Figure 4. (a) Example of trajectories of 6 mm particles in the oscillating grid system. The color bar is the velocity norm. (b) Estimated turbulent Schmidt number as a function of the grid Reynolds number. The legend indicate the particle Reynolds number, the particle diameter and the density ratio with respect to the fluid. The red dash line is the mean value. (c) Normalised depth concentration profiles for a microplastic of 0.1 mm size. The profiles are obtained by integrating eq. (2) using different laws for eddy diffusivity, K_z (constant [50], law of the wall [74], wind and waves [75]). The z has an arbitrary unit because, for each model of K_z, certain parameters are still unknown for plastic pollution, making it impossible to predict the exact depth at which plastics may be found.

In this study, microplastics are modeled by 2 and 6 mm diameter spheres with γ between 0.99 and 1, to represent the upper range of buoyant microplastics densities [18]. They are placed in oscillating grid turbulence (Figure 4 (a)). Indeed, this flow is known to reproduce the same decay laws of wind- and wave-induced turbulence at the ocean surface for dissipation rate and fluctuating velocities [75–78]. Note that in the case of anisotropic and inhomogeneous turbulence, such as oceanic turbulence or oscillating grid turbulence, the Kolmogorov scale varies in space. This is why, in what follows, we use the particle Reynolds number based on the particle rise velocity and the particle diameter instead of St. For information, in [71], St is always of $O(1)$. Optical techniques (Particle Tracking and Particle Image Velocimetry) allowed to measure (i) the rise velocity of the particles, W_p (ii) the depth concentration profiles, $n_p(z)$ and (iii) the vertical profile of $\nu_t(z)$ (see [75] for more details and [79] for extension to oceanic applications).

Firstly, a reduction in W_p of around 60 % is observed over the entire turbulence intensity range investigated. This reduction is of the same order of magnitude as that expected in the literature [66,68]. Secondly, the turbulent Schmidt number for microplastics was estimated to be around 0.03, using an inverse problem approach from the experimental profiles ν_t and n_p (Figure 4 (b)). It depends neither on particle size nor on the ratio of particle density to fluid density, although this is still under debate [72,73]. This finding may be due to the small range of St investigated in this study. Furthermore, for microplastics pollution, the turbulent Schmidt number appears to be constant with respect to turbulence intensity (Figure 4 (b)). However, the value of 0.03 is outside the range of previous values estimated for sediments and tracers, between 0.1 and 7 [70,72,73]. This could be explained by the new range of parameters studied: nearly-buoyant particles of finite size and low volume fraction (between 10 and 1000 times lower than the volume fraction in previous studies) [47,70,73].

Note that another approach is also used to deduce $n_p(z)$, again largely inspired by work on sediment transport in rivers: the Rouse/Einstein approach [74]. It predicts the evolution of the depth concentration profile assuming the so-called law of the wall, an empirical law predicting a linear decrease in eddy diffusivity as a function of distance from the turbulence source (sediment bed or sea surface according to the application). The use of this law in eq. (2) leads to $n_p(z) \propto z^{\mathrm{Sv}}$ (Rouse profile). In this case, Sv is the so-called Rouse number defined as W_p/u_*^w with u_*^w the frictional velocity of the water on the sediment bed/sea surface. An example of Rouse profile is shown in Figure 4 (c) (dashed line) for a microplastic around 0.1 mm size and a sea state corresponding to Beaufort 2 (moderate winds). The advantages of Rouse profile are the reduced number of parameters and the prediction of profile shape as a function of the Rouse number [53,80]. However, for a given Rouse number, the profile shape (and therefore the maximum depth reached by particles) of plastics collected at sea differs from that expected for sediments [48]. To date, the parameters (γ, St, type of flow plus wave influence in the case of floating plastics, etc.) explaining this difference have not been identified. However, if we go back to the original definition of the Rouse number, it appears that it depends on the turbulent Schmidt number, which could explain the disagreements between studies [74]. Indeed, Sc_t is usually set to 1 in the context of plastic pollution [81], while we have shown it could differ from 1 as discussed above.

In Figure 4 (c), depth profiles obtained with other parametric laws for K_z are also shown for comparison (constant eddy diffusivity which has been used historically [50] and another one for wind and waves turbulence from oscillating grid turbulence [75]). As a remark, the z as no unit because, for convenience and due to the debate on the turbulent Schmidt number depending on both particle and flow properties, we consider $\mathrm{Sc}_t = 1$ to plot the three profiles. To date, the question of the "exact" profile to describe turbulent diffusivity remains open. Indeed, depending on the plastic buoyancy, it may be transported by different oceanic processes (See [4, Table 1]) with specific turbulence variations with depth [82–85]. In rivers, the same question arises for the K_z profile, particularly in relation to soil roughness (sand, vegetation, etc.) [86].

In conclusion, the main parameters that control the plastics vertical dynamics using Eulerian description are W_p, implicitly dependant on Re and shape, and $K_z(z)$. These parameters, in the context of plastic pollution, do not solely depend on the Stokes number, which alone does not allow to decouple the effects of finite size (with respect to the Kolmogorov scale), buoyancy and fluid-particle coupling.

Particle settling in wavy flows

Negatively buoyant particles introduced in a wavy flow experience both horizontal and vertical drifts (where we use the term drift to differentiate the long-time transport over many wave periods from the leading order wave-induced oscillatory motion, analogous to Stokes drift for

tracer particles in an irrotational wavy flow). A number of studies have considered this problem theoretically [87–91] and in laboratory experiments [69,92,93], with Sv $\ll 1$. In this case, Sv is defined using U_{SD} (see § 2.1). In the viscous regime (small, slowly settling particles), the particle motion can be modelled as the sum of the fluid velocity and the (orientation-dependent) particle settling velocity. For spheres in this regime, the effective settling is expected to be enhanced by a kinematic effect that is the vertical analogue to the horizontal Stokes drift [88,91]. For small (inertia-less) spheroidal particles, waves result in a preferential particle orientation that is the angular analogue of the horizontal Stokes drift and only a function of the particle aspect ratio λ. This orientation can be predicted by theory [90,92] and observed in experiments even if the particles are inertial [92]. Further, the preferential orientation modifies particle drift, reducing the effective settling relative to random orientation [89,90] and introducing a horizontal drift in the opposite direction to wave propagation [90].

The "Maxey–Riley–Gatignol" equations [94] are a popular choice for modelling inertial spherical particle motion in waves [87–91], but there are several discrepancies and gaps between this choice of model and laboratory experiments. First, the equations are applied without inclusion of the history force though its importance may not be negligible since the unsteady wavy flow produces fluid and particle accelerations that are large (up to approximately 10 % of gravity in experiments). Second, the equation is often applied outside its range of validity with respect to the particle Reynolds number. While the equation is valid for small particle Reynolds number based on the slip velocity, the settling of many plastics (including microplastics) violates this assumption. Last, the relative importance of inertial effects due to the fluid such as wakes for instance (characterized by the particle Reynolds number), and due to the particle (characterized by the Stokes number) are not clearly understood. In experiments where the flow field and particle motion are simultaneously measured, it is found that the particle motion is well described by the simple model where the particle velocity is the sum of the fluid velocity and the particle settling velocity, whether that is in waves [93] or cellular flow [95], at least for both small Re and St. This is in contrast to what is predicted from Stokes number expansions of the "Maxey–Riley–Gatignol" equations. On a related note, the predicted enhancement of the settling velocity in waves if the particle velocity is taken to be the sum of the fluid velocity and the particle settling velocity, is much smaller from theory (approximately 0-2 % [87,88,91]) compared to what is reported in experiments (approximately 20-50 % [69,93]). The experimental results even show that this increase of the settling velocity is larger for particles with small values of the Reynolds number, and also increases with another dimensionless parameter, the so-called wave parameter (H/gT^2, where H and T are the wave height and period respectively).

Given that there is well-developed theory for the behavior of particles in the viscous limit and that there are discrepancies between theory and experiments for inertial particles, future laboratory experiments should seek to carry out further investigations of both small particles whose behavior is characterized by a small Reynolds number and large particles whose behavior is characterized by non-negligible Stokes number and different particle Reynolds numbers. Together with investigating the effects of particle shape, this would clarify whether the effects predicted for small particles are observable and how to correctly model the behavior of larger particles.

Other unresolved processes

Some open questions related to more complex scenarios for vertical transport seem at reach of the current laboratory approaches. The influence of biofilm on the vertical transport has been identified as an important element for near surface dynamics [96], with a model that evidences an oscillating vertical behavior of plastics due to biofilm formation and degradation, this is discussed in § 3.1. The influence of aggregation processes is also mentioned, with or without

influenced of biofilm, leading to different vertical dynamics depending on the nature of the partner in the hetero-aggregation, phytoplankton or sediments [97]. All theses objects are to be studied in turbulent flow conditions.

3. Transformations

3.1. *Buoyancy changes (biofouling and aggregation)*

Since plastic particles have a density similar to water ($\gamma \sim 1$), it is important to consider processes that can alter their density. Biofouling, the process by which a layer of marine biota attaches to the surface of plastics, is one such process. It modifies the density by inducing volume and composition changes, and was observed fairly early on [98], but its characterization is far from obvious and raises a number of questions. Indeed, it is a complex phenomenon influenced by a wide range of parameters (i.e., geographic location, climate, water temperature, nutriments, substrate) [99]. Although never observed, either experimentally or in the field, time-oscillating vertical transport related to life and death of biofilms is used in predictions of plastic pollution transport [96]. Note that the efficiency of biofouling for small microplastics is still under debate as they might be too small for multicellular organisms to attach [100]. If the biofouling plays an important role in the evolution of plastic in the ocean, it has not been tackled yet by physicists mainly as it involves several mechanisms which are not well understood: the growth of the film that depends on the quantity of nutrient available, the hydrodynamical constraint which can erode the film, the quantity of light received by the organisms, etc.

Flocculation (or aggregation) can also change the apparent density of plastic particles. This complex process naturally occurring for small enough particles (typically $\ell_p \leq 100\mu$m) is of similar nature for plastics and natural fine sediments. Due to their polymer nature, plastic particles have the possibility to form homogeneous aggregates as well as heterogeneous aggregates with living organisms, sediments, metal oxides, proteins, etc [101]. Several experiments have revealed that microplastics can rapidly coagulate with biogenic particles [102–104], when in weak concentrations compared to biogenic one. Indeed, biofilm leads also to a reduction in hydrophobicity, which could increase the aggregation rate of the particle with phytoplankton [100,105], ultimately leading to the alteration of the settling properties of flocs or marine snow [97]. In this case, one consider the marine snow to be altered by plastic particles. It remains challenging to quantify the modifications at the scale of the particle (most important for small microplastics), but this biologically-induced flocculation is due to the suppression of repulsive forces for coated particles with biofilms [106].

The alteration of the specific properties of hetero-aggregates (i.e., size, density, porosity and rising/settling velocity) are also influenced by the presence of suspended sediment and salinity gradients [107]. Hetero-aggregates of plastic particles with suspended sediments are a more recent experimental observations that can occurred for nanoplastics with larger particles (nanoplastics of 0.1μm and sediment smaller than 100μm) [108], for particles of similar sizes (microplastics in the range $63-125\mu$m and clay finer than 20μm) [109]. It can also occur for much larger plastic particles than sediment (microplastics in the range $63-125\mu$m with kaolin smaller than 2μm), favored by the presence of surfactants in water and leading to a change from floating to sinking behavior of small microplastics [110].

Although homo-aggregates are also possible for plastic particles in suspension, they remain highly unlikely as plastic pollution is highly diluted in most aquatic environments ($\Phi_v \ll 0.1\,\%$). Nevertheless, some specific configurations lead to this process which is influence strongly by water properties, such as salinity concentrations or even gradients [111]. The influence of the shape of microplastics still needs to be clarified, although it has been shown important at smaller

scales [112]. The global importance of flocculation processes involving plastics is also uncertain, since they mainly influence the dynamics of small microplastics and nanoplastics. The temporal evolution of the properties of aggregates is rarely discussed, although it is of importance for modelling approaches.

Overall, modifications of γ for bio-fouled or agglomerated particles can lead to radical changes in their vertical dynamics (from rising to sinking § 2.2), the changes in their dynamics due to size effects remaining less important (Sz related to the vertical speed mainly). The homo and hetero-agglomerates containing plastic particles are porous particles that are more complex to characterize. Their occurrence is very sensitive to the forces of interactions that can be altered by environmental conditions. This is of importance for interactions with sediments at depth (§ 4.1) or at the coastlines (§ 4.2) as well.

3.2. *Fragmentation*

We saw in previous sections that the mechanical properties of microplastics, such as size, shape and density, play important roles on their dynamics in oceanic flows. Contrary to classical problem in particle laden flows, these mechanical features evolve with time for plastic litters. For instance weathering, erosion and/or fragmentation lead to the formation of smaller and smaller particles with arbitrary shape. In the remaining of this section we will focus on another key ingredient to understand the evolution of the plastic litters in the ocean: the fragmentation process. Indeed the large majority of collected samples floating at sea are fragments [113]. Then a reliable parameterization of the dynamics of microplastics in the ocean cannot neglect the size evolution to reach reliable prediction [114].

Overall mechanism

Microplastic fragmentation is a two-step mechanism. The first step is the degradation of plastic properties by UV, salt, ozone, living organisms, etc. [115]. This leads to an increase of the brittleness of the plastic through a shortening of the polymer chain and the creation of crack into the material [116]. As chemistry is mainly involved in this process, it will not be discussed in details here. However, several aspects of the weathering involved physical mechanisms partly discussed in previous sections. For instance, the quantity of UV absorbed by a microplastic depends on its depth and on its orientation, or the thickness of the layer of biofilm enveloping the particles depends on the shear experienced by the particle, etc. To our knowledge, there is no clear modelling of the timescale of the brittleness evolution of plastic in natural environment based on laboratory experiments, although some recent results for polyethylene are promising [117]. The second step is the fragmentation of the particle in smaller fragments. Several groups have investigated the size distribution of fragments floating at the surface of the ocean by sampling them (see legend in Figure 5 (a)). Several parameters have been investigated like the shape, colors, material, sizes, etc. Here we will focus on this last parameter. Several fragment size distributions measured in different locations are shown in Figure 5 (a). They all have the same shape: a heavy tail for large fragment which can be approximated by a power law proportional to $L^{-\alpha}$ with $\alpha \sim 5/2$ and a rapid decay for particle smaller than $\ell_c \sim 1$ mm. Note that the evolution of the size distribution for plastics smaller than 500 μm is still unclear as it depends on the mesh size of the net used to collect them [118,119]. These smaller particles are also more sensitive to vertical mixing, as we saw previously in § 2, this might induce another bias during the collect. Moreover, the age of the each sampled plastic is not known as it can either have been produced in the 1970s, when the mass production of plastic started, or much more recently. A last remark is as the different timescales involved in the fragmentation processes are unknown [120] and that the measurements of the size distribution is quite recent, there is no clue that the size

distribution reached a stationary regime or is still in a transient one. The plastic length scales have to be compared with the Kolmogorov length scale, η_K (the smallest length scale of the turbulent flow), encountered in the ocean which can be less than 100 μm [121]. Therefore, fragmentation mainly concerns object whose length lies in the inertial range $\mathrm{Sz} = \ell/\eta_K > 1$. The apparent universality of the pdf suggests that a single mechanism is at play for the plastic fragmentation whatever the location on the globe, although the power α is not universal [122]. It should then be possible to model the fragment size distribution and the timescale of fragmentation.

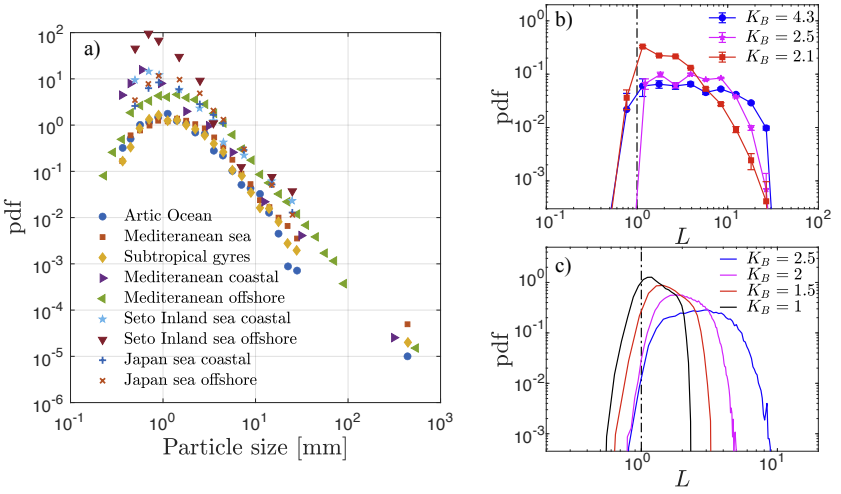

Figure 5. a) Compilation of the fragment size distribution measured at different locations around the world by different teams, data from [113] and [123]. The vertical dispersion is only due to the choice of the normalization of the distribution made by the authors. Experimental b) and numerical c) fragment size distribution of brittle fibers broken in turbulent flow for different brittleness, from [124].

So far two scenarios have been investigated: fragmentation in the swash zone due to breaking waves and fragmentation in the open ocean during storms. The first case has been mainly investigated experimentally by oceanographers. In these experiments, plastics are suspended in a tank filled with water and pebbles or sand grains. The mechanical action of breaking waves is reproduced either by the rotation of an inclined container partially filled [125,126] or by a sloshing experiment where a box containing sand, water and some plastics are set alternatively to a given inclination with respect to gravity [127]. In all these experiments, microplastics are made from the abrasion and the breakup of larger objects and the efficiency of these two mechanisms is not discussed in the interpretation of the data. Moreover, all these studies focused mainly on the global fragmentation rate by measuring the mass/number of microplastics produced from a macro object. They all find an increase of the fragmentation rate with the wave energy and that increasing the grain sizes enhances the fragmentation up to a certain point. Finally, if plastic degradation, mainly due to UV in their experiments, increases the fragmentation rate, it is not required to break plastic litters into microplastics. If these studies highlight the role of breaking waves in the swash zone in the production of microplastics, no theoretical modelling relating the wave energy, the brittleness of the plastic and the grain/pebble size to the fragmentation rate has been developed. This prevents a direct use of these results to predict quantitatively the evolution of the plastic size distribution in the coastal environment.

Fragmentation of brittle plastic

The fragmentation of plastics in open ocean has been investigated recently by physicists. The initial motivation was the modelling of the fragment size distribution which has been measured the first time by [9]. The fat tails was interpreted as a continuous breaking in smaller pieces where an object is broken in n smaller fragments, then each fragment is broken in n smaller fragments, etc [9]. This recursive scenario was inspired by a study on the fragmentation of plastic ball colliding at high speed [128]. The observed cut-off for small fragment sizes cannot be modelled with this approach and new theory is requested to interpret the behavior of the fragment size distribution for small fragments. Similar theoretical approach has been used to predict numerically the evolution of plastics in the ocean [123]. However, the continuous breaking scenario is unlikely to occur in the ocean. Indeed, from a mechanical point of view, breaking smaller and smaller objects requires more and more force or a continuous embrittlement of the particles. If the embrittlement timescale is longer than the fragmentation one, a cut-off length ℓ_c, which depends on the Young modulus E and the shape of the object, and also on the fluid density, kinematic viscosity and the intensity of turbulence [129], might be easily understood with mechanical argument: the probability that a plastic larger than ℓ_c breaks is high whereas plastic smaller than ℓ_c have a very low probability to break [124,130].

This scenario has been investigated experimentally by [124]. They studied the fragmentation of thin glass fiber immersed in a turbulent von Kármán flow driven by the counter rotation of two opposite impellers facing each other. Such flows have been used in several studies in geophysical research as it allows to generate very high Reynolds number in a relatively small facility [131,132] and have some interesting properties for the dynamo instability [133]. The use of glass, a brittle material, allows to use simple model for the fracture mechanism: the material breaks if the constraint is higher than a threshold. They measure the time evolution of the fragment size distribution for different brittleness and compare their results with numerical simulations. In both cases, the size distribution converges toward a peaked distribution with a most probable fragment size of the order of the typical elastic length ℓ_c [129]. They were able to have a quantitative description of the time evolution of the size distribution using the statistics of the deformations for flexible fibers in turbulent flows (Figures 5 (b) and (c)), in good agreement with field data (Figure 5 (a)). One possible refinement could be the continuous input of plastics in the system. Indeed, in their study, the total mass of plastics is fixed contrary to the environmental application, where the flux of plastics entering the ocean is expected to scale with their global production. The modification of the fragment size distribution in that case has recently been investigated theoretically and fits the data relatively well [134]. A second refinement is the time evolution of the brittleness of the particle to capture the ageing of the plastic in the ocean. One important assumption in this model is that the particle length is in the inertial range so larger than the Kolmogorov length. This approximation is valid for microplastics as the smallest lengthscale of the flow can be of the order of 50 μm during breaking wave events [121]. However, this approximation may not be valid for nanoplastics whose length can be smaller than 1 μm. The formation of these nanoplastics may be either due to abrasion of larger objects which have been embrittled by UV radiation or directly by the breaking of particle smaller than the Kolmogorov length. If the former scenario has not been tackled yet, the latter has been investigated numerically. At scales smaller than the Kolmogorov length, the flow is smooth and can be approximated by a linear gradient evolving randomly in time. Bending is then very unlikely. However, depending on the orientation of the particles with the eigenvectors of the rate of strain tensor and of its intensity, the fiber can buckle and break in several fragments [135]. If this scenario might be at the origin of nanoplastics, no quantitative comparison between this model and the measurements on nanoplastics has been done yet.

So far, experiments on the modelling of the formation of microplastic have been focused on the evolution of the fragment size distribution. If this work has been successful, it remains to model the fragmentation rate for particle larger than the Kolmogorov length. Indeed, the fragmentation rates estimated experimentally in non exactly homogeneous and isotropic turbulence (von Kármán flow) and the one estimated numerically in numerical simulation using idealized flow (kinematic simulation) differs from several orders of magnitude [124]. This discrepancy has still to be understood. For particle smaller than the Kolmogorov length, the timescale is determined by the probability that a particle has the right orientation with the gradient of the velocity field and whose amplitude is high enough [135]. This different timescales have then to be compared with the ageing timescale by chemical or biological degradation of plastic to determine if both timescales have to be considered or if the dynamics of the system is governed by only one timescale which is much longer than the other one.

4. Origin and Fate

There are a great variety of sources and sinks for plastic litter in the oceans [136]. Sources (inputs) for plastic can be terrestrial (mismanaged waste [7] entering via rivers [137], estuaries [19], coastlines), offshore (i.e. fishing, shipping), or atmospheric [16,138]. Plastic pollution also exits the ocean environment through a variety of sinks, including beaching or grounding at coastlines, ejection into atmosphere, settling to seafloor and being buried in benthic sediments, or ingestion by biological organisms. One can notice that many environmental compartments play a dual role (source and sink). Here, we focus on some specific sources and sinks that have been investigated both in the laboratory and the field.

4.1. *Plastics in (and as) sediments*

Microplastics in sediments have been observed in many locations for decades, although variability in sampling techniques and analysis has made it difficult to estimate the true extent and impact of microplastics in benthic sediments [139]. The more recent efforts to study plastic litter in deep sediments over the last fifteen years have allowed for better coverage and concentration/mass estimation. Various global estimates have been presented according to statistical analysis of samples based on size and type of locations. Estimates are between 3 and 170 megatonnes with most likely values in the range between 3 and 25 megatonnes [12,13,140]. Most of this deep pollution is accumulated along slopes, more than 60 % of the total being between 200 m and 2000 m with a majority of pieces smaller than 2.5 cm.

Recently, an interdisciplinary approach to describe plastic particles as a specific type of sediment has been discussed, with the key research goals of this framework identified [23,141]. Such an approach has the potential to accelerate progress on modelling the fate and transport of plastic pollution by leveraging the vast existing research on sediment. An important goal, then, is to identify the similarities and differences between the fate and transport of plastics compared with sediments and to start using methods to describe plastic particles that were originally devised for sediments. For example, new conventions for the description of plastics found in the environment would include: plastic class ranges with grades or size ranges based on transport properties; texture or shape descriptions; detailed distribution of sizes using histograms or classical metrics such as the median diameter (d_{50}). Another important goal is to identify the differences between the fate and transport of plastics compared with sediments. The main difference is related to the particle density ρ_p. Whereas the value of 2.6 g/cm^3 is often used for natural sediment particles, with sediment aggregates or flocs spanning a narrow range of

$1-1.4$ g/cm^3, the density of plastics spans a wider range with values both above and below the water density ρ_f, typically covering values such that γ is in the range $[0.03-2]$.

Another important goal is to consider the differences in terms of transport of plastic particles. Since plastic particles are solid objects in a fluid, the various modes of transport for sediments are encountered (bedload, saltation, suspended transport) as well as surface transport (discussed in § 2). The relevant parameter to characterize the different regimes for sediment motion is the Shields number, Sd as defined in Table 2, which is a comparison of the fluid forces on a particle (drag and lift) with its buoyancy. However in the context of plastic particles, due to their low density values compared to ρ_f, bedload transport shall be revisited. More specifically, two processes play an important role: the erosion and deposition behaviors and the corresponding threshold values for the shear stresses at the sediment bed. The first experimental evaluation of the plastic-specific erosion thresholds were obtained for samples collected at sea with $d_{50} \sim 4$ mm [142], more comprehensive studies have covered a wide range of plastic/sediment properties [59,143]. It is clear that much lower critical thresholds values are needed to initiate motion of plastic particles compared to sediment of the same size, and the influence of the shape and size is also of importance. The rationalization of the measured values should include the particle Reynolds number Re, the aspect ratio λ or some shape influence, as well as some description of the size differences between sediment and plastic, in a similar manner than classically made for mixed-size sediments [144], with a hiding-exposure function. Additionally, the influence of the difference in static friction for sediment and plastic has to be considered as well as local forces at play for attractive as well as repulsive interactions, as already discussed when discussing their aggregation in § 3.1. Although the description start to be well-posed, a complete understanding of the physical properties is not yet achieved. Finally, in the context of the specific type of bedload transport called dune migrations, a recent experimental study has described new processes when combining fine sediments and plastic objects covering a very large range of sizes (always larger than the value of d_{50} for the sediments) [145]. The main observations described are changes in dunes morphology due to fast transport of individual or (collective) patches of plastic items that enhances sediment transport as well. Even for dilute concentrations ($\Phi_\nu < 0.1\,\%$), the coupling between poly-disperse sediments with very different erosion/deposition thresholds is important to consider here.

Plastic litter in turbidity currents

We now turn to the specific case of plastic particles that are transported as a very dilute phase along with sediments put in suspensions and flowing as turbidity currents. As presented in a recent review [5], such flows which convey sediments as well as organic matter to the deep ocean are likely to entrain plastic litter as well. Plastic reaching deep sediments are originating from the surface (natural or biologically-induced settling), from the coastal riverine inputs evolving in turbidity currents or are transported by deep flows such as thermo-haline circulation, bottom currents or internal tides dynamics along continental slopes or in canyons. Submarine canyons and ocean trenches are regions of greater concentrations of plastic items. More specifically, canyons have specific topographic and dynamics features that are associated to a funneling effect for turbidity currents, and are often connected to a river input, which altogether make them obvious accumulation zones as confirmed by observations [146].

Nevertheless, it is not straightforward to quantify how much plastic is accumulating there. When plastic particles are suspended in turbidity currents, either by being already present at sources or by erosion of previous inputs in the canyons, some key open questions are to be answered. Where are plastics suspended in the currents? How do they deposit and where are they likely to end in the deposit? One can anticipate that the influence of plastic properties can induce a sorting/differentiation with depth, but also influence the total distance travelled,

etc. Due to the differences in nature of plastic and sediments, one expects a different behavior of plastic than for "classic" polydisperse turbidity currents [5]. Figure 6(a) is an example of setup designed to address those questions [147]. A large reservoir is made of suspended quartz sand (density 2.65 g/cm^3) with grain-size range similar to that encountered in natural turbidite systems ($d_{10} = 35\,\mu$m, $d_{50} = 133\,\mu$m, $d_{90} = 214\,\mu$m) at a volume fraction of 15 %. The resulting current density is 1.25 g/cm^3. The microplastics added to the suspension at a volume fraction $\Phi_v \leq 10^{-4}$ are of two types. Melamine fragments have densities of 1.5 g/cm^3 and a median size of $250 \pm 50\,\mu$m, and polyester fibers have densities of 1.38 g/cm^3, a length of 6 mm and a diameter of 12.5 μm. The injection rate (fixed at 12.5 m^3/h here) and angle of the channel are set to be in hydrodynamic similarity for sediment mobility. Experiments performed at an angle of 8° do not generate a deposit but can be sampled vertically using siphon tubes, whereas deposits can build up for an angle of 4°, but the siphon sampling cannot be reliably done. The experimental setup is nearly two-dimensional, the lateral extent of the tank being 0.2 m.

After a careful analysis of the siphon or deposit samples, the main results from this study, presented in Figure 6(b), are that fibers and fragments have very different behaviors in the turbidity currents and deposits.

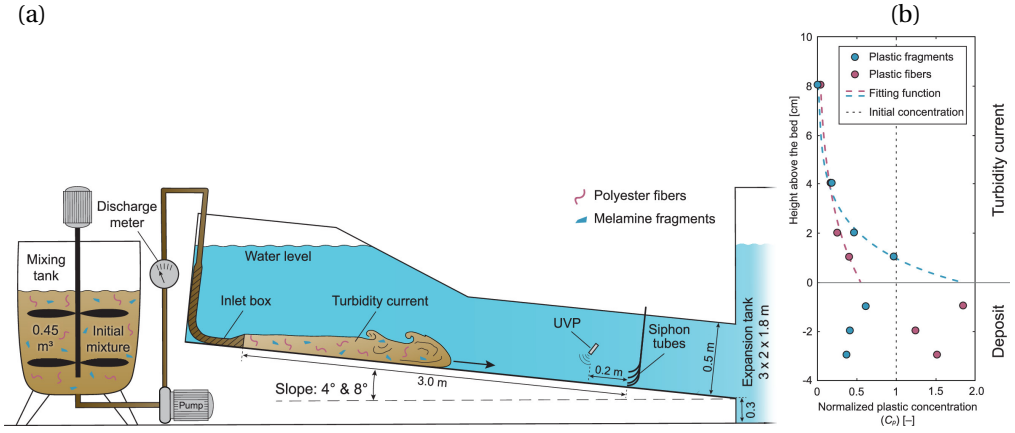

Figure 6. From [147]. (a) Experimental setup used for experiments. (b) Concentration of melamine fragments and polyester fibers in the turbidity current and in the deposits. Values are normalized with the initial concentrations in the mixing tank.

The concentrations profiles for fibers and fragments within the current are similar to the sediment concentration profile (not shown here), with an exponential decay with increasing depth from the bottom. A similar comment can be made for the vertical structure of the deposit, with no clear trends to decipher. Only the relative abundance are different, with fragments dominating over fiber in the suspension, and the reverse order in the deposit.

In [148], additional complexity has been added to this problem by considering a similar experiment but with a more diverse distribution of sediments in suspension, with the mass percentages being 65% quartz sand, 17.5 % silt, 7.5 % clay (all these classes have a density of 2.6 g/cm^3) and 5% Garnet sand (3.90 g/cm^3). The main interest here is to reproduce typical mass and size distributions observed in field studies of turbidity currents. The microplastics particles (1.50 g/cm^3) remain as a dilute phase, since its mass percentage is less than 2.5 % [148]. The experiment is also performed in a more realistic geometry in a wider tank than previously described ($11 \times 6 \times 1.2$ m^3), with levees on a slope to funnel the current, followed by a flat basin filled with fine sand for the deposit to develop in a three-dimensional manner. By analysing

the samples collected at various locations in the deposit from several cumulative injections, the authors have shown that plastic particles are more likely to be observed in levees (inner and outer parts) than in the center of the channel. They are also transported further downstream in the basin plain. These results are in agreement with observations from accumulation zones such as canyons [146].

If the influence of shape has been clearly identified in a simple configuration for turbidity currents, more quantitative studies are still required to investigate the influence of various other factors related to size comparison between plastic and sediments. These results have implications for sediments sampling strategies and analysis. The likeliness of trapping fibers more efficiently has still to be clarified but at least this is confirmed by recent observations [149]. The vertical profiles for plastic should also be related to the turbulent vertical transport described in § 2. The combined erosion/deposition processes in more realistic scenario are also only emerging, the parameter space to cover for relevant values of Shields and particle Reynolds numbers being quite large.

4.2. *Particles at coastlines*

On geophysical scales, the fate and transport of plastic pollution in the coastal environment is controlled by a multitude of physical processes, including winds, internal and surface gravity waves, diurnal heating/cooling, river plumes and estuarine circulations, stratification of the water column, and mean flow and turbulence in the surf and swash zones; these processes are described in more detail in recent reviews [4,17,150–154]. Considering how these processes influence plastic transport, the coastal environment can be a significant source, sink, and/or reservoir for the ocean plastic pollution budget.

Tracking of surface drifters in the ocean as they become beached (or grounded) has allowed for investigating how macroplastics could become beached, showing, for example, that mid-latitude islands may be particularly prone to debris accumulation [155], drifters in estuaries tend to be beached locally within a small number tidal cycles [156], and that the beaching process can be modelled as a diffusion process due to submesoscale eddies [157,158]. Field observations from a plastic spill [159] have shown how physical properties of plastic nurdles can change due to fire (intemperi or inceneration) and interaction with the marine environment, and possibly alter the beaching location. A number of studies have also conducted numerical modelling of plastic fate and transport at geophysical scales informed by field data, showing the importance of considering the coastline as a source, sink, or reservoir. For example, plastic beaching is a significant part of the plastics mass balance, with up to 75 % of all plastics washed up on beaches [85], but the mean beaching time for plastics near coastlines showing some discrepancy with field data [160–162]. For microplastics, there is a prevalence of field data on the plastic concentrations in beach sediments showing the distribution of plastics deposited at coastlines to be highly variable along any particular stretch of a coastline and over time (i.e. [163–168] amongst many others), though the lack of standardisation in field sampling techniques continues to pose challenges for comparing across studies [136].

In the field-based studies using measurements and modelling at geophysical scales, the primary focus is the roles of wind and ocean currents in predicting the transport of plastics. The role of wave-driven processes is often assumed to be subsumed by the wind speed, which ignores the complexities of Stokes drift and surf and swash zone processes mentioned above. Another common simplification is that of the coastline being either a permanent sink for plastics that are beached or a simple source, even if it is recognized that the coastline is a dynamic reservoir that can act both as a source and a sink. In other words, while some plastics can become buried sufficiently deep that they are effectively permanently removed from the ocean environment,

other plastics may become beached and then later resuspended. Note, permanent removal from the ocean environment can also occur due to human action via beach clean-ups or due to animals via ingestion. Finally, it is recognized that, much like sediment, plastics can also be transported along the coastline, but that this is not accurately accounted for in current models or field observations.

Laboratory studies of how plastics interact with a coastline, including investigations of coastlines acting as a source, sink, and/or reservoir, are relatively rare compared to the larger body of research on plastic pollution transport in the open ocean. However, as noted above, the mechanisms of plastic beaching and resuspension are some of the largest uncertainties and unknowns in predictions of the plastics budget at geophysical scales.

Laboratory studies on the coastal sink for plastic pollution (i.e. [33,169–175]) typically track the motion of plastic particles in a physical simulated coastal environment within a wave tank. The focus on wave-driven flow is due to the fact that waves are the primary drivers of flow near coastlines, though the effects of wind and oceanic currents can also be important. Not surprisingly, laboratory studies find that the biggest change in the beaching process for plastic particles is related to whether the particles are positively buoyant or negatively buoyant. Positively buoyant particles ($\gamma < 1$) are biased to be positioned near the top of the water column, which favors onshore motion in wave-driven flow that results in particles having a greater tendency to reach the shoreline and accumulate near the furthest onshore reach of wave run-up. Most studies discuss the likelihood of beaching in the swash zone qualitatively, likely because particle beaching is particularly sensitive to the water level oscillations and circulations particular to each wave tank as well as the beach profile shape and sediment. Larsen et al. [173] performed a more quantitative analysis of beaching by quantifying the beaching time for different plastic particles dropped at different locations along the wave tank. The influence of particle size and shape, coupled with its buoyancy, is brought in via the Sv number based on the particle's terminal rising velocity and the fluid velocity scale. In coastal engineering literature, this dimensionless quantity is called the Dean number (see explanation of the Dean number in, for example, [176]) and it was originally developed to provide a heuristic explanation of the cross-shore motion of sand grains. While these experiments have taken into account the surf zone dynamics, they do not necessarily give a detailed picture of the mechanics of beaching in the swash zone. Davidson et al. [174] filled this gap by using a transient wave to generate a single swash event that carried plastic particles up the beach during the run-up and deposited some of them while returning others to the water. They provide a model to explain their results that includes the introduction of a swash zone Stokes number, where τ_f is based on an experimentally validated model of swash flow [177].

Negatively buoyant particles are biased to be positioned lower in the water column, where the flow is biased to be in different directions depending on the cross-shore location. While there is an onshore directed bias outside the surf zone (albeit smaller than the Stokes drift [33]), there is an offshore directed bias in the surf and swash zones [169], which overall results in particles having a tendency to accumulate near the wave breaker zone at the outer edge of the surf zone. Thus, the dynamics of negatively buoyant plastics has a greater correlation with the dynamics of coastal sediments. As before, the influence of particle size and shape, coupled with its buoyancy, is brought in via the Sv number. While a number of such studies were conducted with a fixed beach profile and without sediment, Guler et al. [171] performed experiments where the beach was made of loose sediment and the beach profile was allowed to evolve while the positions of plastic particles were tracked at specific intervals. They found that the particle shape, size relative to beach sediment, and the shape of the beach profile can all influence the cross-shore location of where negatively buoyant particles accumulate due to factors such as the hydrodynamics of individual plunging wave crests, surf zone flow and turbulence, and the particle's angularity and ability to roll.

As noted above, laboratory experiments are well suited to investigate the interaction of plastics with coastlines. The wave-driven flows that dominate in the coastal environment are usually unresolved in geophysical models and are resolvable in laboratory wave tank facilities. While a number of laboratory studies have investigated how wave-driven coastal dynamics can allow a coastline to act as a sink for plastics, there are a number of questions that remain before to bridge the gaps between the lab and geophysical scales. Existing work obviously shows negatively buoyant and positively buoyant particles have qualitatively different cross-shore dynamics, but a clear understanding of the dominant processes that determine the fate (beaching or burial location) and transport (Stokes drift, turbulent transport, undertow effects) has yet to emerge with different frameworks proposed in different studies (see § 2). It is possible that the cross comparisons between studies are hampered by differences in geomorphic features of the coastline (i.e. beach profile [171]) and the lack of understanding of particle resuspension, as discussed in § 4.1. Relatedly, it may be worth noting that while "microplastics" are defined as plastics whose size is smaller than 5 mm, that definition needs to be reevaluated carefully in the lab so that there is not an outsized influence of inertial effects in plastic particle dynamics (defined via suitable Stokes and Reynolds numbers). Small particles may be significantly influenced by particle and fluid inertia in the shallow depths of swash zone flow in the lab, for instance. Thus, laboratory experiments are well placed to provide a better understanding plastic resuspension (shown to be important in the related problem of resurfacing of unexploded munitions that are buried in beach sediments [178]), alongshore transport and accumulation of plastic debris (analogous to alongshore transport of other debris [179]), and debris interactions with the complexities of coastal canopies such as vegetation and coral [172].

5. Outlook

Laboratory studies presented all along this review have provided significant inputs to the global modelling of plastic marine litter fate and transport. With a slight personal perspective, we want to emphasize here on some specific points that represent significant breakthroughs in the recent years. The influence of shape on plastic behavior in turbidity currents have been clearly identified as very important (§ 4.1) whereas it is not the dominant factor for Stokes drift horizontal transport (§ 2). The influence of vertical velocity (related to γ, smaller or larger than 1, and the size) is the most important parameter to consider in beaching processes (§ 4.2) as well as for vertical transport (§ 2). Finally, there is a clear connection between plastic size distribution and the characteristic length for plastic object to break due to the fluid turbulent agitation (§ 3.2).

Although marine plastic pollution is at first sight associated with solid particles moving in the ocean, we consider of great importance to make new estimates of non-dimensional parameters specific to solid transport with respect to plastic such as the Dean number for beaching, the Shields parameter for erosion, the turbulent Schmidt number for turbulent transport. These parameters based on complex physics already for sediments, are not easy to predict and can lead to unexpected values. This could prevent from misleading guesses having strong influence when extrapolated at the global scale. Across this article, we have often referred to the list of relevant parameters for the description and modelling of marine plastic litter dynamics, described in Tables 1 and 2. We anticipated that some of them shall be influential, such as unbalanced mass distribution [62] or porous particles [180], but to the authors knowledge, these specific issues for plastic pollution still need to be addressed.

Discussions at the end of each section have already emphasized on open questions related to the isolated processes described. To a certain extent, the influence of combining those processes together is also an important path towards a more realistic parameterization of these processes. For instance, one expects the influence of particles aggregation to alter their turbulent vertical

transport and the estimation of the corresponding Schmidt number; a similar comment should hold for the combined horizontal and vertical transport occurring in meso-scale geophysical turbulent flows. The motion of particles at depth in the oceans is also confronted to changes in water properties and the presence of salinity/temperature/density stratification that affect the vertical speed in a complex manner [181]. However, observations [44] have reported the presence of microplastics up to 1000 meters below the surface. Experimental laboratory studies could provide valuable insights into all these processes.

Finally, some new processes for the marine plastic cycle are starting to be investigated but are still in their premises, requiring additional laboratory studies. Atmospheric transport of plastic particles has been identified as a fast route for microplastics, which can travel thousands of kilometers, between countries and over oceans, in a relatively short time (days to weeks) in the atmospheric boundary layer[16,182]. The fluxes at the ocean/atmosphere interface remain hard to estimate, and the first experimental values obtained for particles exiting the ocean have showed an increase of aerosolization with increasing plastic concentration in water and decreasing size [183]. The trapping of plastic particles in Artic sea ice has also been identified as an important "temporary" sink [184] for marine plastic litter. Even if the sources for these microplastic particles are not well identified, it seems essential to understand the trapping mechanism in the phase change of water into ice. Recent experiments have identified the influence of size on the trapping process (micro vs. nano-plastics) [185], the important role of air bubbles at the surface of trapped plastics has also recently been discussed [186]. On a more original aspect, the marine environment with important biological activity is often considered as mucus-rich, with elevated concentrations of exopolymers that modify the rheological properties of sea water. These non-Newtonian fluid-regions have been documented as prone to unusual dynamics of plastic particles [187], with changes in orientation of complex-shaped plastics. Modification of the aggregation processes is also anticipated.

As a final note, we would like to highlight that all the efforts from the research community at large to improve our understanding of marine plastic pollution contribute to revisit and improve our knowledge of some complex geophysical processes. Similar comments could hold for other objects of interest, such as algae, phytoplankton, jellyfish patches, marine snow, etc. However for marine plastic pollution, as already stressed in [4], it is the paradoxical benefit society has gained from a massive pollution it created.

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