Science of the Total Environment 790 (2021) 148009

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic

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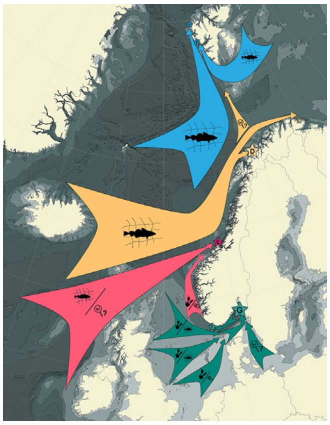
HIGHLIGHTS

- By using oceanic backtracking simulations, potential sources of observed litter at OSPAR beaches are identified.
- Simulated sources of marine plastic fit well with the classification of observed plastic litter types.
- It is highly probable that most of the litter observed on the Arctic OSPAR beaches originates from regional fishing areas.
- Marine plastic originating in central Europe takes more than a year to reach the Arctic by oceanic drift.
- Marine (macroscopic) litter is transported faster than microplastics, and in more diverse directions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 January 2021
Received in revised form 9 April 2021
Accepted 20 May 2021
Available online 27 May 2021

Editor: Susanne Kühn

Keywords:
Plastic pollution
Marine plastic
Ocean drift
Backtracking
OSPAR
Co-production of knowledge

ABSTRACT

Plastic litter is accumulating on pristine northern European beaches, including the European Arctic, and questions remain about the exact origins and sources. Here we investigate plausible fishery and consumer-related sources of beach littering, using a combination of information from expert stakeholder discussions, litter observations and a quantitative tool - a drift model - for forecasting and backtracking likely pathways of pollution. The numerical experiments were co-designed together with practice experts. The drift model itself was forced by operational ocean current, wave and weather forecasts. The model results were compared to a database of marine litter on beaches, collected every year according to the standardized monitoring program of the Oslo/Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). By comparing the heterogeneous beach observations to the model simulations, we are able to highlight probable sources. Two types of plastic are considered in the simulations: floating plastic litter and submerged, buoyant microplastics. We find that the model simulations are plausible in terms of the potential sources and the observed plastic litter. Our analysis results in identifiable sources of plastic waste found on each beach, providing a basis for stakeholder actions.

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https://doi.org/10.1016/j.scitotenv.2021.148009

1. Introduction

With the continuous and increasing production and consumption of plastic since the 1940s–50s, plastic waste is accumulating everywhere on land, in lakes and in the oceans (Bank and Hansson, 2019). A special concern is the degradation of plastic litter into microplastic particles that become small enough to be ingested by animals and potentially transferred across trophic levels. Not even remote areas are spared: several studies show atmospheric and oceanic transport of microplastics to places far from the sources, such as sediments in the Greenland Sea (Bergmann et al., 2017) and in Arctic sea ice (Peeken et al., 2018).

In the marine environment, microplastics are largely produced by weathering and fragmentation of plastic litter at beaches by UV irradiation, temperature changes and physical movements, and are transported by wind, waves, and currents (Andrady, 2011). Marine litter, e.g., larger pieces of plastic, originate both on land and at sea. For example, Deshpande et al. (2020) found that 380 t of plastic from fishing gear are lost at sea in Norway every year. Marine litter stemming from land-based activities is thought to originate mainly from populated coastal areas, however another source of consumer waste on beaches might actually also be (fishing) vessels in nearby waters (e.g., on beaches in Svalbard) (Bergmann et al., 2017; Falk-Andersson et al., 2019). However, knowledge of sources in the sense of the exact location of discharge and those individuals responsible for it is hard to obtain.

As first steps to achieve an overview of marine plastic pollution, the Oslo/Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) has initialized a systematic program for monitoring marine litter on more than seventy beaches in the Northeast Atlantic since 2001. Up to 90% of the items found on OSPAR beaches is made of plastic, while the rest consists of a wide range of materials, including metal, wood, rubber, glass and paper (Schulz et al., 2015, 2019).

Marine litter has also been recorded in the Norwegian-Russian ecosystem surveys in the Barents Sea since 2010. Recordings in the period 2010 to 2016 show that plastic dominated the number of observations: 72% of surface observations, 94% of litter as bycatch in pelagic trawls and 86% of litter in bottom trawls contained plastic (Grøsvik et al., 2018). Litter from fisheries (ropes, strings and cords, pieces of nets, floats, buoys, etc.) dominated recordings of plastic litter both in the pelagic and bottom trawls (ICES, 2019, 2020). When mapping the sea bed along the Norwegian continental shelf, litter was observed in 27% of the video recordings. Background densities in the Norwegian and Barents Seas were found to be 202 and 279 items per km^2, respectively, and most of the litter originated from the fishing industry (Buhl-Mortensen and Buhl-Mortensen, 2017).

Growing political awareness has changed the attitude within the fishing fleet and introduced new practices to handle marine waste (Olsen et al., 2020). Using OSPAR data, Haarr et al. (2020) already found a reduction in beach litter in Northern Norway due to beach cleanups and local reduction of litter.

To further reduce plastic pollution, policy makers need to go beyond collection activities and awareness raising campaigns, and target specific sources and pathways into the ocean. A number of sustainable development principles, originating in the Rio Declaration issued by the United Nations Conference on Environment and Development (UNCED) in Rio in 1992, are applicable to the problem of marine litter. For instance, the precautionary principle states: *In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation* (Rio Declaration 1992, Principle 15). More relevant to the present paper is Principle 16, the 'polluter pays' principle: *National authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment.*

The key objective of the present paper is to contribute to the process of linking findings of marine litter with the original polluters by developing a plastic tracking tool and running experiments with that tool in collaboration with stakeholders.

In order to understand the pathways of marine plastic, trajectory simulations based on ocean current data sets have been used to describe how marine plastic is transported, and where it could accumulate. Such work has been undertaken by van Sebille et al. (2012) on a global scale, using ocean currents derived from Surface Velocity Program drifters. The work highlights regions where floating plastic accumulates over time. For regional scales, current data sets from high-resolution ocean models are required to resolve the complex flow patterns in near-shore regions. Such flow patterns include the time-variant flow due to transient eddies and atmospheric forcing, which can be dominant in the Northeast Atlantic (Strand et al., 2017).

In addition to describing plastic transport by ocean currents, it has been shown that Stokes drift due to waves affects the transport near the surface (e.g. van den Bremer and Breivik, 2018; Röhrs et al., 2021). Larger pieces of plastic that float on the sea surface will also be affected by direct wind drag, changing the effective drift dramatically compared to the drift of fully submerged material (Röhrs and Christensen, 2015). To accurately simulate the drift of marine plastic using a trajectory model, it is therefore necessary to employ wind and wave data in addition to ocean current data. Model frameworks for such simulations have been developed in recent years, e.g., (Dagestad et al., 2018; Delandmeter and van Sebille, 2019); in particular, van Sebille et al. (2019) have already shown that the wave-induced transport affects marine plastic transport.

In order to address potential sources of pollution found at specific locations, backtracking simulations provide a practical tool, e.g., to identify the source polluter of observed oil spills and to locate the origin of an object found drifting. For instance, van Sebille et al. (2019) use a detailed ocean circulation model and a backtracking algorithm to describe the pathways of marine plastic around the Galapagos Islands and highlight potential sources of beach litter. At basin-wide scales, backtracking has also been applied to locate possible sources of marine debris (e.g., Durgadoo et al., 2021). In this study we use the backtracking algorithm to map the most likely sources of marine plastic arriving at particular beach sites, using Monte Carlo simulations that represent various past weather and ocean current situations. We compare the simulation results with beach litter records, and our experiments are designed to specifically address the questions raised by practice experts.

Our main research questions, and how these were identified using a knowledge co-production approach, is described in Section 2.1. In order to address those questions there are several methodological aspects that are presented in Sections 2.2 and 2.3. The results are described in Section 3 and discussed in Section 4. Finally, we offer concluding remarks in Section 4.4.

2. Methods and data

2.1. Research design - co-production of knowledge and research questions

This study derives from a Norwegian research project - "Barricade" - that has adopted an overarching design based co-production of knowledge. This allows us to include various types of knowledge on the theme of marine litter, as the expertise of non-scientist experts is not always codified and accessible in the way scientific knowledge is (Holm, 2003). Given the inherent socio-political implications associated with marine litter, and as means to operationalize the co-production approach, we adopt the notion of *extended-peer review community* (Funtowicz and Ravetz, 1993) to constitute what we call the Barricade Council.

Participants in the Barricade Council represent practice experts. They are: (i) the Governor of Svalbard, (ii) the Norwegian Environment Agency (state administrative body under the Ministry of Climate and the Environment, with mandate to manage the Norwegian marine and coastal environment); (iii) Keep Norway Beautiful (a non-profit association that works against littering and organizes beach cleanups); and (iv) the Norwegian Centre for Oil Spill Preparedness and Marine Environment (a public center of expertise under the Ministry of Transport). Among the scientific experts, this research project involves a transdisciplinary team, with experts from physical oceanography, biological oceanography (marine toxicology) and the social sciences (science, technology and innovation studies).

An important principle underlying an *extended-peer review community* is that practice experts are integral partners in the process of knowledge production. The main function of the Barricade Council is to allow for a two-way transfer of knowledge between the scientific team and the practice experts. In other words, the knowledge of practice experts can be incorporated in the work in a meaningful way, and the findings from the scientific work can be made applicable and useful to a broader set of stakeholders.

The interactions between scientists and practice experts began at the funding stage, when key stakeholders were invited to join the project team. The dialogue across the different types of experts primarily took place at a 2-day "*Marine Plastics Drift Simulation Laboratory*" workshop in Bodø, Norway in September 2019. In preparation for the workshop, the scientific team leveraged existing knowledge of ocean circulation in combination with trajectory models for marine plastic. Then, at the workshop, participants engaged with oceanic drift models operating in real time, trying different experiments in support of the discussions taking place. During this stage, simulations were carried out for different origins and destinations of marine plastic as suggested by the workshop participants. These on-the-fly experiments included both forward and backtracking simulations, in order to create a common understanding of possible outcomes for drift of marine plastics. Finally, the workshop participants agreed on the following questions of particularly interest:

1. Where is the plastic pollution on the selected OSPAR beaches likely to come from?
2. How long does it typically take for the plastic litter to reach the OSPAR beaches?
3. What are the main reasons for the differences in litter found at the various beaches?

We decided to focus on backtracking simulations from the destination beaches in order to identify the relative importance of possible sources. In the backtracking simulations, we modeled the drift of both litter and microplastics, even though only macroscale marine litter is recorded at the OSPAR sites.

The model interface that we used during the workshop depicted a map of the northern North Atlantic - Norwegian Sea - Barents Sea region, and participants were encouraged to brainstorm about where plastic was known to appear on shore and where it was plausible to assume that litter was discharged. Based on this feedback, the scientists ran drift experiments and the results were brought into the discussion to further adjust the experiments.

The simulation outputs became dynamic illustrations of the paths that litter could travel, given knowledge of the weather, waves and oceanic currents. Both for the assessment of the premises and discussion of preliminary findings, the knowledge of practice experts was indispensable. After several simulation rounds, and joint discussion of preliminary findings, the workshop ended with a discussion of implications for policy, strategies for dissemination, and a reflection on the knowledge co-production process. Subsequent interactions between the scientific team and individual members of the council took place as needed for additional input or data during the reworking and refining of the model setup. One participating NGO provided additional data from beach cleanups carried out through citizen science methods of data collection. There were also subsequent rounds of sharing drafts and feedback. The results of this process are the experiments and insights presented in this paper.

2.2. Observations of plastic pollution from OSPAR

We utilize data from the Norwegian OSPAR beaches, which include a wide range of oceanic areas, see Fig. 1: Kviljo (North Sea), Hvaler (Skagerrak), Været and Rekvika (Norwegian Sea), Sandfjordneset (Eastern Barents Sea), and two sites on Svalbard, Luftskipodden and Brucebukta. The OSPAR beaches are cleaned and documented every year according to a OSPAR guideline (Commision, 2010). Data from the Norwegian OSPAR are available through https://beachlitter.ospar.org. We have used the raw data from 2011 to 2017 (2015–2017 on Svalbard).

The litter is categorized into broad groups by the OSPAR guideline, from which we further selected the main plastic litter groups and arranged them into the following classes: 1) nets from fisheries, 2) large plastic items from private consumers, 3) small plastic items from private consumers, 4) plastic caps from bottles, 5) other plastic types from consumer-related sources (such as bags of chips and shotgun shells), see Table 1. For a thorough evaluation of these data, see Falk-Andersson et al. (2019).

Brucebukta is exposed to the prevailing northeasterly winds even though it is located on the sheltered side of a large island; the substrate consists of sand and pebbles. Luftskipodden is facing head-on to the open ocean along a highly exposed coastline, but is sheltered from the prevailing northeasterly winds; the substrate consists of boulders and rocks. Sandfjordneset is a sandy beach facing the open ocean and the prevailing winds, yet faces away from the prevailing direction of the coastal current. Rekvika consists of rocks and boulders facing the open ocean and the prevalent northwesterly winds, but is slightly sheltered from the open ocean by other islands. Været beach consists of rocks and pebbles situated along the sheltered side (relative to the open ocean) of a small island (away from the prevailing westerly winds), on an otherwise highly exposed part of the Norwegian coast. Kviljo is a sandy beach also facing the open ocean, but perpendicular to the prevalent westerly winds. Hvaler consist of mud, rocks and boulders, within a small embayment facing the open ocean and head-on to the prevailing wind direction.

2.3. Backtracking simulations of marine plastic

Backtracking trajectory simulations of plastic particles have been carried out to identify potential origins and pathways leading to the respective OSPAR beaches. The simulations are based on circulation modeling of ocean currents, as well as wave action and wind forcing.

Oceanic drift pathways in the Arctic and Northeast Atlantic are closely related to the main current system (Fig. 1, (Skagseth et al., 2008)), which includes the following: the northward-flowing Norwegian Atlantic Current that transports (relatively) warm and saline Atlantic water; the northernmost continuation of the Atlantic water - the West Spitsbergen Current - that transports the warm, saline waters up to Svalbard; the northward-flowing Norwegian Coastal Current that transports fresher water originating in the Baltic and North Seas and river runoff; and the southward-flowing cold Arctic outflow - The East Greenland Current. The weather is highly dynamic due to the low pressure systems moving eastward with typically west-southwesterly wind directions in the Northeast Atlantic (Bjerknes, 1919) and east-northeasterly directions in the Arctic. These prevailing winds directly affect floating litter and indirectly affect sub-surface microplastics due to wind-driven currents and wave-driven Stokes drift (van den Bremer and Breivik, 2018).

The transport of particles is simulated using OpenDrift, an open source trajectory model with a specific module for marine plastic (Dagestad et al., 2018). In this module, particles are subject to 3-dimensional transport by ocean currents at various depths,

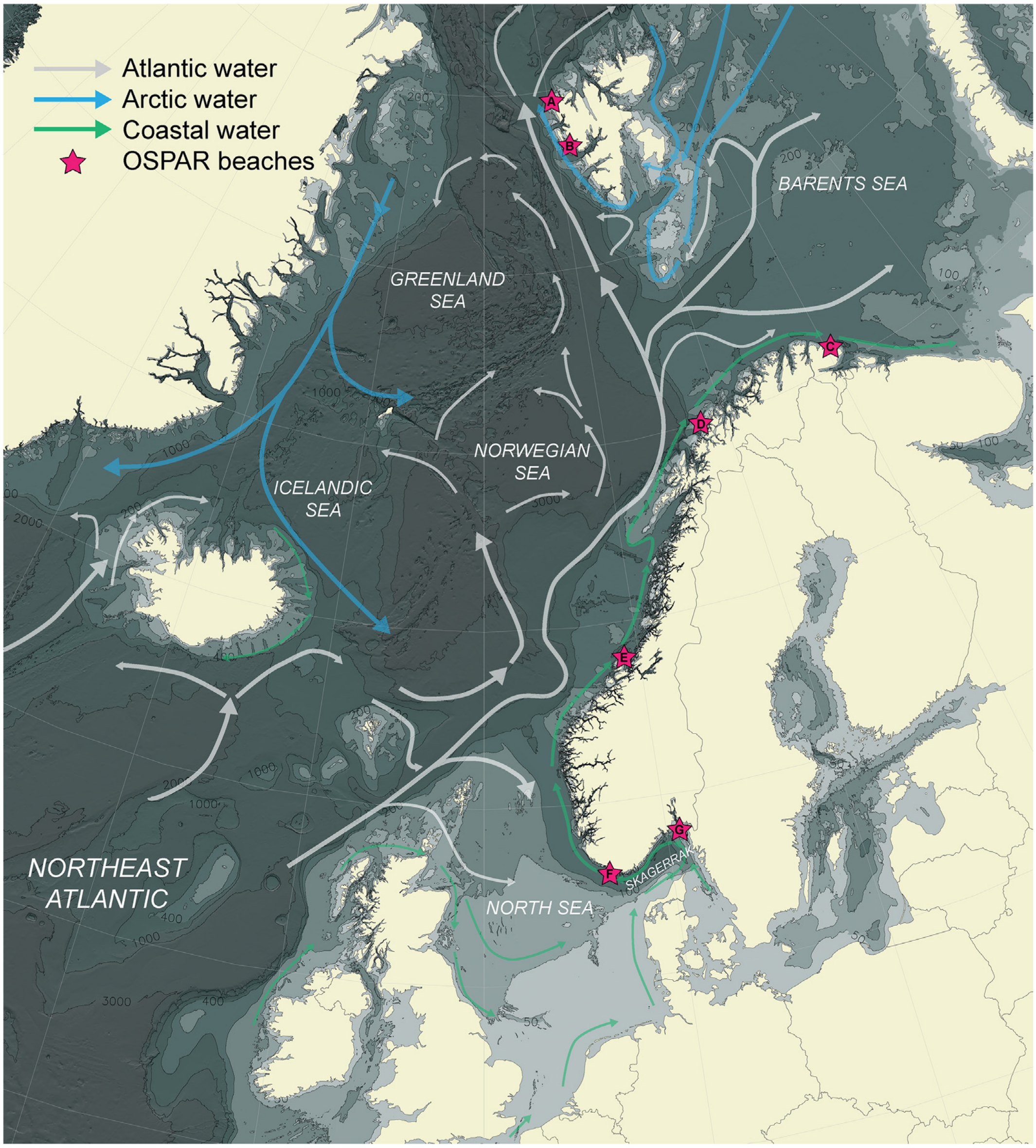

Fig. 1. Overview of the selected OSPAR beaches (red stars) in this study; A) Luftskipodden, B) Brucebukta, C) Sandfjordneset, D) Rekvika, E) Vaeret, F) Kviljo and G) Hvaler. The main ocean currents are labeled accordingly; Atlantic water (gray), Arctic water (blue) and coastal water (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Norwegian OSPAR beaches with main categories of averaged observed plastic pollution for the time period 2011–2017 (2015–2017 on Svalbard); Fish.Net = from fisheries, P.large = large plastic from private consumers, P.small = small from private consumers, P.caps = plastic caps from bottles, P.other = other consumer-related sources (such as crisp bags and shotgun shells). Data are retrieved from https://beachlitter.ospar.org.

Name	[LAT,LON]	String	Fish.Net	P. large	P. small	P. caps	P.other
(OSPAR code)		(32)	(115/116)	(46)	(117)	(15)	(43/18)
Luftskipodden	[79.7,10.4]	13	7	44	26	9	2
Brucebukta	[78.4,11.9]	17	7	24	8	8	1
Sandfjordneset	[70.6,30.4]	35	4	14	6	6	3
Rekvika	[70.0,18.0]	2264	186	1287	832	561	139
Været	[64.0,9.0]	94	0	54	75	5	2
Kviljo	[58.0,6.7]	4	0	21	66	2	1
Hvaler	[59.0,10.7]	5940	664	3897	3905	879	525

to Stokes drift by surface gravity waves, and to wind drag for particles that are floating at the surface. Vertical motion consists of buoyancy and mixing by ocean turbulence, where a random walk scheme (Nordam et al., 2019) with a wind-dependent eddy diffusivity (Sundby, 1983) is used. The implementation of advection and mixing schemes for plastic particles in OpenDrift is analogous to a module for oil droplets, described in detail by Röhrs et al. (2018). The direct wind drag on surface particles is parameterized as being 2% of the wind speed, as found empirically in previous studies (e.g., Jones et al. (2016); Dagestad and Röhrs (2019)). A sensitivity study of this wind drift coefficient is documented in Appendix A.1.

In our simulations we consider two types of plastic particles, litter and microplastics. Litter particles resemble larger pieces of plastic that stay afloat at the surface. Microplastic particles are smaller particles that are positively buoyant but become submerged into the water column. Their buoyancy is described by a uniform distribution of terminal vertical velocities in the range of $w = 0.001–0.02$ m/s. The smallest considered particles have $w = 0.001$ m/s and are approximately neutrally buoyant. We do not consider negatively buoyant (sinking) particles. Sensitivity tests using the OpenDrift model system indicate that negatively buoyant particles, e.g., particles subject to progressed biofouling, become sedimented within 100-200 km drift in a simulation, and similar findings are put forward by (Kooi et al., 2017). Depth distributions of microplastic particles with various terminal velocities in OpenDrift are shown in Appendix A.2, where we discuss how the vertical distribution affects horizontal transport.

Ocean, atmosphere and wave data for input to OpenDrift are obtained from archives of operational forecast models with hourly resolution. These are ocean currents from the Regional Ocean Modeling System (ROMS) implemented on a 4 km horizontal grid of the Nordic seas (Lien et al., 2013; Melsom and Gusdal, 2015), Stokes drift from WAM4 at 4 km horizontal resolution (Gusdal and Carrasco, 2012), and winds from the Integrated Forecast System at the European Centre for Medium Range Weather Forecasting (ECMWF) at approximately 10 km horizontal resolution. Near the coast of Norway and its shelf areas, wind data from a nested atmospheric model, Arome-MetCoOp at 2.5 km horizontal resolution, is used (Müller et al., 2017). These are operational weather, wave and ocean forecast models for which data are available from the Norwegian Meteorological Institute. An overview of the forcing data used and configuration of the particle tracking model is given in Table 2.

Transport simulations are carried out as backwards Monte Carlo simulations covering a total time span of 2 years (2017–2018). Particles (litter and microplastics) are released at the seven OSPAR sites shown in Fig. 1 and then traced backwards, according to their time-inverse geophysical forcing, for a period up to 360 days. Particles are released every 10 days in 36 consecutive release dates. 5000 particles are seeded for each individual release site and date, summing up to 1,260,000 particles being tracked for each plastic type.

3. Results

There are large differences in the amount and type of observed plastic litter accumulating on the seven beaches (Table 1). Hvaler receives by far the largest amounts of litter, whereas Rekvika receives roughly half of the amounts at Hvaler. The other five beaches receive an order of magnitude less plastic litter than the first two. The most common type of plastic found is small pieces of string and rope <1 cm in diameter, followed by large plastic pieces (2.5–50 cm) and small pieces of plastic (<2.5 cm), then fishing nets, see Table 1. The variability among years is roughly equal to the average observations, as expected of the variation around a count (i.e., a Poisson distribution). 37% of items (N is approx. 71,000) observed on the beaches are solely from tentative fishery-related sources, and the majority consist of rope (string) cutoffs as a result of mending nets.

Simulation results are presented in Fig. 2 (Svalbard), Fig. 3 (northern Norway) and Fig. 4 (southern Norway) in terms of average drift ages, i.e., the time required to reach a beach from various places on the maps presented. In the same figures we show cumulative particle concentrations 120, 240, and 360 days previous to stranding.

In order to yield composite estimates for these drift ages and positions, all simulations that cover different stranding dates are summed together. We thereby eliminate the effect of transient weather and current events that govern the drift patterns of a particular time period. The results thus reflect typical conditions prevailing in the years 2017–2018. To quantify the relative importance of potential sources for each beach site, we define a backward-time cumulative concentration (BCC) for a source area A as

$$\mathrm{BCC} = \frac{1}{AT}\int_{t=-T}^{t=0}\int_{A} c(t)dAdt, \tag{1}$$

where c(t) is the time-dependent concentration of particles in backwards simulations starting at a respective beach site for source area A as defined Fig. 5. By integrating from a very long time ahead ($-T$) to zero, we reduce the effect of remote (long time ahead) sources, as nearby sources are evaluated multiple times. This is useful because marine litter degenerates over time, and we do not have the means to conclude on the specific sources of plastic that has drifted for a long time (more than a year). Hence we truncate and discretize the integration,

$$\mathrm{BCC} \approx \frac{1}{N_{tot}T}\sum_{t=-360d}^{1}\sum_{A} n(t) \tag{2}$$

limiting the model simulations to a period of 360 days and noting that few particles have left our study domain within this time period. In the latter approximation, we use the number of particles $n(t)$ residing in the source area A at a given time t, and scale by the total number of particles N_{tot} in the simulation and the number of evaluated time steps T. An evaluation for Eq. (2) is given in Table 3 for each stranding site. Main source areas are highlighted, and numbers are provided for both litter and microplastics.

In general, particles tend to drift northwards (i.e., southwards in the backwards simulations) from the North Sea or Northeast Atlantic towards the Norwegian Sea, Barents Sea and Greenland Sea. In addition, the simulations reveal a strong aspect of horizontal diffusion, i.e., random walk type behavior.

Marine litter and microplastics arriving on Svalbard (Luftskipodden and Brucebukta, Fig. 2) have regional sources from around Svalbard and the Barents Sea, with additional minor pathways from Iceland and the Norwegian Sea (Fig. 2 and Table 3).

The three sites along the northwestern coast of Norway (Fig. 3, Table 3) receive litter from northerly (Barents Sea), northwest-westerly (Norwegian Sea, Greenland or Icelandic Sea) and southerly (North Sea, Northeast Atlantic) directions. However, microplastics reaching these sites originate from southerly or westerly directions only. In southern Norway (Kviljo and Hvaler Fig. 4), marine litter derives

Table 2
Overview of the configuration of drift simulations.

	Algorithm	Data source	Reference
Gray horizontal motion	Time step: 1 h		
Ocean current	Euler advection	Nordic4 ROMS	(Lien et al., 2013)
Stokes drift	Approximated profiles	WAM4	(Breivik et al., 2014; Gusdal and Carrasco, 2012)
Wind drift[a]	2% of wind speed (Appendix A.1)	ECMWF/MEPS	(Müller et al., 2017)
Gray vertical motion	Time step: 1 min		
Vertical mixing[b]	Random walk scheme		(Nordam et al., 2019)
Buoyancy	Terminal velocity between 1 mm/s and 2 cm/s.		(Nordam et al., 2019)
Vertical diffusivity	Based on wind speed	ECMWF/MEPS	(Sundby, 1983)
Gray seeding	5000 elements released every 10th day within a geospatial radius of 10 km from each seeding location.		

[a] Applied only to surface particles.
[b] Applied only to microplastic particles.

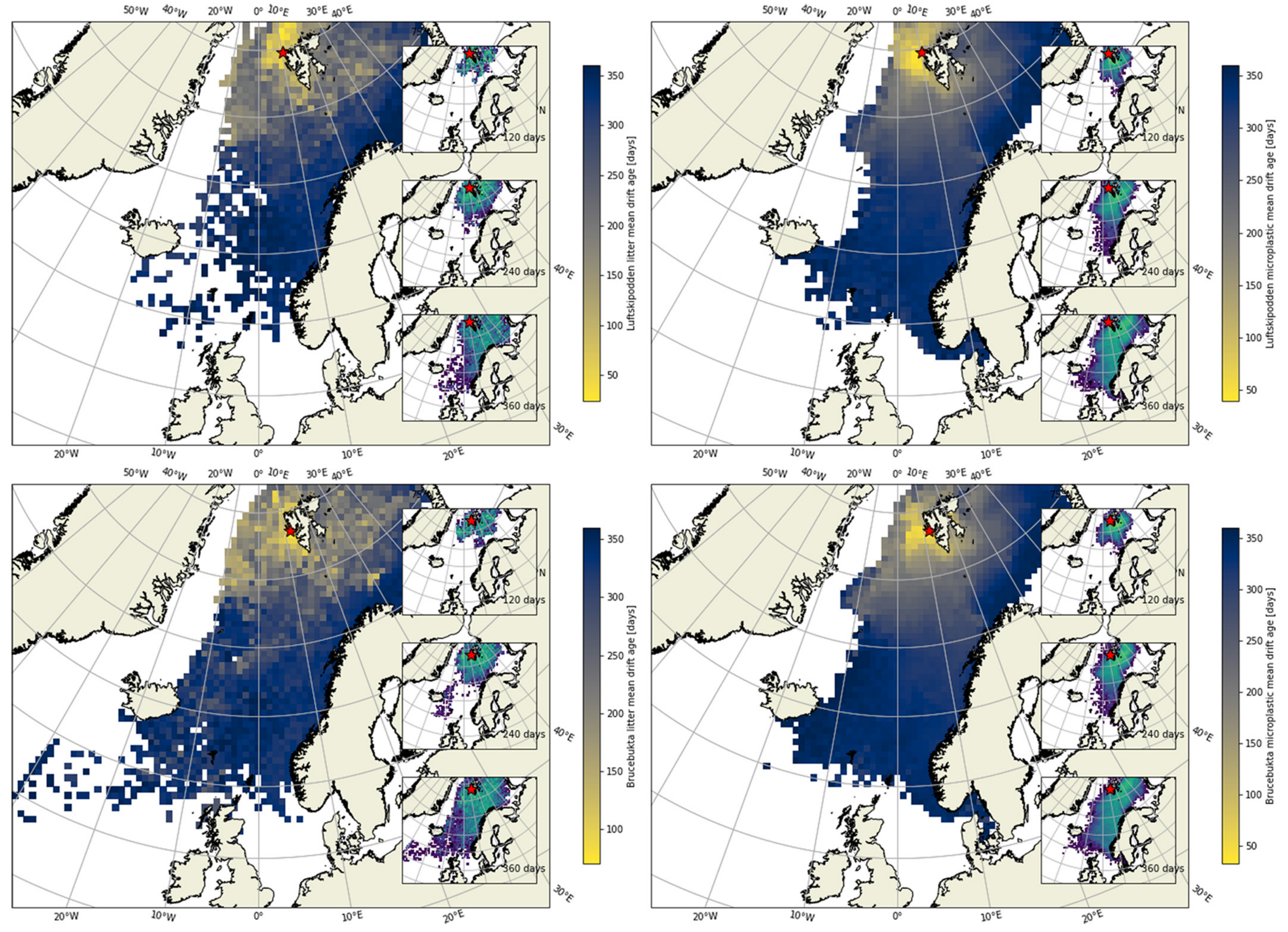

Fig. 2. Average drift of marine plastic reaching each respective stranding site around Svalbard. Main figure shows average drift time to Luftskipodden (top row) and Brucebukta (lower row) for both marine litter (left) and microplastics (right) with average concentration of plastic particles for three times; 120, 270 and 360 days in inset figures.

mainly from the North Sea, while microplastics come to a large degree from the Baltic Sea. There is potentially a long-distance transport from the Northeast Atlantic with the North Atlantic Current, but this involves only a small percentage of the particles. Marine plastic north of 60°N does not reach these two southern sites.

An evaluation of the drift ages shows that litter moves faster than microplastic, e.g., litter from the Northeast Atlantic can reach Hvaler within 50 days and Været within 100 days.

4. Discussion

The drift of marine plastic is discussed in terms of drift simulation results, in comparison with observations at the OSPAR beaches. The backtracking simulations provide a method for evaluating the possible origins of plastic, and whether it is possible for plastic from a particular source to reach a particular beach. The analysis does not consider how much plastic is released at each potential source and therefore our results do not include information on the total amount of plastic reaching each destination site. Conclusions are drawn from drift ages and the most likely origins of plastic litter at each destination.

The OSPAR records from beach sites do not include information about the sources of plastic or plastic waste age. However, the observations do allow for speculation on the type of pollutant since they categorize plastic into types of litter, i.e., whether litter at a beach site is predominantly fishery or consumer-related. By combining the observed amounts of categorized litter with the simulated drift pathways, an increased understanding about the origins of drifting marine plastic is obtained. The model-observation comparison is only available for litter, as microplastics are not being monitored by OSPAR. The microplastics simulations in this work are included for comparison with the plastic litter simulations, in order to shed light on how the drift of the two plastic types differs.

4.1. Heterogeneous observations

The differences in the amount of observed plastic litter between the beaches can largely be explained by distinguishing between fishery-related plastic and consumer-related plastic litter.

Hvaler, which receives the most plastic litter, is located in the more densely populated southern Norway (Oslofjord) and is thus more prone to consumer-related litter. In addition, it is connected to hotspot fisheries and other potential sources in the North Sea region by oceanic transport. Similar to Hvaler, Kviljo is connected to the North Sea, but interestingly only small amounts of plastic are observed here, mostly consumer-related. A significant difference is that Kviljo is a sandy beach parallel to the open ocean, and the observations indicate that most drifting plastic is passing this beach by. In second place in terms of amounts of observed plastic litter, is Rekvika, which has its name from the Norwegian “rek” = drift and “vik” = bay, thereby revealing its historical propensity for collecting marine debris. This beach faces the open ocean where the Norwegian Atlantic Current meets the Norwegian Coastal Current (Fig. 1). The simulations reveal that there are many upstream source regions that have a potential to

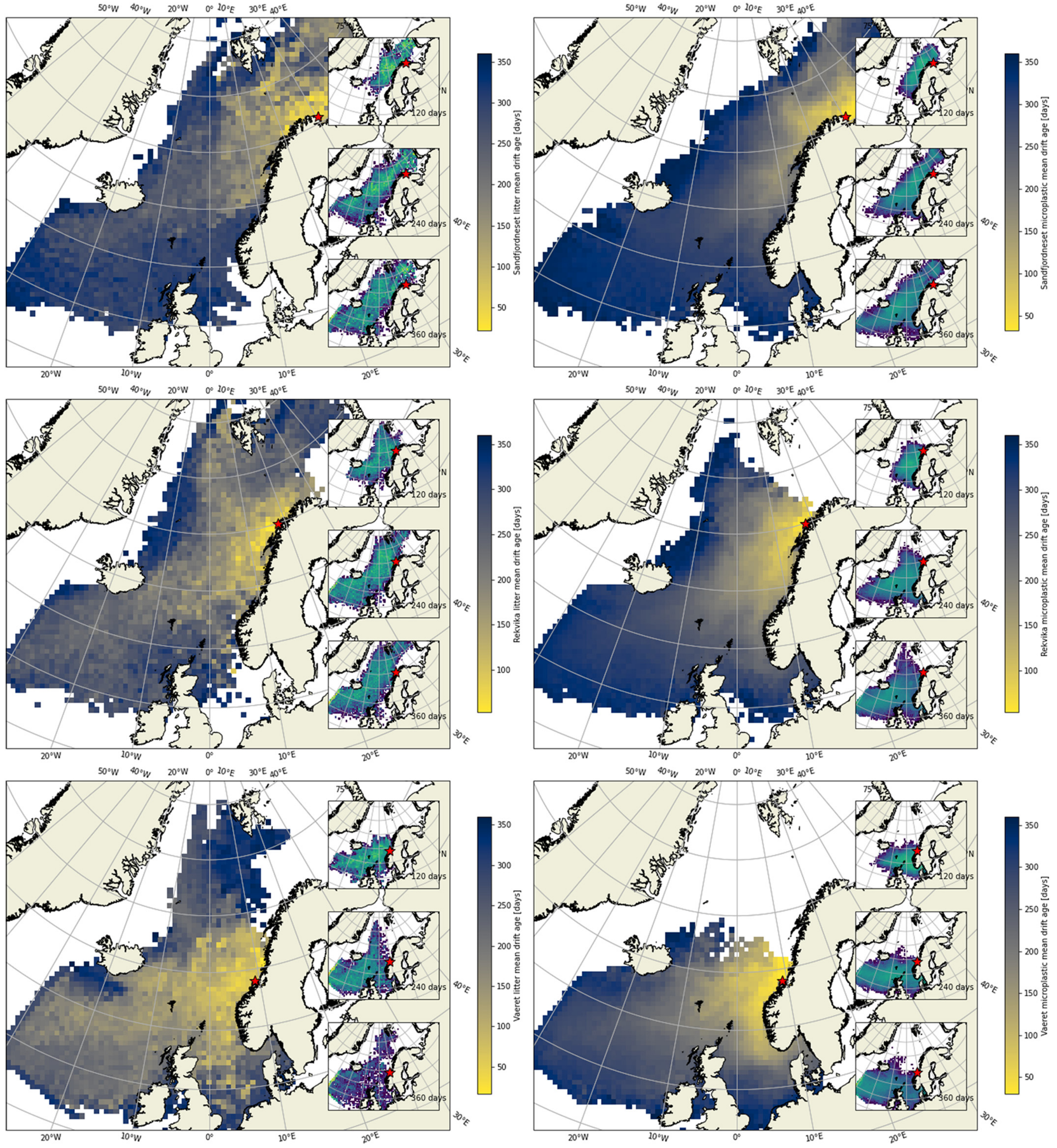

Fig. 3. Average drift of marine plastic reaching each respective stranding site for northern Norway (top two rows) and northwest Norwegian coast (lower row). Main figure show average drift time to Sandfjordneset (top row), Rekvika (middle row) and Været for both marine litter (left) and microplastics (right) with average concentration of plastic particles for three times; 120, 270 and 360 days in inset figures.

provide litter to Rekvika. Like Rekvika, Været is connected to both the Norwegian Coastal Current and the Norwegian Atlantic Current. However, it is located on the sheltered side of an island and would therefore not be expected to receive the same amount of marine plastic litter. The three beaches on the sparsely populated rim of the Barents Sea (Luftskipodden, Brucebukta and Sandfjordneset) receive an order of magnitude less plastic litter than Hvaler and Rekvika, and the plastic is mostly fisheries-related.

The plastic litter observations at Været vs. Rekvika and Kviljo vs. Hvaler (Table 3), as well as the small amounts of plastic observed at the Arctic sites will therefore be discussed in more detail together with the simulations in Section 4.2.

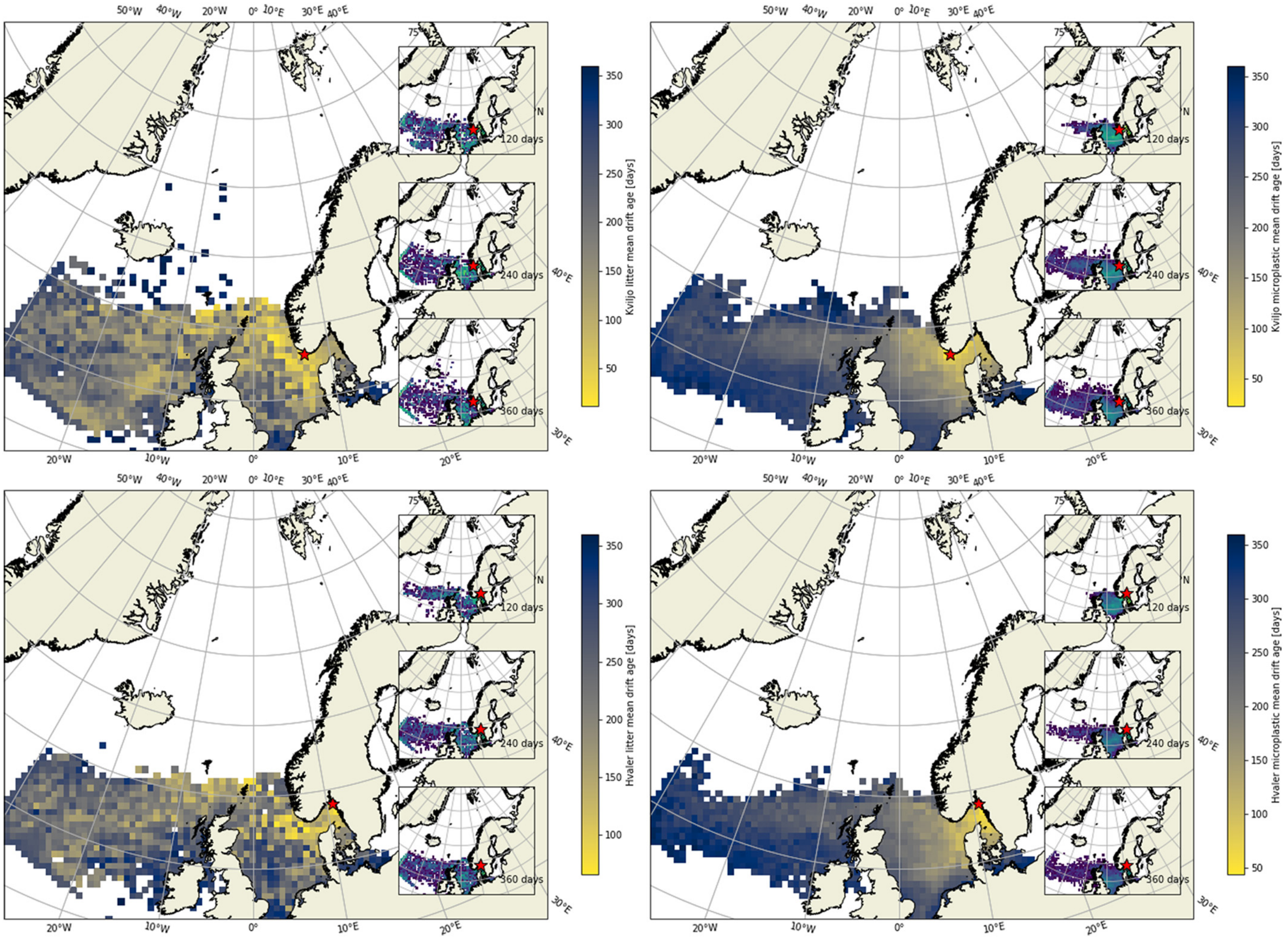

Fig. 4. Average drift of marine plastic reaching each respective stranding site for southern Norway. Main figure shows the average drift time to Kviljo (top row) and Hvaler (lower row) for both marine litter (left) and microplastics (right) with average concentration of plastic particles for three times; 120, 270 and 360 days in inset figures.

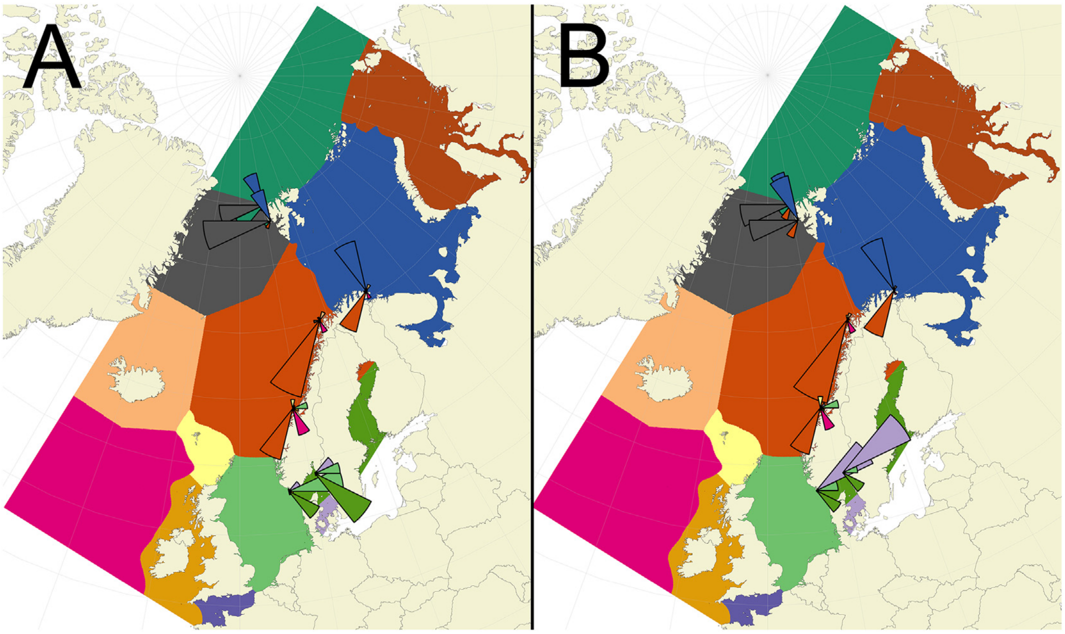

Fig. 5. The main sources of (A) plastic litter and (B) microplastics at each of the seven Norwegian OSPAR beaches. The length of the source sectors are scaled according to the numbers in Table 3 and colored according to the selected source areas in the background.

Table 3
Relative potential sources of litter/microplastics arriving at each Norwegian OSPAR site in percentage, as fraction of total litter arriving at the respective beach sites within a time period of 360 days. These are relative sources not reflecting how much litter/microplastics are emitted in the respective ocean areas. Based on trajectory simulations accounting for currents, wind and waves and a backward cumulative concentration estimate (Eq. (1)). The respective ocean areas are defined in Fig. 5. For each stranding site, the main sources are highlighted in bold text.

	North Sea	Baltic Sea	Icel' Sea	Faroe Sea	Barents Sea	Greenl' Sea	Arct. Ocean	Norweg. Sea	Atlan. Ocean	Skagerak	Irish Sea
Luftskipodden				0	**29/29**	**39/45**	**27**/12	5/**14**			
Brucebukta					**28/40**	**59/43**	6/0	7/6			
Sandfjordneset	1/1		6/2	2/2	**45/47**	2/0		**37/42**	7/4		1/0
Rekvika	0/2		8/4	2/4	3/0	5/0		**69/75**	**11/12**	0/1	1/0
Været	**13/16**	0/5	3/1	8/10				**46/42**	**24/20**	0/4	5/3
Kviljo	**48/19**	**11/55**		2/0					3/1	**30/24**	4/1
Hvaler	**22/13**	**18/66**		1/0					2/0	**55/21**	2/0

4.2. Observation-model synthesis

A main challenge to a meaningful synthesis between model and observational data is the differences in the nature of information provided by the two methods. However, the distinction between fishery-related plastic and consumer-related plastic waste discussed in Section 4.1 provides means to relate the model results to the observed information, particularly when comparing the various OSPAR sites.

While possible sources may span the entire Northeast Atlantic and the Arctic rim, our study confirms that the intensively fished European continental shelf (in particular the North Sea, Norwegian Sea and Barents Sea) may act as a large source of plastic waste for the beaches that receive substantial amounts of fishery-related litter. In our simulations, the Arctic beaches receive most particles from the Barents Sea and the Norwegian Sea where fishing is extensive. These results are empirically supported by surveys performed at sea (Grøsvik et al., 2018; ICES, 2020) and are in accordance with findings by (Schwarz et al., 2019). Also, Bergmann et al. (2017) report that the majority of plastic pollution on Svalbard beaches is fishery-related, and that records from these beaches resemble pollution levels in the surrounding waters. Grøsvik et al. (2018) show that plastic litter is widely distributed in the Barents Sea, although the highest amounts are in the southeastern part. Fishery-related litter is a significant part of plastic litter both in the pelagic and bottom trawls.

Another factor is the large contrast in population density across our study region, which is directly reflected by the fraction of consumer-related plastic pollution reported for each site, see Table 1. Northern Norway and Svalbard are assumed to emit close to zero consumer-related plastic compared to southern Norway and North Sea countries. Accordingly, little consumer-related plastic is reported in the this part of the Arctic. This is confirmed by our simulations (Table 3) showing that the more populated areas (e.g., North Sea, Skagerrak and Baltic Sea) are not a source of litter to the Arctic sites. We therefore suggest that the fishery-related litter at the Arctic sites stems from local sources (the Barents Sea and Norwegian Sea), confirming a statement by Buhl-Mortensen and Buhl-Mortensen (2017) who argue that most of the marine litter on the Norwegian continental shelf and in the Barents Sea has rather local sources and that long-distance transport is not a relevant factor.

While ocean currents do transport water masses from the European shelves to the Arctic, the long drift time - more than a year - required to reach the Arctic (Fig. 2) causes marine litter to be stranded by the action of wind and waves along the coast of Norway before reaching the Barents Sea or Svalbard. Stranding of litter on nearby beaches is also seen on the coast of the United Kingdom (Turrell, 2019). Remote sources (North Atlantic, North Sea) play a minor role for litter in the Arctic and only for long drift times.

4.3. Litter vs. microplastics drift simulations

The difference between plastic litter and microplastics - in terms of our model simulations - is that litter resides at the ocean surface being exposed to wind and waves, while microplastics spend time both near the surface and at depth (Fig. A.2). For marine litter simulations, inclusion of wind drift and Stokes drift is therefore essential (Röhrs et al., 2012; van den Bremer and Breivik, 2018; van Sebille et al., 2019). Simulations indicate that litter drifts faster and spreads wider than microplastics do. Floating plastic litter can drift against mean ocean currents due to strongly varying wind drag, e.g., southwestward net transport along the coast of Norway, against the Norwegian Coastal Current. Submerged microplastics follow the local ocean currents to a larger degree. For both types of plastic waste, interannual variations in drift patterns are expected due to year-to-year variability in wind forcing and ocean current strength, as documented by buoyant drifting cod eggs in the same region as this study (Strand et al., 2017).

Both marine litter and microplastics can arrive on the OSPAR sites from remote places via the North Atlantic Current, taking typically 6 months up to a year. Marine plastic with short drift age has exclusively local sources in the adjacent seas around Northern Europe, but, as seen at Rekvika, the North Sea is a potential source for microplastics (but not plastic litter, see Fig. 3 and Table 3). This is interpreted as microplastics being more isolated from direct wind drag and wave-driven transport, thereby enabling longer transport distances within the boundaries of the ocean currents. In this sense, the drift of microplastics is similar to other passive tracers, e.g., radioactivity (Simonsen et al., 2017).

4.4. Concluding remarks

The simulation experiments presented in this paper have been co-designed by scientists and practice experts, in order to target subject areas where stakeholders experience marine plastic waste to be most prominent. To develop effective policies for avoiding plastic waste, one needs to have better information about the most important sources, in this case where the bulk of marine litter in our specific study region comes from. To answer this question, Fig. 5 was made to provide the stakeholders with distinct information about the main potential sources of plastic using trajectory simulations based on state-of-the art geophysical circulation models.

Documentation of marine pollution at particular sites, the OSPAR beaches, has been a first step in evaluating the degree and nature of the marine plastic pollution problem. We have performed backtracking simulations that shed light on how various potential source regions for plastic litter may contribute to the contamination observed at the OSPAR sites. In a next step, the plastic samples from the individual stranding sites could be analysed further by their age. Using this information together with the simulated drift ages will help us to further narrow down hot-spot sources to the respective sites. Further research is needed to explore what causes inadequate waste disposal in these regions, and to determine the roles of different actors in allowing or preventing litter from reaching the seas.

Marine litter is an example of a post-normal problem, meaning that objective scientific facts and subjective socio-political values are difficult to untangle. Post-normal problems involve high levels of uncertainty, conflict and challenged legitimacy (Funtowicz and Ravetz, 1993). In this context, co-production of knowledge emerges as an iterative process that brings together scientific experts and practice experts. Such collaborations result in research that has both high validity, high legitimacy and high relevance. Results not only add value for the science community, but also impact practice and policy-making (Norström et al., 2020; Jasanoff, 2004). The method of collaboration between scientists and the *extended-peer review community* in the Barricade "Marine Plastics Drift Simulation Laboratory" has improved the scientific design and output of the Barricade project. We hope that the collaboration will make it easier to embed scientific knowledge into the management of marine litter.

CRediT authorship contribution statement

Johannes Röhrs: Conceptualization, Methodology, Numerical simulations, Manuscript preparation, Project administration, Funding acquisition.

Kjersti Strand: Methodology, Analysis of observations, Numerical simulations, Manuscript preparation, Conceptualisation.

Mats Huserbråten: Analysis of observations, Manuscript Preparation, Methodology Knut-Frode Dagestad: Software, Numerical simulations, Sensitivity analysis, Manuscript preparation.

Cecilie Mauritzen: Manuscript preparation, Co-production of knowledge, Conceptualization.

Bjørn Einar Grøsvik: Manuscript preparation, Analysis of observation, Methodology.

Leticia Antunes Nogueria: Manuscript preparation, Co-production of knowledge Arne Melson: Validation, Manuscript editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project has been financed by the Research Council of Norway through the Fram Centre flagship project "Plastic in the Arctic", grant pa052018 "BARRICADE". We also like to express our gratitude to Maiken Bjørkan, Grete Hovelsrud, Ingrid Bay-Larsen and the stakeholder group for the discussions on the study concept, including participants from MarintMiljø (Keep Norway Beautiful), the Governor of Svalbard, WWF Norway and the Norwegian Environmental Agency. We also thank Bruce Hackett for proofreading of the manuscript.

Appendix A. Sensitivity tests and model validation

A.1. Wind drag coefficient for surface particles

For the simulations in this study, the horizontal drift is the linear sum of the ocean current, Stokes drift at the actual depth, plus an additional empirical wind drift component of 2% for litter or microplastics at the very surface. Whereas the wind drift coefficient of 2% is empirically established from previous studies (e.g., Röhrs et al. (2012); Jones et al. (2016); Dagestad and Röhrs (2019); Sutherland et al. (2020)), it is of interest to check to which degree the results are sensitive to the exact value of this coefficient. We have performed 1 year backwards simulations from one of the OSPAR locations — VÃ¦ret – with continuous release of particles. We have performed simulations for microplastics (submerged) and litter (surface) as described in the main text, but for litter we have also performed simulations with a slightly lower (1.5%) and higher (2.5%) wind drift coefficient. The final distribution (1 Jan 2019, 1 year prior to the start of the release at 31 Dec 2019) is shown in Fig. A.1. We see a clear difference in the distribution between the simulation with microplastics, and the 3 simulations with litter and varying wind drift coefficient. There are smaller differences among the simulations with the various wind drift coefficients, but nevertheless we see that the results are fairly sensitive to the value of this coefficient, and thus its accurate assessment is important. However, the differences between the results with various wind drift factors are smaller than their overall difference to the simulation of microplastics.

A.2. Depth distribution for submerged particles

Simulation of microplastic particles exhibits a sensitivity of particle velocity to the vertical position of the particles because i) the ocean current varies with depth (Röhrs et al., 2021), ii) the Stokes drift profile decays rapidly with depth and iii) wind drag is applied only to particles at the surface. The effect of depth distribution on the long term drift of submerged particles has been studied in detail by (Röhrs et al., 2018). In essence, particles near the surface tend to drift partly with the dominant wind direction while particles at depth follow the ocean currents. Hence, the more buoyant a particle, the more it is affected by wind drift. It is therefore important to evaluate the depth distribution of microplastic particles of various buoyancies, e.g., by size. Vertical particle distributions under various wind speeds are shown in Fig. A.2. These depths correspond to expected intrusion depths of observed plastic particles, e.g., (Kukulka et al., 2012), and their dependence on wind speed, as stronger winds tend to mix particles downwards (Sundby, 1983).

A.3. Current velocities from ocean model

The ocean circulation model used, Nordic4 ROMS is the operational ocean modeling system used for ocean forecasts at MET Norway. This model setup, and similar setups of ROMS for the Nordic Seas, are routinely used for particle tracking studies (Asplin et al., 2020). Lien et al. (2013) provide details and a validation of Nordic4 for the period of 2011–2010. Nordic4 current velocities have furthermore been validated against moored current profilers by Melsom and Gusdal (2015). The latter report shows that the model has little predictive skill on mesoscale circulation. However, current statistics in terms of frequency distribution of current speed and directions, as needed for the Monte Carlo simulations in this study, reflect the observations reasonably well. The model slightly underestimates extremes in current speed, most likely due to unresolved current jets, eddies, and fronts. While such features contribute to particle dispersion, they are not expected to have large bearing on the long-term transport by the dominant current systems.

A validation of near-surface current velocities against drifters from the Surface Velocity Program (SVP) for the period of 2017–2018 is shown in Fig. A.3. The data were retrieved from the Copernicus Marine Environment Monitoring Service (CMEMS) portal (https://resources.marine.copernicus.eu), from the product INSITU_GLO_NRT_OBSERVATIONS_013_030. Fig. A.3 shows an under-representation of extreme surface velocities by the ocean model that may be attributed to unresolved mesoscale features, as reported by the validation of (Melsom and Gusdal, 2015). The SVP drifters sample ocean currents at 15 m depth.

Röhrs et al. (2014) show a validation of surface currents against CODE drifters, which measure at 0.5 m depth, for a similar model setup of ROMS (800 m resolution) in a coastal area. In this case the model velocities agree with the drifter velocities within 0.01 m/s when the Stokes drift is added to model velocities, supporting our hypothesis that mismatches in the Nordic4 model are due to unresolved circulation features.

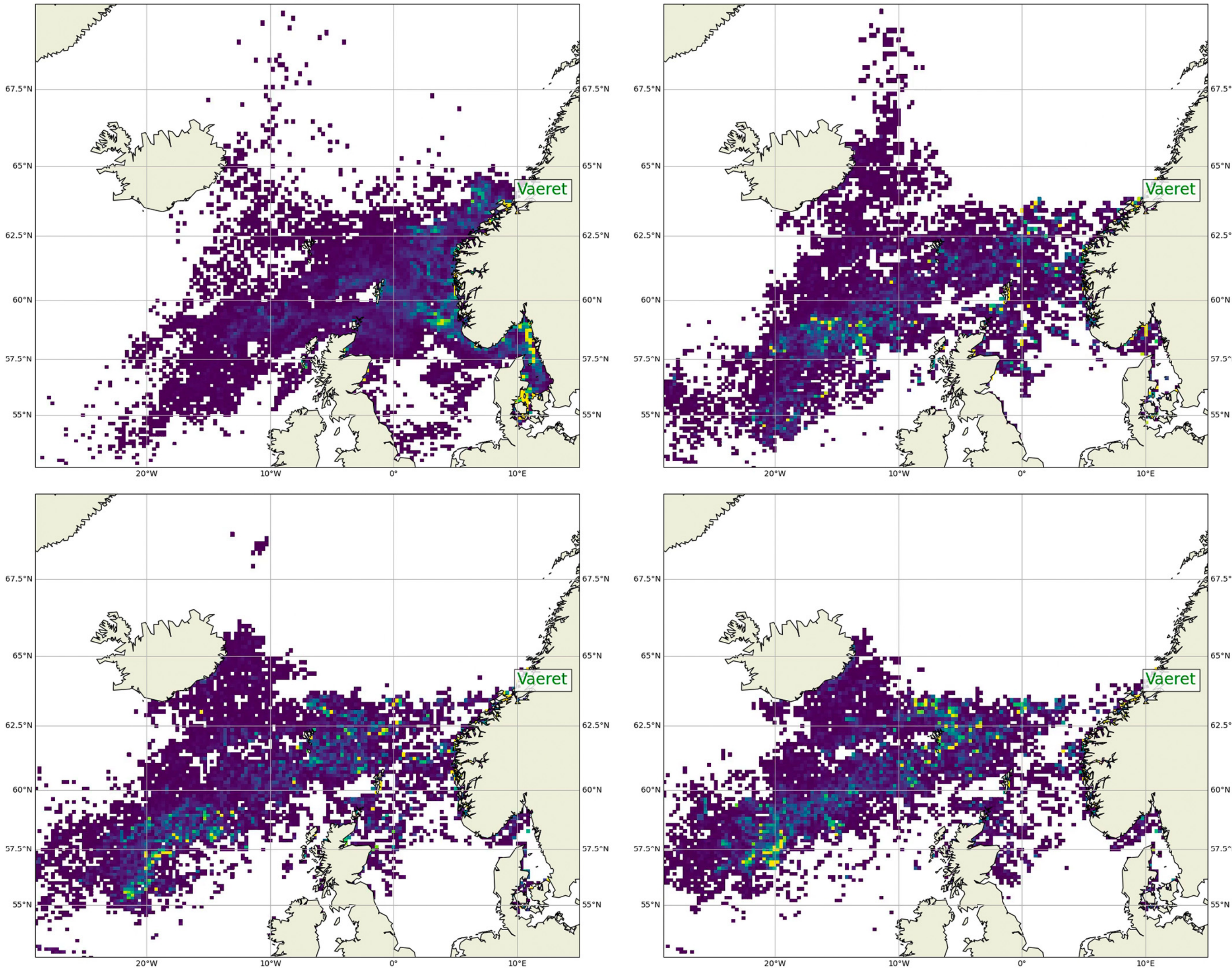

Fig. A.1. Distribution of microplastics (upper left) and litter (other 3 figures) after 1 year backwards simulation with continuous release at location Været starting from 31 Dec 2019. For the litter simulations, 3 different wind drift coefficients are used: 1.5% (upper right), 2% (lower left, and as used in main simulations), and 2.5% (lower right).

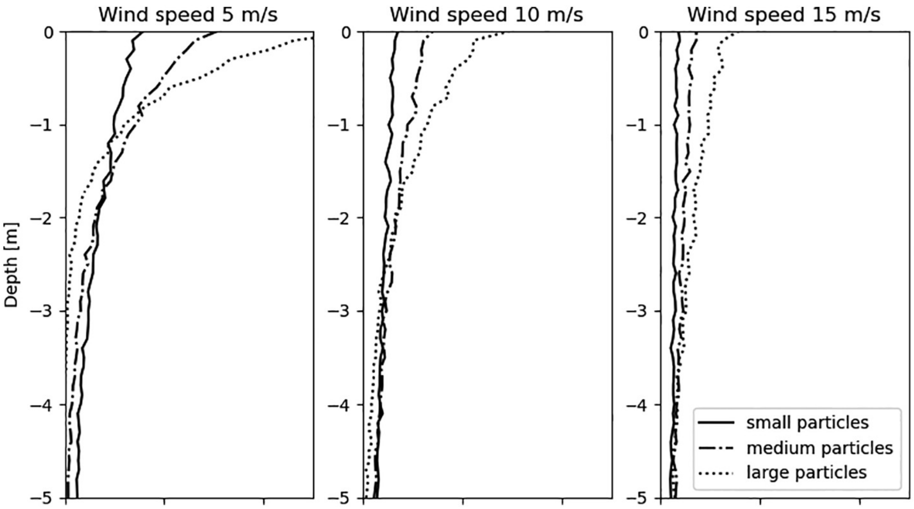

Fig. A.2. Vertical microplastics distributions of simulated particles for three wind speeds and three terminal velocities (small, medium, large particles).

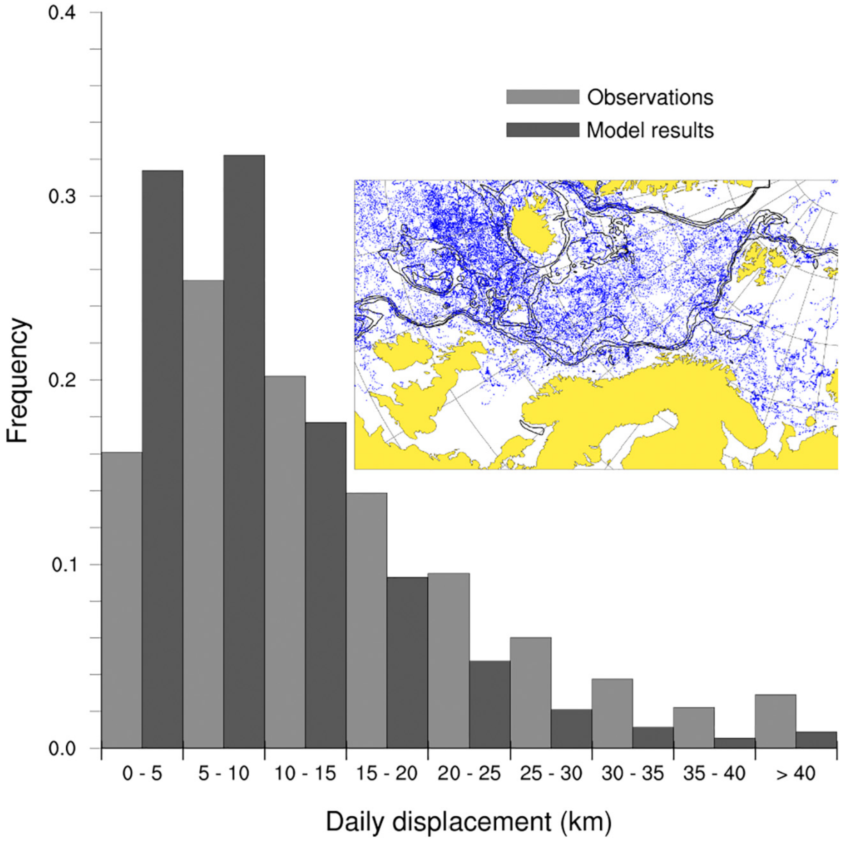

Fig. A.3. Histogram displaying category distributions of daily displacement distances from drifting buoy data and corresponding integrated trajectories based on surface currents from ROMS Nordic4. The buoy data are for drogued drifting buoys, compiled by NOAA AOML. Displayed here are the frequencies for the various distance categories, as specified by the x axis labels. Light and dark gray bars correspond to the distributions from observations and integrated model results, respectively. Insert map: Ocean model domain, with the positions of the drifting buoy observations from 2017 and 2018 shown as blue dots. The number of positions is 35,761. Isolines are drawn for the bottom depth contours of 400 m, 800 m and 1500 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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