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Tracking plastics in the Mediterranean: 2D Lagrangian model

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ABSTRACT

Drift of floating debris is studied with a 2D Lagrangian model with stochastic beaching and sedimentation of plastics. An ensemble of > 10^{10} virtual particles is tracked from anthropogenic sources (coastal human populations, rivers, shipping lanes) to environmental destinations (sea surface, coastlines, seabed). Daily analyses of ocean currents and waves provided by CMEMS at a horizontal resolution of 1/16° are used to force the plastics. High spatio-temporal variability in sea-surface plastic concentrations without any stable long-term accumulations is found. Substantial accumulation of plastics is detected on coastlines and the sea bottom. The most contaminated areas are in the Cilician subbasin, Catalan Sea, and near the Po River Delta. Also, highly polluted local patches in the vicinity of sources with limited circulation are identified. An inverse problem solution, used to quantify the origins of plastics, shows that plastic pollution of every Mediterranean country is caused primarily by its own terrestrial sources.

1. Introduction

Plastic marine debris observed in the Mediterranean Sea is widely distributed over various environmental compartments such as water, coastlines, bottom sediments, and biota (e.g., Suaria and Aliani, 2014; Poeta et al., 2016; Galgani et al., 2000; Fossi et al., 2016) and poses a considerable risk to ecosystems and human health.

In contrast to laboratory trials and field observations of plastic marine litter in the Mediterranean Sea, modeling plastic marine litter is still in a fairly rudimentary state. Recently, only a few numerical modeling studies were performed to predict the pathways and fate of plastics and fill the monitoring gaps on a basin and subbasin scale. The first numerical simulations of plastics in the Mediterranean Sea were performed by Aliani and Molcard (2003) to study the traveling time of species on flotsam from Corsica to the Ligurian coast. In a recent study by Mansui et al. (2015), a Lagrangian particle tracking model was developed to understand how general surface circulation influenced the transport of plastics. The model, initiated from uniformly distributed sources, demonstrated an absence of any permanent sea surface structure able to retain floating items over one year of the model integration. The second relevant conclusion drawn was that the beaching of plastics was a matter of great importance for the Mediterranean Basin.

In an attempt to apply the methodology of Maximenko et al. (2012) and van Sebille et al. (2012) to the Mediterranean Sea, Zambianchi et al. (2017) constructed a Markov chain model to calculate the transition matrices from the historical Mediterranean drifter database (1987–2004). However, beaching as a dissipative process was overlooked, which led the authors to the rather controversial conclusion that long-term accumulation of plastics at the sea surface similar to that in the global ocean occurred in the Mediterranean.

Three numerical modeling studies were carried out for the Mediterranean subbasins. A 2D Markov chain model for the Adriatic Sea was developed by Liubartseva et al. (2016), who postulated that beaching is the only environmental sink for the floating plastic debris. Inputs of plastics from rivers, cities, and illegal dumping along shipping lanes were taken into account. Transition matrices were calculated by means of the Lagrangian oil spill model MEDSLIK-II (De Dominicis et al., 2013) adjusted to the transport of plastics. The semi-enclosed geometry of the Adriatic basin allowed an approximate solution to the open boundary problem, prescribing a zero-influx of plastics through the southern boundary of the extended computational domain. The model overestimated the values of coastal fluxes of plastics (Prevenios et al., 2017), but qualitatively agreed with sampling of microplastics from the sea surface (Gajšt et al., 2016) and the results of bottom trawls (Pasquini et al., 2016).

An ensemble of virtual Lagrangian particles was released under homogenous initial conditions and tracked in the NW Mediterranean over 30 days to compare the model distribution at the sea surface with field data (Fossi et al., 2017). The authors did not focus on the open boundary problem, which could not have a simple solution in the

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computational domain. Beaching of plastics was also not specified, but the model results demonstrated good agreement with observations.

Transport and fate of floating litter particles in the Aegean Sea were studied with a particle-tracking model on monthly and annual scales (Politikos et al., 2017). The particles were released from 5 source clusters associated with big coastal cities, major rivers, ports, maritime and fisheries activity, and coastal activities including tourism. Two additional clusters were imposed in the vicinity of the southern open boundaries to investigate their influence on the solution obtained. Similar to the Adriatic Sea, the semi-enclosed geometry of the Aegean Basin bordered in the south by a chain of islands, including Crete and Rhodes, allowed the authors to resolve the open boundary problem approximately. Although the authors reported and analyzed the distribution of particles in coastal cells over the Aegean Basin, beaching of plastic particles was not specified in the paper. Comparisons with observations showed generally consistent patterns for transport direction and extent.

However, the most striking conclusion can be drawn by comparing the results obtained using the models mentioned above: all of them differ substantially with respect to the predictions of floating debris distributions at the sea surface. Moreover, the global scale modeling summarized by van Sebille et al. (2015) also led to contradictory solutions in the Mediterranean versus the aforementioned basin- and subbasin-scale models. As shown in Table 1, the main reason for such discrepancies might arise from the different setups of the models. These differences reveal that a well-defined model framework for marine litter in the Mediterranean Sea has not yet been established, which is typical of early stages of development due to insufficient knowledge of the problem.

The present study is designed to take the first steps forward in numerically modeling the distribution of plastic debris in three environmental compartments (at the sea surface, on the coastlines, and on the sea bottom) by applying the Monte Carlo technique to algorithms of beaching and sedimentation of plastics. To this end, we (1) quantify emissions of plastics in the Mediterranean, and (2) for the first time in the 2D Lagrangian marine litter modeling, use the combination of sea surface ocean and wave-induced currents (the Stokes drift) calculated directly by means of a coupled hydrodynamic-wave (NEMO-WW3) modeling system (Clementi et al., 2017a) operated under the Copernicus Marine Environment Monitoring Service (CMEMS). Finally, (3) we quantify national source-receptor relationships computing inversely the relative contributions of plastics from different origins.

The manuscript is structured as follows. Section 2 contains details of model setup and implementation including the data about inputs of plastic marine debris in the Mediterranean Sea, the 2D Lagrangian module, its forcing, and integration. Section 3 is used to describe the results of numerical simulations with a focus on the plastics floating at the sea surface, as well as beached and benthic plastics. A discussion of the national source-receptor relationships among the Mediterranean countries is also presented. Finally, in Section 4, we draw conclusions.

2. Models and data

2.1. *Identification of floating debris inputs into the Mediterranean Sea*

Following a map published by Jambeck et al. (2015), we assume that the total annual input of plastic in the Mediterranean Sea is approximately 100, 000 tons per year. Then, we slightly change the cities-to-rivers-to-shipping lanes ratio to values of 50:30:20%, instead of 40:40:20% suggested earlier by Lebreton et al. (2012). The ratio we used seems to be more appropriate for the densely populated and highly urbanized coasts of the Mediterranean, and the relatively small number of rivers flowing into the basin.

The 505 largest cities located inside a 10 km coastal belt, which comprised more than 20, 000 inhabitants in 2013, are taken into account (Brinkhoff, 2010). Total coastal urban population input of 50, 000 tons of

Table 1
Setup specifications for numerical modeling the transport of floating debris in the Mediterranean Sea.

Domain, reference	Type of model	Meteo-oceanographic data, horizontal resolution	Sources of plastics	Number of tracked particles	Integration time[a]	Sinks of plastics
W Mediterranean, (Aliani and Molcard, 2003)	Lagrangian particle tracking	MOM[b] currents, ~12.5 km	West Corsica Channel cluster	$\sim 10^3$	50 days	No sinks
Mediterranean Sea, (Mansui et al., 2015)	Lagrangian particle tracking	NEMO[c] currents, ~6–8 km	Uniformly distributed sources	$\sim 10^4$ per year	1 year	Beaching
Mediterranean Sea, (Zambianchi et al., 2017)	Markov chain model based on the drifter database	Historical drifter dataset, ~50 km bin size	Coastal population	Not specified	10 years	No sinks
Adriatic Sea, (Liubartseva et al., 2016)	Markov chain model based on Lagrangian particle tracking	ECMWF[d] wind at ~12.5 km and AFS[e] currents at ~2.2 km	Coastal cities, rivers, and shipping lanes	$\sim 10^8$ per year	6 years	Beaching
NW Mediterranean, (Fossi et al., 2017)	Lagrangian particle tracking	Tyrreno-ROMS[f] currents, ~2 km	Uniformly distributed sources	Not specified	30 days	Not specified
Aegean Sea, (Politikos et al., 2017)	Lagrangian particle tracking	POM[g] currents, ~7.5 km	7 realistic clusters of sources	$\sim 10^4$ per year	1 year	Beaching
Mediterranean Sea, (present work)	Lagrangian particle tracking	CMEMS[h] MED MFC[i] currents and waves, ~6.5 km	Coastal cities, rivers, and shipping lanes	$\sim 10^9$ per year	4.5 years	Beaching and sedimentation

[a] Integration time includes the spin-up period.
[b] MOM – Modular Ocean Model.
[c] NEMO – Nucleus for European Modelling of the Ocean.
[d] ECMWF – European Centre for Medium-Range Weather Forecasts.
[e] AFS – Adriatic Forecasting System.
[f] Tyrreno-ROMS – Tyrrhenian Regional Ocean Modeling System.
[g] POM – Princeton Ocean Model.
[h] CMEMS – Copernicus Marine Environment Monitoring Service.
[i] MED MFC – Mediterranean Monitoring Forecasting Centre.