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A perspective

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Perspective | Invited Articles

Fluid dynamics challenges in predicting plastic pollution transport in the ocean: A perspective

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Plastic pollution has been observed throughout the world's oceans and estuaries, whether floating at the surface, settled in bottom sediments, washed up on beaches, or ingested by marine life. However, the vast majority of discarded plastics are unaccounted for. The problem of predicting the fate of discarded plastics has spurred fundamental research into fluid-particle interactions in previously unexplored regimes. Through talks and focused discussion groups taking place during a February 2022 online workshop hosted by the Banff International Research Station, theorists, experimentalists, numerical modelers, and observational oceanographers presented recent advances and identified outstanding problems in predicting plastic transport in the ocean, focusing on the role of fluid dynamics. The outcomes of this meeting and discussions that followed are reported upon here.

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I. INTRODUCTION

Hundreds of millions of tons of plastic waste are produced each year [1,2]. A large portion of this waste is improperly discarded and ultimately ends up in the environment, for example, entering rivers through municipal waste disposal or entering the ocean directly through dumping [3,4]. It is estimated that about 20 M tons of plastics enter into the ocean each year [1]. Despite the fact that most plastics produced are lower in density than seawater [2] and should be found floating on the ocean or washed up on shore, estimates based upon observations suggest that only a few percent (less than 300 K tons) of the discarded plastics remain on or near the surface of the open ocean [5]. This discrepancy has raised the question: Where are the missing plastics?

To answer this question, we need an accurate assessment of the rate at which plastic leaves the ocean surface through various processes, e.g., degradation, biological ingestion, settling, and beaching, as well as the rate of transport from one location to another. The scientific community aiming to address this question has predominantly focused upon observations performed by oceanographers (e.g., Ref. [6]), marine biologists (e.g., Ref. [7]), sedimentary geologists (e.g., Ref. [8]), and environmental scientists (e.g., Ref. [9]). However, predictive models have a crucial role in coming up with the ultimate answer to this question. The problem of predicting the ultimate fate of plastic pollution is vast: the density, size, and shape of plastics vary greatly; they can be fragmented into

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smaller pieces, for example, through stresses induced by turbulent flows; their density can change in time due to the accumulation of organic and inorganic deposits. As they are transported and evolve, plastic particles are influenced by fluid dynamics processes over wide-ranging scales, from ocean gyres and currents (hundreds to thousands of kilometers), eddies (tens to hundreds of kilometers), waves and fronts (tens to hundreds of meters), and turbulent mixing processes (millimeters to tens of meters).

The intent here is to review the recent progress and outstanding fundamental fluid dynamics challenges in modeling the transport and evolution of plastic particles in the ocean from the small scales of turbulence to the large global scales of ocean gyres. The ultimate goal of this research is to predict the transport, evolution, and deposition of plastics throughout the world's oceans and estuaries (e.g., Ref. [6]). Numerical simulations of the global ocean are too coarsely resolved to capture the wide-ranging scales of fluid motion that influence the transport of particles [10,11]. These subgrid-scale phenomena include submesoscale processes, the formation of fronts, Langmuir circulation, wave-driven transport, and turbulence. Likewise, global ocean models cannot capture the rise, fall, and transformation of non-neutrally buoyant plastics, especially when the particle properties change over time. Instead, these processes must be parameterized, being informed by theory, idealized high-resolution numerical simulations, and semiempirical models derived from the results of laboratory experiments [12–15]. Here we present recent advances in understanding some of these processes, and we point to areas where more research is required.

Guiding this perspective are the talks and discussions that took place during the Workshop on Predicting Pathways for Microplastic Transport in the Ocean [16], which was hosted by the Banff International Research Station (BIRS) February 21–25, 2022 (recorded talks and slides from many of the speakers can be viewed at Ref. [16]. The workshop broke down the problem of plastic transport into four challenge areas that were addressed through invited talks and by way of discussion groups involving all 70 international participants. In addition to these talks and discussions, this perspective is informed by the published literature and follow-up input from researchers in theoretical, experimental, and numerical fluid dynamics and physical oceanography.

Instead of zooming in from the large scale towards the small scale, we start at the small scale of a plastic particle fully (or partially) submerged in fluid. At this scale, the fundamental role of fluid dynamics in determining the dynamics of plastic particles is most pronounced. Whether a negatively buoyant particle is slowly "raining out" towards the sea floor as it is transported by a river flowing out into the sea, or a very small positively buoyant particle becomes suspended in the water column as it is pushed down by turbulence in the upper-ocean boundary layer, or it attempts to follow the oscillatory motion associated with a large surface gravity wave, what matters is whether the particle's motion is the same as that of a fluid parcel. We will therefore begin by considering finite-size particles, examining the difference between noninertial and inertial particles in Sec. II. Importantly, the properties of a plastic particle do not stay constant during its lifetime, and both particle breakup and biofouling or other accretion onto the particle may be affected by the behavior of the surrounding fluid, as examined in Sec. III. Moving on from the properties of plastic particles in flow, Sec. IV discusses the submesoscale, coastal, and estuarine processes that are especially important for transport of plastic pollution, but for which the properties of the particle itself (as distinct from a fluid parcel) are less important. Finally, Sec. V examines the challenges at the largest scale of modeling global transport. We conclude in Sec. VI by proposing directions for research progress in the near future.

II. CHALLENGES MODELING NONINERTIAL AND INERTIAL PARTICLES

The volume concentration of microplastics in estuaries and the ocean is typically so small that we can neglect particle-particle interactions, focusing our attention on the influence of fluid motion on a single particle.

Noninertial particles are so small that they are carried with the surrounding fluid like a passive tracer except that they can (slowly) vertically rise or settle through the fluid due to their (positive or

FIG. 1. Image showing various shapes of plastic particles gathered in one day from a single beach in Florida (courtesy of Maia McGuire, Florida Sea Grant).

negative) buoyancy. Inertial particles move differently from the surrounding fluid beyond their slow vertical motion due to buoyancy. Compared with past environmental studies of sediment transport ($\rho_p \gg \rho_a$) and bubbly flows ($\rho_p \ll \rho_a$), the relative density of the majority of plastics ($\rho_p \approx \rho_a$), as well as their range of sizes (microns to millimeters) and shapes, puts them in a largely unexplored parameter regime. Predicting the motion of single plastic particles in quiescent, turbulent, or wavy flow thus poses several new challenges.

Typically, two nondimensional parameters are used to classify whether particle motion is inertial or noninertial: the particle Reynolds number, which is a measure of the fluid inertia relative to viscosity around a particle, and the Stokes number, which is a measure of particle inertia relative to the background flow. The equations of motion can be simplified if the particle motion is associated with very small or very large particle Reynolds numbers and Stokes numbers. However, for the motion of plastics, the particle Reynolds number and/or Stokes number are not necessarily small nor large. Furthermore, while the definitions of these numbers typically assume spherical particles of uniform density, plastics can have complex shapes (e.g., see Fig. 1) and variable density. In the ocean environment, the shapes and density distribution are made more complex with the accumulation of biomass. Additionally, a plastic particle's relative density can vary when considering the influence of background density stratification of the ocean.

In what follows, we first define the particle Reynolds number and Stokes number. The remaining subsections focus on research progress and outstanding challenges in modeling inertial particle motion in the presence of waves and the settling of a single particle in (quiescent) fluid as it depends on its shape, density distribution, and background ambient density. These challenges are important for understanding horizontal and vertical transport and dispersion [6]. The settling speed of plastic is especially important for determining the vertical concentration and thereby the overall mass contribution of plastic in the turbulent upper-ocean boundary layer [17].

A. Particle Reynolds number

The particle Reynolds number is a measure of the relative importance of the effects of viscous drag and fluid inertia on the particle. For a non-neutrally buoyant particle, we can use a definition based on the particle's terminal rise (or settling) velocity in stationary ambient fluid, w_t, the diameter of the particle, d_p, and the kinematic viscosity of the fluid, ν:

$$\mathrm{Re}_p = w_t d_p/\nu. \tag{1}$$

The wide range of length scales and densities of plastic particles corresponds to wide-ranging particle Reynolds numbers from $\mathrm{Re}_p \ll 1$ to $\mathrm{Re}_p \gg 1$, with plastics of millimeter scales having intermediate $\mathrm{Re}_p \sim O(1) - O(10^2)$ [18,19]. For spherical particles with $\mathrm{Re}_p \ll 1$, w_t becomes equal to the Stokes settling or rise velocity, $w_S \equiv g' d_p^2/(18\nu)$, in which $g' = g(\rho_p - \rho_a)/\rho_a$ is the reduced gravity of the particle having density ρ_p in ambient fluid of density ρ_a. At moderate Reynolds numbers ($\mathrm{Re}_p \lesssim 800$), drag effects lead to a modified terminal velocity, a convenient empirical approximation for which is

$$w_t \simeq w_S/\mathcal{C}(\mathrm{Re}_p), \quad \text{with} \quad \mathcal{C}(\mathrm{Re}_p) \simeq 1 + 0.15\mathrm{Re}_p^{0.687}, \tag{2}$$

in which $\mathcal{C}$ (known as the Schiller–Naumann coefficient) denotes the increase in drag on a particle relative to that for Stokes settling [20]. Further corrections can be introduced for larger particle Reynolds numbers [21] and for nonspherical particles [22]. Many microplastics exist within the intermediate-Re_p regime where the drag is nonlinear. Moreover, nonspherical microplastics will have a drag coefficient that is a function of their orientation. These complexities pose challenges for theoretical work, and thus laboratory experiments are typically performed to study this regime.

In a nonstationary ambient fluid (whether due to waves or turbulence), the particle Reynolds number should be adapted by replacing the terminal speed in Eq. (1) with the magnitude of the relative velocity between the particle and ambient fluid, $|\mathbf{u}_p - \mathbf{u}|$. Unlike at terminal velocity, for which the buoyancy force and drag force acting on the particle are in equilibrium, in an unsteady fluid other forces must be taken into account [23], including a Basset history force that captures the lagging boundary layer development with changing relative velocity, added mass, and lift forces. While the equations governing the evolution of $\mathbf{u}_p$ can be quite complicated [23,24], these can be simplified depending upon the value of the Stokes number.

B. Stokes number

The Stokes number can be expressed as a ratio of timescales of particle and fluid motion: $\mathrm{St} \equiv \tau_p/\tau_f$. Here, τ_p is a measure of the time for a particle initially at rest in a moving fluid to accelerate to the ambient flow speed. Accounting for the added mass of a particle, a general expression for τ_p is given by (e.g., Refs. [24,25])

$$\tau_p = \frac{1}{\beta}\frac{d_p^2}{12\nu}\frac{1}{\mathcal{C}(\mathrm{Re}_p)}, \tag{3}$$

in which $\beta = (C_m + 1)/(C_m + \rho_p/\rho_a)$, with ρ_p and ρ_a the densities of the particle and the ambient fluid, respectively. C_m is the added mass coefficient, which is $\simeq 0.5$ for spherical particles. For dense particles ($\rho_p \gg \rho_a$), τ_p is the so-called relaxation time, resulting from acceleration due to viscous stress, namely, $\tau_p \simeq (\rho_p/\rho_a)d_p^2/(18\nu\mathcal{C})$; for light particles ($\rho_p \ll \rho_a$), the timescale is dominated by the influence of added mass on particle rise, namely, $\tau_p \simeq d_p^2/(36\nu\mathcal{C})$. The timescale τ_f represents the shortest fluid timescale of interest. In turbulent flow for particles smaller than the Kolmogorov scale, τ_f is given by the dissipation timescale, $(\nu/\epsilon)^{1/2}$, in which ϵ is the energy dissipation rate. For larger particles, τ_f is typically set by a relevant eddy turnover time provided this is larger than τ_p [24]. In nonturbulent wavy flow, the fluid timescale is taken to be the wave period [26].

Most theories have focused upon the large- and small-St regimes for which particle motion with respect to the ambient fluid can be estimated from simple diagnostic equations. For example, if $\mathrm{St} \ll 1$, the particle velocity accounting for background accelerations in the flow is given by the diagnostic equation [27],

$$\mathbf{u}_p = \mathbf{u} \pm w_t\hat{z} + \frac{w_t}{g}\frac{D\mathbf{u}}{Dt}, \tag{4}$$

in which the second term on the right-hand side is positive (negative) for buoyant (negatively buoyant) particles. This equation may be suitable for plastics in the turbulent ocean mixed layer that are slowly rising or settling, for which the Stokes number ranges between $0.001 \lesssim \mathrm{St} \lesssim 0.01$ [28].

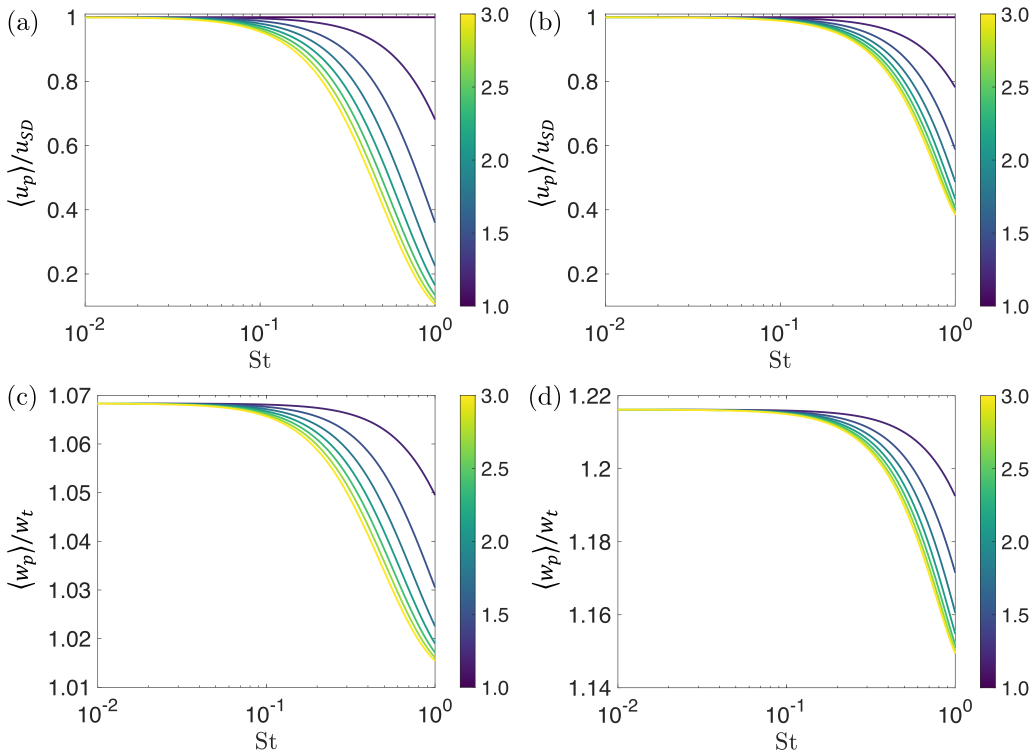

FIG. 2. Horizontal drift of negatively buoyant particles relative to that of passive tracers (St $\ll$ 1) for (a) shallow-water waves ($kh = 0.3$) and (b) deep-water waves ($kh = 3$), and vertical descent speed of particles relative to w_t for (c) shallow-water waves ($kh = 0.3$) and (d) deep-water waves ($kh = 3$), in which k is the wave number and h is the fluid depth. Color bar denotes particle-to-fluid density ρ_p/ρ_a. Adapted from Figs. 3(a), 3(c), 4(a), and 4(c) of Ref. [33].

However, the Stokes number associated with the motion of surface waves is significantly larger and can be $O(1)$ if the waves are breaking.

C. Inertial particles in wavy flow

While inertial particles in turbulence have long been of interest in industrial and environmental flows [29], only recently have the dynamics of inertial particles in wavy flow been examined, being inspired by plastics in the ocean. Predominantly, this has been through a combination of laboratory experiments and idealized simulations [30,31].

Surface gravity waves transport mass by way of the Stokes drift, u_{SD} (see also Sec. IV). Using the Maxey–Riley equation [23], numerical and analytical studies have shown how inertial particles experience an altered Stokes drift, where negatively buoyant particles are transported slower and positively buoyant particles are transported faster [32,33] [see Figs. 2(a) and 2(b)], although experiments have yet to confirm this observation. These same studies also predict that both settling and rising particles will experience an enhanced vertical drift, which is due to both an inertial effect and a kinematic effect. Laboratory experiments have observed enhanced settling of spherical particles under waves [34].

As also shown in Fig. 2, the horizontal and vertical velocities of settling (negatively buoyant) spherical particles (relative to the Stokes drift velocity and the quiescent settling velocity respectively) varies depending upon the Stokes number in the presence of waves, the relative particle-to-fluid density, and the amplitude and wave number of the wave relative to the fluid depth. Whereas tracer particles are transported by waves at the Stokes drift velocity (in the absence of Eulerian-mean currents), the drift is reduced for negatively buoyant particles, while the effective settling velocity is enhanced for all particles. The strongest enhancement in settling velocity is observed for heavy particles with small St in deep water waves. Future work should explore the combined effects of waves and (wind-driven) turbulence moving towards realistic conditions representative of the upper-ocean boundary layer.

All of the above work has considered particles that are fully submerged in the fluid, whereas the most visible form of plastic pollution is found floating on the surface of the ocean. Provided the particle is large enough, inertial effects can again play a role. Recently, and based on earlier work by Refs. [35–37], it has been shown theoretically that sufficiently large and therefore non-Lagrangian spherical floating objects can experience an increase in drift compared to the Stokes drift [38]. The increased drift arises because of two mechanisms. The first arises from an increase in magnitude of the vertical component, as the object starts to oscillate relative to the free surface. The second arises when an out-of-phase variable submergence is resolved in the horizontal direction by the slope of the free surface. As the object's size relative to the wavelength was found to be the main driver of the enhanced drift, significant drift enhancement in the ocean is unlikely for spherical floating plastic objects of realistic sizes [31,38], but could occur for different shapes.

Larger particles floating on the surface can also be influenced by windage: the direct influence of wind exerting drag on the surface of the particle exposed above the sea surface [39,40]. However, these dynamics are less relevant for microplastics.

D. Nonspherical particles and fibers

Microplastics have variable shapes, depending on their provenance. The most common categories of plastics are microfibers, pellets, fragments, and films which can be idealized as rods, spheres, and discs [41]. The theory for nonspherical particles is more complicated owing to complex time-evolving stresses acting on the surface of the particles by the fluid and a tensor representation of the drag and added mass coefficients.

Due to recent interest in plastics in the ocean, many studies have focused on the dynamics of nonspherical particles in surface gravity waves, finding that spheroidal the particles develop a preferential orientation, which can be described through an angular analog of the Stokes drift causing elongated particles to be oriented in the waveward direction [26,42]. This can reduce the settling rate of dense particles as well as reduce the rising rate of buoyant particles. In the laboratory, experiments of settling nonspherical particles in waves indeed showed reductions in settling velocity in a shape-dependent way. However the main mechanism was due to the way that the particles sampled the fluid velocity [34]. Additionally, heavy nonspherical particles were observed in laboratory experiments to disperse more before settling out when in the presence of waves; this increase in dispersion depended on both particle shape and volume [43]. The precise mechanisms controlling the mean transport and dispersion in this system have not yet been described, especially because these observations were of particles with intermediate Reynolds number which are harder to model.

A large share of microplastics produced by human activity are in the form of fibers, particularly from laundry and tire wear [44]. However, modeling long fibers, as well as thin plastic sheets, remains an outstanding theoretical challenge. Such plastics are flexible, and so it is necessary to take into account the elastic-plastic properties of the particles themselves. In a theoretical-experimental study of a flexible-fiber settling in a stationary viscous fluid, the fiber was found eventually to orient itself in U shape independent of its starting orientation [45]. Recent progress has been made in deriving semiempirical estimates for the terminal settling velocity of dense flexible fibers [46]. Motivated by industrial problems such as paper making, there have been a number of experimental studies examining the deformation of flexible fibers in quasi-isotropic turbulent flows [47–49]. It is now possible to simulate numerically the motion of neutrally buoyant rods in turbulence, capturing their tumbling and stretching as it depends on the rod length compared with the Kolmogorov scale of turbulence [50]. The motion, settling, deformation, and possible breakup of plastic fibers in turbulent and wavy fluids offers ample opportunity for future research.

E. Influence of nonuniform particle density

Marine snow and other organisms growing on plastics can cause the density of biofouled plastics to become nonuniform. Recent laboratory studies have shown that the trajectory of settling particles changes qualitatively when the center of mass of the particle is offset from the geometric centroid as a result of rotational torques introduced by the symmetry breaking. For the case of a settling sphere with its center of mass offset from the center of volume, the particles can undergo lateral oscillatory motion and spiraling motion, with large variation in amplitude and behavior depending upon the relative offset [51]. In experiments with cylindrical particles composed of two elements with different densities, the particles reorient and possibly oscillate during their descent depending upon their length [52].

Laboratory tests of settling particles with nonuniform density and intermediate Reynolds number show how both settling velocity, horizontal drift, and orientation behavior are all affected by nonuniformity [53]. Even characterizing complex particle behavior in still water poses a challenge due to the large parameter space: size, shape, and nonuniformity. We expect that particle behavior will become even harder to predict once unsteady flows due to waves or turbulence are introduced. Research progress is anticipated through laboratory experiments and, possibly, *in situ* observations.

F. Influence of nonuniform ambient fluid density

Another consideration in the modeling of settling particles is the influence of background stratification. In an experimental and theoretical study of a dense-sphere settling though a sharp interface in viscous fluid, Camassa *et al.* [54,55] showed that the particle slowed its descent and sometimes temporarily reversed direction as a consequence of upper-layer fluid being drawn downward in the wake of the particle into the more dense lower layer, thus reducing the collective density of the particle and its wake. Laboratory experiments with a large number of dense particles likewise have shown that their descent is delayed when passing through a relatively thick interface even when the density jump across the interface is a small fraction of the density difference between the particle and ambient fluid [56]. Although particles incident upon the interface are quasiuniform in concentration, they descend from the interface in the form of fine plumes, sometimes referred to as leaky ducts [56,57]. There have been some fundamental theoretical and experimental investigations into instabilities of particles at a stratified interface leading to diffusive fingering or convection [58–61]. However, the microscopic self-organizing processes that result in so-called leaky ducts is not well understood. Simulations suggest long-range particle-particle interactions may play a role if the diffusivity of the stratifying agent is sufficiently small [62]. For neutrally buoyant particles at a stratified interface, a distinct mechanism for particle self-organization into horizontal clusters results from diffusively driven flows originating at the sloping boundaries of the particles [63].

Although the influence of stratification upon microplastic settling in the ocean has not been investigated at the microscopic level, observations in Monterey Bay suggest that biofouled microplastics accumulate at highest concentrations in regions of strong stratification [64]. Because biofouled plastics can have complex, semiporous structures extending from their surface, these observations should inspire more fundamental studies examining, for example, porous spheres settling across a density interface [65] and in linear stratification [66].

III. CHALLENGES MODELING PARTICLE TRANSFORMATION

Most past studies of particles in fluids assume the particles are rigid or, if flexible like a fiber, that the volume and mass of the particle do not change. The study of plastics poses a new challenge to modelers. Plastics can transform by breaking up into smaller particles or by having organic or inorganic matter accumulate on them, thus changing both their size and density. Below we review what has been learned by way of observations, laboratory experiments and numerical simulations.

A. Particle breakup

While the majority of plastic in the ocean by mass is composed of large pieces of debris, by number most plastic in the ocean is microplastic [5]. We can categorize the sources of plastics into two broad classes. Primary plastics enter rivers and the ocean directly in their present form, as is the case for fibers from textiles and microbeads in consumer products. Secondary plastics have weathered and fragmented from larger plastic into smaller pieces. Both types of particles can continue to fragment and degrade in the environment, although the rates are still poorly constrained [67]. Observations of the distribution of particle sizes, with most being smaller than 0.3 mm [68], suggests fragmentation occurs after plastics are released into the ocean. However, the processes leading to breakup remain unclear, with fluid mechanics likely playing an important role.

Plastics become more fragile over time with exposure to ultraviolet radiation from the sun [69]. However, this process acts only upon buoyant plastics that are exposed to sunlight near the ocean surface. It is uncertain to what degree the breakup of plastics due to energetic fluid dynamical processes in the ocean are enhanced by photodegradation.

Much of the research on particle breakup has focused on the deformation of plastic fibers in isotropic turbulence through laboratory experiments [47,70] and numerical simulations [71]. For significant bending to occur, the length of the fiber must be larger than the persistence length, which depends on the the bending modulus of the plastic and the viscosity and energy dissipation rate of the turbulent flow. Bending was found to be largest if the persistence length was larger than the integral length scale of the turbulence. If the integral length scale was larger than the persistence length and the fiber length, turbulent motions predominantly acted to stretch the fiber. Although plastic (i.e., nonelastic) breaking of the fiber was not observed in these studies, their results suggest that the minimum size to which a fiber can be broken into by turbulence is set by the integral length scale of turbulence as well as the persistence length. Such scales cannot explain the millimeter size and smaller sizes of plastics found in abundance. Likewise, laboratory studies of rigid fibers [48,49] and flexible disks [72] show that bending, twisting, and stretching forces that would lead to breaking become less pronounced for smaller (<1 -mm scale) particles, as the changes in background turbulent velocity over their extent is too small.

Certainly, much more research should be done to examine particle breakup, specifically determining the role of turbulent fluid dynamic processes. Besides turbulent processes in the ocean, the breakup of some plastics may occur at the coast as waves crash on a beach. However, such processes have not been directly observed *in situ*, and are challenging to reproduce experimentally [73].

B. Biofouling and aggregation

The accumulation of microbes and other organic material on plastics is known as biofouling. This accumulation can occur rapidly for plastics in natural water bodies; over sufficiently long time (days, weeks, or months depending on the size and relative density of the plastic), biofouled buoyant plastics can become more dense and sink [74–76]. This sinking could be an important mechanism to explain part of the discrepancy between the mass of buoyant plastics put into the ocean and what is observed [77–80].

Recent experiments suggest that plastics can act as a nucleation site for the growth of marine snow, which can double the settling velocity, in part due to the effective increase in the particle size [81,82]. Biofilms, microbes, and the accumulation of marine snow form a semipermeable coating around an otherwise solid plastic particle. In some experimental studies, marine snow is grown artificially in a controlled laboratory environment and then extracted for examination of their settling properties in another tank [82,83]. The details of modeling the evolution, transport, and settling of marine aggregates remains a fundamental challenge [84]. The aggregates have an ill-defined shape,

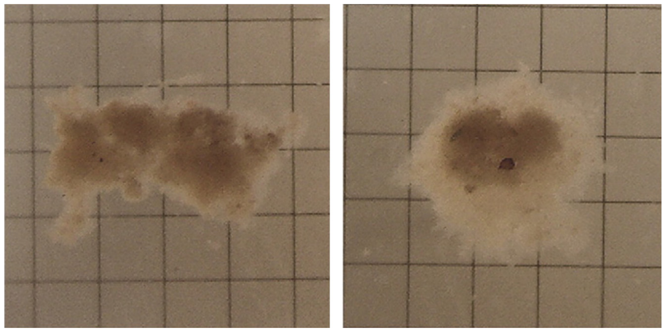

FIG. 3. Images of aggregates grown in a roller tank filled with sea water and a mixed culture of senescent diatoms. The background has a 1-mm scale. Adapted with permission from Fig. 1 of Ref. [83].

as illustrated by the photographs taken of samples grown in the laboratory, shown in Fig. 3. It is possible that more progress can be made by using 3D printers to create fractal shapes more representative of marine snow.

While most studies of plastic aggregation have focused on biological processes, there is some indication that clay suspended in muddy rivers can accumulate onto buoyant plastics rendering them sufficiently dense to settle [85]. Clay particles are micrometer-sized platelike particles that carry a dipolar electric charge. Even though the plastic particles may not carry an electrical charge, detergents in the water can adhere to the plastic and so act as an intermediary to attract clay to the surface of the plastic. Fluid mechanical processes, such as the flow velocity and the level of turbulence present, may have a role to play in this, which is entirely unexplored. Other challenges regarding plastic transport in rivers and estuaries are discussed in the next section.

IV. CHALLENGES MODELING ESTUARIES, COASTAL, AND SUBMESOSCALE OCEAN PROCESSES

When examining plastic transport at scales of tens of meters to tens of kilometers, particle-resolving simulations are not possible. Instead, numerical models of particle transport treat the particles as ideal tracerlike quantities [6] with no nonhomogeneity in their transport and dispersion modeled at scales below the mesoscale. As discussed below, there has been great progress recently in modeling submesoscale ocean processes that show surface convergence at fronts and in Langmuir circulations, where buoyant plastics can accumulate, creating strong nonhomogeneity. Progress has also been made in predicting the transport of (noninertial) particles as influenced by waves on a rotating Earth. Many challenges remain in modeling plastic transport in near-coastal and surf-zone regions including the washing-up of plastics on beaches. The transport in exactly these coastal regions is increasingly recognized as very important to close the global plastic budget; coastal regions are also often very important from an ecological and an economic perspective. Likewise, we have identified several challenges in modeling plastic transport in rivers and estuaries, which in turn are a significant source of plastic waste entering the ocean.

A. Accumulation at submesoscales

The energy-containing scales in the ocean are predominantly associated with mesoscale eddies and currents, i.e., motions on the order of 100 km in horizontal extent. For this reason, and for mathematical simplicity, theories have largely focused upon such scales of motion. Such flows are said to be geostrophic, being dominated by the Earth's Coriolis force. This regime is characterized by the Rossby number, $\mathrm{Ro} = \mathrm{U}/(\mathrm{fL})$, being much smaller than 1. Here U and L, respectively, are the characteristic horizontal velocity and length scales of the flows, and f is the Coriolis parameter,

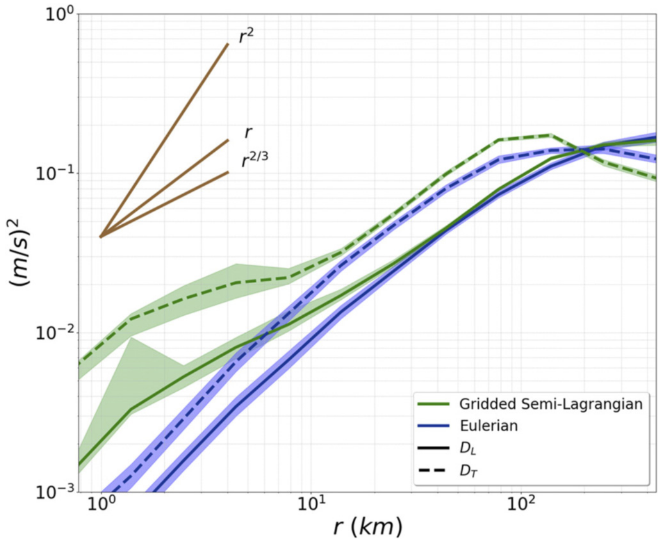

FIG. 4. From simulations of flows in the Gulf of Mexico, second-order structure functions for the longitudinal (D_L: solid) and transverse (D_T: dashed) velocity associated with two separated points in the Eulerian flow field (blue) and with Lagrangian drifters (green). Slopes corresponding to power laws of r^2, r, and $r^{2/3}$ are shown to the upper left. Adapted from Fig. 2 of Ref. [100], ©American Meteorological Society. Used with permission.

a measure of the local angular speed of rotation about the vertical. Mesoscale processes describe, for example, eddies that develop in western boundary currents such as the Gulf Stream and Kuroshio current.

A consequence of geostrophy is that particle transport by mesoscale processes is effectively two dimensional and nondivergent. However, at the submesoscales (on the order of 10 km in horizontal extent), for which Ro ~ 1, the flows can be horizontally convergent or divergent [86–89]. This is particularly important for the study of plastic transport since floating plastics can concentrate at convergence sites affecting global oceanic plastic mass estimates inferred from surface measurements and perhaps leading to efficient opportunities for collection.

Significant progress has been made recently in the study of submesoscale processes in part due to more powerful computational resources and several observational campaigns that focused upon submesoscale dynamics, for example, the MISO-BoB program in the Bay of Bengal [90,91], the GOMRI program in the Gulf of Mexico [92,93], the CALYPSO program in the Mediterranean [94], and the S-MODE program off the coast of California [95]. Of particular interest has been the surface convergence of particles due to the formation of fronts between warm and cold water near western boundary currents [87,96] and due to Langmuir circulations [97], which form under the action of wind and waves that drive counter-rotating streamwise vortices. These form windrows at the surface where the horizontal flow converges along lines between pairs of vortices.

While submesoscale eddies and currents have scales on the order of tens of kilometers, density fronts can be just a few hundred meters wide, a length set by a balance of rotation, fluid inertia, and turbulence [98,99]. Floating Lagrangian drifters are attracted toward the subduction zones associated with these fronts, altering the velocity statistics associated with pairs of drifters at submesoscales. Whereas the corresponding second-order Eulerian velocity statistics exhibit a linear change with separation distance r for both submesoscales and mesoscales, the Lagrangian statistics have a $r^{2/3}$ dependence for scales below $\sim$10 km [100], as shown in Fig. 4. This model prediction has since been found observationally through simultaneous Eulerian and Lagrangian surface measurements [101]. In a separate observational study of floating bamboo plates scattered

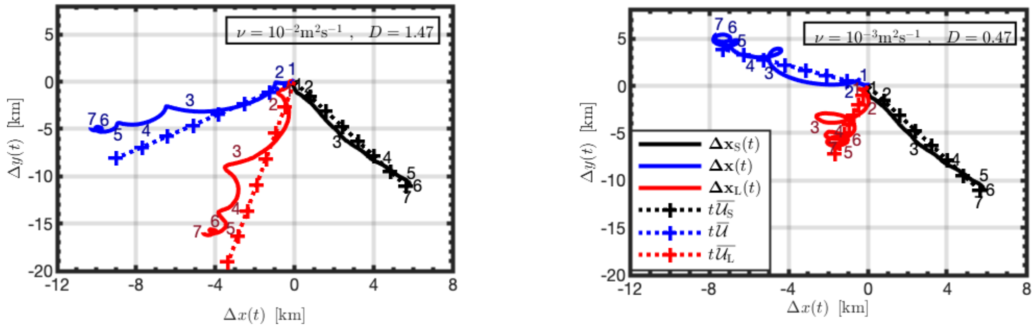

FIG. 5. Predicted displacements associated with the Stokes drift (black), Eulerian-mean Ekman–Stokes velocity (blue), and the Lagrangian-mean velocity (red), using wave and wind data measured by a buoy near San Nicolas Island from 14/05/00 at 15:41 UTC to 22/05/2000 at 09:41 UTC and using an estimate of turbulent diffusivity of (a) $\nu = 10^{-2}\,\mathrm{m}^2/\mathrm{s}$ and (b) $10^{-3}\,\mathrm{m}^2/\mathrm{s}$. The corresponding ratios of the Ekman depth, $\delta_E = (2\nu/f)^{1/2}$, and Stokes depth, $\delta_S = 1/(2k)$, are given by $D \equiv \delta_E/\delta_S$. The dotted lines are the steady responses averaged over the seven days of the study. Adapted from Figs. 4(b) and 4(d) of Ref. [105].

over Langmuir cells, Chang *et al.* [102] found the Lagrangian statistics to vary as $r^{1/3}$ on the scale of tens of meters. These statistics demonstrate that clustering of floating plastic particles can become increasingly enhanced at smaller scales by nongeostrophic motions that allow for horizontal convergence associated with vertical subduction.

B. Transport by surface waves

During the periodic motion of a surface gravity wave, a fluid particle experiences a net drift in the direction of wave propagation, known as Stokes drift, which can change predicted plastic pollution transport when added to global (Eulerian) currents not resulting from waves, shifting convergence regions [103] and pushing microplastics closer to the coast [12,104]. In addition to the effects of particle inertia and shape discussed in Sec. II, there are two other important reasons why the Stokes drift alone should not be the velocity with which plastics on the surface of the ocean are transported.

First, it cannot be emphasized enough that particles are transported with the wave-induced Lagrangian-mean velocity, which is equal to the sum of the Stokes drift and the wave-induced Eulerian-mean velocity. On the rotating Earth and on long enough timescales, the Coriolis force in combination with the Stokes drift drive a Eulerian-mean current in the turbulent upper-ocean boundary layer, known as the Ekman–Stokes flow. This Eulerian-mean current is modeled by the Stokes terms (i.e., the Stokes–Coriolis term and the Stokes vortex force) in the Craik–Leibovich equations [106,107] and needs to be added to the Stokes drift to predict the wave-induced Lagrangian-mean flow with which particles are transported [105,108], or wave and ocean circulation models need to be properly coupled taking account of the Stokes terms in the Craik–Leibovich equations (e.g., Ref. [109]). For realistic estimates of the turbulent diffusivity by a simple constant-viscosity turbulence model, the Eulerian-mean flow resulting from Ekman transport can differ significantly in magnitude and direction from the Stokes drift, resulting in a Lagrangian transport of particles that lies between the displacement predicted by each, as shown, for example, in Fig. 5 (for noninertial particles, $\mathrm{Re}_p \ll 1$). On a global scale, this Ekman–Stokes flow has significant consequences for floating marine litter accumulation patterns [110] and reverses some effects introduced by including Stokes drift alone (cf. Refs. [12,103,104]), whereas including Stokes drift alone overestimates wave-driven transport. Lagrangian structures are also strongly affected by the Stokes terms in the Craik–Leibovich equations [111].

Second, breaking waves are known to transport particles much faster than nonbreaking waves, giving rise to additional transport in the direction of the Stokes drift, with the enhancement as large as 40% in some cases [112,113].

C. Surf-zone processes

One of the most pressing societal concerns resulting from plastic pollution is the accumulation in coastal zones and the washup of plastics on the coast, a process known as beaching. Studies of near-coastal processes, particularly those in the surf zone, have typically focused on coastal engineering applications such as sediment transport [114] or marine biology, focusing on phytoplankton and zooplankton transport [115]. In recent years, increasing attention has been paid to the inner-shelf region connecting the open ocean to the surf zone from a physical oceanography perspective, e.g., through the ONR Innershelf DRI [116]. But many questions remain regarding the connection between the open ocean and coastal regions, and thus the exchange of plastics between them.

Transport processes in the nearshore region (including the surf zone, inner shelf, and part of the midshelf) play a key role in both the beaching of buoyant plastics and their removal from the coast. A rich array of transport mechanisms exist in this region, covered in detail by Ref. [117] and summarized here. Cross-shore exchange of materials including plankton, particles, and pollutants can be driven by processes such as winds, surface waves, rip currents, internal waves, and diurnal heating and cooling. The relative importance of each mechanism can vary in space and time depending on surface forcing, bathymetry, stratification, and turbulent boundary layers in the water column, and surface-wave conditions. Furthermore, transport in this region also depends on the material being transported (including the relative buoyancy of the particles, as discussed above). As highlighted in Ref. [117], there are several areas of future work in modeling particle transport in the nearshore region that are of particular importance to the problem of plastic transport, including the role of submesoscale instabilities in coastal eddies and fronts, interactions between different transport mechanisms, and the representation of the beaching process in regional models (discussed more below). In addition, particle inertia may play an important role in predicting plastic transport; understanding how these additional physics interact with nearshore and surf-zone transport processes is an important avenue of future work. Overall, understanding how marine plastics respond in these complex environments is an important step in understanding their ultimate destination and closing the oceanic plastics budget.

D. Rivers and estuaries

As for the surf zone, the fluid mechanical processes in rivers and estuaries are important, as these are where most plastics enter the ocean through (municipal) waste. Most studies in these regions involve observations with a focus on sedimentology, marine biology, or other environmental aspects [118,119]. Many open questions remain in which fluid mechanics plays a role, for example, to study the transport and possible transformation of plastics when they encounter strong turbulence associated with the tidal zone, and their possible interaction with suspended clay when they come into contact with sea water.

Generally, coastal and estuarine processes can vary significantly depending upon several factors including topography, winds, tides and local currents [120]. Likewise, the source of plastics (e.g., outlets from municipal waste and storm pipes) can be situated at different locations along the coast or upstream in rivers. High-resolution regional models have seen great utility in detailed studies of physical and biogeochemical processes in coastal regions. For example, the SalishSeaCast model has been used to model mixing and plankton dynamics in the Strait of Georgia and Puget Sound [121,122]. Similarly detailed regional models quantifying sources and sinks of plastics in specific coastal regions, guided by parametrizations developed from fundamental fluid dynamics studies, would provide similar key insights into the transport of microplastics from land-based sources into coastal waters and beyond.

V. CHALLENGES MODELING GLOBAL TRANSPORT

Global transport by geostrophically balanced mesoscale eddies and gyre circulations has been actively studied by way of observations, theory, and numerical simulations. However, modeling the transport and settling of plastics in the ocean remains one of the greatest challenges. As with estuarine, coastal, and submesoscale models, particles cannot be resolved by ocean general circulation models and so their transport needs to be parameterized. As discussed below, there has been success in predicting the accumulation of floating plastic waste in the subtropical gyres. More challenging is predicting the vertical and along-coast transport of plastics due to ill-constrained parametrization schemes. Although a combination of observations and statistical modeling is now giving insight into near-coastal transport, challenges remain to understand the underlying physical processes.

A. Surface convergence in ocean gyres

There have been recent advances in predicting the fate of plastics in the global ocean using a combination of numerical simulations and statistics. One of the first major advances provided a prediction for the accumulation of floating plastics in the subtropical gyres of oceans [123]. These gyres have an anticyclonic circulation associated with them, and so correspond to regions of convergence due to Ekman transport. Later models showed the importance of including inertial (on the timescale of the Earth's rotation) effects on relatively large floating plastics [40,124].

B. Parameterizing vertical transport

Koelmans *et al.* [125] recently attempted to predict the timescale for buoyant plastics to settle below the ocean surface layer. Their model neglected fluid dynamical processes, forming a prediction based on two ordinary differential equations for the time change in mass of macroplastics and plastics in the ocean surface layer accounting for estimated inputs, fragmentation rates, and removal due to sedimentation resulting from biofouling. The model predicted that the majority of buoyant plastics entering the ocean would settle below the ocean surface layer within three years. However, the parameters used to predict fragmentation and sedimentation rates depended on ill-constrained empirical estimates. Attempts to predict vertical transport in this manner are useful for giving estimates for settling rates and for pointing to areas of fluid dynamical research that would be most beneficial to improve vertical transport predictions. The greatest sensitivity was found for the estimate of settling rate in comparison with the fragmentation rate. This suggests that a research priority should be to develop a better understanding of how biofouling changes the density and settling rate of plastics.

C. Near-coastal transport

In a recent study, it was shown that once plastics are released near the coast, approximately half are deposited back on shore (beaching) on a timescale of a month, with approximately 40% sinking over the course of about 80 days, and with about 10% remaining afloat [13]. Thus, except around islands and near western boundary currents (e.g., the Gulf Stream and Kuroshio), numerical models suggest that most plastics released into the ocean from estuaries drift less than 100 km from release [15], as shown in Fig. 6. In the model by Onink *et al.* [15], it was necessary to parametrize the effect of beaching and resuspension by exponential probability distributions with ill-constrained e-folding times for both processes. A better understanding of plastic beaching is needed to improve these models. Beaching of plastic particles is not trivial to model, as demonstrated by observations of plastic pellets (nurdles) that were spilled off the coast of Sri Lanka due to the shipwreck of the X-Press Pearl in May 2021. The shipwreck had also caught on fire, causing many of the pellets to burn, melt, and agglomerate together. Differential transport was inferred between the burned pellets, which washed up on shore near the shipwreck, and pristine pellets, which washed up further along the coast [126]. This case study demonstrated how the physical properties of the plastic can affect their transport in the ocean and their beaching.

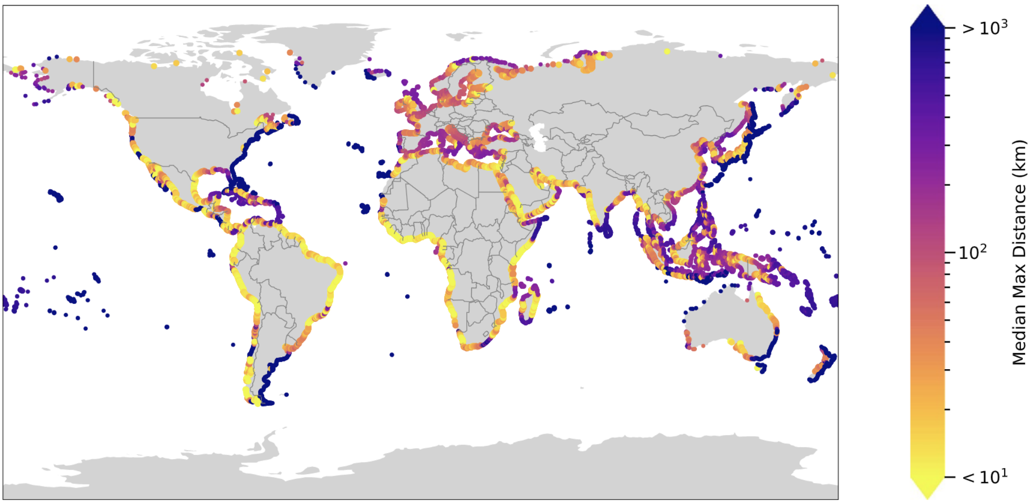

FIG. 6. The median maximum distance from shore reached by particles released nearshore as predicted by simulations of Onink *et al.* [15] [from their Fig. 2(c)].

VI. SUMMARY AND FUTURE DIRECTIONS

The problem of predicting the fate of plastic pollution in the ocean has inspired new research into previously underexplored fluid dynamics phenomena, particularly regarding Lagrangian transport of inertial buoyant and negatively buoyant nonspherical particles. The ultimate aim of these studies is to guide the development of regional and global models for the transport, settling, and deposition of plastic pollution. While crude parametrizations have been developed for small-scale processes not captured by coarse-scale global simulations, there is great room for improvement. Data is also lacking: estimates exist for the mass and types of produced plastic, but the size, shape, and density of plastics released at the source is unclear, with most observations reporting simply on number of plastic particles or their net mass. It is not in the purview of fluid mechanics community to perform such observations. However, data-driven studies have huge potential in identifying the most important fluid mechanical processes in a way that scaling arguments and perturbation methods traditionally have in the field of fluid mechanics. To aid these, the fluid mechanics community should provide better guidance about what information is needed to guide and prioritize its work.

As well as reviewing recent research progress, we have identified numerous outstanding fluid mechanics problems that could potentially be solved with present computational and experimental resources to develop better informed parametrizations to be included in global models. In particular, there is ample opportunity to explore the following: the behavior of particles that are not rigid, oddly shaped, not uniformly dense, and change over time due to biofouling in the turbulent, wave-driven upper-ocean boundary layer; the nonuniform accumulation of floating particles at submesoscales (and smaller), which are presently also at the forefront of climate change research; and the complex coastal environment with its multitude of competing fluid mechanics processes and its large potential contribution to closing the global oceanic plastic budget.

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