Predicting Pathways for Microplastic Transport in the Ocean

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1 Overview of the Field

Hundreds of millions of tons of plastic waste are produced each year. A large portion of this waste is improperly discarded and ultimately ends up in the environment; e.g. entering rivers through municipal waste disposal or entering the ocean directly through dumping [21]. It is estimated that about 20M tons of plastics enter into the ocean each year [4]. Despite the fact that most plastics produced are buoyant, 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 300K tons) of the discarded plastics remain near the surface of the open ocean [34, 33]. This discrepancy has raised the question: where are the missing plastics?

The scientific community aiming to address this question has dominantly focused upon observations performed by oceanographers, marine biologists, sedimentary geologists and environmental scientists. However, the ultimate answer to this question must come through predictive models. It is for this reason that our workshop aimed to assemble researchers from across the spectrum of applied mathematicians, fluid dynamicists, physical oceanographers, engineers, and others to identify outstanding gaps in our understanding of the dynamics of plastic transport in the ocean.

The problem of predicting the ultimate fate of plastic pollution is vast. The density, size and shape of plastics vary greatly, they can be broken down into smaller pieces through stresses induced by turbulent flows, their density can change in time due to the accumulation of organic and inorganic deposits. As the particles evolve they are influenced by fluid dynamics processes over wide-ranging scales from ocean 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). Our workshop participants had wide-ranging expertise in mathematical theory, numerical modelling and laboratory experiments, exploring dynamics from the microscopic to global scale. Ideas were shared through talks and lively themed discussions at our workshop, in which recent scientific advances where presented and pressing outstanding issues and possible solutions were brainstormed.

2 Recent Developments and Open Problems

Our workshop broke down the problem of microplastic transport by identifying four challenges in modelling microplastic transport. These were addressed through invited talks and by way of discussion groups involving all participants. Recent developments and open problems in each of these four challenge areas are discussed below.

2.1 Challenges modelling non-inertial and inertial particles

Non-inertial particles are so small that they are carried with the surrounding fluid like a passive tracer. In contrast, relatively large microplastics are inertial, meaning that the particles move differently from the surrounding fluid. Several factors influence the behaviour of inertial particles in fluid flow including their buoyancy, size, shape and the nature of the background flow, whether it is stationary, oscillating (due to waves), or turbulent.

A measure of the importance of particle buoyancy and size relative to the fluid viscosity is the particle Reynolds number, $\mathrm{Re}_p = w_s d_p/\nu$, in which w_s is the settling/rising velocity in stationary fluid (which depends on buoyancy), d_p is a measure of the particle size, and ν is the kinematic viscosity. A measure of the importance of particle inertia in turbulent flow is the Stokes number, $\mathrm{St} \equiv \tau_p/\tau_\eta$, in which $\tau_p \simeq w_s/d_p$ is the particle relaxation time and $\tau_\eta = (\nu/\epsilon)^{1/2}$ is the dissipation time scale in which ϵ is the energy dissipation rate. If $\mathrm{Re}_p \ll 1$ and $\mathrm{St} \ll 1$, the particle is non-inertial and experiences Stokes drag.

With this as background, our workshop identified the following as some of the most significant open problems in modelling the motion of a plastic particle in fluid flow:

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 microplastics on millimeter scales having $\mathrm{Re}_p \sim 1$. To simplify the equations of motion, existing theories have focused on the large and small Re_p regimes; few studies of weakly inertial particles have intermediate Re_p.

2. Microplastics in the turbulent ocean mixed layer have Stokes numbers in the range $\mathrm{St} \sim 0.001 - 0.01$; below surface waves, the range is $\mathrm{St} \sim 0.1 - 10$ [11]. As with the particle Reynolds number, most theories have focused upon the large and small St regimes. Inspired by the problem of microplastic transport, only recently have the dynamics of particles in wavy flow with $\mathrm{St} \sim 1$ been examined. Predominantly this has been through laboratory experiments with room for much more to be explored.

3. For mathematical convenience, most theories of particles in fluids assume they are spherical. However, the shapes of particles vary greatly from polygonal plates and shards to fibers. Further complicating matters, is that sufficiently long fibers and thin plastic sheets are flexible. And so it is necessary to take into account the elastic-plastic properties of the particles themselves.

4. While there have been great advances in the past decade developing numerical simulations that resolve the motion of individual and a small collection of particles in fluid flow, at present, most models are limited to assuming the particles are spherical. Although still numerically challenging, much could be learned about the evolution of a (possibly biofouled) particle in steady descent and in turbulence by devising methods to examine more complex particle shapes. These models could also explore in more detail the influence of background stratification on settling and particle aggregation.

2.2 Challenges modelling particle transformation

Plastics can transform by breaking up into smaller particles. It is also possible for organic or inorganic matter to accumulate on plastics, thus changing both their size and density. Our workshop identified the following open questions:

1. There have been some recent studies of particle break-up in turbulence, focusing upon fibers that are long compared to the dissipative scales of turbulence. It remains unclear how particles continue to break up when they are smaller than the dissipative scales (on the order of 1 millimeter).

2. The plasticity of a particle determines threshold stresses that lead to fracturing and break-up of particles. Observations show that plastics exposed to sunlight become more fragile, though this is expected to occur over relatively long times and only for buoyant plastics near the surface. The influence upon particle plasticity of sunlight is not well understood, with a pressing need to quantify the time-scale for particle transformation in this way.

3. The accumulation of microbes and other organic material on plastics is known as biofouling. All plastics in the ocean become biofouled on the scale of days. 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. But at depth they can remineralize and become buoyant again. These dynamics have been observed in the field, but the microscopic processes are poorly understood, although laboratory experiments are beginning to provide insights.

4. A biofouled plastic has an ill-defined shape, with microbes and the accumulation of marine snow forming a semi-permeable coating around the otherwise solid plastic particle. The influence of this coating upon particle transport and settling remains poorly understood, as does the influence upon the degradation of the coating by turbulence and flow around an inertial particle.

2.3 Challenges modelling estuaries, coastal and submesoscale ocean processes

The energy containing scales in the ocean are predominately associated with mesoscale eddies and currents. For this reason, and for mathematical simplicity, theories have largely focused upon such motion (on the order of $100\,\mathrm{km}$ horizontal extent) for which the motion is geostrophic, being dominated by the Earth's Coriolis force. This regime is characterized by the Rossby number, $\mathrm{Ro} = UL/f$, being much smaller than 1. Here U and L, respectively, are the characteristic velocity and horizontal length scales of the flows, and f is the Coriolis parameter, 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. The submesoscale has become increasingly studied in the past decade, facilitated by more powerful computational resources that permit high-resolution simulations of small-scale structures in large-scale flows. As discussed below, coastal and estuarine processes have not been so well studied in the context of particle transport.

Our workshop identified the following open questions

1. Great progress has been made in understanding surface convergence due to submesoscale processes, such as the formation of fronts between warm and cold water near western boundary currents. Simulations can also resolve convergence due to Langmuir circulations which form under the action of wind and waves that drive counter-rotating streamwise vortices forming windrows at the surface. However, global-scale ocean processes do not have the resolution to capture these processes. And so better parameterizations should be developed to predict the formation of fronts and windrows from coarse resolution models.

2. There has been significant progress in understanding Lagrangian transport by surface waves, as they are influenced by wind stress, Coriolis forces and the Stokes drift [31, 20]. Most of this work has focused upon the transport of passive particles ($\mathrm{Re}_p \ll 1$). Predictions of transport could be improved by drawing on results from experiments examining inertial particles of different shapes and density below waves.

3. One of the most pressing societal concerns is the wash-up of plastics on the coast, a process known as beaching. A relatively small number of physical oceanographers study near-coastal processes, particularly those in the surf-zone; this region is predominantly studied by civil and coastal engineers, whose focus has traditionally been more on sediment transport than buoyant particle transport. More work could be done examining the process of beaching of buoyant microplastics, as well as their removal from the coast by riptides.

4. As with the surf-zone, oceanographers have not focused much upon processes in rivers and estuaries, although these are the sites through which most plastics enter the ocean through municipal waste. More could be done, in particular, 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.

5. Coastal and estuarine processes can vary significantly depending upon several factors including topography, winds, tides and local currents. Likewise the source of microplastics (e.g. outlets from municipal waste and storm pipes) can be situated at different locations along the coast or upstream in rivers. This points to the need to develop regional models quantifying sources and sinks of microplastics.

2.4 Challenges modelling global transport

The ultimate goal is to predict globally where plastics ultimately deposit after being released into the ocean. However, numerical simulations of the global ocean are too coarsely resolved to capture the formation of fronts and other surface convergent phenomena, and they certainly cannot capture the rise and fall of the plastics themselves. Instead these processes must be parameterized being informed by theory, idealized high resolution simulations and semi-empirical models derived from the results of laboratory experiments [16, 22, 14, 27].

Our workshop identified the following open questions

1. While crude parameterizations have been developed for small-scale processes not captured by coarse-scale global simulations, there is great room for improvement, as described above. In some regions, the influence upon settling particles of density stratification (accounting for the change of temperature and salinity with depth) should be considered.

2. Limited observations remain a large obstacle to predicting particle transport. While estimates exist for the mass and types of produced plastic, 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. While it is not in the purview of our modelling community to perform such observations, we could provide better guidance about what information is needed to guide and prioritize our work.

3 Presentation Highlights

Being an entirely online workshop with participants primarily in Europe and North America, we chose to have only 12 talks, leaving room for discussion among all participants in Gathertown following the talks. Between Monday and Thursday, the invited opening talk gave an overview of research in each of the themed challenge areas described above. These were followed by two more focused research talks. A summary of the talks and group discussions was presented by the organizers on the Friday, followed by a general discussion of future directions.

Synopses of the invited summary talks are given below.

1. Michelle DiBenedetto: *Is shape important to plastic transport?*

   After providing an overview of the primary problem with predicting microplastic transport, namely where is the missing plastic, Dr DiBenedetto discussed progress in predicting the influence of shape upon particle settling below waves. Laboratory experiments showed that long elliptical particles became oriented in the waveward direction which can reduce the settling/rise rate of negatively/positively buoyant particles [18, 17].

   Such measurements are important for the interpretation of observations. Typically plastics are extracted by droguing nets near the ocean surface. Using the model by Kukulka [23], the distribution below the surface is assumed to be exponential. However, this model does not take into account the differential rise and fall of different-sized particles. Indeed, more careful observations show that the distribution changes significantly between $0.5\,\mathrm{m}$ from the surface and below. All this suggests that surface measurements underestimate the amount of plastic near the ocean surface by a factor of 3-13 [7]

   She also presented a case study of the X-Press Pearl nurdle spill off the coast of Sri Lanka in May 2021. Nurdles, or pre-production plastic pellets, spilled out a wrecked container ship onto the beaches of Sri Lanka. The shipwreck had also caught on fire, causing many of the nurdles to burn, melt, and agglomerate together. Differential transport was inferred between the pristine nurdles and the burned nurdles from observations of where they washed up on the beach [15]. This case study demonstrated how the physical properties of the plastic can affect their transport in the ocean.

2. Margaret Byron: *The influence of shape, size and density distribution on microplastic transport in environmental flows.*

Dr Byron began by reviewing mechanisms for particle transformation though biofouling [25, 29, 24]. and fragmentation. 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 [8, 30]. Dr Byron presented a new consideration regarding the settling of biofouled plastic particles. It is usually assumed that the particles have uniform density. However, the very fact that marine snow and other organisms grow on the plastics means that the density of the biofouled plastics is non-uniform. Through laboratory experiments using particles composed of two elements with different densities, she showed that the particles reorient and possibly oscillate during their descent depending upon their length [2].

Regarding particle break-up into smaller pieces, observations of the distribution of particle sizes, with most being smaller than $0.3\,\mathrm{mm}$ [1], suggests fragmentation occurs after plastics are released into the ocean. However, the processes leading to break-up remain unclear. Some plastics become more fragile over time with exposure to heat and ultraviolet radiation from the sun [36]. But this is a relatively long-time process. Turbulent processes, particularly those associated with breaking waves can lead to particle break-up. However, recent research has shown the bending, twisting and stretching forces leading to breaking become less pronounced for smaller particles over which there are smaller velocity changes over their extent [6, 19, 5, 35, 26]

3. Baylor Fox-Kemper: *Dispersion and dissipation: Turbulence statistics for the mesoscale to finescale with plastics on the move.*

   Dr Fox-Kemper demonstrated how submesoscale processes can result in convergence zones at the surface through Langmuir circulations and the formation of density fronts. These various mechanisms were recently discussed in a review paper [13].

   Through the observations of floating bamboo plates scattered over Langmuir cells, Chang et al [12] compiled the statistics of floating particles collecting at the convergence locations. Such surface convergence also occurs at density fronts between warm-cold and/or fresh-salty water. While eddies and currents may have scales on the order of tens of kilometers, the fronts can be just a few hundred meters wide, a length set by a balance of rotation, fluid inertia and turbulence [3, 9].

   What is clear in all these studies is to recognize that the dynamics at and below submesoscales differs qualitatively from mesoscales. The latter processes are dominated by currents and eddies that transport particles but do not lead to surface convergences observed at smaller scale [32, 10]. A major goal is to improve predictions of these convergence sites where floating plastics gather, and so can more efficiently be collected.

   Through a combination of theory and numerical simulations, the clustering statistics as a function of separation distance, r, were found to vary as $r^{1/3}$ about Langmuir cells, $r^{2/3}$ for submesoscale fronts and r^1 at the mesoscale [28]. The signal for convergence does not show up in an Eulerian frame, but in a Lagrangian frame, indicating the importance of the Stokes drift and the need to track fluid parcels in numerical simulations.

4. Erik van Sebille: *Whose plastic is that? Using Bayesian inference to attribute microplastic sources and sinks.*

   Dr van Sebille presented recent advances in predicting the fate of plastics in the global ocean using a combination of numerical simulations and statistics. Although the models are still in their early stages of development, they are already providing important insights, suggesting that once plastics are released near the coast, approximately half are deposited back on shore (beaching) on a time-scale of a month, with approximately 40% sinking over the course of about 80 days, and with about 10% remaining afloat [22]. Thus, except around islands and near western boundary currents (e.g. the Gulf Stream and Kuroshio), most plastics released into the ocean from estuaries drift less than 100km from release.

4 Scientific Progress Made

As intended, the significant progress was made through the cross-fertilization of ideas stemming from different disciplines. Standing out amongst the progress made was the strong emphasis on assessing plastic transport using Lagrangian transport models, and using Bayesian analysis to assess sources and sinks of microplastics.

Perhaps the greatest progress was made in identifying the numerous outstanding problems, and identifying the "low hanging fruit", being those problems that could potentially be solved with present computational and experimental resources so as develop informed parameterizations that could be used in coarse resolution global models.

One example of potential immediate benefits of the workshop to Canadians is the discussions spurred by Susan Allen, U. British Columbia, who is part of a team trying to improve regional modelling of the Salish Sea with their simulation "SalishSeaCast". Dr Allen raised specific points about what processes in SalishSeaCast were well-modelled and what processes were poorly constrained or inadequately modelled due to lack of observations or a poor understanding of the physical and biological processes involved. This spurred several focused discussions aiming to improve deficiencies in the regional model, resulting in the development of new collaborations.

5 Outcome of the Meeting

As evident from feedback following the meeting, participants expressed great excitement at the breadth and depth of topics covered both in talks and during Gathertown discussions.

The immediate benefits of the workshop include the wide-ranging new collaborations that have been created and past collaborations that have been reinvigorated by topics raised. New links have been forged between numerical modellers who have been developing different simulation methods, but see the potential for advancement through technology exchange. New interdisciplinary collaborative partnerships were formed between researchers focusing on fundamental fluid dynamics and applied mathematics on one hand, and researchers interested in biological and environmental applications on the other.

Finally, it is the intention of the co-organizers to prepare a review paper covering the content of lectures and discussions that took place during the workshop. This will be submitted to Physical Review Fluids, with due acknowledgement to the Banff International Research Station. The paper will thus reach out to the wider international community, broadening the base of collaborative activities already established by the workshop.

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