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Predicting the dispersion and beaching of floating plastics from the 2019 MSC Zoe accident in the North Sea using numerical simulations

Bachelor Thesis

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Abstract

In the night of the 1st to 2nd of January 2019, 342 containers fell of the ship the MSC Zoe, north of the Dutch Wadden Islands. The cargo of the ship contained small plastics like HDPE-granulates and pellets, but also larger buoyant plastic, which ended up in the North Sea. To study the effects of this huge environmental disaster on the ecosystem and to clean up the debris, we need to know how all this plastic will disperse through the North Sea and where it will end up. To predict this we used a numerical model which simulated particles, like HDPE-granulates and pellets. We ran simulations in the first two months of 2019 and additionally in 2016, 2017 and 2018 to make a comparison and better prediction. The effects of the currents, tides, Stokes drift and wind drag of 2.5% on the particles were studied. To incorporate these processes we used data made available by CMEMS and data from ERA5. Futhermore, the results of 2019 are compared to observations of the HDPE-granulates from waddenplastic.nl. Sinking of particles was not included in our model, but we shortly review the difference it would make in our results. The prediction we draw from our results is that the plastic of the MSC Zoe will mainly be transported along the coasts of Germany and Denmark to Skagerrak. HDPE-granulates and pellets will beach in the Netherlands, Germany and Denmark or end up at the bottom of the German Bight or Skagerrak. Larger plastics have a higher probability to beach in Sweden or Norway and could also end up on the bottom of Skagerrak.

Contents

1 Introduction

In the night of the 1st to the 2nd of January 2019, 342 containers fell off the container ship named the MSC Zoe in front of the Dutch coast, north of the Wadden Islands. The contents of these containers were big items like TVs, car parts, chairs, shoes, clothing, washing machines and toys, but also bags of plastic pellets, HDPE-granulates and toxic dibenzoyl peroxide and lithium batteries. 19 containers and 265 container parts were salvaged and 22 containers washed ashore on the Wadden Islands. A lot of the containers opened and spilled all their content in the ocean [33]. The loss of this many containers was partly due to the extreme weather: there was a strong north-west wind blowing accompanied by waves of 6 meters and higher. Additionally, the crew of the ship did not notice that containers were falling off for about 5 hours [2].

1.1 Consequences of the accident

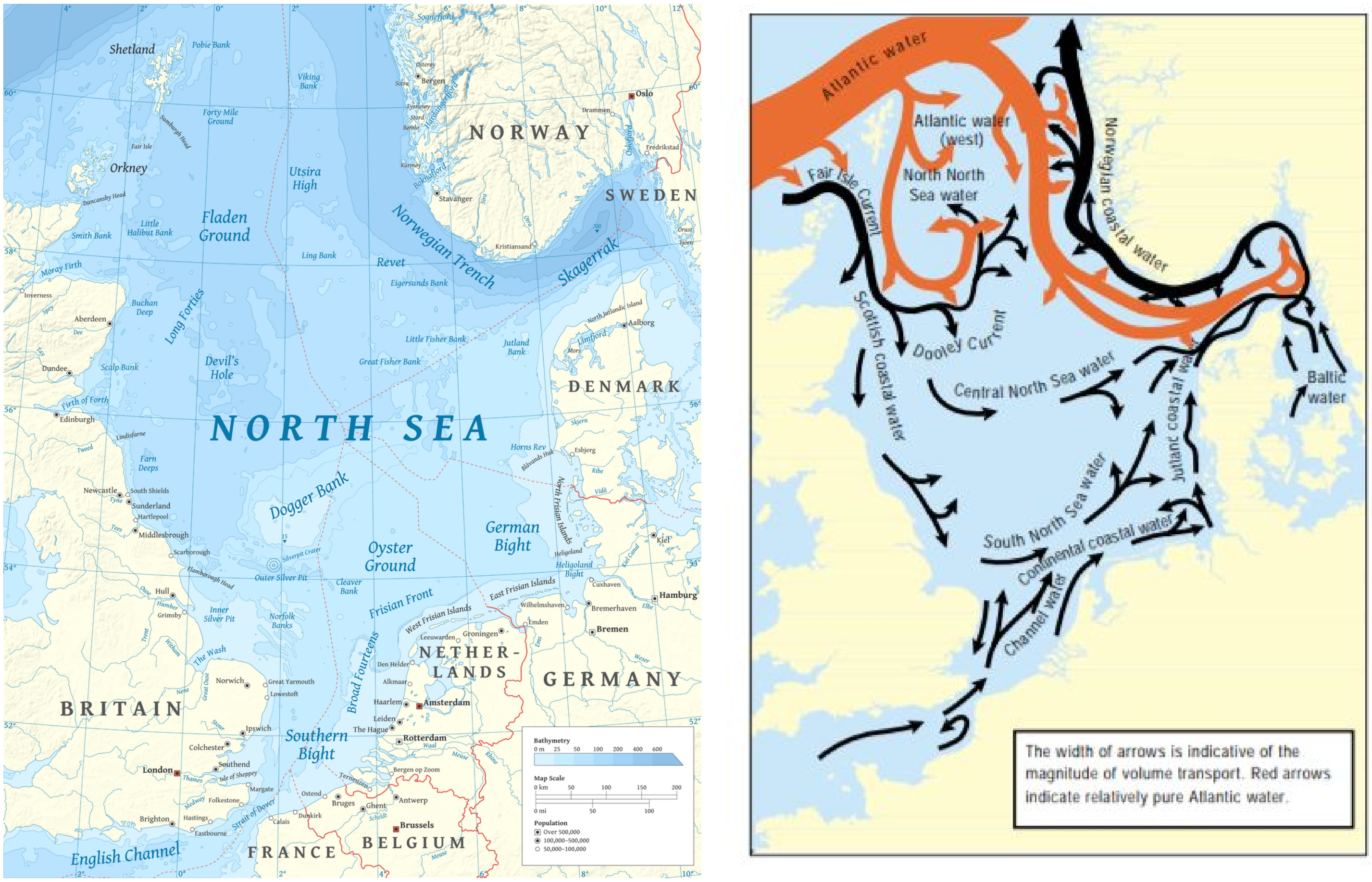
The plastic debris of the MSC Zoe which is now drifting in the North Sea and washing up on shores can have a bad influence on the ecosystem. There is already a lot of litter in the North Sea. Kammann et all. reported in 2018 that the mean litter abundance on the seafloor of the North Sea is 16.8 items/km^2 where 80% of the items were plastic [15]. The plastic of the MSC Zoe will have an effect on the marine life. Especially the small plastic pellets and HDPE-granulates will have a huge influence as they are hard to clean up and can be ingested by animals [25]. This ingestion can lead to blockage and accumulation of materials in the gut/gills, injuries, like ulcers, reduced reproduction and death [19, 28]. Reports show that over 260 different species have ingested or have been tangled in plastic. In the North Sea 95% of 1,295 beached fulmars carcasses contained plastic, because they mistake the plastic for food [28]. This shows that the marine life in the North Sea will be affected by the plastic of the MSC Zoe. In addition to the effects on the ecosystem the plastics can have an influence on our health, because some plastics, such as pellets, contain toxic chemicals which transfer into the food chain [28].
Besides the plastic of the MSC Zoe is a problem for boats and the fishery. The debris can interfere with ship propellers and become stuck in fishing nets and wreck fishing gear [19].

1.2 Numerical models

If we want to know the effect of the debris of this huge disaster we need to know how it will disperse through the North Sea and what the fate of this plastic will be. The importance of using numerical model simulations in these cases is shown by Hardesty et al. (2017) [12]. In our research we used such numerical model simulations to investigate the different influences of the currents and tides, the Stokes drift and wind drag on the dispersion and beaching of the floating plastic of the MSC Zoe. We especially focus on the HDPE-granulates and pellets, but in section 6 we will also briefly discuss the effect on bigger plastics. The data from 2019 was only available for the first two months. We also ran simulations in 2016, 2017 and 2018 to study the differences and similarities between all the years, so we could make a prediction of what will happen to the plastic. If we later find the plastic of the MSC Zoe on beaches in Europe and in bottom trawls of the North sea, we can check if our model is correct. Therefore this huge disaster brings an opportunity for improving numerical modelling of plastic. Especially since distribution of plastic is less understood in complex coastal waters and shelf sea regions, like the North Sea [10].

1.3 Study area

The MSC Zoe lost the containers north of the Wadden Islands in the North Sea, so we will focus on the dispersion and beaching of the plastic in this area. The North Sea is a shallow shelf sea, bound by the coasts of Belgium, Denmark, England, France, Germany, the Netherlands, Norway, Scotland, Sweden and the English Channel (at 5° W), the Northern Atlantic (at 62° N, 5° W) and Baltic Sea (via Skagerrak and Kattegat). The mean depth of the North Sea is about 70 meter. Depth increases towards the north to about 150 meter. The maximum depth is 700 meter in Skagerrak. The surface area of the North Sea is 575300km^2 and the water volume is 54000km^3. The tides in the North Sea are largely semi-diurnal and progress cyclonically anticlockwise. The largest amplitudes of tides are along eastern England and the German Bight and the



(a) North Sea [11]

(b) Main current pattern in North Sea [24]

Figure 1: North Sea with the names of important geographic areas and main current pattern

smallest are in the Southern Bight and along western Denmark [14] (see figure 1a for the names of the geographic areas).
In the North Sea the mean currents form a cyclonic circulation as seen in figure 1b. Inflow takes place along the Norwegian Trench, east of the Shetland Islands and between Shetland and Orkney Islands. Outflow mainly takes place along the Norwegian coast. Most of the water flows eastward and a small part flows along Scotland and England. Before the water leaves the North Sea almost all water comes through Skagerrak [24].

1.4 Previous Research

Gutow et all. [10] looked at the trajectories of floating litter and distribution of litter on the seafloor in the south-eastern North Sea. In this research the floating plastic initially drifted to the north, along the Danish coast, where a lot of particles beached and to Skagerrak, where a lot of particles were trapped by eddies. The particles then beached on the Danish, Norwegian or Swedish coasts or exited Skagerrak to the north along the Norwegian coast. They also found out that the wind drag had a significant influence on where the particles ended up. With a wind drag of 1% a large part of the particles beached on the German and Danish coast and more particles beached on the Swedish coast. Schönfeld et all. also did numerical simulations of particles in the North Sea in 1994, where the particles were transported into Skagerrak. In Neumann et all. [23] they investigated the transport of marine litter in the southern North Sea, where they simulated particles released near 54°N and 7°E. Those particles moved fast out of the German Bight. When a wind drag of 5% was included more particles were transported to the coastal regions and the particles moved faster northward, westward and in north-west direction. We expect that our particles will also be transported to the north and into Skagerrak.

In this thesis we will first give some theoretical background on the processes which we incorporated in our model. Second we will discuss our model and simulations. We included the currents, the tides, diffusion, Stokes drift and wind drag. We will explain how these processes were integrated into our model and what data we used. We then illustrate what kind of simulations we ran to obtain our results. Before we evaluate our results we give a short description of the weather conditions in each year. Our results are split in two parts: the results of the simulation of 2019 and the results of our simulations in 2016, 2017 and 2018, so we can compare those two parts. In the discussion we will among other things touch on the subject of sinking of the particles, which we did not include in our model. Lastly we will draw a conclusion and make a few suggestion for further research.

2 Theoretical background

In our model the behaviour of the particles depends on the currents, tides, diffusion, Stokes drift and wind drag. We will explain what all these processes are and what kind of influence they have on the particles in this section. The particles we simulate flow with a combined current, this current is a combination of the surface current and the tidal residual current. In section 3.1.1 we discuss what kind of data we used to incorporate these currents.

2.1 Diffusion

Particles in the ocean are influenced by random turbulent fluctuations and in numerical models of geophysical fluid systems these are unresolved. These turbulent motions are called turbulent diffusion. The random turbulent fluctuations are complex, so it is not possible to determine these exact [6].
In numerical models the effect of turbulent diffusion is taken into account by means of adding a random walk. This leads to the following turbulent velocities:

$$u = R_x(t) * \sqrt{2 * D/\delta t}, \tag{1}$$

$$v = R_y(t) * \sqrt{2 * D/\delta t}, \tag{2}$$

where the eddy diffusivity is D and R_x and R_y are random numbers from a uniform distribution with zero mean and variance one [10]. The use of a uniform distribution instead of a Gaussian distribution is sufficient when the time steps δt are small [6].

2.2 Stokes drift

Stokes drift is essentially the difference between the Lagrangian and the Eulerian average of the flow velocity of a particle. Stokes drift is directed along the wave propagation and is a property of the wave. This means that the dispersion of floating plastic is more influenced by Stokes drift, than the dispersion of non-floating plastic. In the Lagrangian frame an individual fluid parcels is tracked and the frame moves with this fluid parcel. The Eulerian frame is a stationary reference frame. The difference between the wave-averaged velocity in these frames is called the Stokes drift. The Stokes drift velocity is the net velocity that follows from the small displacement that the fluid parcels experiences during one cycle of the wave [32] (see figure 2).

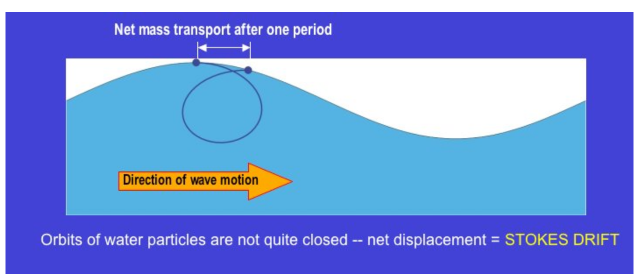


Figure 2: Stokes drift explained [22].

2.3 Wind drag

When a plastic particle is buoyant and floats on the ocean it can be affected by the wind, especially when a large area of the particles extends above the sea surface. The wind blows the particle and it will move relative to the ocean. The ocean will however apply a drag force as a result. If the ocean water was not viscous this would lead to a rolling motion over the sea surface (see figure 3)[4]. We call the additional velocity which the particle will experience as result of the wind, wind drag. The wind drag is determined by a wind drift factor W, which leads to the following equation for the additional wind drag velocity:

$$\mathbf{v}_{winddrag} = W * \mathbf{v}_{wind} \tag{3}$$

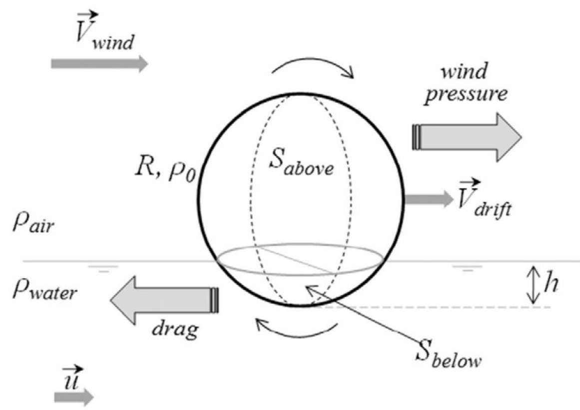


Figure 3: Forces acting on a buoyant sphere. The sphere would roll over the oceans surface if the water was not viscous [4].

with $\mathbf{v}_{wind}$ the velocity of the wind 10 meter above the sea surface.
If we combine the currents, tides, diffusion, Stokes drift and wind drag the total velocity of the particle becomes:

$$\mathbf{v} = \mathbf{v}_{ocean/tides} + \mathbf{R}(t) * \sqrt{2 * D/\delta t} + \mathbf{v}_{stokes} + W * \mathbf{v}_{wind}. \tag{4}$$

3 Method

In this section we will discuss how we incorporated the different processes in our model and what kind of simulations we ran.

3.1 Model

For the simulations we use PARCELS (Probably A Really Computationally Efficient Lagrangian Simulator), a Lagrangian framework which tracks virtual particles in a hydrodynamic flow field [18]. It essentially solves the equation for the Lagrangian particle trajectory:

$$\mathbf{X}(t+\delta t) = \mathbf{X}(t) + \int_t^{t+\delta t} \mathbf{v}(\mathbf{x}(t'), t')\, dt'. \tag{5}$$

Where $\mathbf{X}(t)$ is the position of the particle and $\mathbf{v}(\mathbf{x}(t), t)$ is the velocity field at that location.
To solve this equation we let PARCELS use a fourth-order Runge-Kutta scheme with time steps δt of 10 minutes. It has an accuracy of $O((\delta t)^4)$ [1]. It has four function evaluations per time step and is given by

$$\begin{aligned}
\mathbf{Y_1} &= \mathbf{X}(t),\\
\mathbf{Y_2} &= \mathbf{X}(t) + \frac{\delta t}{2}\, \mathbf{v}(\mathbf{Y_1}, t),\\
\mathbf{Y_3} &= \mathbf{X}(t) + \frac{\delta t}{2}\, \mathbf{v}(\mathbf{Y_2}, t+\delta t/2),\\
\mathbf{Y_4} &= \mathbf{X}(t) + \delta t\, \mathbf{v}(\mathbf{Y_3}, t+\delta t/2),\\
\mathbf{X}(t+\delta t) &= \mathbf{X}(t) + \frac{\delta t}{6}\left[\mathbf{v}(\mathbf{Y_1}, t) + 2\,\mathbf{v}(\mathbf{Y_2}, t+\delta t/2) + 2\,\mathbf{v}(\mathbf{Y_3}, t+\delta t/2) + \mathbf{v}(\mathbf{Y_4}, t+\delta t)\right].
\end{aligned} \tag{6}$$

The trajectories of the particles are then calculated on a 2-dimensional A-sgrid. In the cell (j, i), where the particle is located, the field f is interpolated. This results in:

$$f(x, y) = \sum_k \phi_k^{2D}(\xi, \eta) F_k, \tag{7}$$

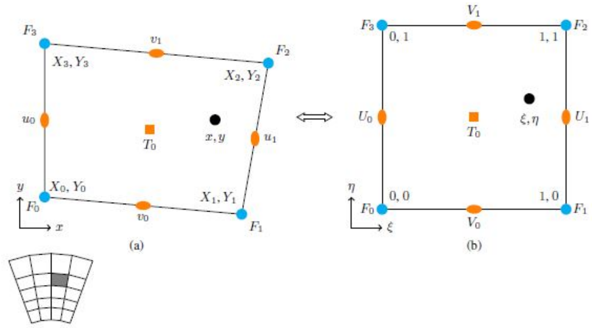


Figure 4: Nodes of a A-grid cell (blue nodes) with (a) coordinates in physical cell and (b) coordinates in unit cell. (The orange nodes are for a C-grid, which we do not use) [8].

with

$$
\begin{aligned}
x &= \sum_k \phi_k^{2D}(\xi,\eta) X_k, \\
y &= \sum_k \phi_k^{2D}(\xi,\eta) Y_k,
\end{aligned} \tag{8}
$$

where ϕ_k^{2D} are the bi-linear Lagrange polynomials, F_k with $k = 0, ..., 3$ are the four nodal values of the cell, (ξ, η) are the coordinates in the unit cell, (x, y) are the coordinates in the physical cell and (X_k, Y_k) are the coordinates of the cell vertices (see figure 4). The Lagrange polynomials are:

$$
\begin{aligned}
\phi_0^{2D}(\xi,\eta) &= (1-\xi)(1-\eta), \\
\phi_1^{2D}(\xi,\eta) &= \xi(1-\eta), \\
\phi_2^{2D}(\xi,\eta) &= \xi\eta, \\
\phi_3^{2D}(\xi,\eta) &= (1-\xi)\eta
\end{aligned} \tag{9}
$$

[8].
The behaviour of the particles in this model depends on the currents, tides, diffusion, Stokes drift and wind drag. We will explain these effects in the next subsections. Sinking of the particles is not included in this model. Beaching however is included. The model checks every time step if the particle is still moving. If it has stopped moving it saves the particle's position and age and deletes it from the model. In reality the processes of beaching is a lot more complicated: particles can re-enter the ocean, which in time depends on the wind and water levels. There have been few studies about the actual process of beaching, which makes it even more complicated to simulate [30]. In Gutow et al. [10] the particles were pushed over the model boundary when they were close to shore and then were considered beached and in Lebreton et al. [20] a particle was considered beached if the particles were located in a cell adjacent to a shoreline cell.

Every 24 hours the model gives back data about the particle positions, the age of the particle and if the particle has beached. If the particles have beached, it will also give back the location and time of beaching.

3.1.1 Currents and tides

Firstly we needed to include the currents in the surface layer of the ocean and the tidal residual currents. To include the currents and tides in the model, we use data made available by the Copernicus Marine Environment Monitoring Service.

For 2017 till 2019 we use an ocean physics analysis and forecast of the European North-West Shelf which is based on the version 3.6 of Nucleus for European Modeling of the Ocean (NEMO) [29]. The data has a spatial resolution of $0.016° \times 0.016°$ from (16° W, 46° N) to (10.5° E, 62.75° N). It gives hourly instantaneous values of the sea water velocity (including currents and tides). Furthermore, to include Skagerrak and Kattegat, we use an ocean physics analysis and forecast of the Baltic Sea based on the Hiromb-Boos Model (HBM) [13]. This data has a spatial resolution of 2km $\times$ 2km from (9° W, 53° N) to (30° E, 66° N) and a temporal resolution of one hour.

For the year of 2016 both these datasets were not available, so we used a lower resolution ocean physics analysis and forecast based on the Forecasting Ocean Assimilation Model 7km Atlantic Margin model(FOAM AMM7) nested in the Met Office global ocean model. The hydrodynamics of FOAM AMM7 come from NEMO and are coupled with the European Regional Seas Ecosystem Model(ERSEM) [21]. The data has a resolution of $0.111° \times 0.067°$ from (20° W, 40° N) to (13° E, 65° N). This data includes Skagerrak and Kattegat as well, therefore we do not need additional data for the Baltic Sea for 2016.
All current data includes the tidal residual currents.

3.1.2 Diffusion

The particles in the ocean are also influenced by turbulent diffusion, as explained in section 2.1. The random diffusion with eddy diffusivity D in this model is defined as

$$D = D_0 * (l/l_0)^{4/3} \tag{10}$$

where the reference diffusivity is $D_0 = 1$ m^2/s, the length scale of the local grid resolution is l and the reference length scale is $l_0 = 1$ km. We use the same definition as Neumann et al. [23].

We use three different datasets with different spatial resolutions for the currents, so our diffusivity $D = D(x,t)$ is dependent on time and position. For 2017 till 2019 this means that D is around 1.33 m^2/s for the North Sea and 2 m^2/s for the Baltic Sea. For 2016 D is 7 m^2/s in the North Sea and Baltic Sea.

3.1.3 Stokes Drift

Stokes drift is incorporated in our model. We used data from ERA5 which is an atmospheric reanalysis of the global climate of the European Centre for Medium-Range Weather Forecasts(ECMWF) [5]. The data is generated using Copernicus Climate Change Service Information 2019. The data gives the velocity of the Stokes Drift in the u- and v-direction. This data was available in all years and covers all our areas of interest. It has a resolution of $0.25° \times 0.25°$ and a temporal resolution of 1 hour.

3.1.4 Wind drag

The data from ERA5 is also used to determine the velocity of the wind s[5]. The resolution of the data is $0.25° \times 0.25°$ and it gives hourly values of the wind speed at 10 meters above the sea surface.

To include the wind drag we assume that the wind drift factor W is 0.025. This factor is determined by Stanev et al. (2019) [27] to best fit wooden drifters in the North Sea. We do not simulate wooden drifters in our model, but floating plastic, especially HDPE-granulates and pellets. However, we still think that a wind drag of 2.5% is the best. We will discuss our choice for this wind drift factor further in section 6.3.

3.2 Set-up simulations

In total we ran 14 different simulations to obtain our results. The containers from the MSC Zoe were found in different areas in front of the coast of the Wadden Islands, see figure 10. We chose to let our particles start in two lines in front of the coast. One from (4.8° E, 53.55° N) to (6.4° E, 53.8° N) and one from (4.8° E, 53.65° N) to (6.4° E, 53.9° N). Each of the lines contained 5000 particles, which are evenly distributed along the two lines. The containers from the MSC Zoe fell off board between 20:00 and 02:00, so we released all the particles at 23:00 on the 1st of January.

First we ran three different simulations that started on 1 January 2019, one with only the currents and tides included, one with the addition of the Stokes drift and one that included the wind drag. These simulations gave output every 24 hours, so to get higher resolution density plots of the beaching, we also ran 2 simulations that gave output every 6 hours. One of those included Stokes drift and the other additionally considered wind drag.

The data for 2019 is only available for the months of January and February, so we also ran simulations for 2016, 2017 and 2018 to get a better view on the possible options of dispersion and beaching of the plastic. The simulations of 2016, 2017 and 2018 all also started on the 1st of January, but tracked the particles for one year.

To evaluate the distribution of the floating plastic the percentage of particles passing through a grid cell is determined as well as the mean age of those particles when passing the cell. To evaluate the beaching of the plastic the percentage of particles beached in a grid cell is calculated. The age of the beached particles is given in a histogram per coast.

4 Weather conditions

Before we discuss the results of the simulations we will briefly illustrate the weather conditions on 1 and 2 January of each year, so we can better interpret the results. The conditions were measured in Hoorn on the island of Terschelling and are seen in figure 1 [16]. The first thing we want to point out is that the wind direction in 2019 is very different from the wind direction in 2016 and 2018. In 2019 there was a northern/north-western wind dominating so the wind was directed to the Wadden Island, which will have a influence on the beaching. The second observation is that in 2017 the wind direction changed almost 100° from 1 to 2 January, the direction on 2 January is quite the same as in 2019, so the results of 2019 will probably the most similar to those of 2017.

In table 2 and 3 the mean wind speed, wind direction and wave directions of each month in every year is given. These values are determined with the ERA5 data [5] using the monthly mean values and calculating the average in the North Sea.

	Mean (m/s)	Max hourly (m/s)	Max (m/s)	Direction
2016				
1 January	4.7	9	15	152° (SSE)
2 January	11.1	13	17	115° (ESE)
2017				
1 January	7.9	11	15	232° (SW)
2 January	6.8	9	16	328° (NNW)
2018				
1 January	8.8	13	20	232° (SW)
2 January	7.3	13	18	218° (SW)
2019				
1 January	10	12	20	315° (NW)
2 January	7.5	12	21	356° (N)

Table 1: Weather conditions each year on 1 and 2 January measured at Hoorn Terschelling. The mean wind speed (Mean), the maximum hourly mean wind speed (Max hourly), the maximum wind speed (Max) and the dominant wind direction (Direction) is given [16].

Year	2019		
Month	Speed(m/s)	Wind(°)	Wave(°)
January	7.5	288	293
February	6.6	235	252

Table 2: Weather conditions in 2019. Monthly mean values were taken from the ERA5 data and we determined the average of values in the North Sea. The mean wind speed (Speed), the dominant mean wind direction (Wind) and the dominant mean wave direction (Wave) are given [5].

Year	2016			2017			2018		
Month	Speed(m/s)	Wind(°)	Wave(°)	Speed(m/s)	Wind(°)	Wave(°)	Speed(m/s)	Wind(°)	Wave(°)
January	7.9	173	204	6.6	248	278	7.2	205	236
February	7.2	260	277	7.5	159	166	6.6	143	225
March	5.7	264	282	6.2	239	278	6.8	103	75
April	5.8	257	287	6.5	283	290	5.8	186	225
May	5.7	62	265	5.3	207	250	5.0	95	151
June	4.9	265	286	6.1	248	268	5.6	300	304
July	5.5	252	262	5.4	256	278	4.9	273	290
August	5.9	258	278	5.6	246	261	5.5	252	259
September	5.5	188	220	5.7	173	235	7.1	251	270
October	6.8	80	58	8.1	258	264	7.2	260	277
November	7.0	236	272	7.4	269	279	7.0	140	152
December	7.2	246	261	7.7	267	279	7.2	218	251

Table 3: Weather conditions in 2016, 2017 and 2018. Monthly mean values were taken from the ERA5 data and we determined the average of values in the North Sea. The mean wind speed (Speed), the dominant mean wind direction (Wind) and the dominant mean wave direction(Wave) are given [5].

5 Results

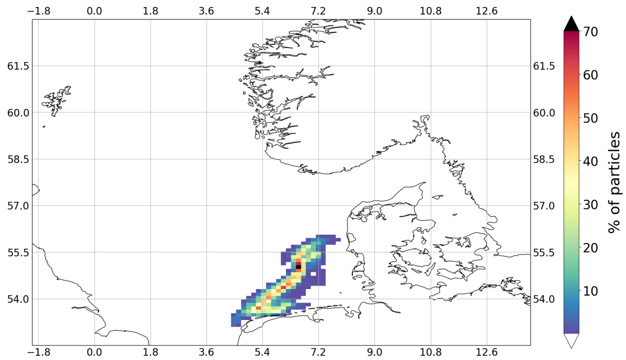
The results are discussed in two parts. Firstly we consider the results of the simulations of 2019. Secondly we will discuss the results of 2016, 2017 and 2018 and compare those to 2019.

5.1 2019

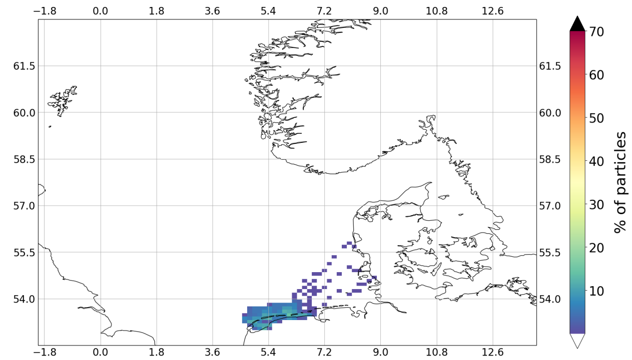
The simulations for 2019 were run first. As explained in section 3.2, 10000 particles started at 23:00 1 January 2019 in two lines in front of the coast of the Wadden Islands. These were tracked for 2 months. First we discuss the dispersion of the particles through the North Sea and second we discuss the beaching of the particles.

5.1.1 Distribution

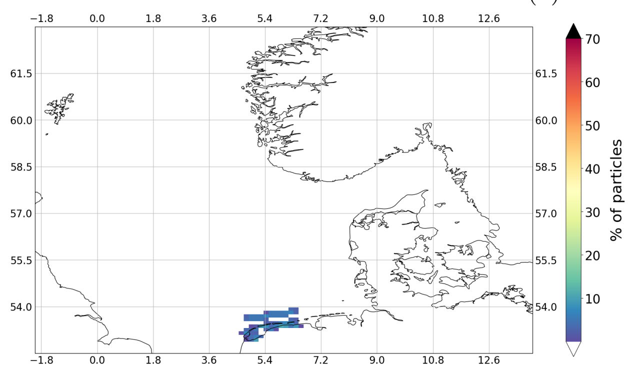
In figure 5 the dispersion of the particles through the North Sea in the three different simulations we ran, is shown. These included one where only the currents and tides were taken into account, one where also Stokes drift is included and one where also a wind drag of 2.5% is included. When only the currents and tides are taken into account, as seen in figure 5a, the particles all drift towards the north-east. In these two months they do not drift further north than 55.99°N. In figure 5b the dispersion is shown for when Stokes drift is included. Almost all particles are washed directly ashore and only 0.01% of particles made it to the coast of Denmark. When the wind drag of 2.5% is taken into consideration, as seen in figure 5c, all particles washed directly ashore. We clearly see the influence of the wind on the dispersion of the particles. The north/north-western wind (as mentioned in section 4) causes the particles to drift almost directly to the Wadden Islands. In the section 5.1.2 we will further discuss the beaching of the particles.



(a) Only currents and tides

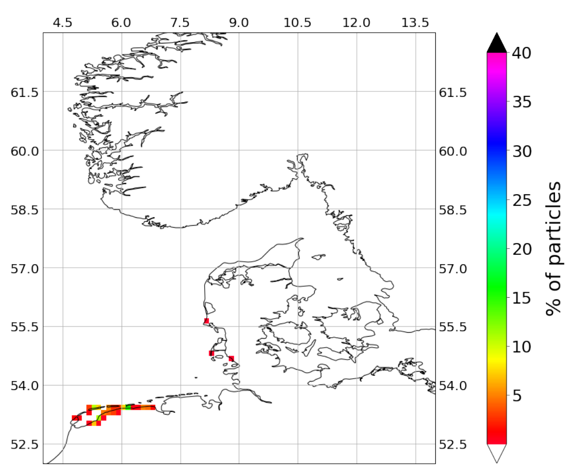


(b) With Stokes drift

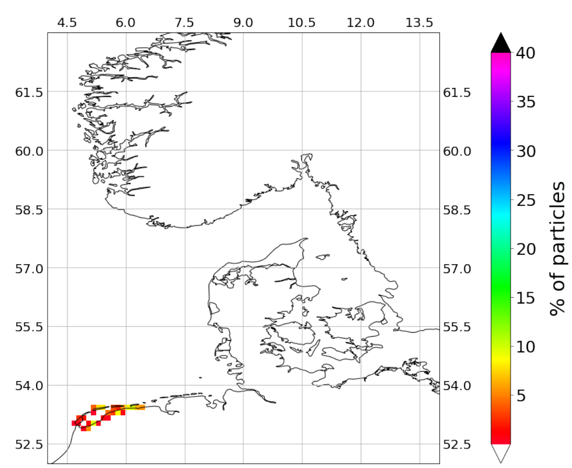


(c) With wind drag of 2.5%

Figure 5: Dispersion of particles in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. Then the percentage of particles passing each cell was determined in the three different cases: (a) simulation with only the currents and tides, (b) simulation with additional Stokes drift and (c) simulations with additional Stokes drift and wind drag of 2.5%



(a) With Stokes drift



(b) With Stokes drift and wind drag of 2.5%

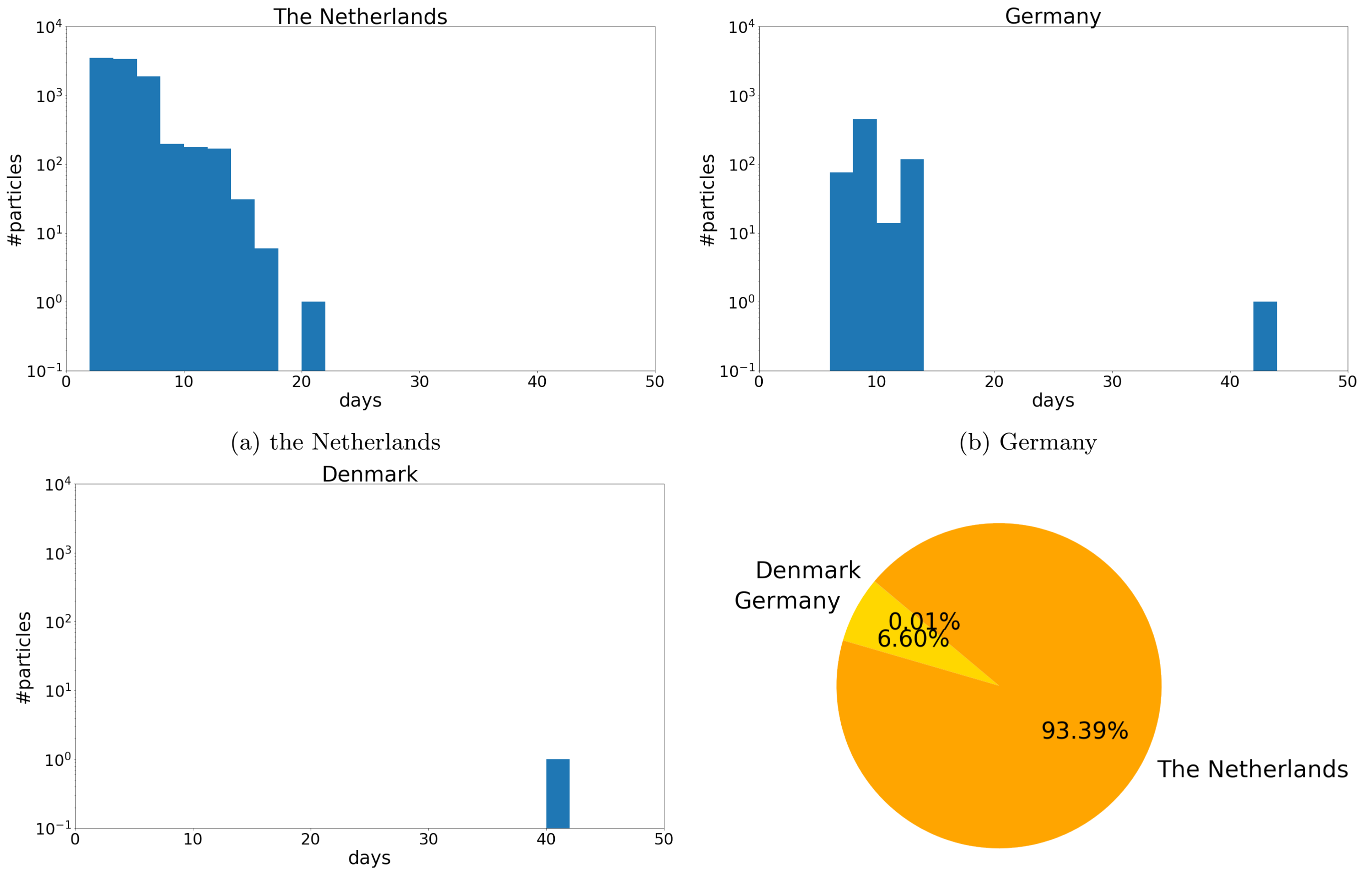
Figure 6: Density of beached particles in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. Then the percentage of particles passing each cell was determined in the two different cases: (a) simulation with Stokes drift and (b) simulations with Stokes drift and wind drag of 2.5%.

5.1.2 Beaching

The density of beached particles is shown in figure 6. Without Stokes drift and wind drag there is no beaching. With Stokes drift included almost 93.4% of the particles beach in the Netherlands. A few particles (6.6%) beach in Germany and only 0.01% of the particles beaches in Denmark. We notice in figure 7, that within 25 days all particles that beach on the Dutch coast have washed ashore, when Stokes drift is included. In less than 15 days particles reach Germany and the one particle which beaches in Denmark takes 41 days to beach. When the wind drag is taken into account, everything beaches in the Netherlands. The particles all wash ashore within 4 days, as seen in figure 8. In these results of the simulations with Stokes drift and with additional wind drag, we definitely see the influence of the wind. As indicated in the introduction and in section 4 there was a storm and the wind was directed to the Wadden Islands on 1 and 2 January 2019, which was the cause of the accident, but this also lead to all particles beaching in our simulations.
We have furthermore run two simulations with output every 6 hours instead of 24 hours, to get more precise results about the beaching of the particles with Stokes drift and with the additional wind drag of 2.5%. In figure 9 we zoomed in on the Dutch coast to examine the beaching of the particles. In both simulations we see high densities of beached particles on the coast of Friesland and on Terschelling. When the wind drag is included, additional to the Stokes drift, the particles are less dispersed over the coasts of Friesland and Groningen and therefore the densities are higher. In figure 11 the percentage of particles beached in each of the areas is given. The first subfigure, figure 11a shows the results of the research of waddenplastic.nl done by the University of Groningen [31]. What directly stands out is that in all cases nothing beaches on Vlieland, the second Wadden Island from the west. In the simulations where wind drag is included more particles beach in Groningen, Terschelling and Schiermonnikoog, but less in Friesland, Texel and Ameland, than in the simulations where only Stokes drift is incorporated. The difference is the greatest in Friesland and Texel (4.26% and 3.35% respectively).

If we review the results of the research of waddenplastic.nl [31], one of the biggest differences is that there are also particles that have beached on Rottums. (These are Rottumerplaat and Rottumeroog, the two Islands east of Schiermonnikoog.) The second difference is that a lot more particles have beached in Groningen and Schiermonnikoog. There are a few things that could have caused this difference, which we will discuss in 6.1.

That all particles beached in our simulation does not entirely mean that this is what happened in reality. In reality there are more processes that influence the dispersion of the particles. Also there are uncertainties in our model, which we will further discuss in section 6. This is why we have chosen to do all the three different simulations in 2016, 2017 and 2018, so we can compare those to the simulations of 2019 and make a prediction.



(a) the Netherlands

(b) Germany

(c) Denmark

(d) Percentage of beached particles per area.

Figure 7: In figures (a)-(c) the distribution of the age of beached particles on the coast of the Netherlands, Germany and Denmark is shown. Figure (d) gives the percentage of particles beached on those coasts. The simulation included currents, tides and Stokes drift. 10000 particles were released at 23:00 on the 1st of January of 2019 and tracked for 2 months.

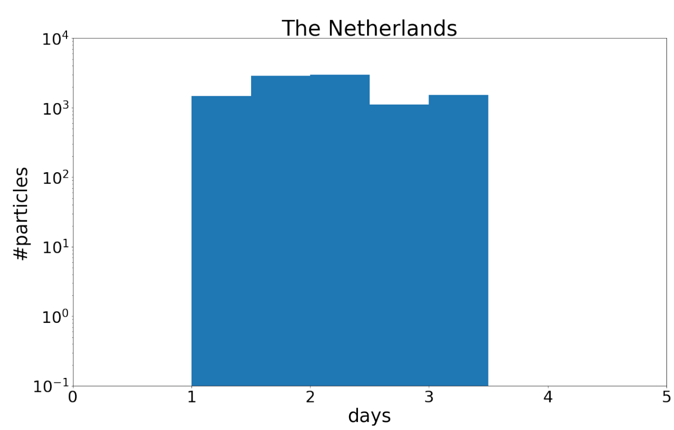
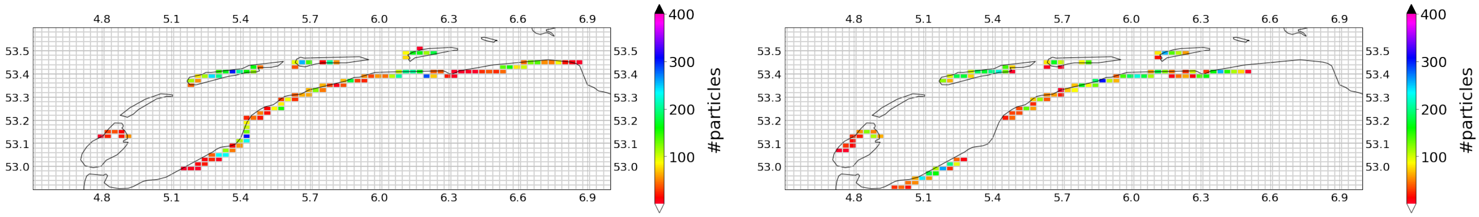


Figure 8: The distribution of the age of beached particles on the coast of the Netherlands in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. The simulation included currents, tides, Stokes drift and wind drag.



(a) With Stokes drift

(b) With Stokes drift and wind drag of 2.5%

Figure 9: Density of beached particles on the coast of the Netherlands in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. The model gave output every 6 hours. Then the percentage of particles passing each cell was determined in the two different cases: (a) simulation with Stokes drift and (b) simulations with Stokes drift and wind drag of 2.5%

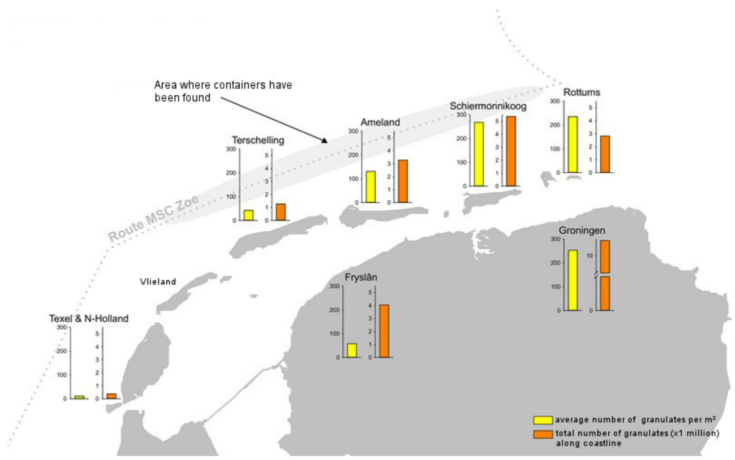
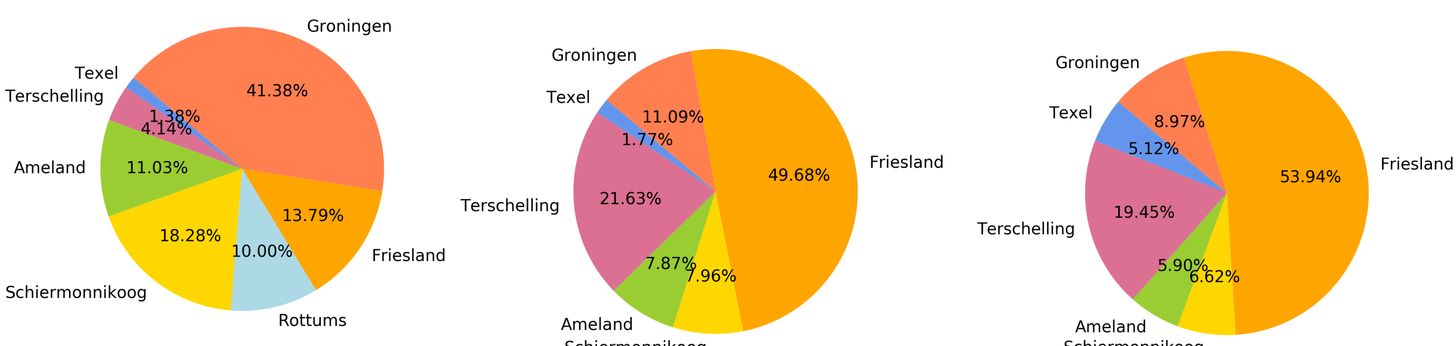


Figure 10: Result of the report of the waddenplastic.nl of Groningen University [31].



(a) Report of waddenplastic.nl of Groningen University [31]

(b) With Stokes drift

(c) With Stokes drift and wind drag

Figure 11: Percentage of beached particles in certain areas in the Netherlands. For simulations in 2019 with Stokes drift(b) and with wind drag of 2.5%. Figure a show the percentage of beached particles from the MSC Zoe in 2019 reported by waddenplastic.nl from Groningen University

5.2 2016 untill 2018

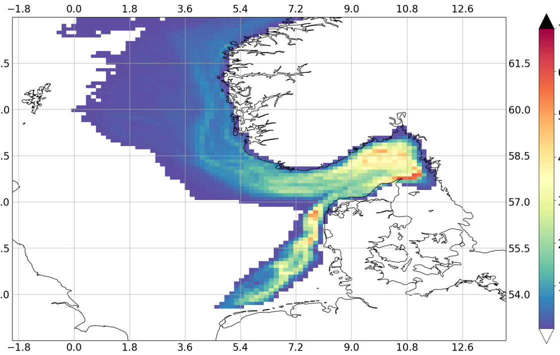
5.2.1 Distribution

As explained before we only have data from January and February in 2019, so if we want to make a prediction of where the plastic which is still floating in the ocean is going, we can take a look at previous years to see if there are similarities.

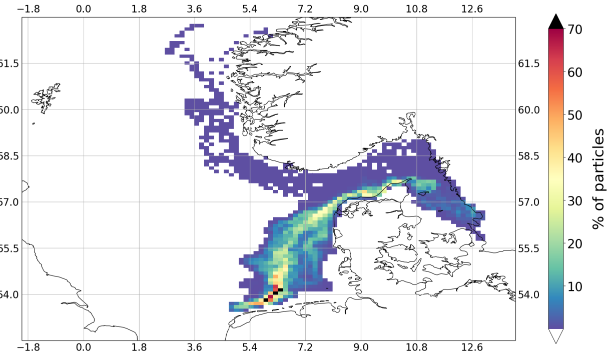
In figure 12 the distribution of particles from the simulations with only the currents and tides are shown. We can see some similarities, each year the particles are drifting towards Skagerrak and some of the particles eventually leave Skagerrak to the north along the coast of Norway. This is what we would expect if we look at the main currents in the North Sea shown in figure 1b. In 2016 and 2018 the particles are more dispersed throughout the North Sea, this is probably caused by wind. In 2018 there was an extreme easterly wind [27] prevailing from 19-02-2018 until 08-03-2018. That is from 50 until 67 days after the release of the particles in our model. Extreme changes in wind direction will also influence the surface currents. If you would like to study the age of the particles in appendix A, additional figures are given with the mean age of the particles passing each cell for each year.

The distribution of particles throughout each year, when taken Stokes drift into account (figure 13) show less similarity. Still, the particles drift north towards Denmark each year, but in 2018 a lot of the particles beach in Denmark and do not reach Skagerrak. In 2018 particles move faster to the north because of the Stokes drift, which leads to earlier beaching of the particles, which we will discuss later in section 5.2.2. In 2017 the particles drift closer to the coast of the Netherlands and Germany than when Stokes drift was not taken into consideration. When the age of the particles is about 30 days they suddenly drift to the west and after about 60 days they drift back to the east and into Skagerrak. In table 3 we see the cause of this sudden, but swift drift to the east, since in February the wind and waves are suddenly directed to the north-north-west. This leads to more dispersion throughout the ocean. In 2016 Stokes drift causes the particles to first drift more to the west, but they still end up in Skagerrak. This is also caused by the wind, which was directed to the north-west in the beginning of January 2016. Actually 2016, 2017 and 2018 are very different from 2019. In 2019 almost everything beached in the Netherlands within 20 days. This is probably due to the stormy weather and the wind and waves which were directed to the south.

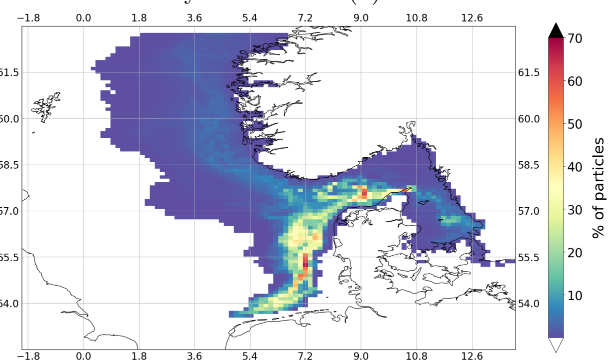
If we look at figure 14 we see what happened when wind drag was also a part of our simulation. In 2016 the additional wind drag clearly increases the effect which the Stokes drift had. The particles drift even more to the west, until the wind changes direction and the particles are blown into Skagerrak. In 2017, just as in 2019 everything beaches in the Netherlands. In the simulation where we only take Stokes drift into account, we already noticed that particles were drifting close to the coasts of the Netherlands and Germany. The additional north-western wind increased this effect. In 2018 particles do still reach Skagerrak and even a few leave to the north along the coast of Norway. What is fascinating however is that the results of the simulation with Stokes drift and with additional wind drag are quite different. The wind drag causes particles to drift more to the east and this leads to less beaching in Denmark and more particles reaching Skagerrak. As already mentioned, there was an extreme westward wind dominating in the end of February and beginning of March [27]. If we study the difference between the wind and wave direction (table 3) in February and March, we see a difference of about 82° and 28° respectively. Especially the contrast in February is quite big; consequently there is a greater difference in the results between our simulations with only Stokes drift and with additional wind drag. In 2018 you can clearly see the changes of the wind direction in our results. The last thing we also want to point out is that in every year the particles disperse less through the ocean and move faster than in the other simulations. This means that the wind has more effect on the dispersion of the particles than the diffusion and surface currents.



(a) Particles were released at 23:00 1 January 2016

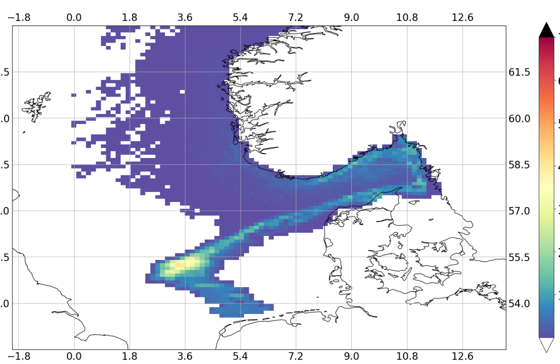


(b) Particles were released at 23:00 1 January 2017

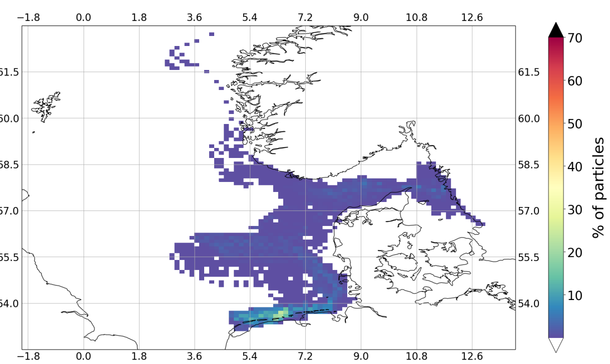


(c) Particles were released at 23:00 1 January 2018

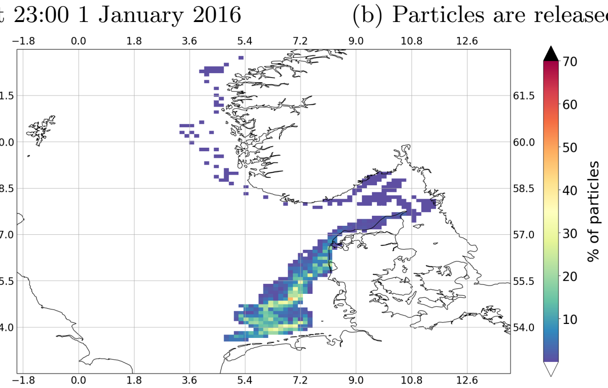
Figure 12: Dispersion of particles in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. Then the percentage of particles passing each cell was determined. In these simulations only the currents and tides were taken into account.



(a) Particles are released at 23:00 1 January 2016

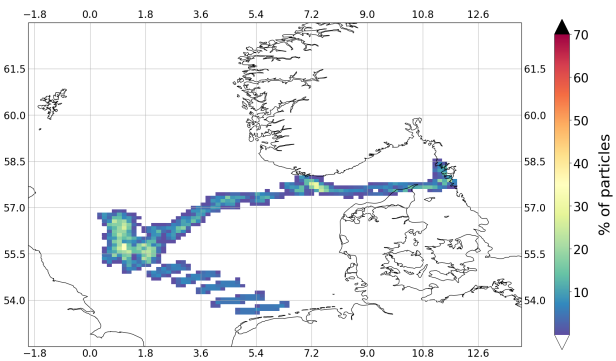


(b) Particles are released at 23:00 1 January 2017

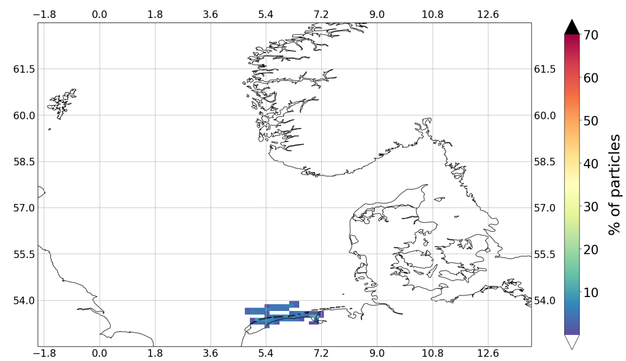


(c) Particles are released at 23:00 1 January 2018

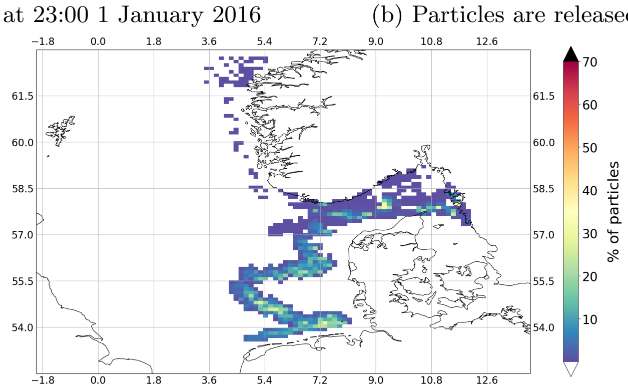
Figure 13: Dispersion of particles in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. Then the percentage of particles passing each cell was determined. In these simulations only the currents, tides and Stokes drift were taken into account.



(a) Particles are released at 23:00 1 January 2016



(b) Particles are released at 23:00 1 January 2017



(c) Particles are released at 23:00 1 January 2018

Figure 14: Dispersion of particles in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. Then the percentage of particles passing each cell was determined. In these simulations only the currents, tides, Stokes drift and a wind drag of 2.5% were taken into account.

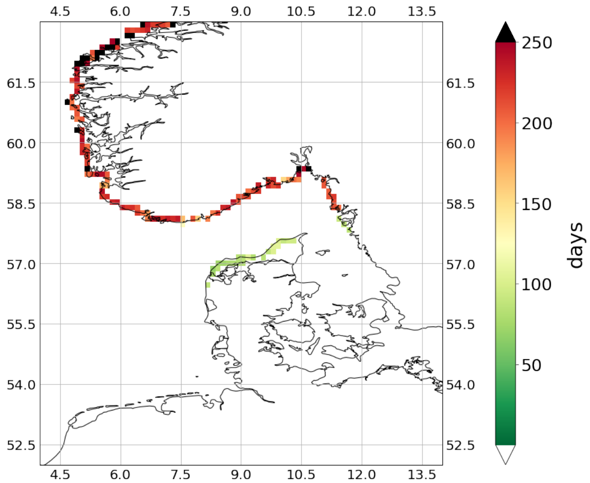
5.2.2 Beaching

In all simulations that were run in 2016, 2017 and 2018 particles beached. We will now discuss these results in the three different cases, with only currents and tides, with additional Stokes drift and with wind drag as well.

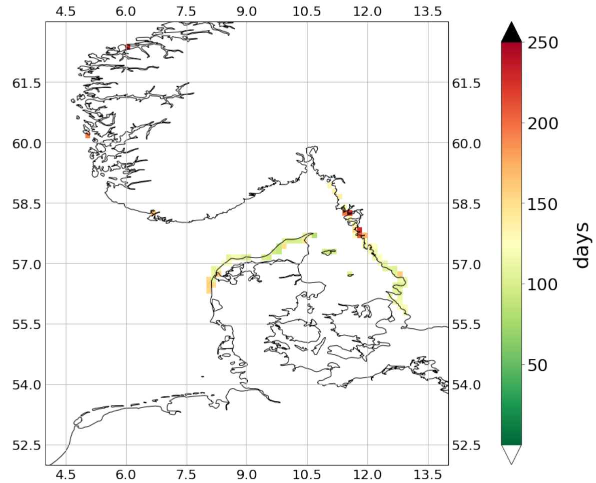
In the simulations where we only incorporated the currents and the tides, no particles beach in the Netherlands or in Germany in all the three different years. In 2016 the most particles (78%) beached on the coast of Norway, but in 2017 a really small portion (0.04%) of the particles beaches there. In 2017 and 2018 most of the particles (80% and 66% respectively) beach on the shore of Denmark, especially on the northern coast (see figure 15 and 16). What is also notable is that in 2017 all particles beach on average in 100 to 150 days, which is far earlier than in 2016 and 2018, where particles even beach in more than 250 days. As we have seen in section 4, the wind in 2018 and 2016 was directed more to the west for some time. This can lead to a change in surface currents, which will influence the particles residence time in the ocean.

When Stokes drift is included less particles wash ashore on the Norwegian coast in all years (see figure 18) . We especially see a big difference in 2017 where almost all particles actually beach in the Netherlands and Germany (64% and 27%), which is very interesting because in 2019 all particles beached in the Netherlands with Stokes drift. This could make us believe that the conditions in 2017 and 2019 were more identical to each other than in 2016 or 2018. If we look at the weather conditions (table 1-3) we indeed see more similarities between 2017 and 2019, especially the conditions on 2 January are more alike than those in 2016 and 2018. In 2016 62% of particles beach in Norway, but in 2018 almost all particles (99%) beach on the Danish coast, mainly in the north as before. We definitely notice a lot of difference in beaching between the years when Stokes drift is included. What is also noteworthy is that in each year the particles beach faster when we do take Stokes drift into account (see figure 17). This is what we expect, because in every year the Stokes drift (which is in the same direction as the waves) is mainly directed to the east-south-east, which causes more particles to beach in Denmark, Germany and the Netherlands.

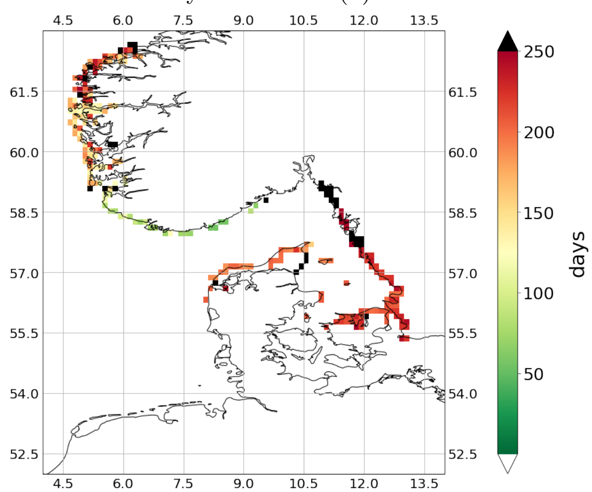
This would also make us expect that when wind drag is included the particles will beach even faster, as the wind often increases the effect of the Stokes drift, as waves usually propagate in about the same direction as the wind. We can indeed observe this effect in figure 17. Furthermore, the wind drag leads to less of a dispersion of the beached particles and higher density of beached particles in certain areas (to study this effect look at the additional figures in appendix A). In 2017 particles only beach in the Netherlands and Germany, where more than 75% actually washes on the Dutch shores. In 2016 and 2018 it actually causes beaching of 84% and 72% of particles respectively, in Sweden, while without wind drag in 2018 no particles beached on the Swedish coast and in 2016 it was a really small percentage (8%) of particles which beached there. In figure 17 we can also see that the location of beaching in Sweden is almost the same in 2016 and 2018. This is because of the influence of the wind on the particles which are blown into Skagerrak and then directly onto the Swedish coast.



(a) Particles are released at 23:00 1 January 2016

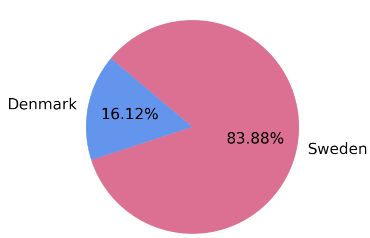


(b) Particles are released at 23:00 1 January 2017

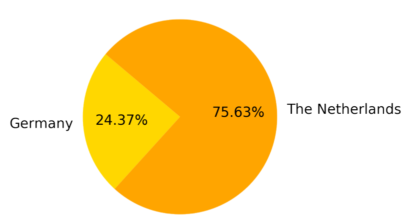


(c) Particles are released at 23:00 1 January 2018

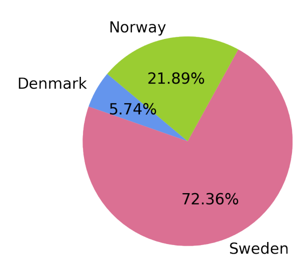
Figure 15: Average age of beached particles in each cell in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations only included currents and the tides.



(a) Particles are released at 23:00 1 January 2016

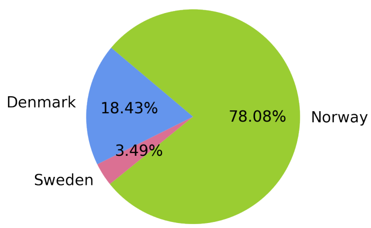


(b) Particles are released at 23:00 1 January 2017

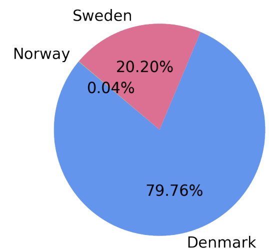


(c) Particles are released at 23:00 1 January 2018

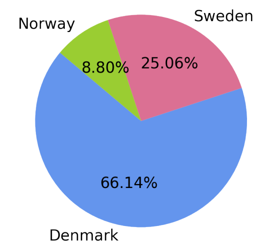
Figure 20: Percentage of particles beached in certain areas in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides, Stokes drift and wind drag of 2.5%.



(a) Particles are released at 23:00 1 January 2016

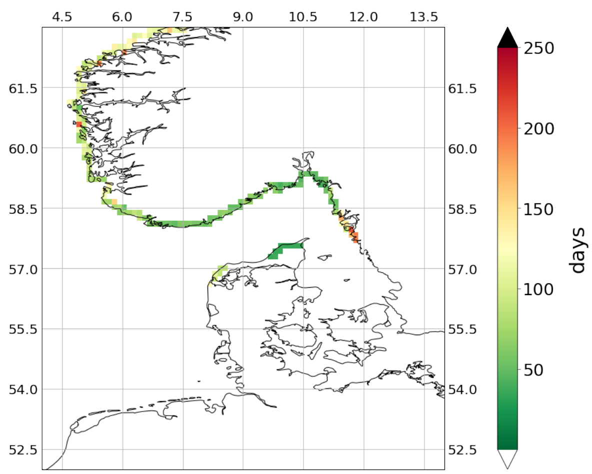


(b) Particles are released at 23:00 1 January 2017

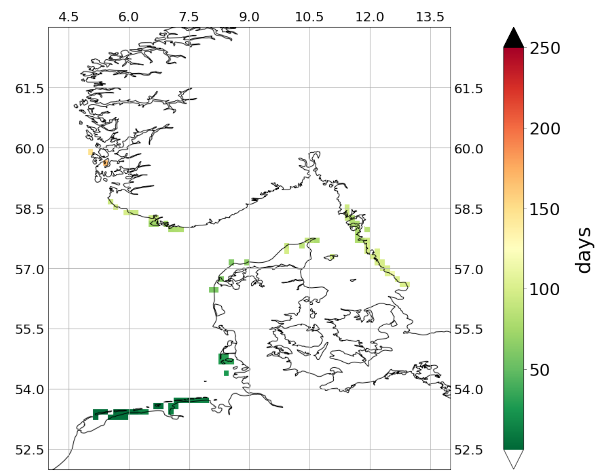


(c) Particles are released at 23:00 1 January 2018

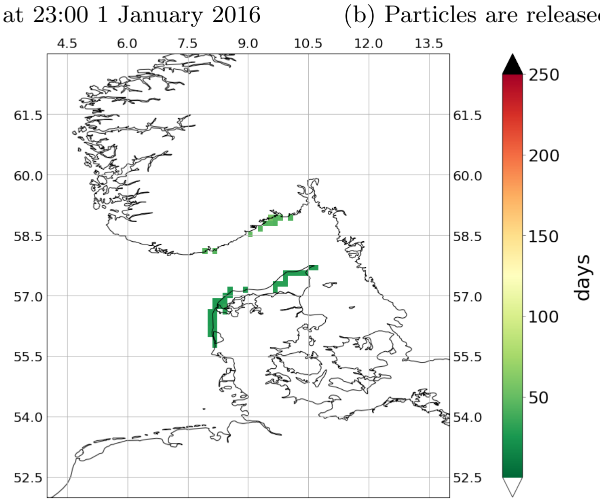
Figure 16: Percentage of particles beached in certain areas in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations only included currents and the tides.



(a) Particles are released at 23:00 1 January 2016

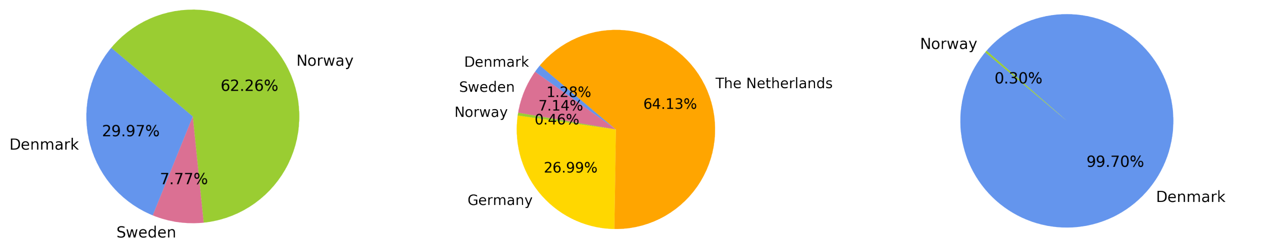


(b) Particles are released at 23:00 1 January 2017



(c) Particles are released at 23:00 1 January 2018

Figure 17: Average age of beached particles in each cell in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides and Stokes drift.

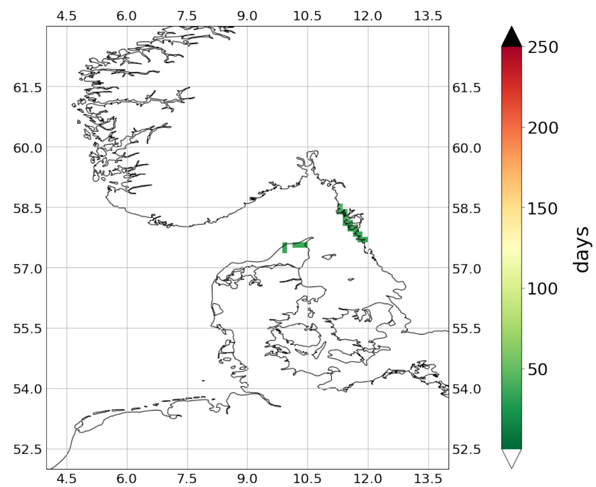


(a) Particles are released at 23:00 1 January 2016

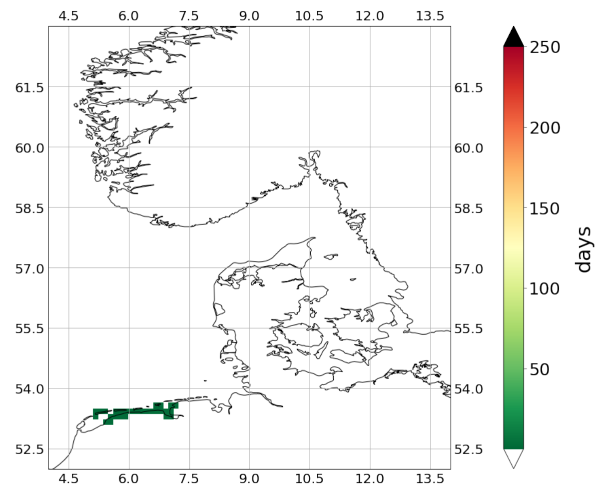
(b) Particles are released at 23:00 1 January 2017

(c) Particles are released at 23:00 1 January 2018

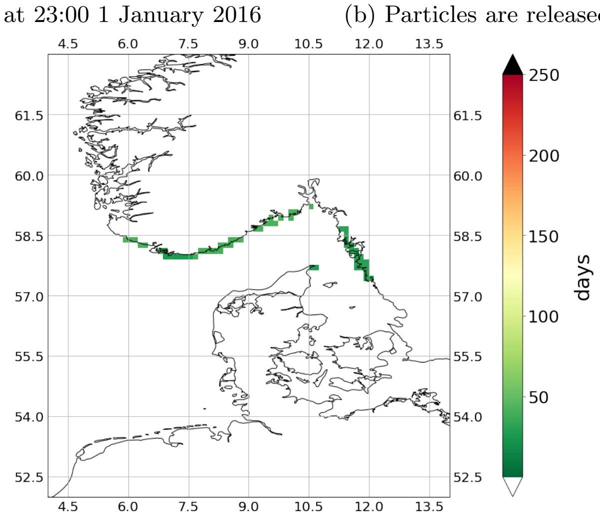
Figure 18: Percentage of particles beached in certain areas in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides and Stokes drift.



(a) Particles are released at 23:00 1 January 2016



(b) Particles are released at 23:00 1 January 2017



(c) Particles are released at 23:00 1 January 2018

Figure 19: Average age of beached particles in each cell in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides, Stokes drift and wind drag of 2.5%.

6 Discussion

6.1 Release locations and beaching

Containers fell of the MSC Zoe for about seven hours and the captain of the ship only noticed it after four hours [2]. This means that there is a broad spectrum of times and places of when the containers fell off. It is also not known when which container fell off the ship and when certain containers opened and spilled their content into sea. This means that there is a great uncertainty in the release time and place of the particles in our model.

As we observed in section 5.1.2 there was a difference in our results and in that of the waddenplastic.nl research [31]. In their research the density of beached HDPE-granulates was higher on the eastern Wadden Islands and in Groningen. Firstly it could be that all containers fell from the ship more to the east than in our model. Secondly it is possible that a higher number of containers fell from the ship more to the east; in our model the release locations of the particles are evenly distributed on two lines in front of the Wadden islands. Something else we need to realize is that the results of the research only include HDPE-granulates, which could implicate that the containers that contained HDPE-granulates fell off the ship later than some of the containers with other kinds of cargo. This could also be the cause of the difference between our model and the result of the research. To know what the exact cause is we would need to run our simulations again, but with other release locations for the particles.

Next to this uncertainty of release locations in our simulations, particles in our model which have beached can not be pushed back in to the ocean, when they beach the particles are deleted from the simulation. In reality plastics that have beached can re-enter the ocean, this especially often happens during storms and spring tides [35]. In 2019 when the containers fell of the MSC Zoe a storm was raging, which could have led to plastics re-entering the ocean. This would mean that our results of 2019 with Stokes drift and additional wind drag included are not a good reflection of the reality, because in those simulations all particles beached in a short timespan on the Dutch coast.

6.2 Diffusion

In our model we have different diffusivities in different areas and years, because of the difference in spatial resolution of the data. The diffusivity D differs from 1.33 to 7. We based our calculations on Neumann et al. (2014)[23], who based it on Schönfeld et al.(1995)[26], just like Gutow et al. (2018)[10]. In [10] $D = 15.9\text{m}^2/\text{s}$ when the spatial resolution is $\frac{1}{9}^\circ \times \frac{1}{5}^\circ$ (ca.7.4km). However in Schönfeld et al.(1995)[26] $D = 2.5\text{m}^2/\text{s}$ with a resolution of 1 nautical mile ($=\frac{1}{60}^\circ$lat) and $D = 27.3\text{m}^2/\text{s}$ for 6 nautical miles. In our model the spatial resolution of the data is quite high, with the highest resolution being $0.016^\circ \approx \frac{1}{60}^\circ$, which leads to low diffusivities. According to Schönfeld et al(1995)[26] our diffusivity should be a bit larger, but it is still in the same order of magnitude.

6.3 Wind drag

The wind drift factor is an item of discussion in a lot of research. We will examine a few of these discussions here. We used a wind drift factor of 2.5% as Stanev et al. [27] determined for wooden drifters of 10 × 12 cm in the North Sea in 2018. In this study they also investigated the wind drift factor of GPS drifters, which were made to follow the current in the upper 0.5 meter of the ocean and are much less exposed to the wind. These drifters have a length of 50 cm, the upper part (surrounded by Styrofoam) has a diameter of 14 cm and the lower part has a diameter of 9 cm. Stanev et al. [27] determined the best fit for these drifters to be 0.3%, so negligible. The Stokes drift however had a bigger contribution to the best fit. For both the wooden drifters and the GPS drifters they observed that when Stokes drift was unknown, an increase of about 1% of the wind velocity was needed to match the effect of the Stokes drift. They also investigated surface drifters in Callies et al. [3]. They looked at two different type of surface drifters in the German Bight. One of cylindrical shape which is 10 cm in diameter, 32 cm in length and extends 80 cm above the sea surface. The other one is a sphere with a diameter of 20 cm and half of it extends above the sea surface. Both had a drogue of 50 cm attached to them. This resulted in a best fit, for the upper 5 meter of surface currents, where the wind drift factor was 0.6% without Stokes drift, which had about the same result as incorporating only 50% of the Stokes drift. In Dagestad and Röhrs [7] they studied the wind drag contribution to drifters in the North Sea and Norwegian Sea, but these were more buoyant drifters. In their research the result for the wind drift factor for iSphere drifters (39cm diameter, 31cm height and without drogue) was 3% when Stokes drift was included and 4% when Stokes drift was not incorporated. This is a little bit higher than Stanev et al determined for their wooden drifters, but the contribution of the Stokes drift is the same, 1%. The studies we just mentioned all based their wind drift factor on drifters, so lastly we want to point out the research of Yoon et al. [34] where they modelled drifting of marine litter in the Japan Sea. They based the wind drag on the ratio of cross sections below and above the sea surface, the wind pressure and wind velocity.

As we have seen different wind drag factors are determined in this research. We choose to use the wind drift factor of 2.5% of the wooden drifters in Stanev et al. [27], because their properties are the most similar to the floating plastic particles we wanted to simulate. The reason we still mention all these different wind drift factors is to demonstrate that it is not possible to exactly know what the influence of the wind on plastic will be. Small plastic, like HDPE-granulates will not stay afloat all the time, which makes it even harder to determine this influence.

6.4 Sinking

The biggest limitation in our model is that sinking of the particles is not included. Plastic particles can loose their buoyancy because of biofouling and other processes. There is still little known about when plastic starts sinking and how fast it sinks. Most plastic particles do not sink with constant speed when they start sinking, but oscillate up and down in the ocean [17]. The properties of the plastic also play a big role. The size and density of the plastic particle have a huge influence on the sinking. This makes it all more difficult, especially in this thesis where a lot of different plastic items have fallen of the MSC Zoe. Even if we only focused on one kind of plastic, like the pellets and HDPE-granulates, it is still hard to incorporate sinking. Kooi et al.(2017)[17] actually modelled the effect of biofouling on microplastics. The model predicts what happens to particles of certain size and density; when they will start sinking, with what kind of speed they will sink and if they will oscillate vertically. In this study they were interested in particles made of HDPE, which is what pellets and HDPE-granulates are made of. Bags of pellets and HDPE-granulates were part of the cargo of the MSC Zoe [33]. In Kooi et al. (2017)[17] they looked at particles ranging between 10 mm and 0.1 μm. The HDPE-granulates of the MSC Zoe are 0.5 mm and the pellets are 4-5mm [33]. Kooi et al.(2017)[17] predict that these particles will start sinking after 24 to 26 days. The settling velocity will be between 1000 and 5000 meter per day. If we review our simulations where only the currents and tides were included we see that this would lead to a lot of plastic ending up on the sea floor of the German Bight - this is also the case when Stokes drift is incorporated - but more particles could then end up on the bottom of Skagerrak. Lastly, if we look at the simulations with additional wind drag, we observe that particles in our simulations in 2016 and 2018 reach Skagerrak even faster, which would cause even more particles to end up on the bottom of Skagerrak. If we review the results of the beaching of the particles, the sinking would lead to a higher percentage of beaching on the coast of Denmark and Germany, since less particles will reach Sweden or Norway. If you want to study the age of the particles or the distribution of age of beached particles you can consult appendix A, where additional figures are shown.

Not only small plastic like the pellets and HDPE-granulates were cargo of the MSC Zoe, also far bigger buoyant plastic, like My Little Ponies (toys similar to rubber duckies). Fazey and Ryan (2016)[9] researched the effects of biofouling on the surface longevity of marine plastics. They included bigger plastic particles of HDPE (50x50x4 mm in size), this is still not as big as some of the plastic from the MSC Zoe, but will provide a better estimate. The result of the research was that bigger plastics from 1 to 10000 mm^3 in volume took 30 to 70 days to start sinking. They saw that besides the volume of the plastic particles, the size of surface area is important. More volume leads to a longer set off for sinking, but if the ratio surface area to volume becomes bigger plastic tends to have a shorter set off for sinking, but it still ranges between 30 and 70 days. If we would incorporate this sinking in our simulations, the bigger plastics would not end up in the German Bight, but in Skagerrak, if we look at the simulations with only the currents and tides included. If we review the results of the simulations with Stokes drift, also a lot of plastic will end up on the seafloor of Skagerrak and this is the same if we look at the simulations with additional wind drag. For the beaching this would mean that the ratio between particles beaching in Denmark/Germany/the Netherlands and Sweden/Norway will also change, because the percentage of particles beaching on the coast of Denmark, Germany and the Netherlands will be larger, at least in the case of the simulations with only the currents and tides and the additional Stokes drift. When looking at the simulations with also the wind drag incorporated, we see that most particles beach within 40 days, which is less than 70 days, so not all particles will have started sinking and will still beach.

7 Conclusion

What we observe from our results is that the dispersion of particles in 2019 shows most comparison to the dispersion in 2017. When only the current and tides are taken into account, the particles in all four years drifted towards the north. In 2016, 2017 and 2018 a lot of particles were transported through Skagerrak and we expect that this is what will happen to the particles in 2019, only considering currents and tides. Of course the particles floating on the oceans surface are not only affected by the currents and tides, so we also looked at the influence of the Stokes drift. In 2019 Stokes drift resulted in all particles beaching in the Netherlands as a result of strong winds directed towards the south. We compared our results of beached particles to those of waddenplastic.nl [31] and noticed that there was a difference. The HDPE-granulates were found more on the beaches of the eastern Wadden Islands and Groningen than in our results. In 6.1 we concluded that there could be a few different explanations for this all depending on the release locations of our particles. Here we also discussed the way beaching is simulated in our model and how this could have influenced our results of 2019. To make a better prediction of what will happen in 2019 we also studied the results of our simulations of 2016, 2017 and 2018. In those years not all particles beach in the Netherlands, when Stokes drift is included. The results of these simulations, in combination with the uncertainties in our model, make us suspect that not all plastic beached in the Netherlands in the beginning of 2019. The Stokes drift will cause the plastics still drifting in the ocean to be transported along the coast of Germany and Denmark towards the north and into Skagerrak. As for beaching the effect of Stokes drift will be that plastic will wash ashore more on the German and Danish coast than in our simulation of 2019. Lastly we included a wind drag of 2.5% in the model, this caused the beaching of all particles in 2017 and 2019. However in 2016 and 2018 particles mainly beached in Sweden. To predict the effect of the wind on the particles from the MSC Zoe is hard, because in our simulation everything beaches immediately on the Dutch coast in 2019 and in 2017 (which we concluded was most similar to 2019) also all particles wash ashore in the Netherlands. What we could expect is that plastic will beach in Sweden as in 2016 and 2018 was the case, but to make a real prediction about the influence of the wind, we should study the effects of the wind more.

As discussed in 6.4 incorporating sinking in our model would lead to different results. Especially the percentage of beached particles in the certain areas would be affected. Sinking will cause a higher percentage of particles beaching on the coast of Denmark and Germany and it will also result in particles ending up on the bottom of the German Bight and Skagerrak.

Our overall prediction is that the plastic of the MSC Zoe will drift towards Skagerrak along the German and Danish coast. Small plastics like HDPE-granulates and pellets will probably mostly end up on the bottom of Skagerrak and some will end up on the sea floor of the German Bight in front of the west coast of Denmark. Beaching of these plastics will largely happen on the coasts of the Netherlands, Germany and Denmark. The bigger buoyant plastics like the my little ponies could also end up on the bottom of Skagerrak, but as those plastics take longer to start sinking, more of them will probably end up on the beach than on the sea floor. In comparison to the smaller plastic, a higher percentage of the larger plastics will reach the Swedish and Norwegian coast.

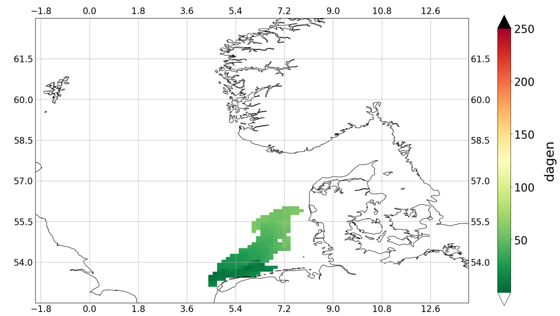
8 Future research

If we look at our discussion in section 6, there are a few different changes that could be made to the model. As discussed in 5.1.2 the results of the research of waddenplastic.nl [31] were a bit different from our results, which could have a few reasons. It would be very interesting to investigate what causes this difference. To do this you would have to run the simulations again, but with different release locations of the particles. We would suggest to also release particles more east of our locations or to have a higher density of release locations in the east instead of the now equally distributed locations. In our model we chose to track 10000 particles, but this can definitely be increased in further research. Besides releasing more particles in the east, it would be of added value, if you also track more particles, to disperse the releasing locations more in front of the coast. Now the particles are released on two lines, while in reality the locations where containers fell off the ship were more dispersed. Next to adjusting the release locations and number of particles, the diffusion coefficient could also be determined in a different way. As already made clear in section 6.2 in Schönfeld et al.(1995)[26] the diffusivity corresponding to the resolution of our data would be bigger. I do not think this will make a lot of a difference, since the diffusivity we use is still in the same order of magnitude, but the diffusivity in Schönfeld et al.(1995)[26] is about 88% bigger. We also discussed the wind drag in section 6.3, where we showed the wind drift factor of different researches. I think that the results of Callies et al. [3] are especially interesting, since they found out that in the upper 5 meter of the ocean there was a best fit with only incorporating 50% of the Stokes drift. Of course this would not apply to pure floating plastic, but plastic does not stay afloat forever, as already noted. If you would incorporate sinking in this model, it would be very nice to look at the effect of Stokes drift on these particles as they sink.

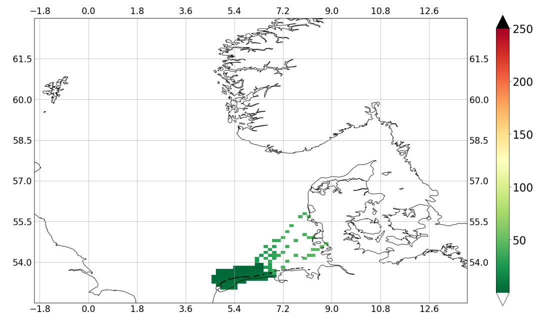
To investigate if our model is a good approximation of reality it would be very interesting to collect more data about where plastic from the MSC Zoe ends up, like the research of waddenplastic.nl [31]. To get this data bottom trawls of the German Bight and Skagerrak should be conducted. It would especially be interesting to do this in Skagerrak. Conducting beach surveys on the coasts of Germany, Denmark and Sweden could also be a big contribution to getting a better view on what has happened to the plastic. What will be difficult is to distinguish the plastic from MSC Zoe and other sources. It would be good to focus on plastic with distinguishable appearances, like all the kinds of toys which were part of the cargo of the MSC Zoe.

A Additional figures

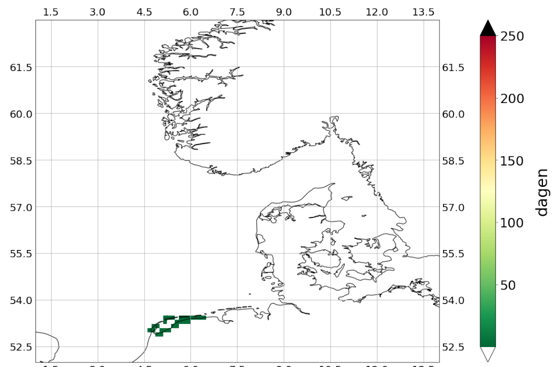
A.1 2019



(a) Only currents and tides

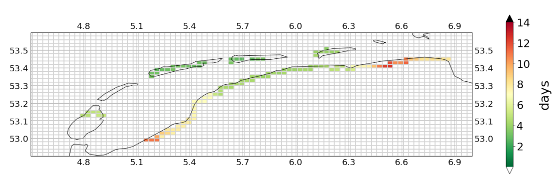


(b) With Stokes drift

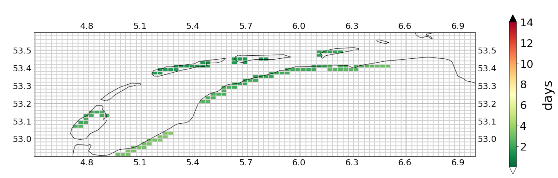


(c) With wind drag of 2.5%

Figure 21: Average age of particles which passed each cell in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. Then the average age of the particles passing each cell was determined in the three different cases: (a) simulation with only the currents and tides, (b) simulation with Stokes drift and (c) simulations with Stokes drift and wind drag of 2.5%

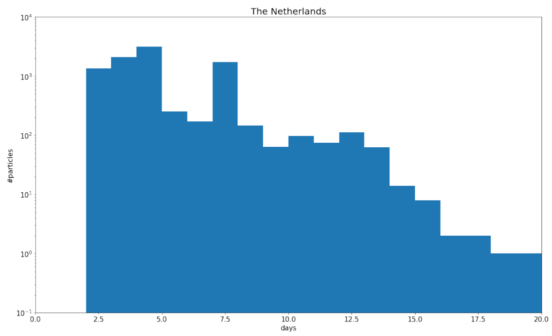


(a) With Stokes drift

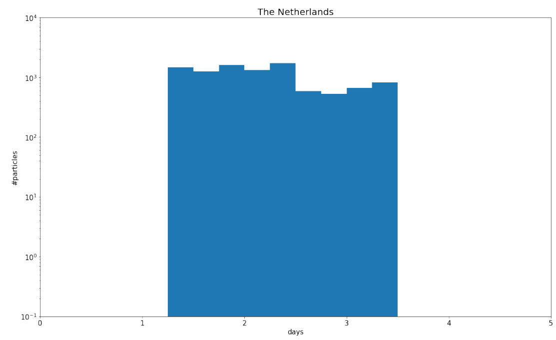


(b) With Stokes drift and wind drag of 2.5%

Figure 22: Average age of beached particles in each cell in 2019. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. Output was given each 6 hours. Then the average age of the particles beaching in each cell was determined in the two different cases: (a) simulation with Stokes drift and (b) simulations with Stokes drift and wind drag of 2.5%



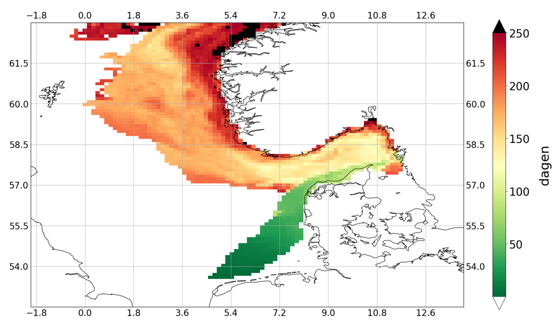
(a) Wit Stokes drift



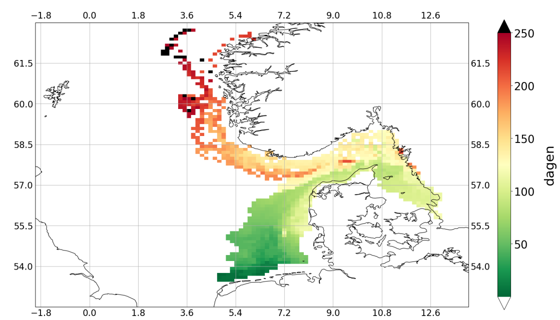
(b) With Stokes drift and wind drag of 2.5%

Figure 23: The distribution of the age of beached particles on the coast of the Netherlands is given. 10000 particles were released at 23:00 on the 1st of January and tracked for 2 months. Output was given every 6 hours. The distribution was determined in two different cases: (a) simulation with Stokes drift and (b) simulations with Stokes drift and wind drag of 2.5%

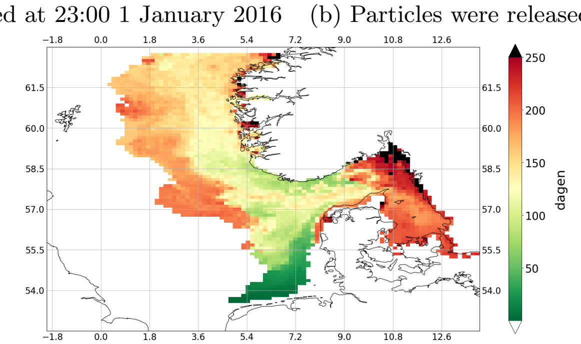
A.2 2016, 2017 and 2018



(a) Particles were released at 23:00 1 January 2016

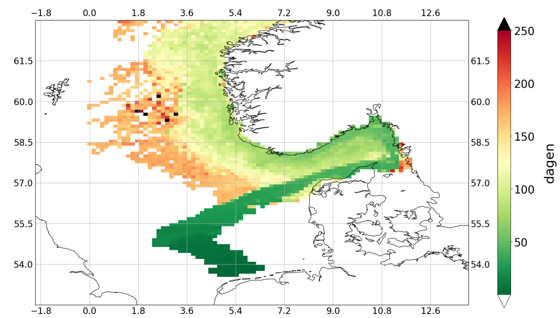


(b) Particles were released at 23:00 1 January 2017

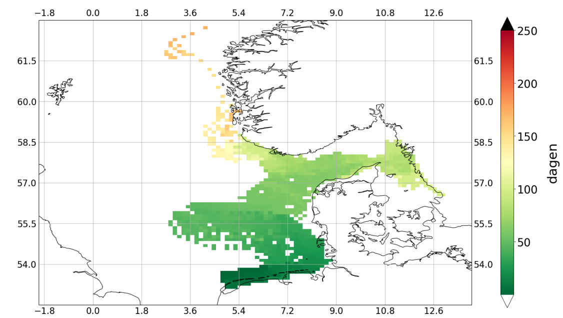


(c) Particles were released at 23:00 1 January 2018

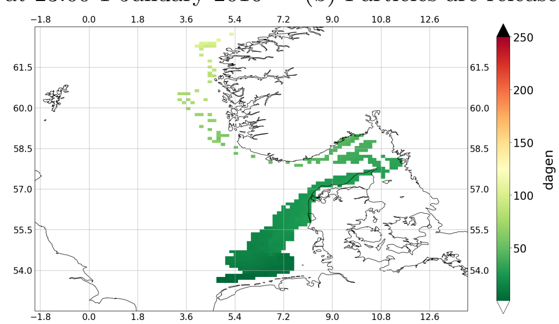
Figure 24: Average age of particles passing each cell in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. In these simulations only the currents and tides were taken into acount.



(a) Particles are released at 23:00 1 January 2016

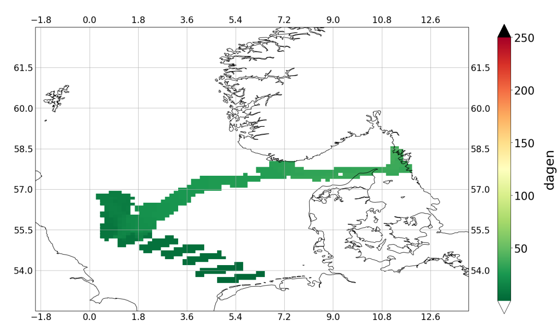


(b) Particles are released at 23:00 1 January 2017

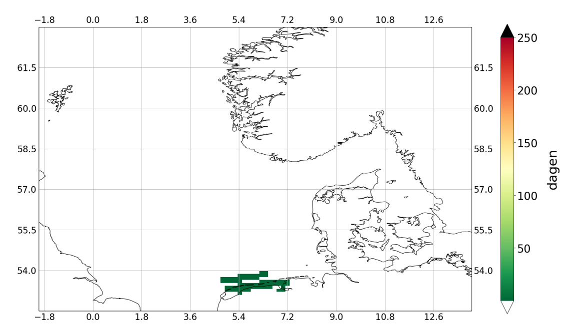


(c) Particles are released at 23:00 1 January 2018

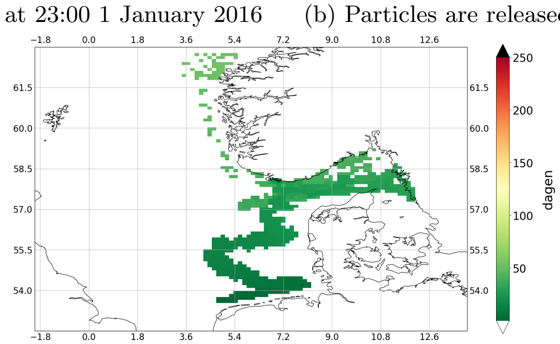
Figure 25: Average age of particles passing each cell in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. Then the percentage of particles passing each cell was determined. In these simulations only the currents, tides and Stokes drift were taken into acount.



(a) Particles are released at 23:00 1 January 2016

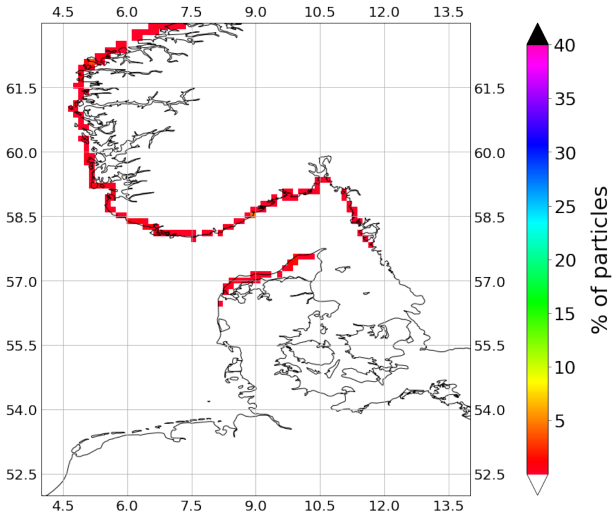


(b) Particles are released at 23:00 1 January 2017

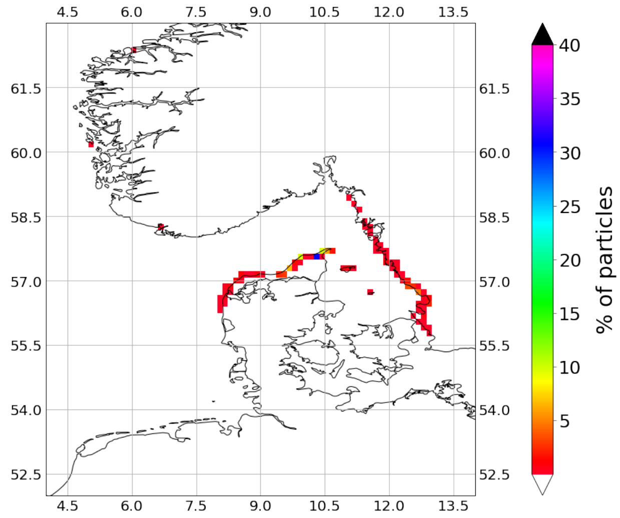


(c) Particles are released at 23:00 1 January 2018

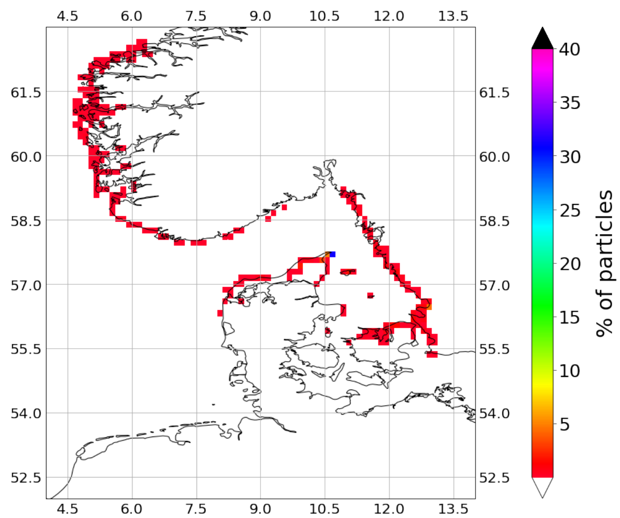
Figure 26: Average age of particles passing each cell in 2016(a), 2017(b) and 2018(c). 10000 particles were released at 23:00 on the 1st of January of each year and tracked for 1 year. Then the percentage of particles passing each cell was determined. In these simulations only the currents, tides, Stokes drift and a wind drag of 2.5% were taken into acount.



(a) Particles are released at 23:00 1 January 2016

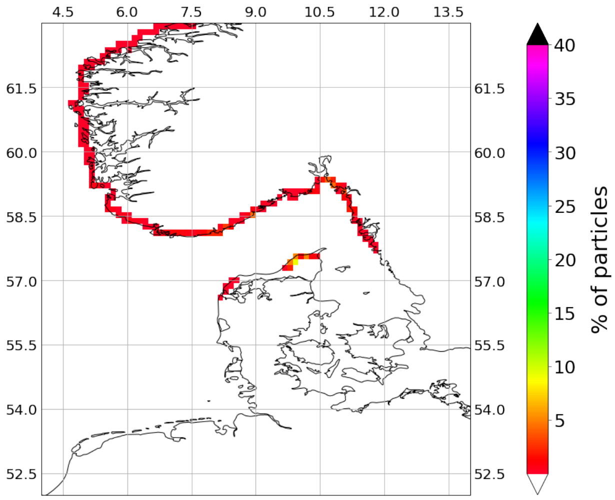


(b) Particles are released at 23:00 1 January 2017

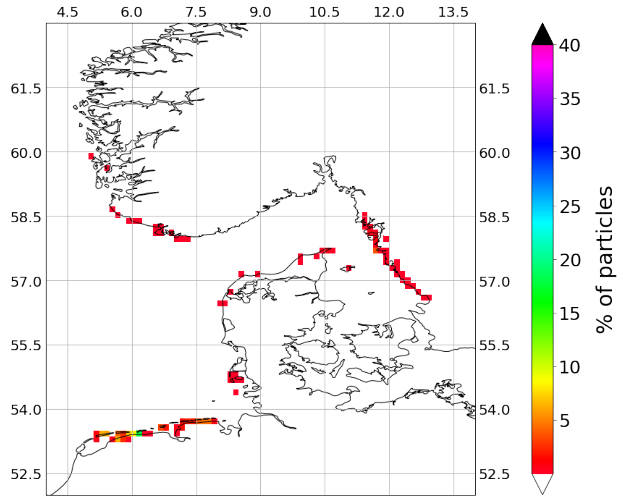


(c) Particles are released at 23:00 1 January 2018

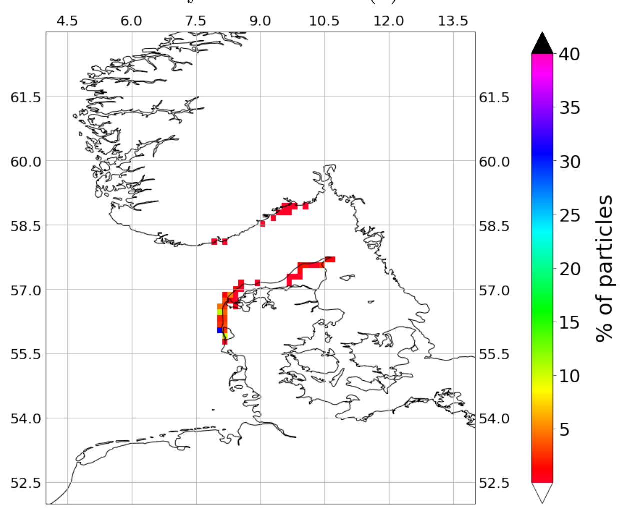
Figure 27: Density of beached particles in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations only included currents and the tides.



(a) Particles are released at 23:00 1 January 2016

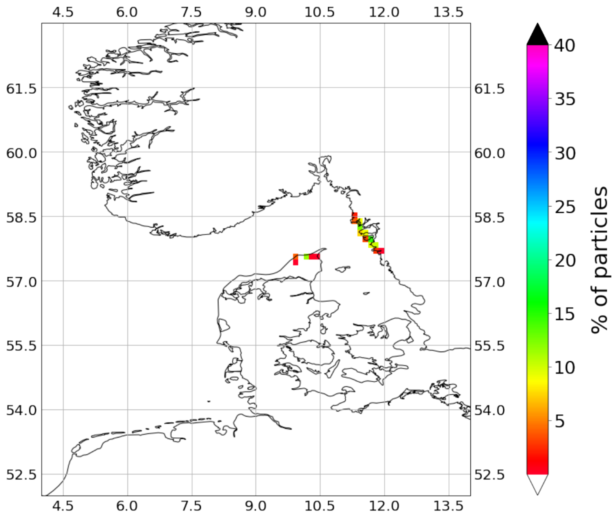


(b) Particles are released at 23:00 1 January 2017

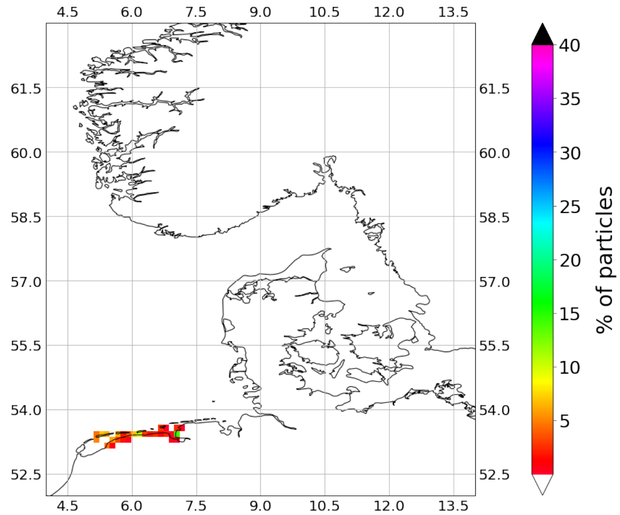


(c) Particles are released at 23:00 1 January 2018

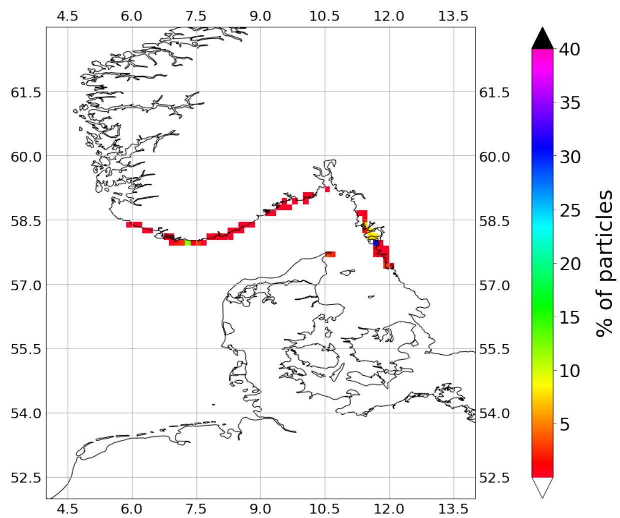
Figure 28: Density of beached particles in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides and Stokes drift.



(a) Particles are released at 23:00 1 January 2016

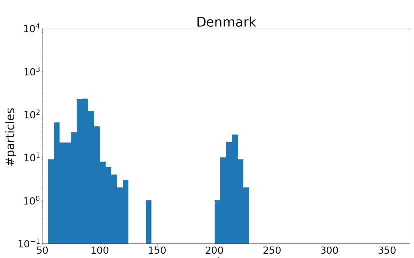


(b) Particles are released at 23:00 1 January 2017

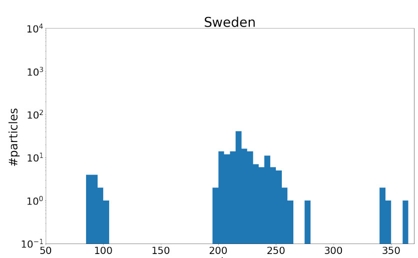


(c) Particles are released at 23:00 1 January 2018

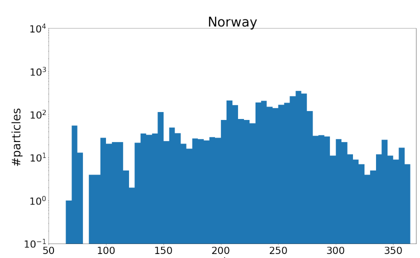
Figure 29: Density of beached particles in 2016, 2017 and 2018. 10000 particles were released at 23:00 on the 1st of January each year and tracked for 1 year. These simulations included currents, the tides, Stokes drift and wind drag of 2.5%.



(a) Denmark

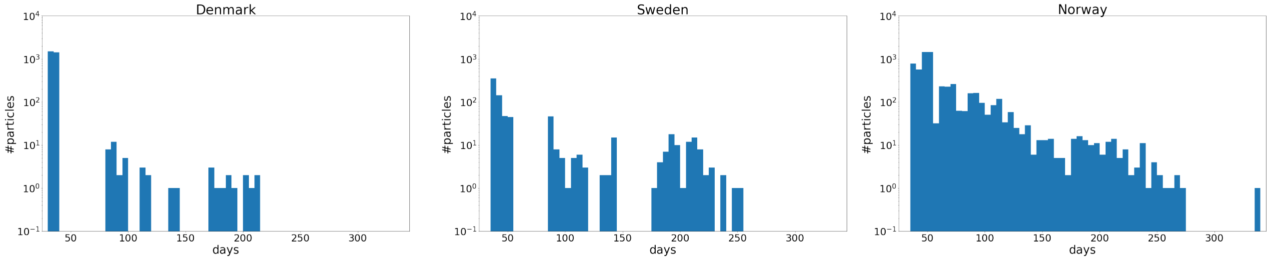


(b) Sweden



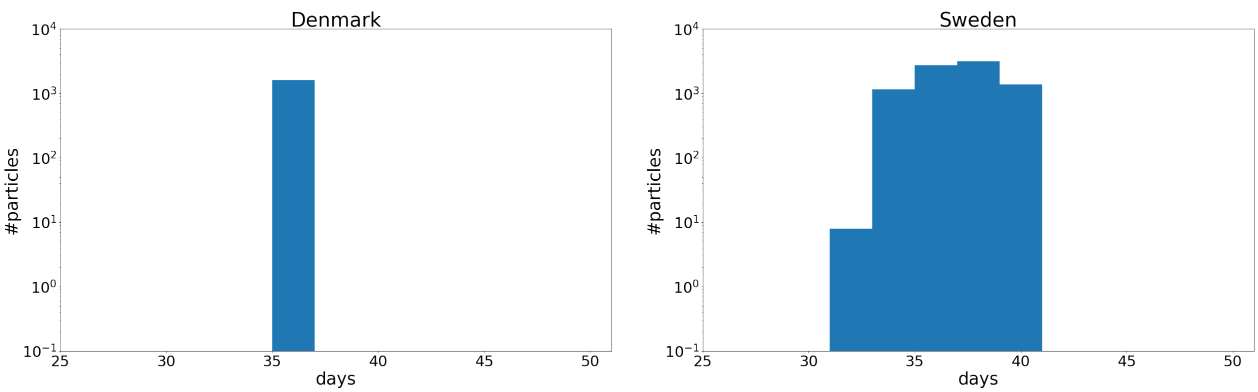
(c) Norway

Figure 30: The distribution of the age of beached particles on the coast of the Denmark, Sweden and Norway is shown. The simulation included only currents and tides. 10000 particles were released at 23:00 on the 1st of January of 2016 and tracked for 1 year.



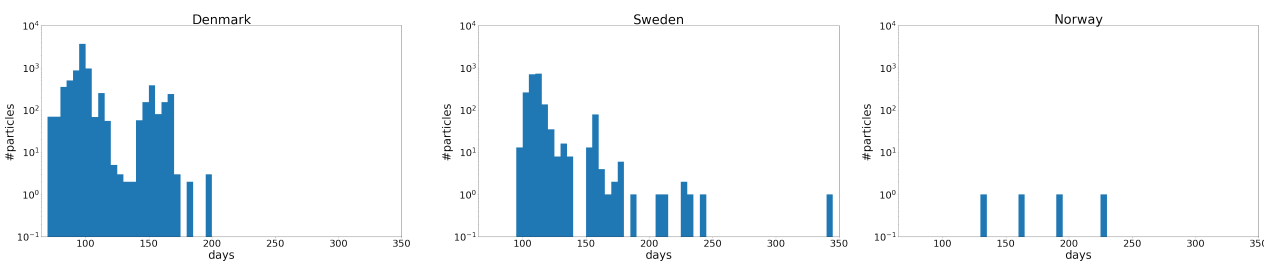
(a) Denmark (b) Sweden (c) Norway

Figure 31: The distribution of the age of beached particles on the coast of the Denmark, Sweden and Norway is shown. The simulation included currents, tides and Stokes drift. 10000 particles were released at 23:00 on the 1st of January of 2016 and tracked for 1 year.



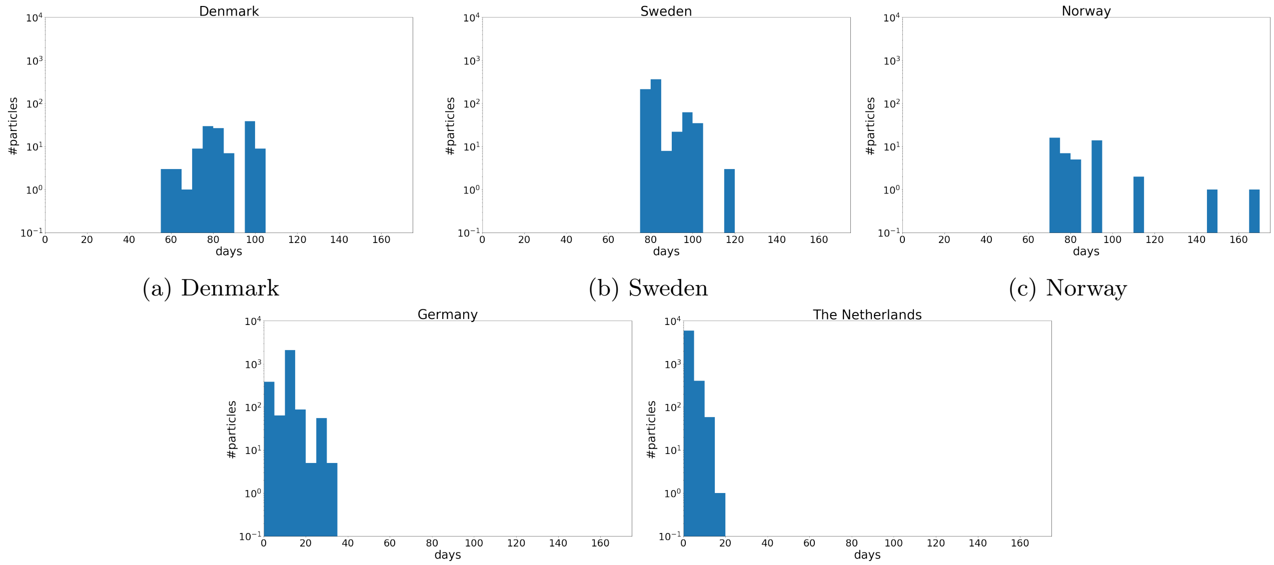
(a) Denmark (b) Sweden

Figure 32: The distribution of the age of beached particles on the coast of the Denmark and Sweden is shown. The simulation included currents, tides, Stokes drift and wind drag of 2.5%. 10000 particles were released at 23:00 on the 1st of January of 2016 and tracked for 1 year.



(a) Denmark (b) Sweden (c) Norway

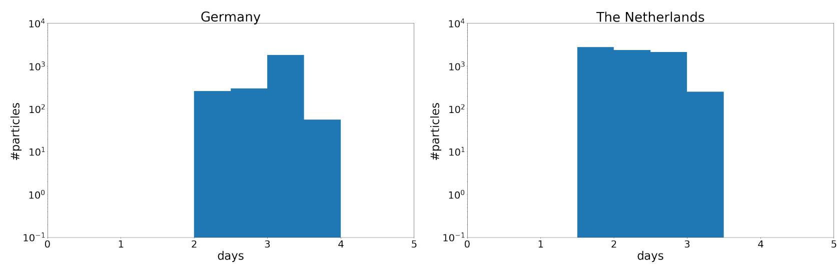
Figure 33: The distribution of the age of beached particles on the coast of the Denmark, Sweden and Norway is shown. The simulation included only currents and tides. 10000 particles were released at 23:00 on the 1st of January of 2017 and tracked for 1 year.



(a) Denmark (b) Sweden (c) Norway

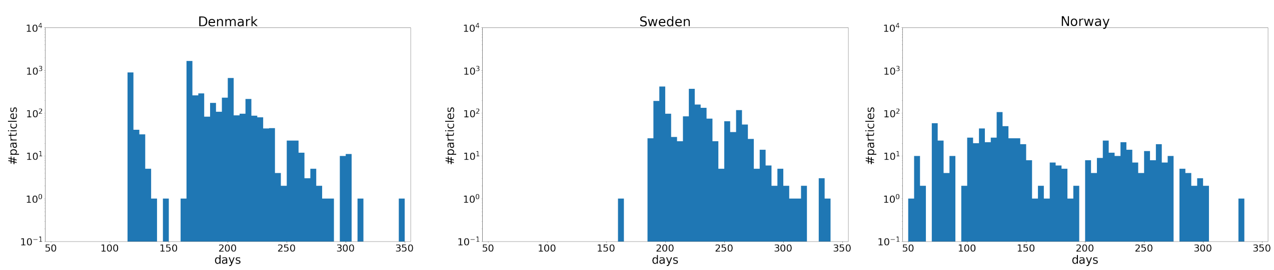
(d) Germany (e) The Netherlands

Figure 34: The distribution of the age of beached particles on the coast of the Denmark, Sweden, Norway, Germany and the Netherlands is shown. The simulation included currents, tides and Stokes drift. 10000 particles were released at 23:00 on the 1st of January of 2017 and tracked for 1 year.



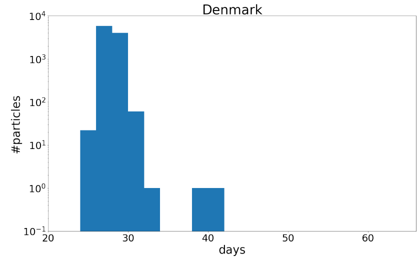
(a) Germany (b) The Netherlands

Figure 35: The distribution of the age of beached particles on the coast of the Germany and the Netherlands is shown. The simulation included currents, tides, Stokes drift and wind drag of 2.5%. 10000 particles were released at 23:00 on the 1st of January of 2017 and tracked for 1 year.

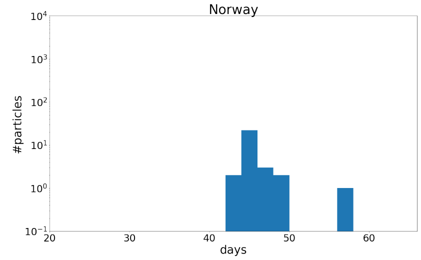


(a) Denmark (b) Sweden (c) Norway

Figure 36: The distribution of the age of beached particles on the coast of the Denmark, Sweden and Norway is shown. The simulation included only currents and tides. 10000 particles were released at 23:00 on the 1st of January of 2018 and tracked for 1 year.

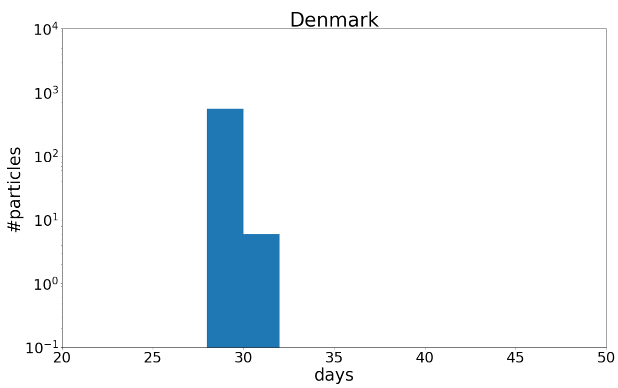


(a) Denmark

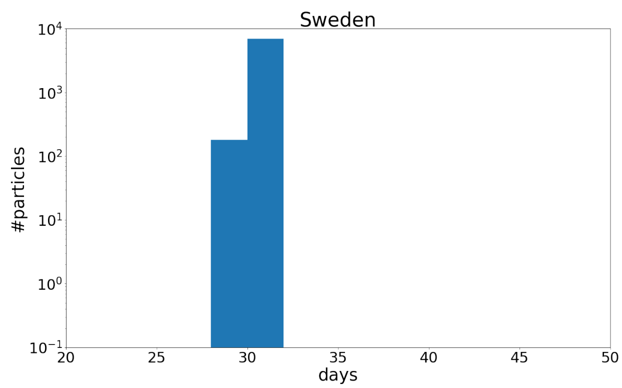


(b) Norway

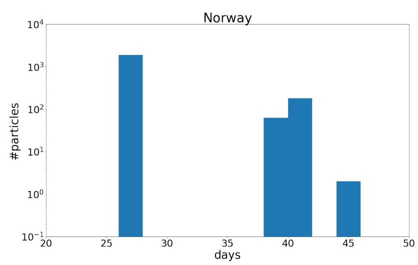
Figure 37: The distribution of the age of beached particles on the coast of the Denmark and Norway is shown. The simulation included currents, tides and Stokes drift. 10000 particles were released at 23:00 on the 1st of January of 2016=8 and tracked for 1 year.



(a) Denmark



(b) Sweden



(c) Norway

Figure 38: The distribution of the age of beached particles on the coast of the Denmark, Sweden and Norway is shown. The simulation included currents, tides, Stokes drift and wind drag of 2.5%. 10000 particles were released at 23:00 on the 1st of January of 2018 and tracked for 1 year.

B Second appendix

```
#example of code of the simulation in 2019 with currents, tides, Stokes drift
#and a wind drag of 2.5 percent included

from parcels import FieldSet, ParticleSet, Variable, JITParticle, AdvectionRK4, ErrorCode,
NestedField, VectorField
from parcels import rng as random
import numpy as np
import math
from datetime import timedelta

#importing datasets of currents and tides the North Sea
filenames1 = {'U': "cmems2019*uo.nc",
              'V': "cmems2019*vo.nc"}
variables1 = {'U': 'uo',
              'V': 'vo'}
dimensions1 = {'lat': 'lat',
               'lon': 'lon',
               'time': 'time'}
indices1 =  {'lon': range(1, 956), 'lat': range(1, 1238)}

fieldset = FieldSet.from_netcdf(filenames1, variables1, dimensions1, indices = indices1)

#importing datasets of currents and tides in Baltic Sea (in 2016 this is not needed)
filenames2 = {'Ubaltic': "databaltic/cmemsuo2019*.nc",
              'Vbaltic': "databaltic/cmemsvo2019*.nc"}
variables2 = {'Ubaltic': 'uo',
              'Vbaltic': 'vo'}
dimensions2 = {'lat': 'lat',
               'lon': 'lon',
               'time': 'time'}
indices2 = {'lon': range(1, 765), 'lat': range(1, 771)}

fieldsetbaltic = FieldSet.from_netcdf(filenames2, variables2, dimensions2, indices = indices2)

fieldset.add_field(fieldsetbaltic.Ubaltic)
fieldset.add_field(fieldsetbaltic.Vbaltic)

fieldset.Ubaltic.units=fieldset.U.units
fieldset.Vbaltic.units=fieldset.V.units


fieldset.Unorth = fieldset.U
fieldset.Unorth.name = 'Unorth'
fieldset.Vnorth = fieldset.V
fieldset.Vnorth.name = 'Vnorth'
fieldset.Unorth.units=fieldset.U.units
fieldset.Vnorth.units=fieldset.V.units

 #Making a nested field of the North Sea an Baltic Sea data
U = NestedField('U', [fieldset.Ubaltic, fieldset.Unorth])
V = NestedField('V', [fieldset.Vbaltic, fieldset.Vnorth])
```

```
fieldset.U = U
fieldset.V = V
fieldset.U.units = fieldset.Unorth.units
fieldset.V.units = fieldset.Vnorth.units

#importing data of Stokes drift
filenames3= {'Ustokes': "datastokes/era5u_component_stokes_drift2019*.nc",
             'Vstokes' : "datastokes/era5v_component_stokes_drift2019*.nc"}
variables3 = {'Ustokes': 'ust',
             'Vstokes': 'vst'}
dimensions3 = {'lat': 'latitude',
                'lon': 'longitude',
                'time': 'time'}


fieldsetwind = FieldSet.from_netcdf(filenames3, variables3, dimensions3)
fieldsetwind.Ustokes.units=fieldset.U.units
fieldsetwind.Vstokes.units=fieldset.V.units

fieldset.add_field(fieldsetwind.Ustokes)
fieldset.add_field(fieldsetwind.Vstokes)

#making a vector field of the data of Stokes drift
uv_stokes = VectorField('UVstokes', fieldsetwind.Ustokes, fieldsetwind.Vstokes )
fieldset.add_vector_field(uv_stokes)


#importing data of the wind
filenames4= {'Uwind': "datawind/era510m_u_component_of_wind2019*.nc",
             'Vwind' : "datawind/era510m_v_component_of_wind2019*.nc"}
variables4 = {'Uwind': 'u10',
             'Vwind': 'v10'}
dimensions4 = {'lat': 'latitude',
                'lon': 'longitude',
                'time': 'time'}

fieldsetwind = FieldSet.from_netcdf(filenames4, variables4, dimensions4)
fieldsetwind.Uwind.units=fieldset.U.units
fieldsetwind.Vwind.units=fieldset.V.units

fieldset.add_field(fieldsetwind.Uwind)
fieldset.add_field(fieldsetwind.Vwind)

#making a vector field of the data of Stokes drift
uv_wind = VectorField('UVwind', fieldsetwind.Uwind, fieldsetwind.Vwind )
fieldset.add_vector_field(uv_wind)

#definition of diffusion
def Diffusion(particle, fieldset, time):
    lat = 111341
    lon = 62355
    if particle.lon < 9 :
        dx = math.sqrt(0.016 * lat * 0.016 *lon)
        D = (dx/1000)
```

```
        power = (4/3)
        particle.lat += random.uniform(-1., 1.) * math.sqrt(2*math.fabs(particle.dt)
                        * math.pow(D, power)) * (1/lat)
        particle.lon += random.uniform(-1., 1.) * math.sqrt(2*math.fabs(particle.dt)
                        * math.pow(D, power)) * (1/lon)
    if particle.lon >= 9: #different diffusion parameter in the Baltic Sea
        dx = 2000
        D = (dx/1000)
        power = (4/3)
        particle.lat += random.uniform(-1., 1.) * math.sqrt(2*math.fabs(particle.dt)
                        * math.pow(D, power)) * (1/lat)
        particle.lon += random.uniform(-1., 1.) * math.sqrt(2*math.fabs(particle.dt)
                        * math.pow(D, power)) * (1/lon)

#definition of Stokes drift
def Stokes(particle, fieldset, time):
    (u_stokes, v_stokes) = fieldset.UVstokes[time, particle.depth, particle.lat, particle.lon]
    particle.lon += u_stokes * particle.dt
    particle.lat += v_stokes * particle.dt

#definition of wind drag
def Winddrag(particle, fieldset, time):
    (u_wind, v_wind) = fieldset.UVwind[time, particle.depth, particle.lat, particle.lon]
    particle.lon += 0.025 * u_wind * particle.dt
    particle.lat += 0.025 * v_wind * particle.dt

# this class makes it possible to save the status of beaching of the particle
class PlasticParticle(JITParticle):
    beached = Variable('beached', dtype=np.int32, initial=0.)
    beached_lon = Variable('beached_lon', dtype=np.float64, initial=0.)
    beached_lat = Variable('beached_lat', dtype=np.float64, initial=0.)
    beached_time = Variable('beached_time', dtype=np.float64, initial=0.)

#checks if particle is beached
def beaching(particle, fieldset, time):
    u, v = fieldset.UV[time, particle.depth, particle.lat, particle.lon]
    if u<=10**(-12) and u>= -10**(-12) and v<=10**(-12) and v>=-10**(-12):
        particle.beached = 1
        particle.beached_lon = particle.lon
        particle.beached_lat = particle.lat
        particle.beached_time = time
        particle.delete()

#defining release locations
lons = np.append(np.arange(4.8, 6.39969, 0.00032), np.arange(4.8, 6.39969, 0.00032))
lats = np.append(np.arange(53.55, 53.8, 0.00005), np.arange(53.65, 53.9, 0.00005))
#release times
times = np.repeat(np.datetime64('2019-01-01T23:00'), 10000) #release time

#making the particle set of 10000 particles
pset = ParticleSet(fieldset=fieldset, pclass=PlasticParticle,
                             lon=lons, lat=lats, time= times, lonlatdepth_dtype=np.float64)
```

```
#deletes particle if error Out of Bounds is thrown
def DeleteParticle(particle, fieldset, time):
    particle.delete()

#combining all processes
kernel = pset.Kernel(AdvectionRK4) + pset.Kernel(Diffusion) + pset.Kernel(beaching)
        + pset.Kernel(Stokes) + pset.Kernel(Winddrag)

#advecting the particles for 2 months, with time steps of 10 minutes and output every 24 hours.
#In 2016, 2017 and 2018 particles are advected for 1 year.
pset.execute(kernel,
             runtime=timedelta(days = 58),
             dt=timedelta(minutes=10),
             recovery={ErrorCode.ErrorOutOfBounds: DeleteParticle},
             output_file=pset.ParticleFile(name=
                                            "OUTCMEMS201910000p2m624hbalticdiffstokeswind.nc",
                                            outputdt=timedelta(hours=24)))
```

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