Targeting Marine Plastic Pollution With Numerical Data Modeling:

Predicting Plastic Transport in Massachusetts Bay Through Flow Map Composition

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Research Plan

Environmental Engineering

A. Rationale

a. Motivation

The ubiquity of plastics in today's world is evidenced by the abundance of plastic litter in the environment, causing serious and worsening pollution. Plastics were first introduced in the early twentieth century, but the presence of plastic particles in the ocean was only first reported by scientists in the 1970's, when global production was less than 50 million metric tons. Since 1950, global plastic production has been increasing exponentially: 311 million metric tons were produced in 2014 and a projected 850 million metric tons will be produced annually by 2050 (Lebreton et al. 2012; Law 2017). This rapid growth in plastic use owes itself, in large part, to the immense popularity of plastic components and intense consumption of disposable plastic packaging in a wide variety of industries today. Of the annual global plastic production mass, more than one-third of that amount is used to produce disposable plastic packaging, which is discarded within one year of production (Lebreton et al. 2012). About 85% of total plastics demand consists of seven commodity thermoplastics, used in almost all market sectors (Law 2017). Unfortunately, while the use of plastics has become more prevalent, it is clear that plastic-recycling infrastructure and technology have not. In Europe, only 30% of postconsumer plastics were recycled in 2014; in the United States, this number drops to 8.8% and is likely even lower for many developing countries (Law 2017). This insufficient in recycling efforts leads to serious environmental consequences, as much of the plastic is often discarded and accumulates in the oceans. Currently, an estimated 60-80% of all marine debris is plastic, and plastic is more abundant than plankton by a ratio of over 6:1 (Lebreton et al. 2012).

Plastics are a class of synthetic, hydrocarbon-based polymers typically derived from fossil fuels. During production, plastics are enhanced with additives to improve their performance and appearance, resulting in their desirable properties such as abundant forms, strength, durability, light weight, and electrical insulation. These properties not only increase the versatility and, thus, the popularity of plastics in the modern world, but also contribute to their persistence in the environment. Today, plastics are extremely resistant to biodegradation and are easily transportable by wind and water, leading to their widespread marine distribution (Law 2017).

Most marine plastics originate from landfills, litter, and discarded fishing and aquaculture gear and other plastic materials from boats. Only a small minority of plastic wastes on land are recycled or incinerated, with most discarded into landfills or littered into the environment (Lebreton et al. 2018). As a result, enormous volumes of plastic waste are kept intact in the environment, and a large portion of this eventually enters the oceans through runoff, local bodies of water emptying in oceans, coastal deposits, excess accumulations, and general poor management of plastic waste deposits on land. In addition, marine vessels frequently discard fishing gear, aquaculture materials, and other plastic waste directly into the ocean, contributing to the abundance of dangerous pollution such as “ghostnets" (Lebreton et al. 2018). Once in the ocean, plastic particles are exposed to solar radiation and wave action, resulting in their breakdown via photodegradation and fragmentation. The weathering of plastic fragments generates microplastic and nanoplastic particles that are not only difficult to detect and remove, but also especially damaging for organismal and human health (Cozar et al. 2014). Marine plastics pose serious threats to environmental, human, and organismal health as a result of interactions such as entanglement, ingestion, obstruction, chemical leaching, and toxic bioaccumulation (Law 2017). Because these particles simultaneously persist and fragment, plastics in the ocean become more widespread and difficult to remove with passing time. Thus, to reduce treatment costs and environmental damage, more efficient and targeted removal methods are needed. To achieve this, numerical modeling of ocean dynamics could be used to predict plastic transport and direct cleanup efforts.

b. Passive Advection Modeling

The transport of passive particles, or particles whose motion depends on external factors and not independent movement, in atmospheric and ocean dynamics is governed by the advection equation (Kulkarni and Lermusiaux 2019). In most practical situations, advective fluid transport is affected by external factors

and processes such as diffusion, reaction processes, and properties of the advected passive particles. Advective transport itself is governed by the following classic partial differential equation (PDE), which models change in multivariable functions using one or more partial derivatives, (Kulkarni and Lermusiaux 2019)

$$\frac{\partial \rho(x,t)\alpha(x,t)}{\partial t} + \nabla \cdot (\rho(x,t)v(x,t)\alpha(x,t)) = 0.$$

(Equation 1)

In Equation 1, $\boldsymbol{\alpha}$ is the `tracer', *i.e.* the scalar quantity representing the particle whose transport is to be modeled; $\boldsymbol{v}$ is the specified dynamic velocity field on which advection is simulated; $\boldsymbol{\varrho}$ is the density of the fluid; and ***(x, t)*** denotes the spatial and temporal coordinates of the specific particle studied. To solve for the solution ***(x, t)***, which describes the location ***x*** of the targeted particles at a specific time ***t***, simple analytical methods can be used only when the velocity fields has well-defined initial and boundary conditions. However, in most real-world cases, this does not hold true and the equation must be solved numerically to examine the evolution of the tracer. This presents difficulties with large, realistic problems, as the solving becomes numerically expensive, numerical diffusion lowers accuracy and computational challenges result. (Kulkarni and Lermusiaux 2019)

Two different approaches exist to model particle advection, namely the Eulerian and the Lagrangian perspectives. In Eulerian modeling, flow is studied in static “boxes" through which particles move, and the focus rests on comparing particle inflow and outflow in each “box" to determine overall advective patterns. In Lagrangian modeling, the trajectories of individual particles are traced as they move through time and space. There is no advection term describing mass flow across grid boundaries, since the grid deforms with material flow and volume changes; thus, conservation equations for mass, momentum, and energy are simple and can be efficiently solved. Moreover, boundary conditions are easily imposed and material interfaces are smoothly tracked. Collectively, all particle movements follow Lagrangian Coherent Structures (LCS), which are computationally derived and direct the convergence and divergence of flow trajectories. (Zhang et al. 2017) Hence, while Eulerian models are popular for their use of a fixed reference grid, Lagrangian models are more computationally efficient compared to Eulerian models, especially as dimensions of the target region increases (Jain et al. 2016). Prants et al. (2011) simulated surface transport and mixing of water masses in the Japan Sea using Lagrangian trajectories computed for particles in a velocity field generated by a numerical circulation model. The resulting map of LCSs revealed mesoscale eddies and their structures, different phases of coastal flow, and particle trajectories on a large scale. (Prants et al. 2011)

B. Research Description

a. Engineering Goals

This study will aim to develop a model of plastic transport in Massachusetts Bay, MA (Figure 1) for forecasting of plastic distribution over time, with focus on realistic source regions as an initial condition. With an input of velocity field simulations or data over a specified time period, the model will be able to output figures of initial plastic distribution - based on the initial concentration conditions set - and final plastic distribution over the time period.

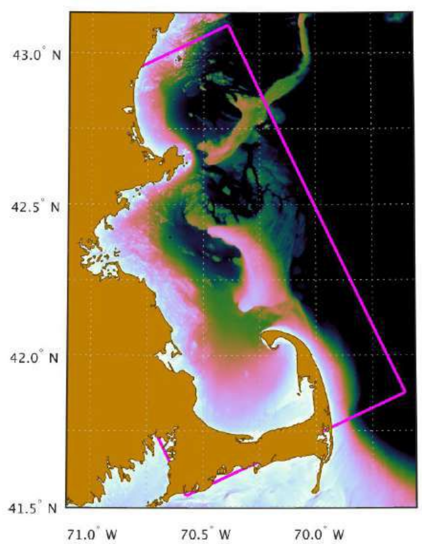

Figure 1. The region that will be modeled is enclosed by the pink rectangle above and includes Massachusetts Bay, Cape Cod Bay, and Boston Harbor, and the mouths of two major rivers, Charles River and Merrimack River. (Kulkarni and Lermusiaux 2019)

b. Hypotheses

Based on previous research by Prants et al. (2011), the final plastic distribution will be influenced by and reflect the prevailing wind and ocean currents in the area.

c. Expected Outcomes:

Based on previous research conducted by Kulkarni and Lermusiaux (2019), the model will output diagrams of initial distribution of plastic at a given time $t = t_{initial}$ and final distribution of plastic at a given time $t = t_{final}$. These diagrams, after interpretation, will indicate how plastic particles have traveled between time $t = t_{initial}$ and $t = t_{final}$. The final plastic distributions, at time $t = t_{final}$, will correlate to both the initial plastic distribution at $t = t_{initial}$ and the influence of major wind and ocean patterns in the area.

C.

- **Methodology**

Overview

An existing model for passive transport provided by the Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS) Group at the Massachusetts Institute of Technology (MIT), which utilizes a composition-based advection method developed by Chinmay S. Kulkarni and Pierre F. J. Lermusiaux (Kulkarni and Lermusiaux 2019), will be modified to incorporate 7 initial source condition cases. Simulated Navier-Stokes current velocity fields of Massachusetts Bay, MA, will be generated independently by the MSEAS Group for two time periods: June 6, 2001 through June 26, 2001 and July 25, 2019 through July 30, 2019. The 2001 dataset will be of lower resolution but longer duration than the 2019 dataset, allowing for a comparison of model results with varying resolutions and over different time periods. This study will focus on the forecasting function of the model: diagrams of plastic concentration distribution will be calculated at different times (time $t = t_{inirial}$ for both time periods, t = 1 day, 7 days, and 20 days for the 2001 time period, and t = 5 days for the 2019 time period) to generate a progression of plastic movement. Resulting trends in particle movement will be analyzed to draw conclusions about general plastic flow patterns in Massachusetts Bay. Sample flow maps will also be computed to display and further clarify the functioning of the model.

Existing Model Numerical Methodology

In this section, the existing model, which utilizes a novel numerical methodology developed independently by the MSEAS Group (Kulkarni and Lermusiaux, 2019), is briefly explained. The model utilizes a composition-based advection method that represents the transport of a passive tracer over a velocity field in terms of (x, t), or spatial (location) and temporal (time) coordinates, with a numerically solvable equation over the discretized spatio-temporal domain. Flow maps, which describe fluid movement from a time $t = 0$ to given time $t = T$, will be computed for each discrete spatial parcel on the velocity field. The solutions will represent the starting positions and ending positions of spatial parcels, which will each represent individual fluid parcels and particles. The domain will be discretized into small spatio-temporal intervals, and flow maps will be calculated for each of these intervals and then composed to obtain the complete flow map over time $t = [0, T]$.

Implementation of Location Cases

The passive tracer model (developed by Kulkarni and Lermusiaux 2019), detailed above in the section titled "Existing Model Numerical Methodology", will be modified in this study. Initial plastic distribution based on common sources of plastic will be incorporated into the tracer as an initial condition to create a new model of oceanic plastic transport that more accurately simulates plastic pollution in the real world. The following cases of initial plastic sources will be modeled:

- **Case 1**: Uniform source along the coastline, only.
- **Case 2**: Point source in the ocean, only.
- **Case 3**: Merrimack River, only.
- **Case 4**: Charles River, only.
- **Case 5**: Both the Merrimack River and the Charles River, weighted based on river flow output.
- **Case 6**: Uniform coastline source (Case 1) and the Merrimack River and the Charles River, weighted based on river flow output (Case 5).
- **Case 7**: Uniform source across entire domain.

Modification of the model will be performed by editing the MATLAB code of the original model (developed by Kulkarni and Lermusiaux 2019). Specifically, a new function, which will set initial source as a condition for flow map computation, will be added to the base code and incorporated into the flow map computations.

- **Risk and Safety**

1. *Human Participants Research*: **N/A**

2. *Vertebrate Animal Research*: **N/A**
3. *Potential Hazardous Biological Agents Research:* **N/A**
4. *Hazardous Chemicals, Activities, and Devices*: **N/A**

- **Data Analysis**

The model will output diagrams of plastic distribution at various times of the given time period, detailed in the section titled "Overview" above. In the sample flow maps, the colors of the diagrams will denote initial position; thus, particles can be traced from an initial position to final positions across different time intervals. In the diagrams generated through the source concentration cases, the colors of the figures will represent plastic concentrations, with red being the highest concentration and blue being the lowest concentration. In both cases, interpretation and analysis of the diagram can be done by examining the colors and their changing positions between the diagram at time $t = 0$ and time $t = t_{final}$.

D. Bibliography

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Project Summary

No Addendums Exist