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Regional approach to modeling the transport of floating plastic debris in the Adriatic Sea

S. Liubartseva [a,*], G. Coppini [b], R. Lecci [b], S. Creti [b]

[a] Centro EuroMediterraneo sui Cambiamenti Climatici, Bologna, Italy
[b] Centro EuroMediterraneo sui Cambiamenti Climatici, Lecce, Italy

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ABSTRACT

Sea surface concentrations of plastics and their fluxes onto coastlines are simulated over 2009–2015. Calculations incorporate combinations of terrestrial and maritime litter inputs, the Lagrangian model MEDSLIK-II forced by AFS ocean current simulations, and ECMWF wind analyses. With a relatively short particle half-life of 43.7 days, the Adriatic Sea is defined as a highly dissipative basin where the shoreline is, by construction, the main sink of floating debris. Our model results show that the coastline of the Po Delta receives a plastic flux of approximately 70 kg(km day)$^{-1}$. The most polluted sea surface area (>10 g km^{-2} floating debris) is represented by an elongated band shifted to the Italian coastline and narrowed from northwest to southeast. Evident seasonality is found in the calculated plastic concentration fields and the coastline fluxes. Complex source–receptor relationships among the basin's subregions are quantified in impact matrices.

1. Introduction

Plastic pollution in the marine environment is of increasing concern due to the great threat to human health and the stability of marine ecosystems, and adverse economic impacts on coastal communities (Eriksen et al., 2014; Thompson et al., 2009).

The spatial and temporal distributions of plastics in the marine environment depend on input locations and the time-varying intensity of sources, which are highly uncertain. However, ocean currents, waves, and wind control the transport of plastics, redistributing them at sea until they eventually wash ashore or sink. The high complexity and multiscale versatility of the dynamics of the upper mixed layer of the ocean, where the majority of plastics float, must be taken into account.

In order to identify the pathways of floating marine litter under such uncertain conditions, several numerical simulations were performed for different geographical areas varying from global to regional scales. Contributions of geostrophic currents, Ekman drift, Stokes drift, and their combinations in the North Pacific were simulated by Kubota (1994). Developing Kubota's approach, Martinez et al. (2009) demonstrated the appropriateness of using a high-resolution current field to determine the impact of mesoscale activity on the trajectories of particles. Yoon et al. (2010) enriched the methodology, switching from homogeneous source distribution to more realistic inputs into the Japan Sea from the largest cities and rivers, applying output from the Japan Sea Forecasting System.

Remarkable progress toward flexibility in plastic litter modeling was achieved by Maximenko et al. (2012), who suggested a Markov chain model that represents transporting properties of the upper mixed layer, allowing the separation of the input distributions from the dynamics of the upper mixed layer. Once the Markov chain model was built, the evolution of particle concentration from any source could be calculated, and various hypotheses of input distributions could be tested efficiently. A global set of historical trajectories of drifting buoys deployed in the Surface Velocity Program and Global Drifter Program (1979–2007) was used for the calculation of a transition matrix. The methodology was improved by van Sebille et al. (2012), who extended the buoy dataset, introduced the seasonal transition matrices, and imposed marine litter inputs related to the coastal population density.

Using directly integrated particle trajectories, Lebreton et al. (2012) took into account terrestrial sources from rivers and cities, and marine inputs from major shipping lanes. Long-term drift of floating debris in the world's oceans was simulated assuming an increase in input intensity.

Recently, marine plastic modeling was carried out on a regional scale to explain local source–receptor relationships in the southern North Sea (Neumann et al., 2014). In the Mediterranean Sea, marine litter drift was simulated in an effort to find permanent accumulation structures such as so-called garbage patches (Mansui et al., 2015). No permanent sea surface structures able to retain floating items in the long-term were found. However, some relevant coastal features were obtained at a basin scale. For example, the coastline between Tunisia and Syria was found to be the most littered with plastics, while the western Mediterranean demonstrated rather low coastal impact.

* Corresponding author.
E-mail address: svitlana.liubartseva@cmcc.it (S. Liubartseva).

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Assuming that marine litter particles can be considered passive Lagrangian tracers, it is important to mention Pizzigalli et al. (2007), who, for the first time, built a Markov chain model for passive tracers in the Mediterranean Sea using the Lagrangian model coupled with the Mediterranean Forecasting System (Pinardi et al., 2003). They focused on seasonality in calculated statistics and introduced coastal-approach-maps to find coastlines that are at risk of pollution originating from the sea.

To a certain extent, transport of plastic marine litter is similar to the transport of satellite-tracked Lagrangian drifters, which have been intensively deployed in the Adriatic Sea. The results obtained in the drifter experiments conducted by Falco et al. (2000), Poulain (2001) Lacorata et al. (2001), Ursella et al. (2006), Veneziani et al. (2007), Poulain and Hariri (2013) were invaluable for verification of model results on distribution of floating debris in the Adriatic Sea.

Focusing on a key role of uncertainty in the plastic debris inputs, Isobe et al. (2009) tried to reconstruct sources of plastic debris solving an inverse problem (backtracking). The main complication of this problem arose from the irreversibility of diffusion computed using the random-walk technique (Csanady, 1973). Recently, when micro-plastics became widely recognized as an acute problem, 3D modeling was developed for meso- and micro-plastics (Isobe et al., 2014). Some relevant parameters in floating debris modeling, which are comparable with those we use in our calculations, are extracted from the literature cited and summarized in Table 1.

In the present work, for the first time we (1) develop the Markov chain model based on coupling the Lagrangian MEDSLIK-II model (De Dominicis et al., 2013a,b) with the Adriatic Forecasting System (AFS) ocean currents simulations and ECMWF surface wind analyses to simulate the plastic concentrations at the sea surface and fluxes onto the coastline that originated from terrestrial and maritime inputs; (2) identify source–receptor relationships among the subregions of the Adriatic Basin solving both the direct and inverse problems; and (3) present the results in terms of impact matrices.

The manuscript is organized as follows: in Section 2 the data on sources of floating debris in the Adriatic Sea, the Lagrangian model, and the ocean forecasting system are presented; Section 3 contains descriptions of the Markov chain model; and Section 4 presents results and discussion. Finally in Section 5, we draw conclusions.

2. Data and models

2.1. Identification of floating debris inputs into the Adriatic Sea

According to recent estimations by Jambeck et al. (2015), the total annual input of plastic in the Adriatic Sea was 10,000–250,000 tons in 2010. In an effort to be more consistent with the previous estimates of the mass of floating plastic debris cited in Jambeck et al. (2015) we use a lower limit of 10,000 ton year $^{-1}$ in the present work. Following Lebreton et al. (2012), we assume that 40% of the marine litter enters the basin through rivers; 40% through coastal urban populations; and the remaining 20% is derived from shipping lanes. They yield 4000, 4000, and 2000 ton year $^{-1}$, respectively.

Average annual discharges into the Adriatic Basin from the 62 largest rivers are extracted from a database implemented by Verri et al. (2014). The discharge of the Po River is distributed among its nine greatest distributaries in proportion to their respective runoffs. Eight rivers entering the north Ionian Sea are included in order to take into consideration

Table 1
Relevant parameters in floating plastic debris modeling.

Domain, reference	Meteo-oceanographic data	Distribution of inputs		Interaction with coastline	Number of Lagrangian particles	Time of integration
		Spatial	Temporal			
North Pacific (Kubota, 1994)	COADS climatology (1970–1979)	10°×10° homogeneous grid	Instantaneous release	No-slip conditions	50	5 years
South Pacific (Martinez et al., 2009)	OSCAR based currents (1993–2001)	1°×1° homogeneous grid	Instantaneous release	No-slip conditions	Large number, not specified	8 years (1993–2001)
East China Sea (Isobe et al., 2009)	Quick scatterometer wind and POM based currents	Two point sources	Instantaneous release	Beaching after 12-h stagnation	20000	76 days
Japan Sea (Yoon et al., 2010)	Currents based on Japan Sea Forecasting System (2003–2006)	Inputs from largest basin's rivers, cities and, the Tsushima Strait	Every month release (2003–2006)	Beaching	47676 particles a year	4 years (2003–2006)
Mediterranean Sea (Pizzigalli et al., 2007)	Lagrangian model dataset based on currents provided by Mediterranean Forecasting System (2000–2004)	1/8°×1/8° homogeneous grid	Every week release (2000–2004)	No-slip conditions	In the Markov chain model: 400000 particles a week	28 days
Global ocean (Maximenko et al., 2012)	Lagrangian dataset of satellite-tracked drifting buoys (1979–2007)	1/2°×1/2° homogeneous grid	Instantaneous release	Beaching after 5-day stagnation	In the Markov chain model: large number, not specified	10 years
Global ocean (van Sebille et al., 2012)	Lagrangian dataset of drogued and non-drogued drifting buoys (198x–20xx)	Inputs from coastal urban population	6 pulse releases a year	No-slip conditions	In the Markov chain model: large number, not specified	1000 years
Global ocean (Lebreton et al., 2012)	6-year dataset provided by US Navy's Global Atmospheric Prediction System and HYCOM/NCODA ocean circulation model	Inputs from impervious surface area, coastal population and shipping lanes	Releases evenly distributed over each year	Beaching	Over 9.6×10^{6}	30 years
Southern North Sea (Neumann et al., 2014)	BSHcmod: operational weather and ocean circulation models	Two local clusters with homogeneous distributions inside	One release in 28 h (2000–2008)	No-slip conditions	200	90 days
Mediterranean Sea (Mansui et al., 2015)	NEMO based currents	10×10 km homogeneous grid	Everyday release (2001–2009)	Beaching, stagnation, recirculation off shore	3287	Two runs: one year and 3 months
Adriatic Sea (present work)	Lagrangian model dataset based on ECMWF wind and AFS currents (2009–2015)	Inputs from largest Adriatic rivers, cities and shipping lanes	One release in 10 days (2009–2015)	Beaching after 10-day stagnation	In the Markov chain model: over 6×10^{10}	6 years (2009–2015)