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University of Plymouth

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Numerical models to track the origin and drift of pharmaceutical flotsam in the English Channel

Alizee De Groodt

Project Advisor: [Prof Daniel Conley](), School of Biological and Marine Science, University of Plymouth, Drake Circus, Plymouth, PL4 8AA

Abstract

Marine plastic pollution is an increasing problem that has serious impacts on the environment. The sources, pathways and fate of plastics in the ocean are still poorly understood, especially for marine pollution coming from marine-based sources. In November 2018, a high number of pharmaceutical bottles named 'Otrivin' started to beach in high numbers along the English Channel. Research was initiated to investigate the likely origin of the bottles. In this study, we continue this research using the observational data from 2018-2019 and two numerical ocean models to hindcast the likely origin of the bottles, but also assess whether the effect of Stokes drift can have a significant influence on the particles in a sea mainly driven by strong tidal current. Data of the surface currents and Stokes drift from both Copernicus Marine Environment Monitoring Service (CMEMS) and the European Centre for Medium-Range Weather Forecasts (ECMWF) was used to calculate the trajectories of the particles. Two experiments were run in both ocean models which enabled comparison of the results and verification of their accuracy. The first part of the experiments simulated the trajectories of the particles back in time, from the time they were found, until September 2018. In the second part of the experiments, the results from the backtracking experiments were used as the initial location to run a simulation forward in time. Lastly, simulations run with the effect of Stokes drift showed that for some locations, the effect of the tide will be stronger, while in other locations the effect of Stokes drift is stronger. While few uncertainties arise, overall, the results from all the experiments suggest a likely zone of origin in the middle of the Channel.

Keywords: Marine plastic pollution, flotsam, Numerical Modelling, Lagrangian, English Channel, CMEMS, ECMWF, Otrivin

Introduction

The general definition for marine anthropogenic debris indicates any solid material that has been manufactured or processed by man and, after its use, has entered the marine environment (United Nations Environment Programme, 2005). Today, plastic is almost ubiquitous due to the wide range of its applications such as food packaging, technology, fishing gear but also medical uses (Frias, 2018). Despite the global recognition that marine plastic is a threat to wildlife (Gregory, 2009; Peltier et al., 2020; Galgani et al., 2015; Duncan et al., 2018; Stelfox et al., 2016; Steer, and Thompson, 2020; Napper, and Thompson, 2020), economies (McIlgorm et al., 2011), and human health (Wright et al., 2017), the global production of resins and fibers continues to rise exponentially. It is important to address that plastic is seen as a general material that it is all the same just because it is called the same, but in practical application, each object is an individual particle that floats and moves in the water in different ways (Ocean Cleanup, 2017).

It is widely assumed that most of the “marine plastic pollution comes from countries in Southeast Asia where there aren’t adequate waste management systems but in reality, most of the litter, we find along the coast has come from local areas” (Thompson, quoted in Bounds, 2019). Sustained monitoring of litter is therefore crucial to understanding the abundance, pathways and impacts of marine pollution but it can be time-consuming and costly when it is done purely from observational data (van Sebille et al., 2020). Instead, numerical modelling can address these issues by computing the trajectories of a given object, substance or, organism into an ocean model.

The study of transport and mixing in geophysical flow is an active area of research which is now commonly used for the spreading of pollutants such as oil and nuclear waste (Arkhipov and Shapochkin, 2019, Breivik& Allen (2008)) search and rescue missions (Durgadoo et al., 2019), fish distributions (Headlam, 2020) and monitor the pathways of marine pollution from coastal and tsunamis disasters (Maximenko et al., 2018, Kaandorp et al., 2020).

Little is known of where exactly plastic debris comes from and how they behave with the physical, chemical and biological processes of the ocean.
While most of the marine pollution comes from land-based sources (80%), few research have focused on the increasing pollution that comes from sea-based sources (20%) which also play an important role and are the least famous. Discarded fishing nets make up to 10% of all reported plastic and have devastating consequences on wildlife. Another important source of ocean pollution are containers falling from ships releasing their content. According to the World Shipping Council (2020 cited in, International Institute of Marine Surveying, 2020), approximately 1390 of them are lost at sea each year. This number is highly approximated as these are only the reported containers.

Otrivin bottles are nasal decongestants that were spotted in high numbers in December 2018 at Lannacombe beach by reporter Kristen Bounds (Facebook, 2020). She launched an appeal on social media to see if other people had found these bottles and in two weeks more than a thousand of them were reported as far as Thorpeness, France and the Netherlands.

Along with Professor Richard Thompson (Thompson et al., 2004; Thompson, 2017), research was started in January 2019 to find the possible source of the bottles but, after a few months, it was terminated as their origin could not be identified. The bottles were originally manufactured by CIBA (Chemical industries Basel), one of the largest pharmaceutical companies in the early century. However, in 1996, the company merged to form Novartis AG, and in 2018 it was bought by the largest pharmaceutical company GlaxoSmithKline (GSK, 2018). This means that the Otrivin bottles that were found along the Channel are old prototypes which do not exist on the market anymore. Knowing that around 500 container ships pass by the English Channel daily, one of the assumptions is that the Otrivin bottles found along the Channel, could possibly come from a cargo ship that has lost some of its containers during rough weather. However, as the container ship could not be identified, the other assumption is that the container has actually fallen into the ocean and broke open into the Channel approximately two years ago.

Very few studies have gathered data on flotsam, especially in the English Channel. This study is an opportunity to add information on the little literature that exists on flotsam in the Channel. By using the data on the stranding location of the Otrivin bottles, the specific aims are first to use two Lagrangian particle-tracking models to hindcast the most likely origin and trajectories of the pharmaceutical bottles. Secondly, we assess whether the Stokes drift, which is an important factor in moving objects in the ocean, could have a potential influence on the Otrivin trajectories and, lastly, we validate the models by simulating the trajectories of the particles forward through time from the inverse modelling results.

Apart from studying the likely origin of the Otrivin bottles, the results of the study can provide useful insight for the development of new approaches to tackle marine pollution that comes from local areas.

Methodology

Theory

The transport of objects (and substances) over the surface of the ocean is commonly referred to as drift (Hackett et al., 2006) and its movement from one location to another is dependent on the properties of the object and the governing hydrodynamic processes of the environment (Aillot et al., 2008).

Objects that are computed into the numerical models will be referred to as particles. The trajectory of a floating object starting at a given position and time is moved forward or backward in time using the velocity description from the data. The Eulerian approach is based on the integration of the advection-diffusion equation on a fixed set of grid points in space which describes the motion of the particles at a specific location as time passes. On a global scale, Eulerian models can simulate particles similar to how tracers are used to study temperature and salinity (van Sebille et al., 2020). The second approach makes use of the equations of motion in a Lagrangian framework to determine the trajectory of the particles (Calò et al., 2018; Hinata et al., 2020a; Hinata et al. 2020b; van Sebille et al., 2020). This means that the properties of each particle are measured as it changes position. Another advantage of this approach is that particles can be advected backward in time, which allows to investigate the likely origin of the particles (Calò et al., 2018). This approach is commonly used in oceanography to analyse the three-dimensional transport of seawater and is the approach used in this paper.

As mentioned earlier, each object behaves differently in the water depending on its size, shape and, chemical composition (Ocean Cleanup, 2020). To determine the origin of plastic debris in the marine environment, knowing the types of polymer used can provide a potential indication (Sadri and Thompson, 2014). The most used and produced plastics in the world are polyethene (PE), polypropylene (PP), polyvinyl chloride, polystyrene and, polyethene terephthalate. Otrivin bottles are small plastic flacons made of Polyethylene (PE) with a size of less than 10 cm (Figure 1) which makes them highly buoyant over the surface of the sea. However, the bottles were found without a cap and so we assume that the bottles were partially submerged or floating just under the surface.

Table 1: The different densities of each plastic are exposed in comparison to the surface seawater.

Type	Density (Kg/m3)
Polyethylene (PE)	920
Polypropylene (PP)	895
Polyvinyl Chloride	1100
Polystyrene (PS)	1000
Polyethylene terephthalate	1380
Surface Sea Water	1024

Study site

The English Channel is a narrow arm of the Atlantic Ocean separating the northern coast of France and the south coast of England. It is one of the smallest seas of the

Figure 1. Picture of the Otrivin bottles found along the English Channel (Tamar Powlesland).

European continental shelf with an area of about 29,000 square miles (75,000 square km). The main water masses found in the Channel are a combination of the

North Atlantic current (NAC), the North Sea water (NSW) and, the run-off from the rivers. The Channel exhibits relatively shallow water that decreases from 400 to 120 feet(120 to 35metres) at the Strait of Dover coupled with a width that gradually narrows from 150 miles on the western side to 21 miles at the Strait of Dover. The bathymetry of the Channel is shown in Figure 2. The data was downloaded from the Gebco (General Bathymetric Chart of the Oceans) website (www.gebco.net) and plotted on Python. The shallow water and bathymetry of the Channel force the volume of water to concentrate in a very small area and thus results in impressive mean spring tidal ranges that can reach up to 12m in Saint-Michael's Mount Bay (D.

Idier et al., 2012). Subsequently, tidal current speeds can range from afew cm/s-1 to about 5 m/s-1 in Northwest of Cotentin headland (SHOM, 2000, Idier et al., 2012).

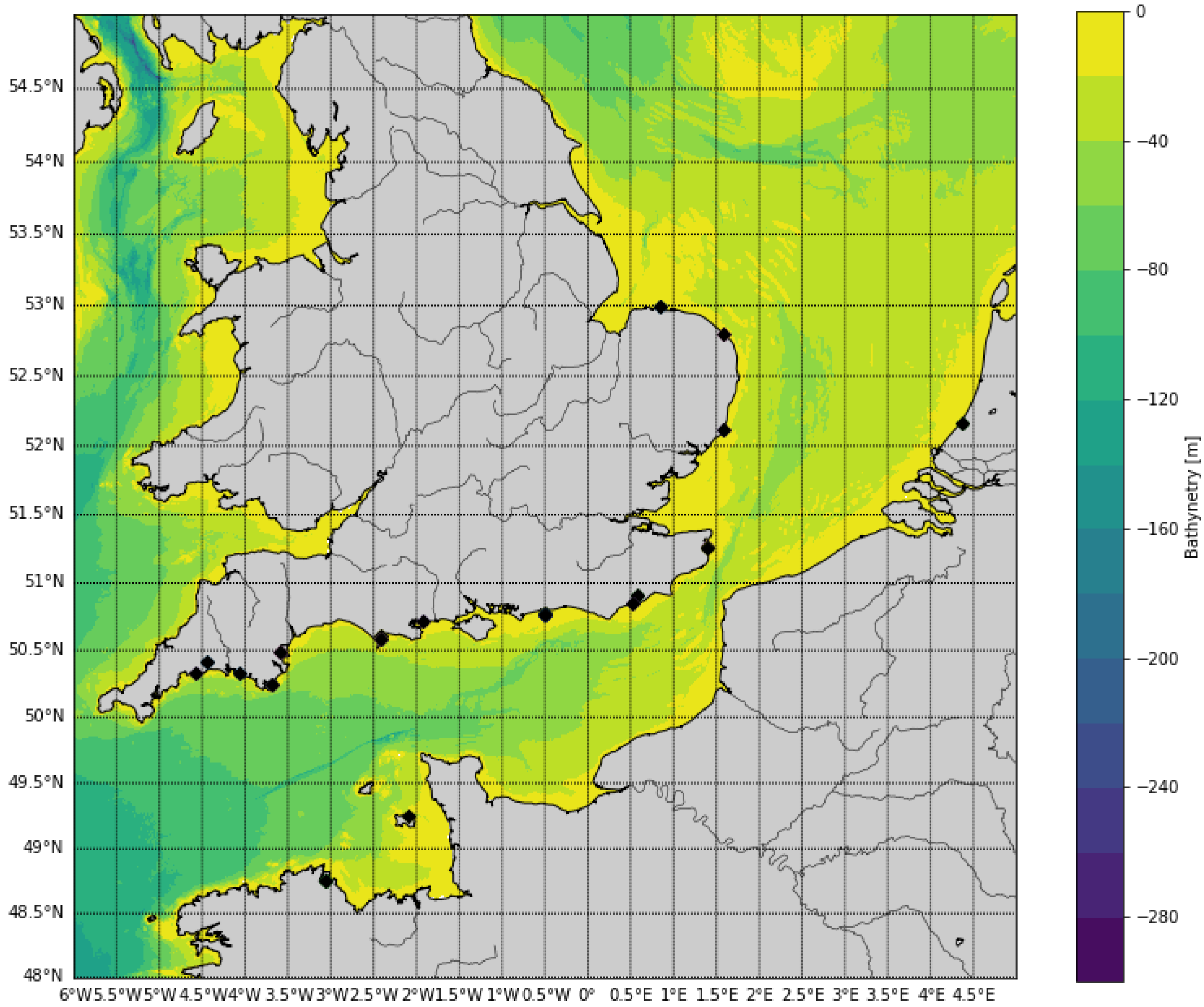
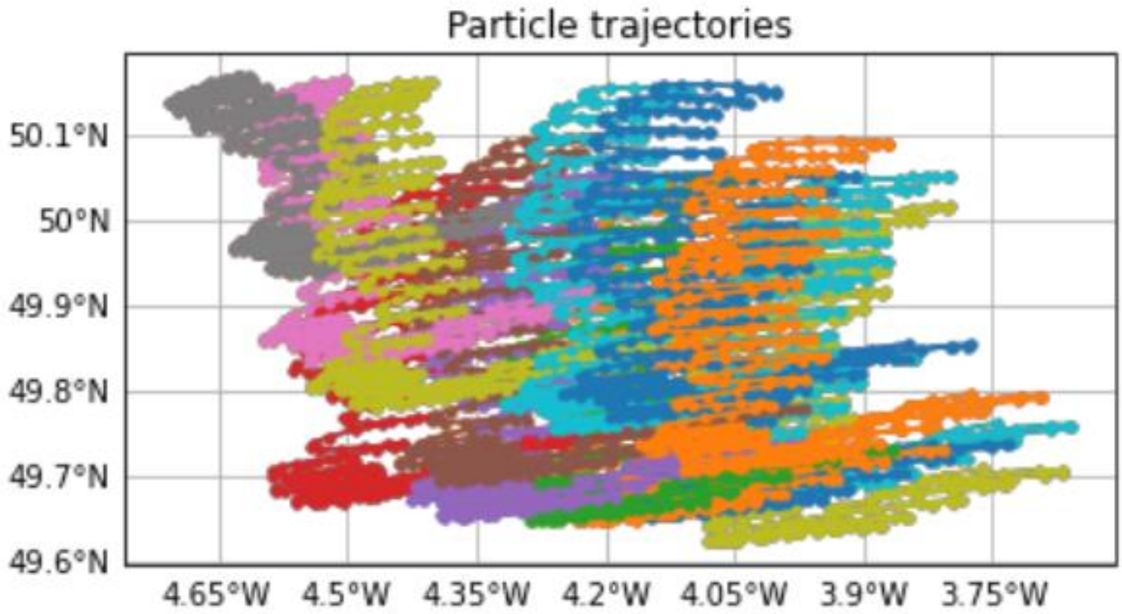


Figure 2: The bathymetry of the English Channel shows substantial shallow differences that vary from 120m at its most western side to 45-35m at the Strait of Dover. Figure created on python notebook with Gebco data. GEBCO Compilation Group (2021) GEBCO 2021 Grid (doi:10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f)

Tides

Tides are the rhythmic rise and fall of the sea level caused mainly, but not only, by the gravitational attraction of the Moon and the Sun. More specifically, they are slow-moving waves that increase in amplitude as they travel from the open ocean to the continental shelf (Wright et al.,1999). The constraint of the Channel geometry and the influence of the Coriolis force results in tides that move in one direction for one cycle, and in the opposite direction for the next cycle. A simulation of the particles for one month shows the semidiurnal cycle where particles follow the ebb (fall) and flood (rise) of the tide twice each day (Figure 3). The final result of this sequence shows the overall trajectory of the particles and more importantly their origin. Thus, tidal currents transport the particles from one beach to another with the tidal phases. An example of this periodic transport of objects on the surface of the ocean can be observed in Figure 3, where particles follow the east and west movement as the tide



lowers and rises.

Figure 3: The back-and-forth movement of the particles following the periodic cycle of the tide. During flood, particles travel to the East while during ebb tide they are moved to the west. Note that each color represents the trajectory of a single particle. Simulation run on Ocean Parcels.

Waves

The last important factor taken into account for the transport of the particles in this study is waves. Depending on the size, shape and buoyancy, wave and wind forces must be either ignored or included. Although the surface dynamics of the Channel are a combination of the tides, wind stress, freshwater influx, meteorological forcing, and waves (Haëck, 2018), the effect of the wind is only effective on objects with an area that is protruding out of the water (van Sebille et al., 2020). Therefore, the effect of the wind is negligible for this study as we assume that the bottles are floating partially or just under the surface.

On the other hand, a particle that is floating on the surface of a wave will experience a net drift in the direction of the wave propagation known as the Stokes drift (Breivik, 2008), represented in Figure 4. Conceptually, the Stokes drift is the mean time difference between the Eulerian and Lagrangian velocities (Wu et al., 2019) and can be a dominant factor in the advection of objects on the sea surface (Breivik, 2008).

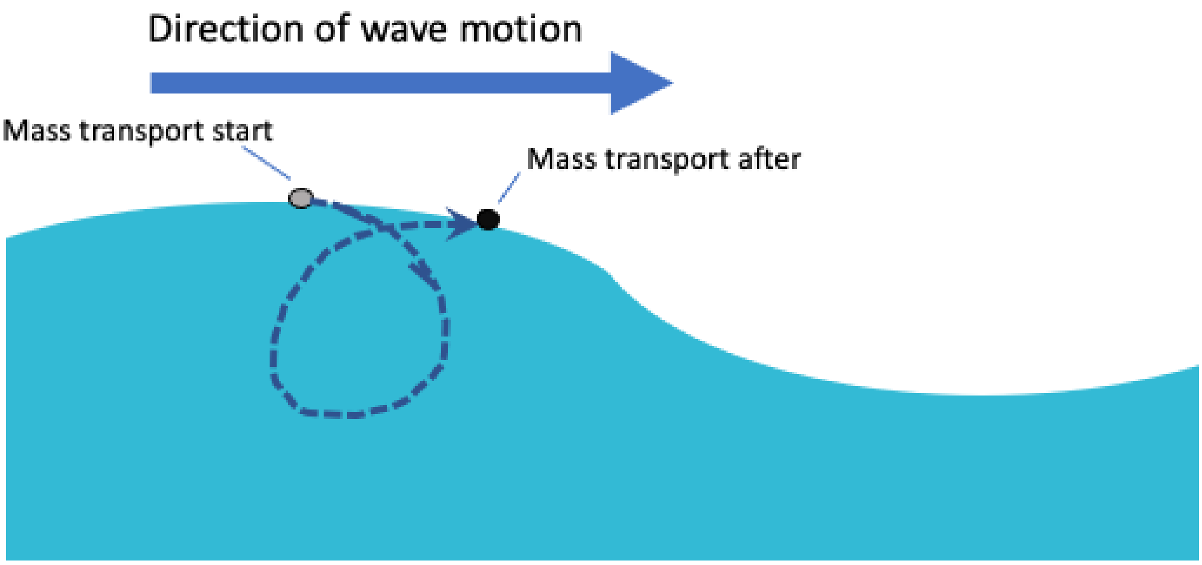


Figure 4: Net drift of a particle with the Stokes drift, diagram based on image from Denison-University (2014, as cited in Abdelaal, and Oumeraci, 2017).

Methodology and Data

To provide a historical context of the Otrivin bottles found along the Channel, several different sources were compiled. Most of the information came from Facebook beach cleaning volunteer pages such as 2minbeachclean, Isle of wight beach cleaning volunteers and Lego lost at sea, which received around 1600 records of the Otrivin flacons coming from as far as France and the Netherlands. The locations were reported in the form of private messages, public posts or comments made on beach cleaning volunteer pages. All the reports were compiled on a map which can be visualized on a bespoke Google Map (2019) showing all the Otrivin Bottle locations.

Coastal observations

To get a better visualization of the stranded bottles and their dates, a 'bubble map' was created on Matlab (Figure 5). Between November 2018 and April 2019, 1600 Otrivin Bottles were reported along the Channel. The highest quantity of the bottles is represented by green circles ranging from 200 to 495 and are only seen in the southern beaches of Cornwall/Devon where at least 800 bottles were found between November 2018 and January 2019. Before this date, no one had seen or received reports of the plastic Otrivin flacons. While these are only the locations at which the bottles were accessible to find, we assume that many more bottles have beached in many areas that cannot be reached by land.

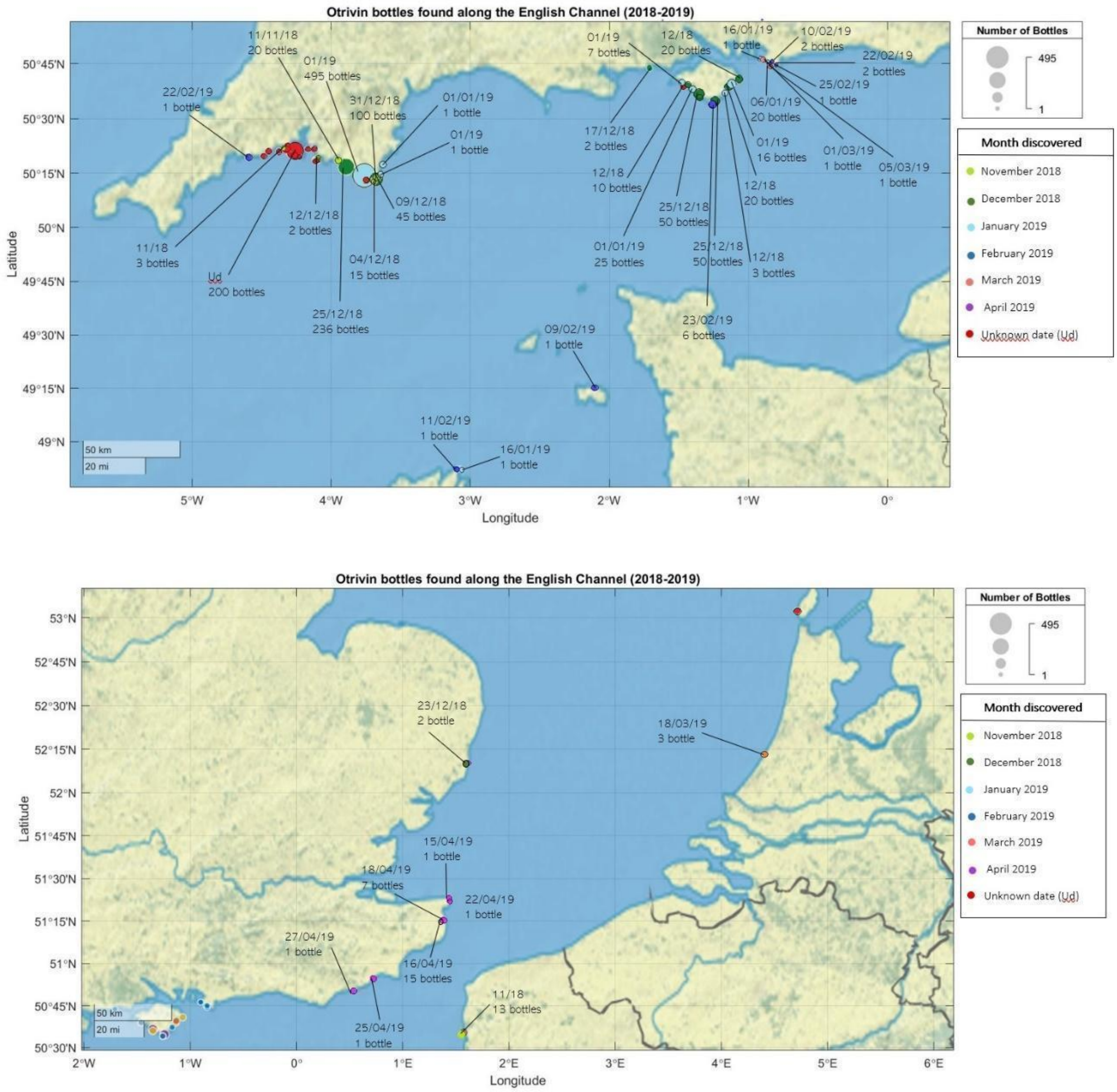


Figure 5: Map showing the concentration of the Otrivin bottles along the Western (top) and Eastern (bottom) sides of the English Channel. "Bubbles" represent the quantity while colours represent the month at which they were found. Red bubbles represent dates that were not defined. Maps created with Matlab.

Numerical ocean models

The Lagrangian experiments were performed using two numerical Ocean models. The first one is Ocean Parcels (Probably A Really Efficient Lagrangian Simulator), an open-source Python-based framework for Lagrangian particle modelling which simulates the advection of virtual objects based on the classical Runge-Kutta method (RK4). The model considers the C-grid layout of NEMO and has already been used successfully for various research such as the inverse modelling of sources and sinks of floating plastic in the Mediterranean (Kaandorp et al., 2020), the backward trajectories of microplastics from the Beaches of Cyprus (Duncan et al., 2018), the plastic debris concentration in oceanic surface water of the Antarctic Peninsula (Lacerda et al., 2019) and the influences of tidal currents on transport and accumulation of floating microplastic in the ocean (Sterl et al., 2020).

The second model is Open Drift which is also an open-source Python based framework for Lagrangian particle modelling created at the Norwegian Meteorological Institute. It is designed to be used with any drift calculations in the Ocean and Atmosphere, and millions of particles can be simulated in a short amount of time (from 30 minutes to an hour). In contrast, due to the type of laptop used, the experiments run on Ocean Parcel would take on average an hour and a half for short runs (15 days) up to 6 hours for the longest runs (7 months). So, Open Drift was much more practicable to use and most of the experiments were done with this model. It is also fairly simple to use and has been previously used in search and rescue operational model (Breivik, 2008) and more recently for research on oil slick transport (Jones et al., 2016).

The simulations of the particles were conducted using a Regional Ocean Modelling System (ROMS) downloaded from the Copernicus Marine Environment Monitoring Service (CMEMS) consisting of global analysis and forecast product IBI-MULTIYEAR-PHY-005-002 available at: https://resources.marine.copernicus.eu/. The model solves the three-dimensional finite-difference primitive equations in spherical coordinates discretized on an Arakawa-C grid and assumes hydrostatic equilibrium in addition to the Boussinesq approximation. The primitive equations are discretized on a horizontal resolution of 1/12o (6-9 km) which is a refined subset of the so-called “ORCA”, commonly used in other Nemo-based largescale and global modelling experiments. For this research, the velocity fields used to move the particles in the model are the sum of the wind and waves velocities downloaded from the ERA-5-interim reanalysis provided by European Centre for Medium-Range Weather Forecasts (ECMWF) available at: http://apps.ecmwf.int/datasets/, and more importantly, the tidal currents downloaded from CMEMS as zonal (u) and meridional (v) sea surface velocities which are simulated as fast external gravity waves on a non-linear split explicit free surface (Shchepetkin and McWilliams, 2005). An important note is that for all the simulations, particles stayed on the sea surface as the codes used in both models did not account for vertical motion such as sinking.

Otrivin simulations

To locate the major origins of the Otrivin bottles identified along the Channel in 2018, two different methods were used in both ocean models. In the first section, simulations are run with the Ocean Parcels model while the second part is run with Open Drift. By using both models, the results can be compared and confirm that the models are working accurately. We can expect some differences between the models as they do not work the same way. Furthermore, the size of the particle was set as default and resulted in a big radius of only one particle. This means that the locations of the particles have much less accuracy than in Open Drift. In this model, the property of the particle can be changed easily and therefore a high number of particles can be moved in a given radius. Additionally, Open Drift has many different variables that can be added easily such as the Stokes drift which as we will see is a significant factor that influences the trajectory of the particles.

In the first section, particles are tracked backwards in time and allowed to explore the areas of the Otrivin spill (assuming they come from a container spill). The total number of particles differs for each simulation depending on the locations and the model. The experiments using Ocean Parcels had a maximum of 100 particles, in contrast to Opendrift which was simulated with at least 5000 particles at each location. To integrate the trajectories of the particles, the classical fourth order Runge-Kutta is used in both models. Different simulations are performed to investigate the possible origin location of the Otrivin bottles. With Ocean Parcels, particles only move with surface tidal currents, while in Open Drift both tidal currents and the Stokes drift is used.

In simulation A, particles were tracked backward in time from all the locations of the coastal observations (Figure 5) for 200 days. Each location was set with the date at which the bottle was found, so as the model was running, the particles would move only at their specified date. To support the results of this experiment, we perform another simulation from the region of the earliest bottles found and run it from January 2019 to September 2018 and another one from the locations of the bottles that were reported at the same date. All the simulations show similar results on the origin of the particles. Besides, particles on Open drift were advected with the effect of Stokes drift to see how it influences the trajectories of the particles and the likely origin.

In simulation B, the positions of the backtracking results were used to check the consistency of the advection scheme. In most of the cases, the particles were moved to or near the backtracking (reported) locations. Lastly, a forward simulation is run on a random starting line in the Channel to rule out the possible starting points of the particles.

Results

Particle-tracking simulations

Numerical model 1: OceanParcels

<u>Simulation A</u>
For this first part of the simulations, the trajectories of the Otrivin bottles were computed into the numerical model Ocean Parcel. 50 particles were tracked backward in time from their reported location (Figure 6) between the 28 of April 2018 and the 1st of September 2018. Each particle was set to its specific date and only

moved when the model reached its date. This means that as the model would run backwards in time, particles would only move when their specified time was reached. The model computes the trajectories with a negative time step Δt of 60 minutes.

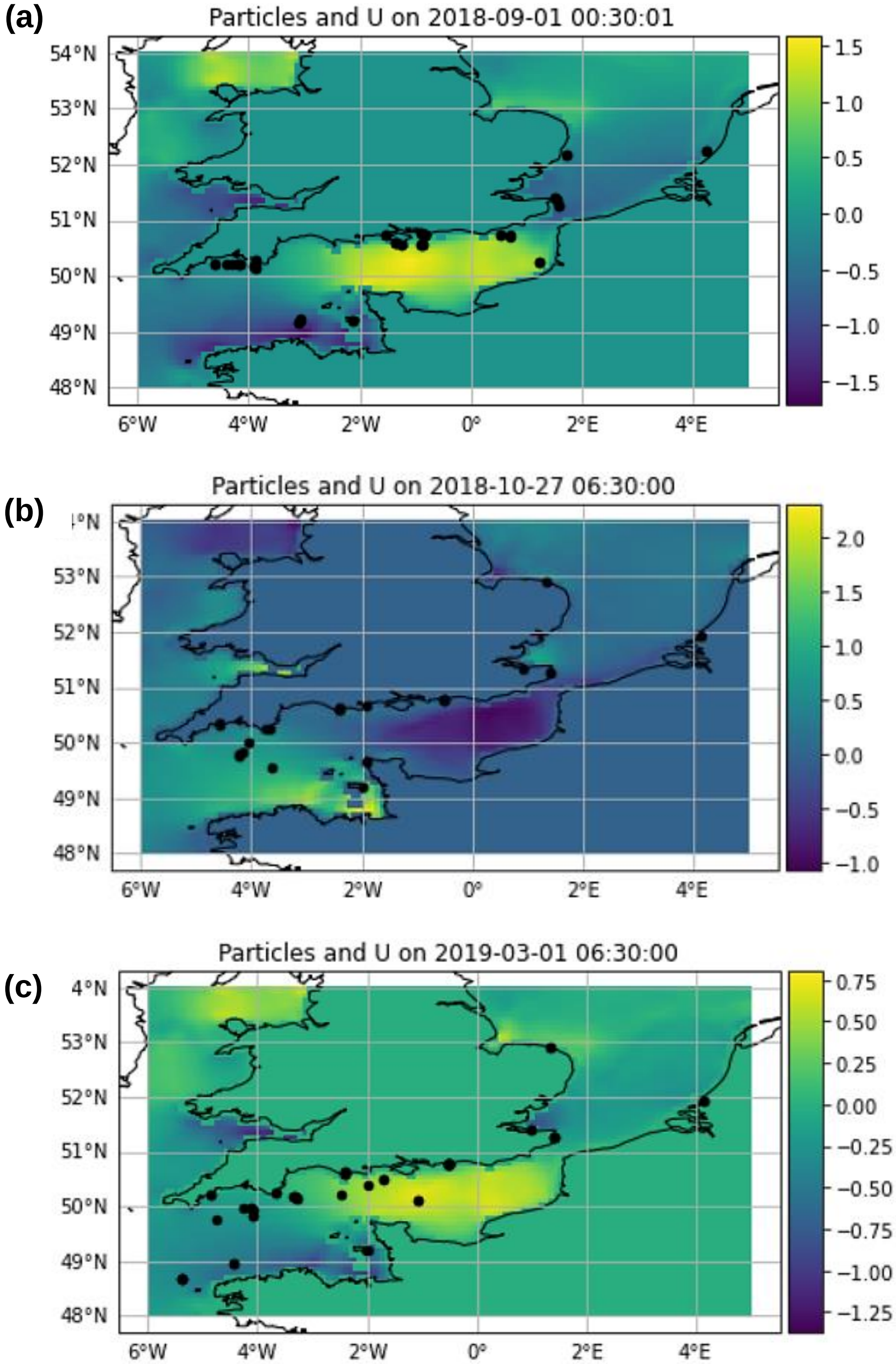


Figure 6: Position of particles backward in time.

For the second part of the experiment (Figure 7), particles were tracked backwards in time from the first reported locations of the Otrivin bottles which were stranded along Whitsand Bay up to Salcombe beach (50º25500 N, -4.500121 W) on November 2018. To get an idea of where they come from, 100 particles were released on the 11th of November and tracked backwards in time. In the first 15 days (Figure 7.b) particles moved southwards in direction to France before changing direction and moving eastward into the Channel (Figure 7.c). For the next month, most particles moved westward whilst some others moved southward.

Simulation B

The following experiments show the trajectories of the particles forward in time. 30 virtual particles were released offshore on a random location line between -5º5 49º2 and -3º 49º75 (Figure 8a) on the 1st of October 2018, which is roughly one month prior to the first reported bottle. The particles are advected until the 20th of December 2018 (Figure 8b). From Figure 9, we can observe that after the 50 days simulation, the particles most on the left drift to the Atlantic Ocean or up until the Bristol Channel, while particles on the far right are subject to the strong tides and drift up to the Isle of Wight. Surprisingly, the particles situated in the middle drift directly towards the coast that is in front and seem to be caught in small eddies (Figure 9)

Numerical model 2: Open Drift

Simulation A

Following the experiment run with OceanParcels in the first part of simulation A (Figure 6), the same simulation is run with Open Drift. The locations that are computed for this simulation are much more accurate as they can be plotted much closer to their beached position than in the experiment of Ocean Parcel. The particles in this simulation are advected backwards in time for 220 days with a Δt of 60 minutes.

What is interesting with this new numerical model is that the Stokes drift can be computed easily into the model and enables to compare the trajectories with and without the effect of waves. The effect of the Stokes drift (Figure 10a) moves most of the particles to the west side of the Channel and with much more dispersion, while particles only subject to tidal currents (Figure 10b) stay closer to the middle of the channel.

To understand the trajectories from Figure 10 in more detail, the simulation was sliced into shorter run times. In Figure 11, we can observe that for the first 60 days, particles that beached along Norfolk and Hasting are moved inside of the Channel (west). Similar trajectories can be observed between the current + Stokes drift (red) and the current only (grey). If we continue running the model for a further 30 days, more particles are moved and tend to drift further into the Channel.

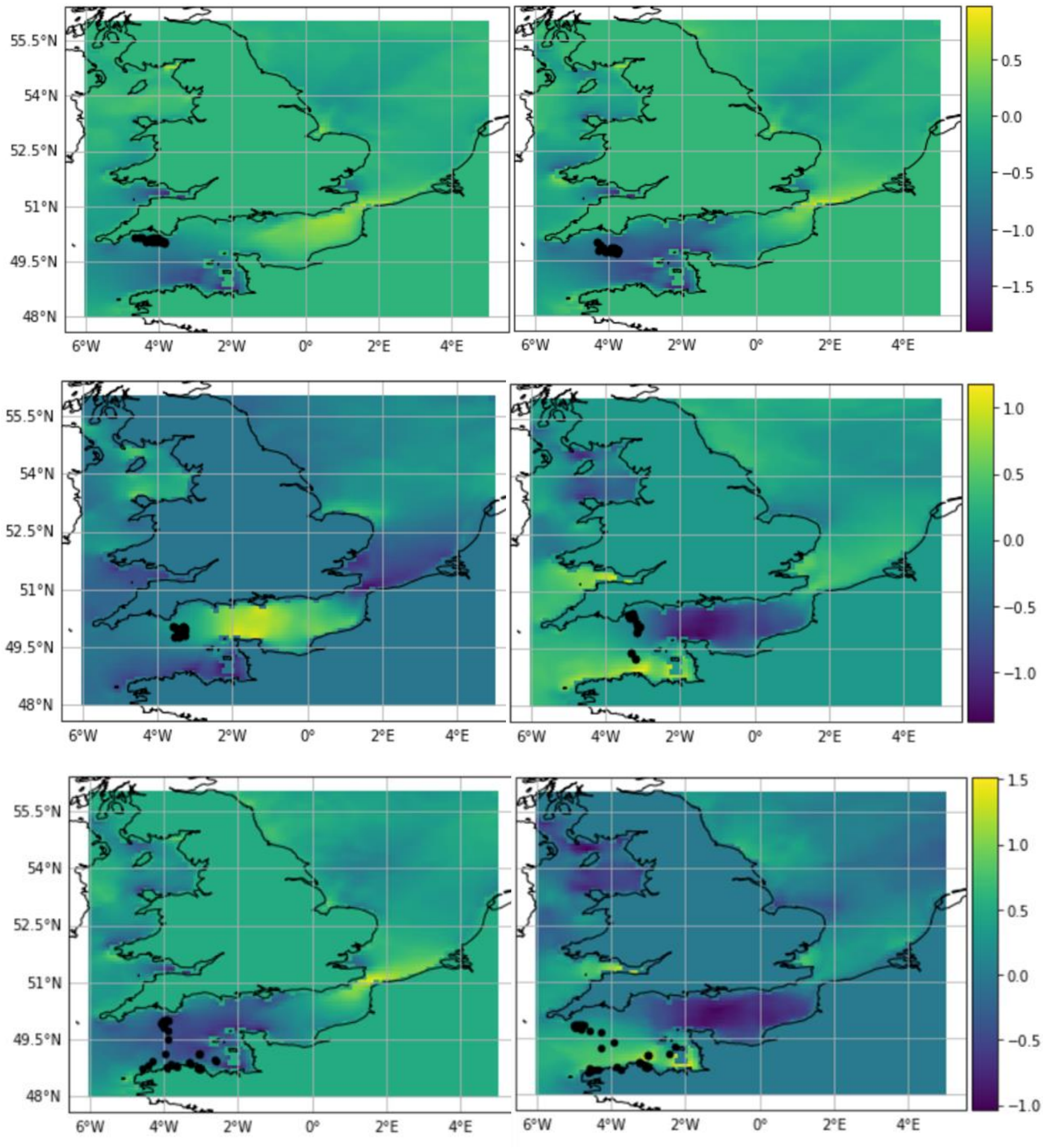


Figure 7. Position of particles backwards in time. Dates move back in time from left to right and top to bottom. Particles were released within a radius of 50 km (50º 28291, -4º22772). The colour bar represents the surface current (u) on the last day of the simulation. Simulations are run with Ocean Parcels.

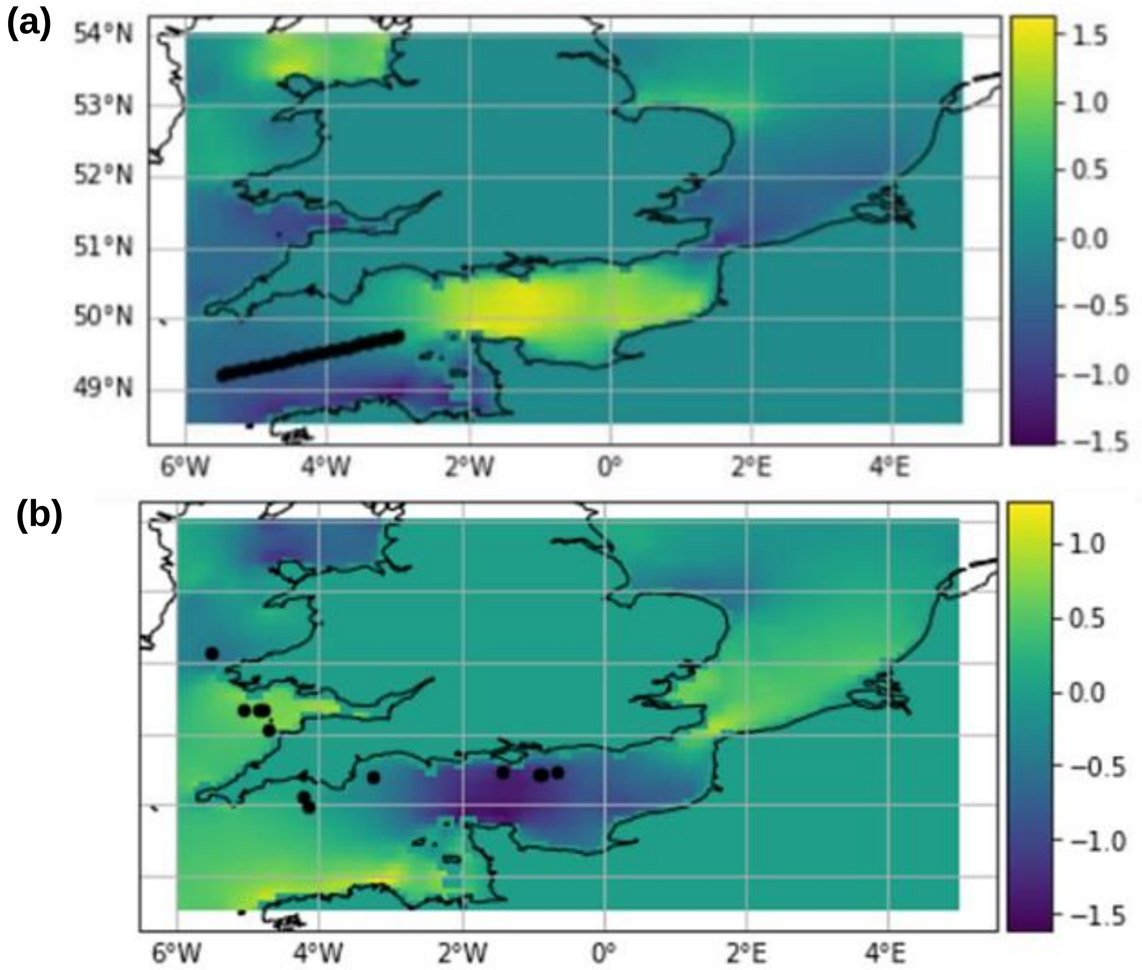


Figure 8: (a) Position line of particles between -5°5:49°2, -3°:49°75 on the 1st of October 2018 for the forward tracking simulation, **(b)** Position of particles 2 months later on the 20th December 2018. The background is the eastward (u) surface current on the first day of simulation. Simulation run on Ocean Parcels.

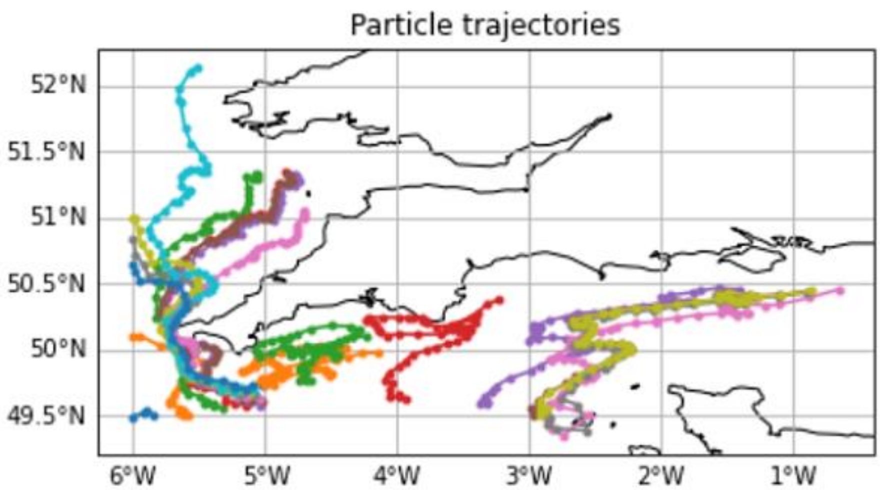


Figure 9: Trajectories of particles run from the random starting line 5º5 49º2 and -3º 49º75 between the 1st of October and 20th December of 2018. Note that each color line represents the trajectory of each particle at the starting position showed in Figure 10 and finishing as seen in Figure 11. Simulation plotted on Ocean Parcels.

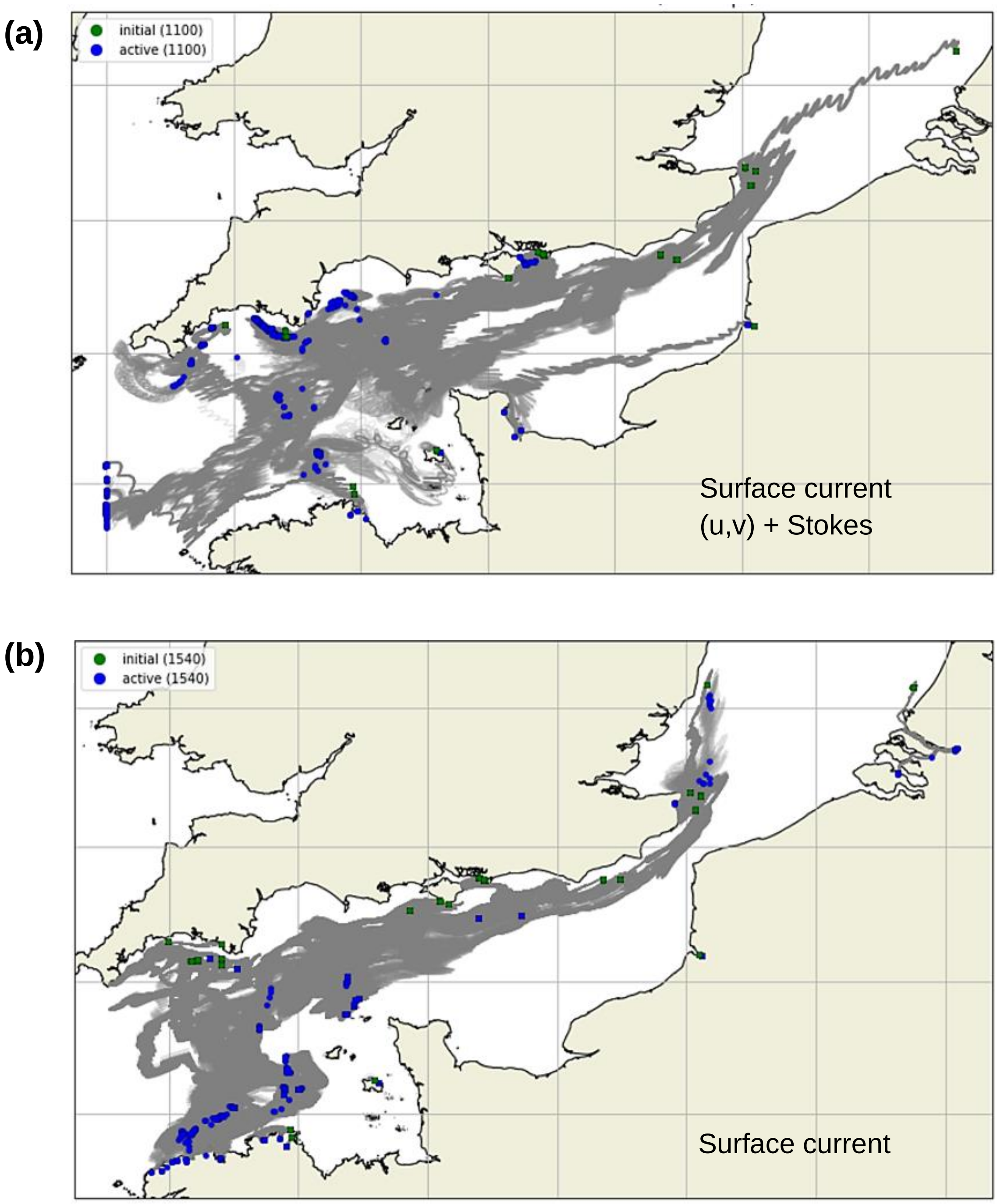


Figure 10: Trajectories of particles back in time from their reported location from 30th April 2019 to September 15th 2018. The top figure **(a)** are the trajectories of particles with the surface current(tide) + Stokes drift, while the bottom figure **(b)** are trajectories only with the surface current (tide). Red dots (initial) are the initial positions and blue dots (active) are the last positions. Simulations are run with Open Drift.

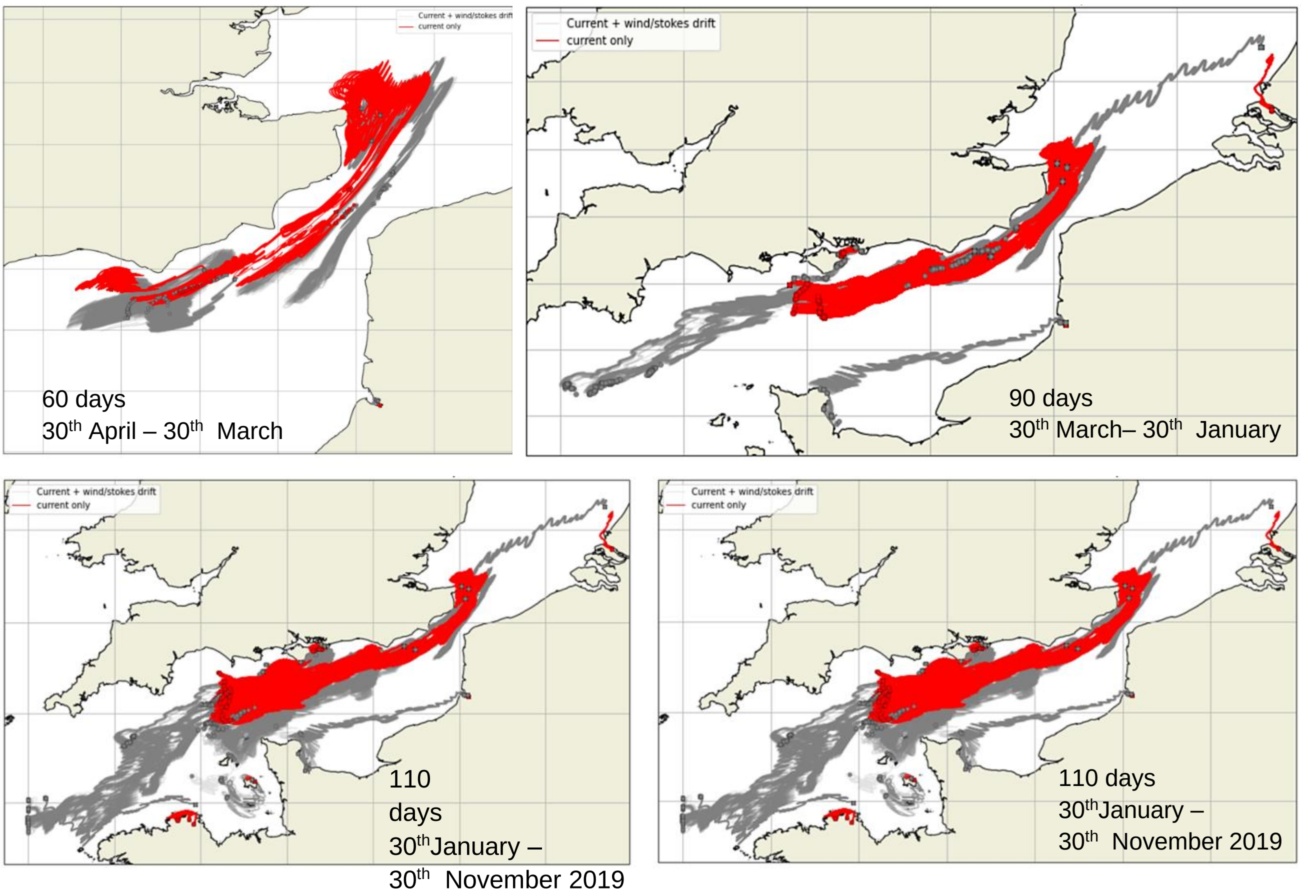


Figure 11: Backward tracking simulation. Dates move back in time from left to right and top to bottom. Particles were released from the reported locations of the Otrivin bottles between 30th April 2019 (top left) to 1st September 2018 (bottom right). Grey lines are particles with the surface current + Stokes drift while red is the surface current only. Simulations are run with Open drift.

At some locations, the current has more effect and in other locations, it is the Stoked drift that dominates. If we look at the location around the Isle of Wight, particles that are moved only by the current (tides) stay around the same locations while the particle subject to Stoke drift are moved further westerly. Another example can be observed in the Netherlands where the particles move onshore with the tidal currents only, whereas with the additional influence of the Stokes they are moved offshore to the coast of England.

<u>Simulation A.2.</u>

In the next part of the simulation particle are tracked backwards in time between the geographical location 50º 315954, -4º391410 and 50º16364N, -3º81497W. This is the area where the earliest particles were reported (November 2018). As the bottles were only found in beaches that were accessible by land, we assume that many more bottles have been stranded in many different other locations. To simulate all the possible bottles in that area, 200 particles were computed on a radius of 50 km stretching along the coast of Whitsand bay and Plymouth area. Furthermore, as the date of the bottles is not known, 200 particles wet set to move every 24h from the 30th of November 2018 until September 2018. This simulation showed similar results with Ocean Parcel, in the first month particles tend to move to the south, while in the second month they change direction and move easterly.

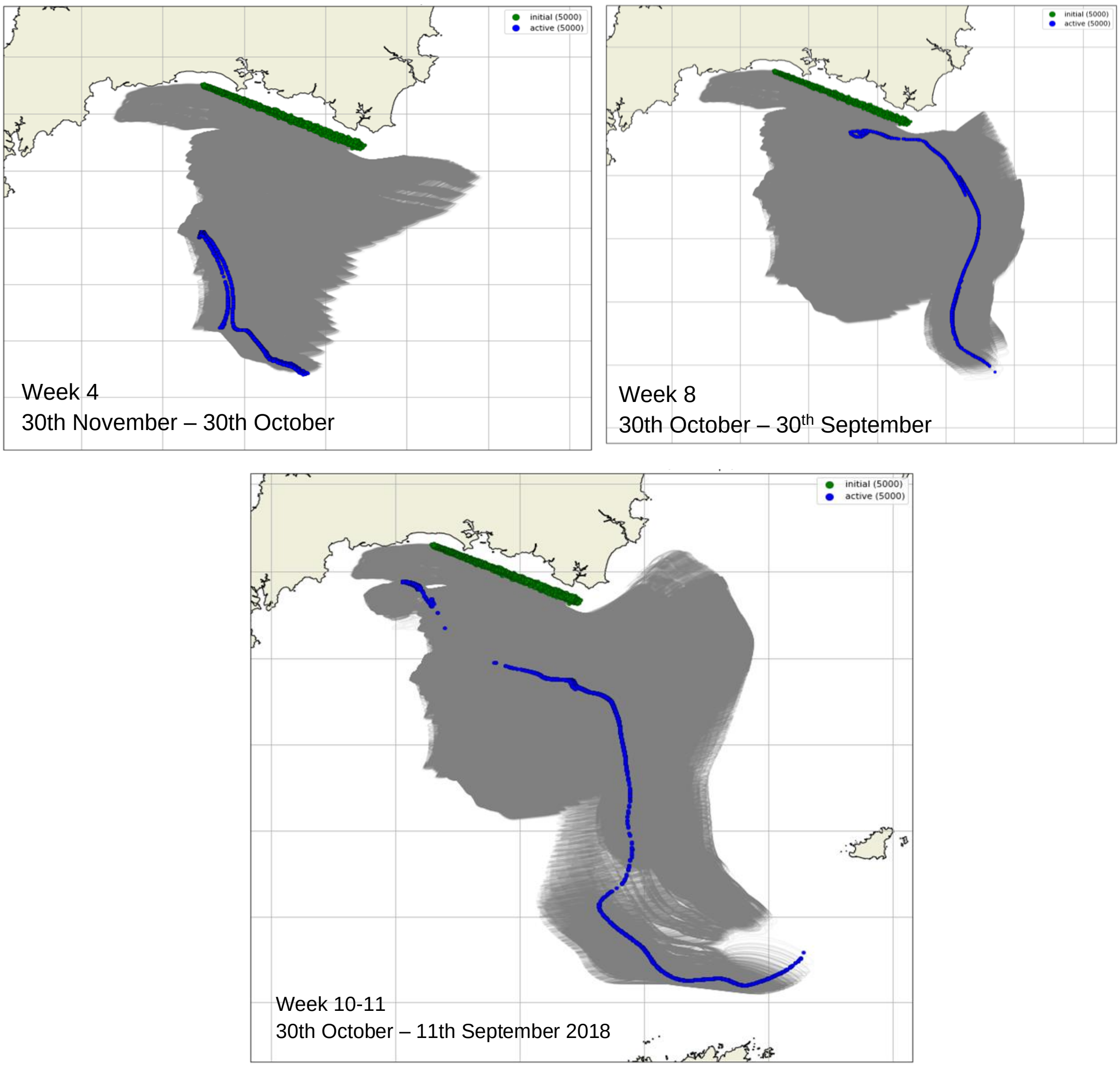


Figure 12: Trajectories of particles back in time from the 30th of November 2018 to the 11th of September 2018. The particles are run only with the influence of the eastward tidal surface current (u). The green dots are the initial positions, and the blue are the last positions. Simulation is run with Open drift

Discussion

Trajectories of the particles

Duration of simulations

In this study we assessed the likely origin of the Otrivin Bottles but also whether the impact of Stokes drift had a positive impact on the drift of the particles. By running the same experiment in Ocean Parcels and Open drift we can verify that the trajectories of the particles are not completely unrealistic. In the simulation run with Open Parcels (Figure 8 and 9) particles were advected from the 30th of April which is the last reported date of the pharmaceutical in that research. To keep short and consistent research, the simulations are only run until the last bottles reported which is the period where most of the Otrivin were found. However, these bottles are still washing up today along the Channel. This is described in the last section of this paper.

In the simulations run with Open drift, particles were released every day for 2 months from the 30th of November 2018 to September 2018. The simulation is run only with the effect of the surface current (u) and shows a similar pattern to the simulation run with OceanParcels but with much more accuracy. Particles that were released close to November 2018 are the ones that have moved the furthest south while particles that moved last (close to September) are the ones that are closest to the coast of England. The average of the dates showed that particles that were moved between mid-September and the beginning of October are the particles that reached the same result as in the simulation with OceanParcels.

Models result validation

The simulation A (backtracking) run with both models showed that the area with the highest amount of trajectories in September 2018 was between south of Portlemouth and northwest of Guernsey on the radius of 50km approximately. However, purely from this simulation, we cannot determine where particles aggregate. Two further simulations are run to show why this area could be the probable origin (spill) of the Otrivin bottles.

In the following experiment, 1000 particles on a radius of 5 km were advected backwards in time with a $time\ step, \Delta t$ of 3600 seconds from the location with the highest quantity of bottles (50º199711N, -3º759281W Ditch End, Portlemouth) between the 15th of January to the 15th of September (120 days). As we can observe in Figure 20, the red trajectories (only surface current) show a similar pattern as the simulation run from Whitsand bay and Plymouth region (Figure 13) where particles concentrate between Portsmouth and the Channel Islands while the Stokes drift moves the particles much further to the entrance of the Channel.

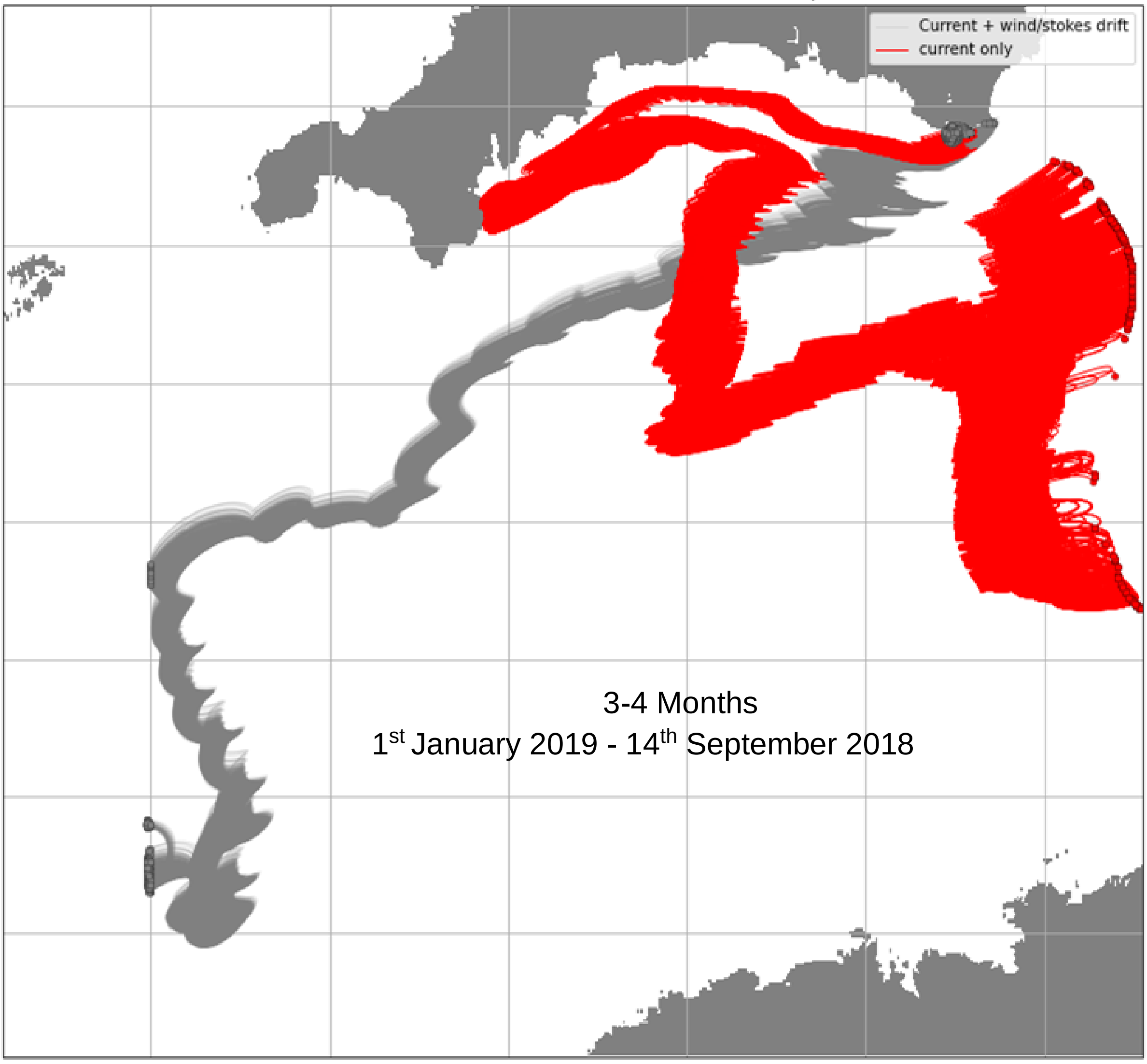


Figure 13: Backtracking between 1st of January 2019 to 15th September 2018 from Ditch End, Portlemouth which is the location with the highest quantity of Otrivin bottles reported. Simulation was run on Open drift. Note that red trajectories are only surface current while grey ones have the Stokes drift added. Simulation run with Open drift.

To further complement these assumptions, a final simulation back in time is run from the 25th of December 2018. What is particular of this date, is that 100 Otrivin bottles were found on three different locations at that same date. Using Open drift, 500 particles were simulated at each location on a radius of 2km for 3 months. As expected, the particles show similar results with the previous simulations. Particles with only the influence of tidal currents (red) coming from the Isle of Wight take on average two month to reach the area designated as the likely origin area and actually meet at the same time the particles coming from Lannacombe beach.

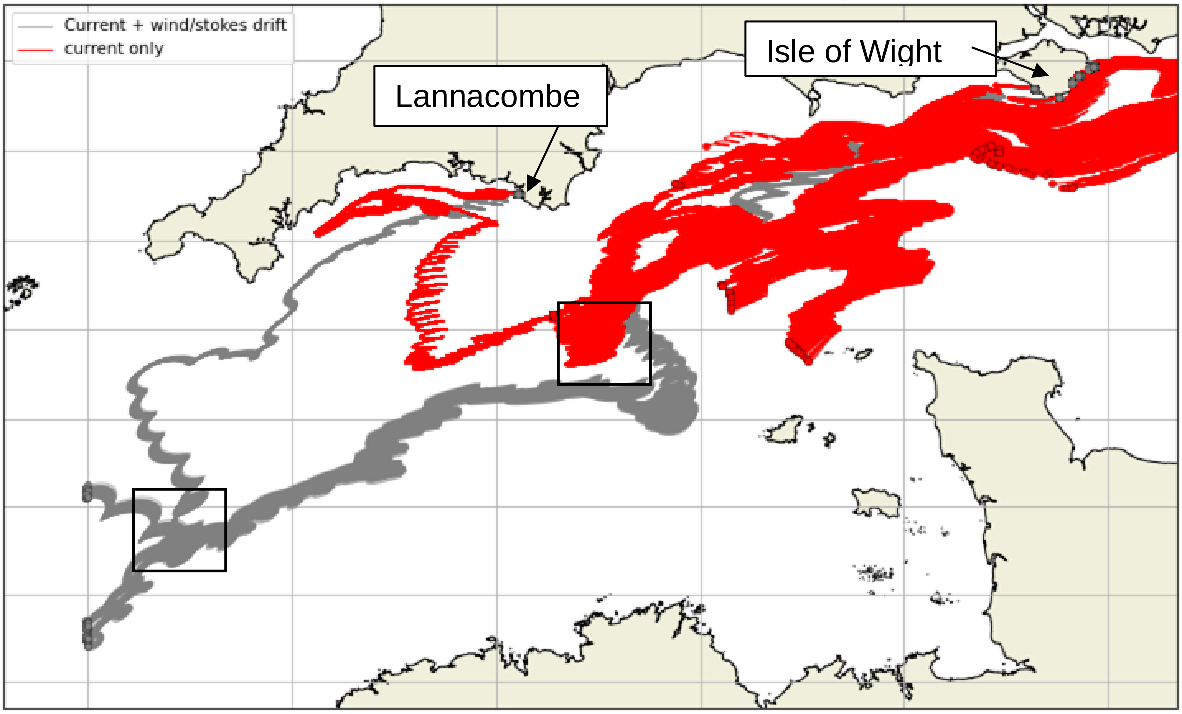


Figure 14: Backtracking of particles from 25th of December to 15th of September. The trajectories under the influence of both factors and from both locations meet at the same time in September 2018.

Contribution of Stokes drift

In the previous sections, we analysed the likely month of when the Otrivin bottles started to move apart from each other, which enabled to run the simulations more efficiently. Also, the results of the models were validated based that the simulations run on both models yield fairly the same results.

At the beginning of this research, it was assumed that because the trajectories with the Stokes drift did not match with the results of Parcels, then the effect could be neglected. However, if we take a closer look at the individual trajectories of the particles two assumption arises. Looking back at simulation A from the Open drift model (Figure 15), some particles have a completely different trajectory when they are influenced with and without the stokes drift. The particles interested are highlighted with coloured squares (the same colour square means the same particle).

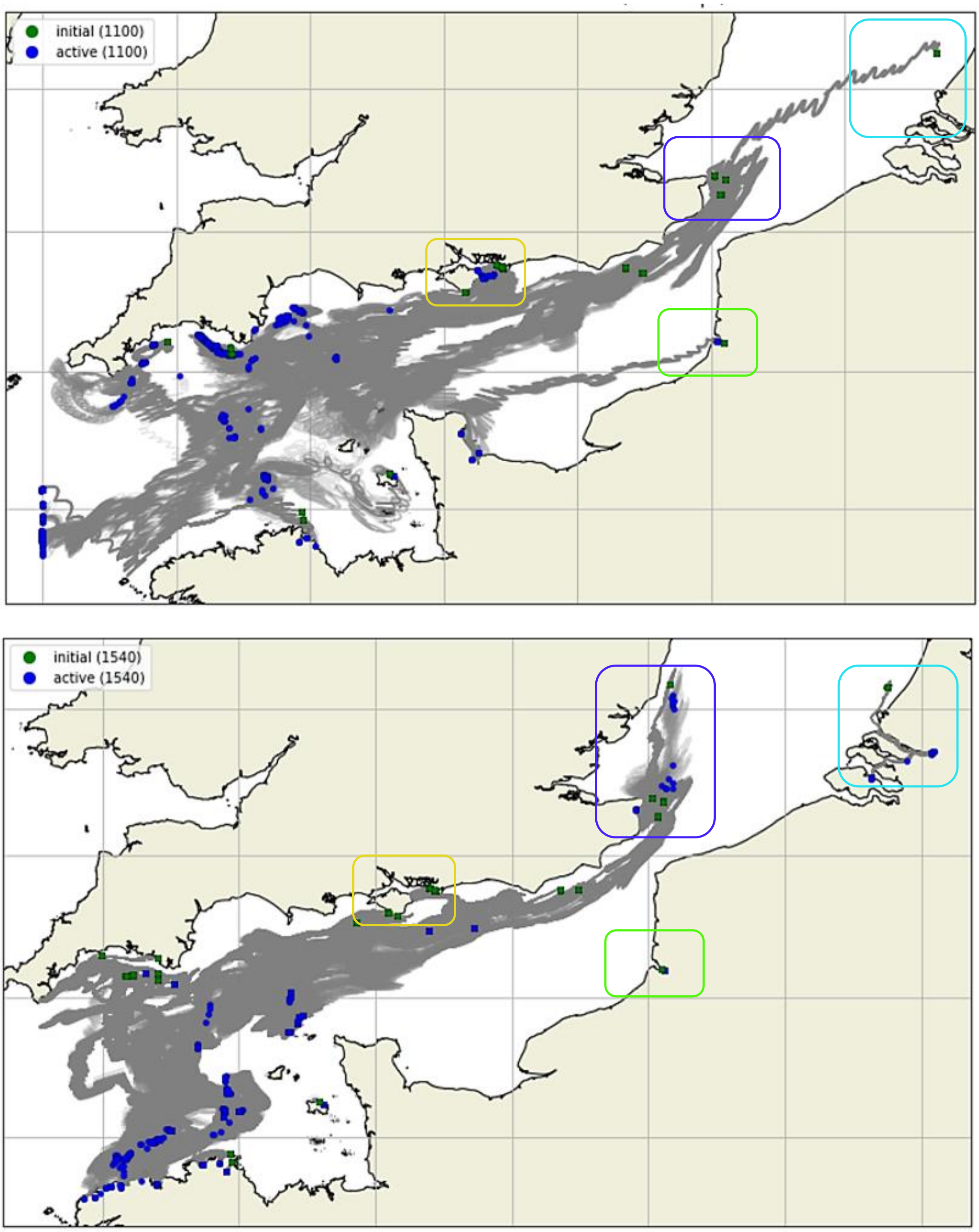


Figure 15: Particle trajectories with the effect of Stokes drift (top) and without stokes drift (bottom). The differences are significant in the origin and trajectories of the particle.

The first assumption of these significant differences could be from the rivers that are close to these particles. According to Brylinski et al. (1991), variations in salinity and temperature show the existence of a ‘coastal river’ where freshwater discharge from the coast is separated from offshore waters by an unstable tidal front and was shown to have a significant impact on the movement of Planktons in the Channel. A similar idea is supported by Sadri and Thompson (2014) which show that stratification and mixing processes between the saline and freshwater are important factors affecting the positions of buoyant items such as plastic. The other assumption is that locations that are near the strait of Dover (dark and light blue squares) experience a much stronger effect of the Stokes drift than at other locations inside the Channel. As described in the theory section, the Strait of Dover is one of the shallowest parts of the Channel with an average depth of 45m. In addition, it is the narrowest part where France and England are only separated by approximately 20 miles (32km). Therefore, any hydrodynamic forces that pass by this ‘funnel’ will have their proprieties increased because of the conservation of mass.

For particles located in the green and yellow square, the effect of the Stokes could be intensified because the tidal current velocities decrease. For example, the small tidal ranges at the Isle of Wight tidal could explain why particles would only move to the west if the effect of the Stokes drift is included (Idier et al., 2012).

Forward tracking

Lastly, we investigate one more simulation to test if the most likely area of origin described earlier is accurate enough. From simulation B run in the result section, 50 particles were computed on a random starting line stretching from the entrance of the Channel 49º314261N, -5º051554W to a location between Portlemouth and la Hague 49º933131N, -3.032441W. This experiment allowed to rule out the possible starting location of bottles by looking at the original position of the green, red, purple and yellow trajectories, which are the ones that moved closest to the beached Otrivin bottles. The position and timing of these subsampled particles were used to initiate a forward experiment to determine whether they would move near the reported locations of the bottles. 100 particles are computed on a new initial starting line between 49º712315N, -3º676093W and 49º402255N, -3º426980W from the 15th of September 2018 until the 30th of April 2019. Figure 16.b. shows the results where we can see that most of the particles reach near the locations of the Otrivin bottles. Above latitude 49º8 particles are advected to the region of southern Cornwall, hence supporting the results found in the backtracking experiments.

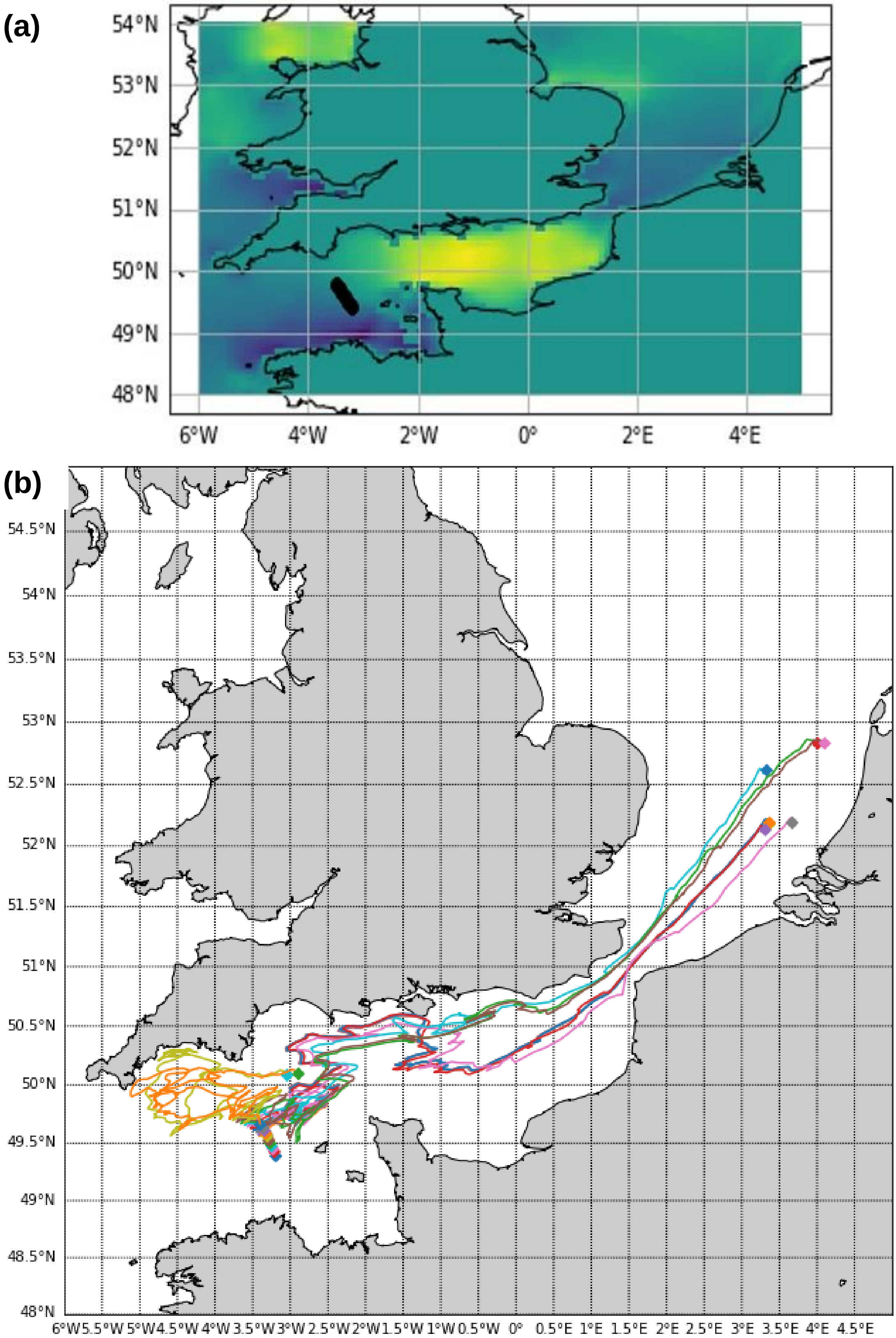


Figure 16 (a) Forward tracking from the result locations of the backtracking experiments A between September 2018 and April 2019 (Simulation run on Ocean particles). **(b)** The initial position and figure on the right are the trajectories of all the particles for 7 months (Simulations are run with Open drift).

Uncertainties
Firstly, most of the errors in the runs come from the fact that the English Channel has intricate surface currents which are difficult to model accurately. While the surface current data downloaded from CMEMS yields similar results to TPX07, the forces affecting the surface currents in nearshore regions must be manually computed in order to improve the accuracy. Nevertheless, the results found with the inverse and forward model in comparison with the coastal observations, show a most probable region for the spill lying between 49º4, -3º2 and 49º9 and -3º8.

Secondly, uncertainties in the trajectories of the particles arise from the fact that the models used for this research do not consider vertical movement. In both models, the particles are advected by setting the vertical component to zero, which forces each object at each time step to remain at the given constant depth and density. Thus, a small error is introduced at each time step which accumulates as trajectories are calculated. The overall solution is therefore not precisely accurate, and the trajectory of each experiment differs. Finally, the computation of the particle trajectories could be improved by using other numerical methods than the fourth order Runge-Kutta such as using a random walk model (Scheijen, 2018).

Additional note
It should be noted that this research only focused on the Otrivin bottles that were reported on the map created at the beginning of the research. Since the year of the original research (2019), Otrivin bottles are still regularly found along the beaches of the Channel. One of the last reports was on the coast of Guernsey in June 2020 where 56 bottles were found during a beach clean sealordphotography (2020).

According to Haëck (2018), the residence time of the particles in the Channel take between 5 and 13 months to leave the Channel through the Strait of Dover. Those who are still inside the Channel after this time are beached on the coast. Tides are the principal factor for retaining objects inside the Channel, although they have very strong velocities, the back-and-forth motion of the particles impedes rapid flushing out of the Channel (Doodson, Corkan and Proudman, 1932). Furthermore, temporary eddies are formed along the coast of Channel and especially around the Channel Islands. In simulation B (Figure 17) the effect of these eddies can be observed as particles advected close to Whitsand bay and Plymouth area do not keep a straight line and are caught in these small temporary eddies.

Around the Channel Islands, Longuet-Higgins (1970a, 1970b) showed that an oscillating force caused by the tides results in two waves circulating around the Islands in opposite directions. By running a simple forward simulation starting in front of the Islands of Guernsey and Jersey, we can observe the transport of objects circulating around them (Figure 17). However, this is a highly simplified visualization which should be studied in more details.

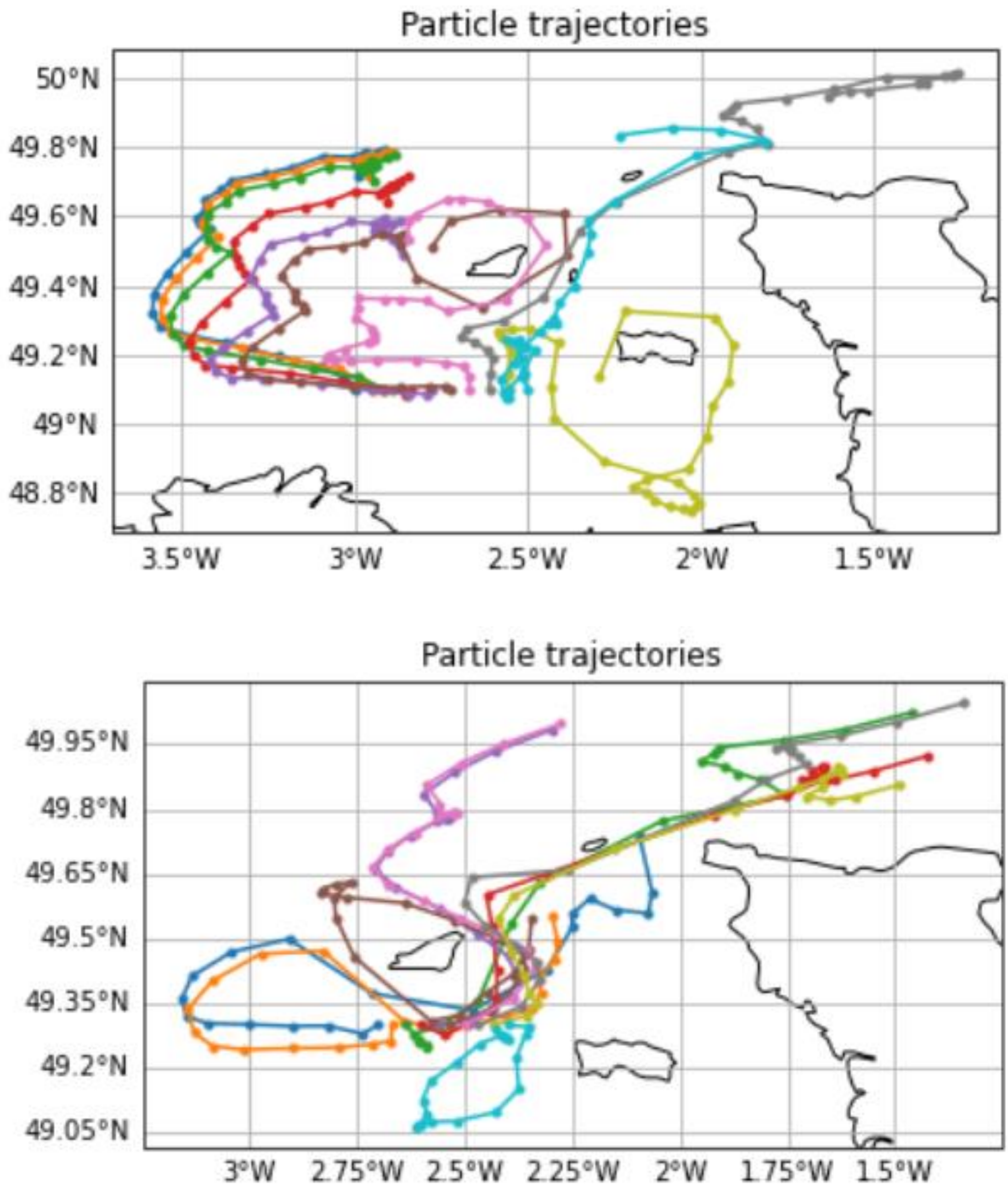


Figure 17: Forward tracking simulation of particles near Guernsey and Jersey Island between the month of October and November 2018. (Top) particles are advected for 30 days and (bottom) particles are advected for 2 months.

Conclusions

The objective of this research was to try to understand the origin and trajectories of the Otrivin bottles that started to beach along the English Channel in 2018.
The coastal observations gathered in 2019 were computed into two Lagrangian particle-tracking models to investigate the possible origin of the spill of the bottles.

The principal goal of this research was to find the exact origin of the bottles and what was the exact reason that they ended up floating along the Channel. However, as the brand no longer exists, finding the log information on the cargo vessel that transported the bottles is almost impossible as these types of information are kept private from the public. So, the aim and objectives of this research were to find the best possible location from where the bottles started to move apart from each other and subsequently, beach to the coast.

From the inverse and forward methods, it was concluded that their region of origin was between south of Portlemouth and north of Guernsey. Furthermore, the effect of Stokes drift on the particle behaviour was observed in a region where tides are the main driving force for surface currents. This non-linear effect which results from the wave field in the ocean was found to have a significant effect on specific locations that experienced several forces at the same time. However, there are still uncertainties on how the wind affects the bottles as it is not known how exactly they float in the Channel.

Furthermore, some uncertainties and errors in the models could also have influenced the results. Overall, this study showed the utility of Lagrangian tracking models to track the origin of flotsam, but also the importance to incorporate marine pollution such as flotsam into forensic science to reinforce laws on the spills of containers.

Future works

A suggestion for future research for this study would be to repeat the simulations but with a more detailed model that represents the surface currents accurately. In addition, it would be useful to include the data of the wind to see its interaction with tidal currents and the drift of the bottles. Furthermore, a brief introduction was given to the circulating currents occurring around the Channel Islands which should be further tested and verified. Further research could be done on the results, for example, continuing to run the model until now and seeing where particles have moved after they left the Channel. Finally, interesting research would be to use Lagrangian models to locate ‘upstream impacts’ (Robinson, 2017) that affect marine protected areas in the UK and incorporate actions to tackle these issues.

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