Implementation of Stokes Drift into a Particle Model

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Date: February, 2020

1 Introduction

When particles are floating in water or on the surface of water, they display an orbital motion which is created by waves. However, it appears that the motion in the forward direction does not exactly equal the motion in the backward direction. In fact, besides motion of oscillation, the particles also tend to have a motion in the direction of the wave propagation. This phenomenon is called the Stokes drift [1].

Particle models often model this Stokes drift by taking a certain percentage of the wind velocity that is measured at 10 meter height. However, when you model the influence of the wind and waves on a particle by a single coefficient, the properties of the particles, such as shape and weight, are not directly taken into account. As a consequence, if for example the wind is blowing very hard, it would exert more force on the particle, causing the particle to go harder than if the wind is blowing very slow. But when a fixed value is taken, the modelled influence on the particle will always be the same, regardless of the wind speed. This was also noticed by Tang et al. [2], who found that for their drifters a percentage of 0.5% works best at low wind speeds while a percentage of 2.1% is better for higher wind speeds. Hence, taking a fixed percentage to approximate the Stokes drift will lead to underestimation or overestimation at wind speeds of other magnitude. In addition to this, in [3] it was observed that the wind speed and the Stokes drift do not always have the same direction, which gives another disadvantage to the method of taking a certain percentage of the wind speed.

In order to avoid those drawbacks, the influence of the wind and waves on the particle might be described better by modelling the waves and derived Stokes drift directly, as suggested in [4], in combination with modelling the effects of the wind on the particle separately via the inclusion of wind drag. Since the Stokes drift as computed from the JONSWAP spectrum depends on the spectral significant height and peak period which have the same direction as the Stokes drift, this might solve the direction problem. Furthermore, when modelling the wind drag, one also needs to include some properties of the particle. Hence, this would solve the particle property issue.

In this report, it is investigated whether the JONSWAP spectrum would be a better predictor for the Stokes drift than taking a certain percentage of the wind speed measured at 10 meter above the water surface. To verify the performance of both approaches, their results are compared to two different real-life cases. In the first case, a cargo ship lost 342 of its containers in the North Sea which caused a part of the content of these containers to wash ashore on some of the islands in the Wadden Sea. In the second case, 7 drifters were released in the German Bight and were tracked using a GPS tracker.

2 Stokes drift

In 1847 George Gabriel Stokes noticed that fluid particles do not travel in closed orbits [1]. That is, when undergoing a periodic motion their forward motion is not completely compensated by their backward motion. Since the particles stay for a longer period underneath the crest moving forward than underneath the trough moving backward, together with the fact that at greater heights larger velocities are obtained [5], the particles tend to have a net drift in the direction of the wave propagation (figure 2). This net drift is called the Stokes drift. More generally Stokes drift is defined as the difference between the Lagrangian average of a flow field and the Eulerian average of a flow field:

$$\text{Lagrangian} = \text{Eulerian} + \text{Stokes drift}.$$

Where in the Lagrangian case the particle is followed in space and time and in the Eulerian case the space is fixed and one observes particles within that fixed space, a stationary reference frame [5].

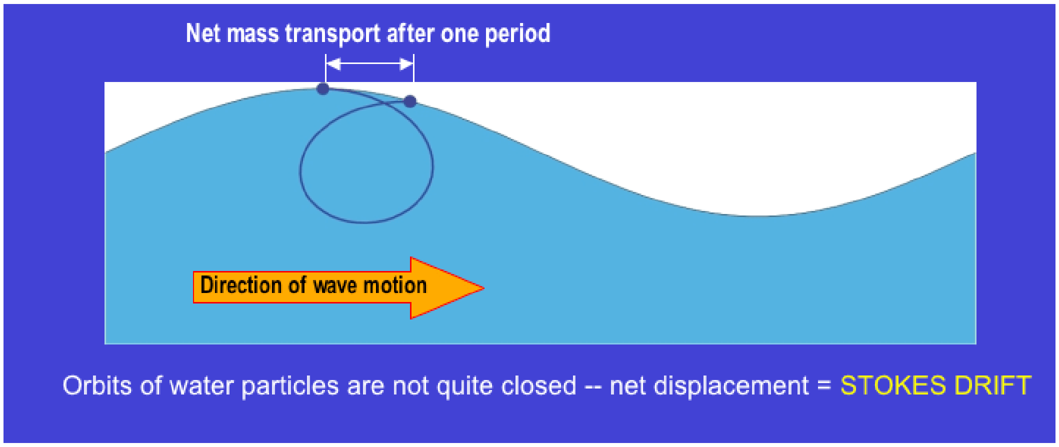


Figure 2: During orbital motion, particles experience a net drift in the direction of the wave propagation. This is called Stokes drift [6].

2.1 Representation of the Stokes drift

In 1969 Kenyon [7] derived the Stokes drift as

$$\mathbf{u}_s = g \int \int_{-\infty}^{\infty} F(\mathbf{k}) \frac{\mathbf{k}}{\omega} \left[\frac{2k \cosh(2k(z+d))}{\sinh(2kd)} \right] \mathrm{d}\mathbf{k},$$

where g is the gravitational acceleration, $F(\mathbf{k})$ is the energy spectrum, $\mathbf{k}$ is the wavenumber vector, ω the radian frequency, $k = |\mathbf{k}|$ is the magnitude of the wavenumber vector, z is the vertical coordinate and d is the bottom depth. Since we are interested in particles drifting on the surface of the ocean, we considered deep water (that is, for $kd \to \infty$ we have $\tanh(2kd) \to 1$ and $gk = \omega^2$ [8]) and assumed the vertical coordinate to be zero, $z = 0$, then this equation can be simplified (see Appendix A) into

$$\mathbf{u}_s = \frac{16\pi^3}{g} \int_0^{\infty} f^3 F(f) \mathrm{d}f,$$

where $f = \frac{\omega}{2\pi}$ is the frequency and $F(f)$ the frequency spectrum [9]. Now, defining the moments of the wave spectrum as $m_n = \int_0^{\infty} f^n F(f) \mathrm{d}f$ and since for deep water $H_{m_0} \approx 4\sqrt{m_0}$ [8] we can simplify this even further as follows

$$\mathbf{u}_s = \frac{16\pi^3 m_3}{g} = \frac{16\pi^3 m_0}{g \frac{m_0}{m_3}} = \frac{\pi^3 H_{m_0}^2}{g T_3^3}, \tag{1}$$

where T_3 is the third period with $T_3 = \sqrt[3]{\frac{m_0}{m_3}}$.

2.2 JONSWAP spectrum Stokes drift

In this study it is tested whether modelling the influence of the wind and waves on a particle using the Stokes drift and including the wind separately, leads to better results than if both wind and waves would be represented by a single coefficient. For this, the Stokes drift can be derived from a wave spectrum. However, if the information about the spectrum is incomplete, we can also use a parametrized wave spectrum like for example the Pierson-Moskowitz spectrum or the JONSWAP spectrum. For the convenience of this study, the JONSWAP spectrum was chosen because information about the spectrum, significant wave height and peak period was available, but other parametrized spectra could have chosen as well.

In order to find a spectrum that is able to describe the spectra of the ocean, researchers of the JOint North Sea Wave Observation Project (JONSWAP) [10] measured wave spectra along a distance of 160 km into the North Sea. From the collected data, they observed that the peak of the spectra is sharper than the Pierson-Moskowitz (PM) spectrum describes given by

$$F_{PM}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right],$$

where f is the frequency, α corresponds to the Philips constant and f_p is the frequency of the peak of the spectrum. While Pierson and Moskowitz assumed that if the wind blows with a constant velocity for a long time over a large area, the waves will eventually reach the same speed as the wind, the scientists of the JONSWAP found that the waves do not come into an equilibrium with the wind but continue to grow with distance or time [11]. Therefore these scientists concluded that the spectrum should have the same shape as the Pierson-Moskowitz spectrum, but with an enhanced peak which should be represented in the spectrum by an peak-enhancement factor. As a consequence, the JONSWAP spectrum is given by [10]

$$F_{JONSWAP}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right] \times \gamma^{\exp\left[-\frac{1}{2}\left(\frac{f/f_{peak}^{-1}}{\sigma}\right)^2\right]},$$

where the shape parameters α and f_p are the same as before, γ is the peak-enhancement factor and σ is the peak-width parameter defined by

$$\sigma = \begin{cases} \sigma_a & \text{for} \quad f \leq f_p \\ \sigma_b & \text{for} \quad f > f_p \end{cases}.$$

Since, for the JONSWAP spectrum the third period is equal to [9]

$$T_3 = 0.680 \frac{1}{f_p} = 0.680 T_p,$$

this means that the expression for the Stokes drift (equation 1) from before results into

$$\mathbf{u}_s = 3.18 \frac{\pi^3 H_{m_0}^2}{g T_p^3}.$$

This JONSWAP Stokes drift now only depends on the gravitational acceleration, g, the significant wave height, H_{m0}, and the peak period, T_p. We will compare its performance with taking a 1.6% of the wind speed at 10 meter height.

3 Bretschneider formula

For the first more simple model set-ups we used the Bretschneider formula to calculate the significant wave height and peak period that are needed to determine the JONSWAP Stokes drift [12], which are given by

$$\begin{aligned} H_s &= \frac{0.283U^2 a_1}{g} \tanh\left(\frac{0.0125}{a_1}\left(\frac{gF}{U^2}\right)^{0.42}\right) \\ T_p &= \frac{1.08 \cdot 2.4\pi U a_2}{g} \tanh\left(\frac{0.077}{a_2}\left(\frac{gF}{U^2}\right)^{0.25}\right), \end{aligned} \tag{2}$$

with

$$a_1 = \tanh\left(0.530\left(\frac{gd}{U^2}\right)^{0.75}\right) \qquad \text{and} \qquad a_2 = \tanh\left(0.833\left(\frac{gd}{U^2}\right)^{0.375}\right),$$

where U is the wind velocity at 10 meter height, g is the gravitational acceleration, d is the bottom depth and F is the fetch, the length of the sea over which the wind blows. Here it is assumed that the wind has blown for a long time in one direction and that the wind speed and bottom depth are uniform along the fetch. The average depth of the North Sea near the coast of the Netherlands and Germany is estimated at 30 meter. Furthermore the fetch is taken to be equal to the distance over which the wave spectra in the JONSWAP were measured, that is, 160 km.

4 Particle velocity

To derive the velocity of the particle we assume that the mass of the particle does not change over time such that we can use Newton's second law to derive the force balance of the particle as was also done in [13]:

$$M' \frac{d}{dt} = F_a + F_w + F_{wave},$$

with

$$M' = m + km',$$

where M' is the total mass, u_p is the velocity of the particle, F_a is the air force, F_w is the water force, F_{wave} is the wave force, m is the mass of the particle and km' is the added mass. An accelerating particle moves the surrounding water when moving through the water. As a consequence, we also need to model this mass of displaced water, which is done by assuming that the displaced volume is moving with the object. Therefore the mass of this volume is added to the mass of the particle.

Since the amount of water that is displaced depends on the shape of the particle, the coefficient k is needed to specify the added mass.

If the floating particle is in equilibrium, the sum of the forces should add up to zero such that

$$F_a + F_w + F_{wave} = \frac{1}{2} C_{D_a} \rho_a A_a (u_a - u_p)|u_a - u_p| + \frac{1}{2} C_{D_w} \rho_w A_w (u_w - u_p)|u_w - u_p| = 0.$$

Here, C_{D_a} and C_{D_w} are the drag coefficients for air and water, ρ_a and ρ_w are the air density and water density, A_a and A_w are the projected frontal areas of the particle above and below the surface of the water and u_a and u_w are the air velocity and the water velocity. Furthermore, since Stokes drift has the same direction as the wave propagation we add the the Stokes drift velocity, u_s, as a wave force, F_{wave}, to the water velocity and obtain the following balance of equations

$$\frac{1}{2} C_{D_a} \rho_a A_a (u_a - u_p)|u_a - u_p| + \frac{1}{2} C_{D_w} \rho_w A_w (u_w + u_s - u_p)|u_w + u_s - u_p| = 0.$$

Following the reasoning of [4] we first assume that the sum of the water and Stokes velocity is lower than the velocity of the air: $u_w + u_s < u_a$. As a consequence, the particle velocity, u_p, should be in between the sum of the water and Stokes velocity and the wind speed: $u_w + u_s < u_p < u_a$. This means that the term $(u_w + u_s - u_p)|u_w + u_s - u_p|$ is negative and the relation can be further simplified by taking the last term to the other side and taking the square root on both sides as follows

$$\begin{aligned}
0 &= \frac{1}{2} C_{D_a} \rho_a A_a (u_a - u_p)^2 - \frac{1}{2} C_{D_w} \rho_w A_w (u_w + u_s - u_p)^2 \\
&\Leftrightarrow C_{D_a} \rho_a A_a (u_a - u_p)^2 = C_{D_w} \rho_w A_w (u_w + u_s - u_p)^2 \\
&\Leftrightarrow \underbrace{\sqrt{C_{D_a} \rho_a A_a}}_{>0} \underbrace{(u_a - u_p)}_{>0} = \underbrace{\sqrt{C_{D_w} \rho_w A_w}}_{>0} \underbrace{(u_w + u_s - u_p)}_{<0} \\
&\qquad \text{and} \quad \underbrace{\sqrt{C_{D_a} \rho_a A_a}}_{>0} \underbrace{(u_a - u_p)}_{>0} = \underbrace{-\sqrt{C_{D_w} \rho_w A_w}}_{<0} \underbrace{(u_w + u_s - u_p)}_{<0}.
\end{aligned}$$

Because the first statement of the roots does not hold, we need the second statement. Rewriting this second statement gives us the final particle velocity

$$u_p = \frac{k_a u_a + k_w (u_w + u_s)}{k_w + k_a}, \tag{3}$$

where $k_a = \sqrt{C_{D_a} \rho_a A_a}$ and $k_w = \sqrt{C_{D_w} \rho_w A_w}$. Now, if we assume that the wind speed is lower than the sum of the water velocity and the Stokes velocity, such that $u_a < u_p < u_w + u_s$, we can apply the same procedure and we finally end up with the same result. The expression of the particle velocity in equation 3 thus holds for both the x-direction and the y-direction.

4.1 Wind velocity near the surface

Since wind speeds are often measured at 10 meter height, we will use the logarithmic wind profile to calculate the wind velocity, u_a, near the sea surface. Assuming the flow has the same direction as the wind and we have neutral stability condition, the logarithmic wind profile is given by [14]

$$u_a(z) = \frac{u_*}{\kappa} \ln\left(\frac{z - z_d}{z_0}\right),$$

where $u_a(z)$ is the wind velocity at height z, u_* is the friction velocity, κ is the von Karman's constant which is equal to 0.4, z_d is the zero-plane displacement and z_0 is the roughness length. The zero-plane displacement is the vertical height above the water surface where a wind velocity of zero can be achieved due to obstacles at the surface. Because in our case we assume a sea without obstacles, we have $z_d = 0$. Furthermore, the roughness constant is the height at which the wind velocity theoretically becomes zero if z_d is absent. For open sea this constant is equal to $z_0 = 0.0002$ [15]. As a consequence, the logarithmic wind profile can be expressed as

$$u_a(z) = \frac{u_*}{0.4} \ln\left(\frac{z}{0.0002}\right).$$

Now, if we assume that we know the values of the wind velocities at 10 meter height, the friction velocity u_* can be calculated as follows

$$u_* = u_a(10) \frac{0.4}{\ln\left(\frac{10}{0.0002}\right)},$$

which means that the wind velocity at every desired height can be obtained by

$$u_a(z) = u_a(10) \frac{\ln\left(\frac{z}{0.0002}\right)}{\ln\left(\frac{10}{0.0002}\right)}. \tag{4}$$

Note, however, that for very small particles with a size of only a few millimeters, the part that is floating below the water surface may actually be in the viscous layer. This means that this expression might not be accurate for very small particles.

5 Case: MSC Zoe

5.1 Case Description

On 1 January 2019 a ship of the Mediterranean Shipping Company (MSC), called MSC Zoe, is on her way from Antwerp (Belgium) to Bremerhaven (Germany). That evening the wind is gaining strength in northwestern direction with a force up to 8 Beaufort. But until 19:45 the wind does not cause the MSC Zoe any trouble yet. However, when the ship turns into the northeastern direction (see figure 3), the waves are moving perpendicular to the length of the ship and the ship is starting to tilt to port and starboard (figure 4a). According to the measurements of a measure point in the North Sea, the wave height achieved values of 5 meter and higher around that time [16]. As a consequence of these high waves, the MSC Zoe tilted up to at least 30 degrees and probably hits the seafloor, causing containers to start falling overboard [17]. Despite of the loss of the large number of containers, on board no one seems to notice anything and the ship continues its speed and coarse. Only around 02:00 on January 2nd the crew remarks that something is wrong and the MSC Zoe is suddenly steered 90 degrees to the left heading to the deeper sea lane proceeding with a lower speed. Two hours later the accident is reported to the Haveriekommando in Germany and around 07:00 in the morning the Haveriekommando takes over and accompanies the ship to Bremerhaven [16].

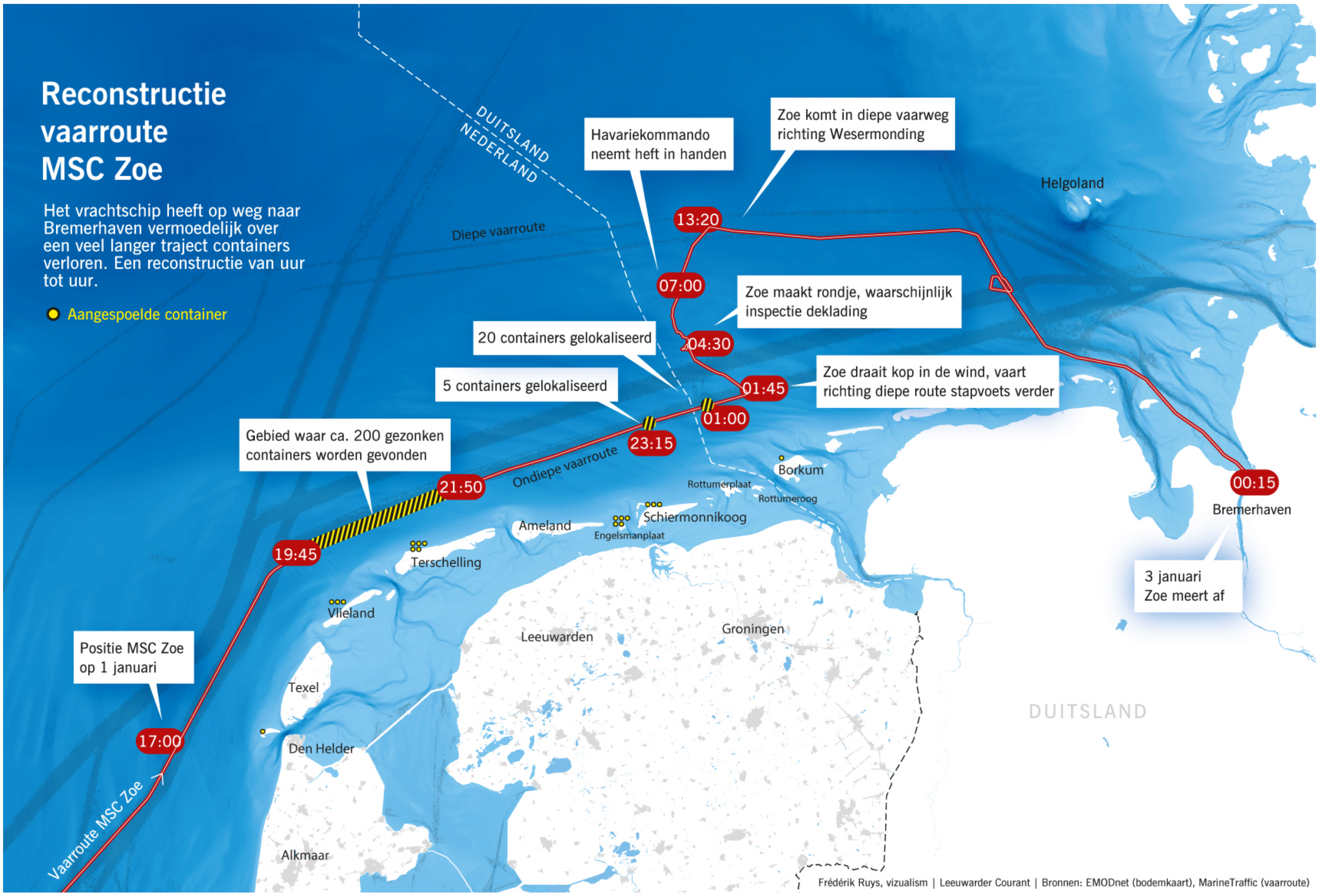
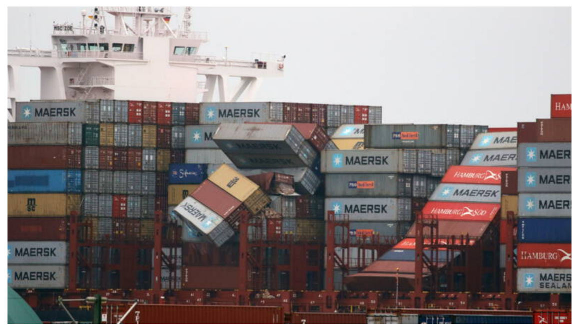


Figure 3: Reconstruction of the track of the MSC Zoe above the Dutch and German Wadden Islands. The yellow dots represent the containers that washed ashore. The sunken containers are given by the the yellow and black stripes [16].

In the end, 342 containers fell of the MSC Zoe, from which a lot of their content washed ashore on the Dutch and German Wadden Islands [18]. After the accident the beaches were littered with televisions, toys, shoes, incandescent light bulbs, chairs, children's clothing, car parts and many other plastic materials (figures 4b,4c,4d). But also some bags with toxic chemicals, such as benzoyl peroxide, drifted through the North Sea and stranded on land [19]. Soon after the event, a lot of citizens and the army came to the islands starting to clean up the beaches [20]. Rijkswaterstaat, a Dutch government agency that is responsible for the quality of the water in the Dutch part of the North Sea, helped cleaning up both the beach and the sea [21]. Unfortunately, despite of the big effort of these different parties, one year later the cleaning is not finished yet. The North Sea still contains 800.000 kilogram of waste and the beaches are still polluted with mostly plastic granules[22].

(a) Animation of the tilting of the MSC Zoe [23].



(b) Containers of the MSC Zoe [18].

(c) Island full with trash from the MSC Zoe [20].

(d) Collected HDPE granules[24].

Figure 4: Images related to the accident of the MSC Zoe.

Although the accident is a disaster for both the animals living in the affected area and sea and for nature [25], it also provides an opportunity for research. One of the containers that ruptured open contained large bags of high-density polyethylene (HDPE) granules (figure 4d), which are mainly used for the production of plastic products such as shampoo bottles, containers and toys. These microplastics have a high density of around 940 kg/m^3 and a size of only a few millimeters [26]. Since also the bags broke, these plastic granules ended up into the water and at the beaches. After the accident, the University of Groningen created a platform where people were able to report the amount of HDPE granules they had counted. After a period of more than two months 24 million granules were reported [27]. Because the location and time of the ship MSC Zoe is known and the finding place of many microplastics were registered, the MSC Zoe case seemed an opportunity to verify our particle model.

5.2 Expected behaviour

In order to get an impression of the behaviour we can expect of the particles, both the Stokes drift velocity based on the JONSWAP spectrum and the Stokes drift velocity using 1.6% of the wind speed at 10 meter height are plotted, shown in figure 5. Here, the Stokes drift is calculated using the Bretschneider formula (equation 2) and the values of both Stokes drift expressions are obtained by considering a range of values for the wind speed at 10 meter height. From this plot we see that the JONSWAP Stokes drift is approximately equal to the 1.6% wind Stokes drift for values of the wind velocity below 2.5 m/s. For wind velocities higher than 2.5 m/s and lower than 13.5 m/s, we would expect that the particles modelled by the JONSWAP Stokes drift would go faster than the particles modelled by the 1.6% wind Stokes drift. The opposite is expected for wind speeds with values higher than 13.5 m/s.

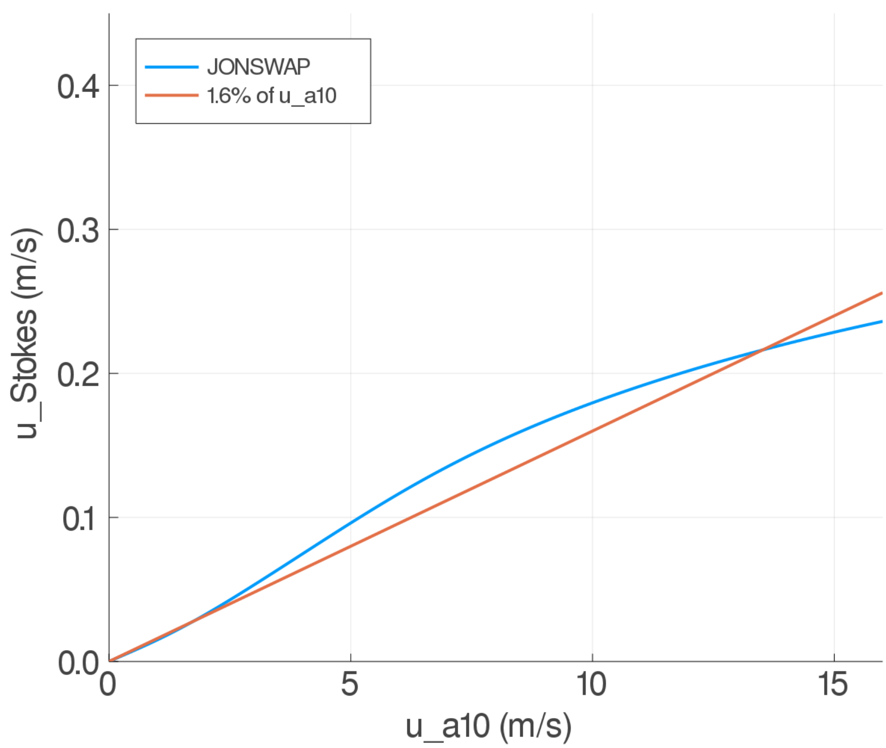
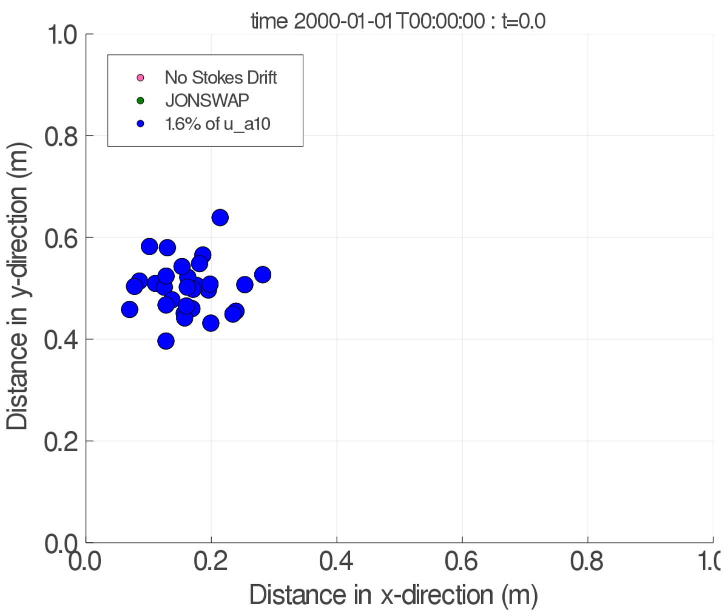


Figure 5: Plot of the Stokes drift velocity calculated with the JONSWAP spectrum and the Stokes drift velocity calculated by taking 1.6% of the wind velocity at 10 meter height against the wind velocity at 10 meter height.

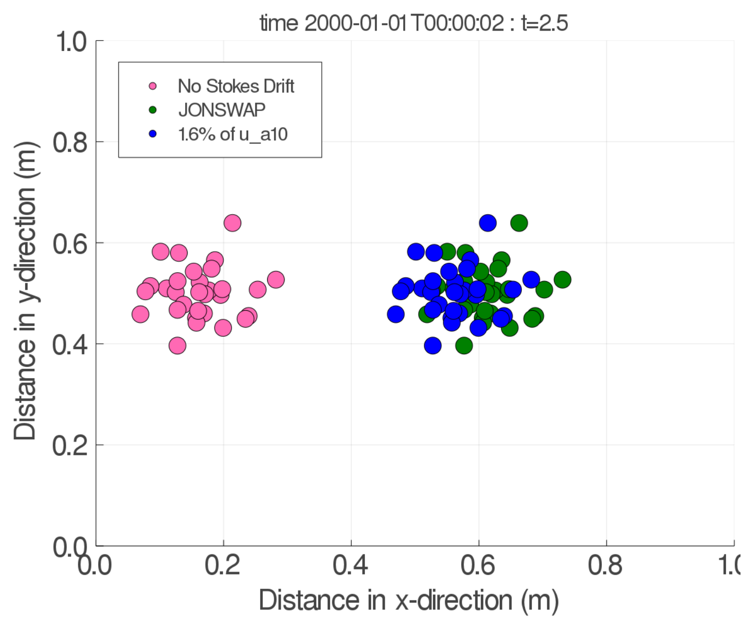
5.3 Stokes drift in one-dimension

In the first very simple set-up, only the Stokes drift was modelled in only one direction. That is, u_w, k_w and k_a in the particle velocity equation (equation 3) were set to zero and all values in the y-direction have been ignored. Furthermore, the wind speed at 10 meter height was fixed at 10 m/s and the Bretschneider formula were used to calculate the significant wave height and peak period. In figure 6a the begin position of the particles are shown, where the pink markers represent the particles without Stokes drift, the green markers represent the particles with the JONSWAP Stokes drift and the blue markers represent the Stokes drift modelled by taking 1.6% of the wind velocity at 10 meter height. The three groups of particles were given the same starting location.

Figure 6b shows that after 2.5 seconds the particles with JONSWAP Stokes drift and 1.6% wind Stokes drift both travelled in the x-direction, while the particles without Stokes drift, as expected, did not leave their initial position. We can see that the JONSWAP particles travelled slightly faster than the particles modelled by 1.6% of the wind speed, which is according to the plot in figure 5 also the expected behaviour for a wind velocity of 10 m/s.



(a) Starting position.



(b) Position after 2.5 seconds.

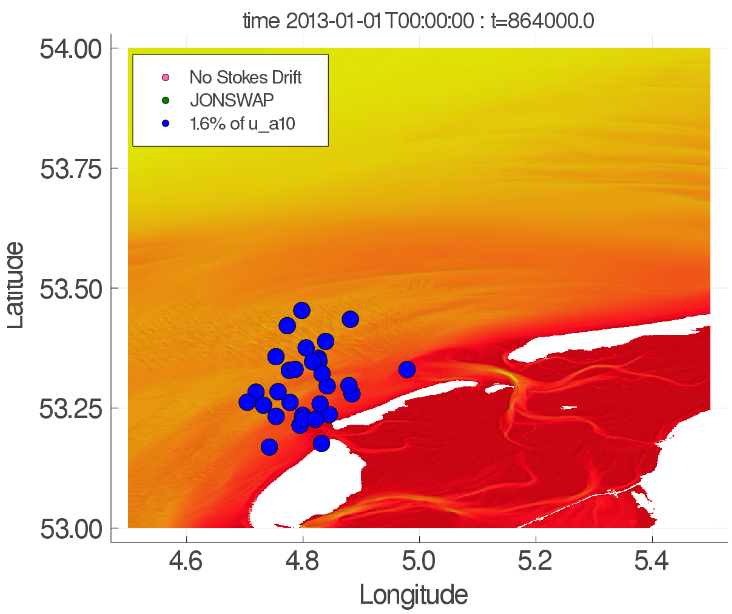
Figure 6: Plots of the three particle groups showing the effect of the Stokes drift in the x-direction. The pink markers represent the particles with no Stokes drift, the green markers represent the particles with the JONSWAP Stokes drift and the blue markers represent the particles with 1.6% of the wind Stokes drift.

5.4 DCSM-FM water velocity data

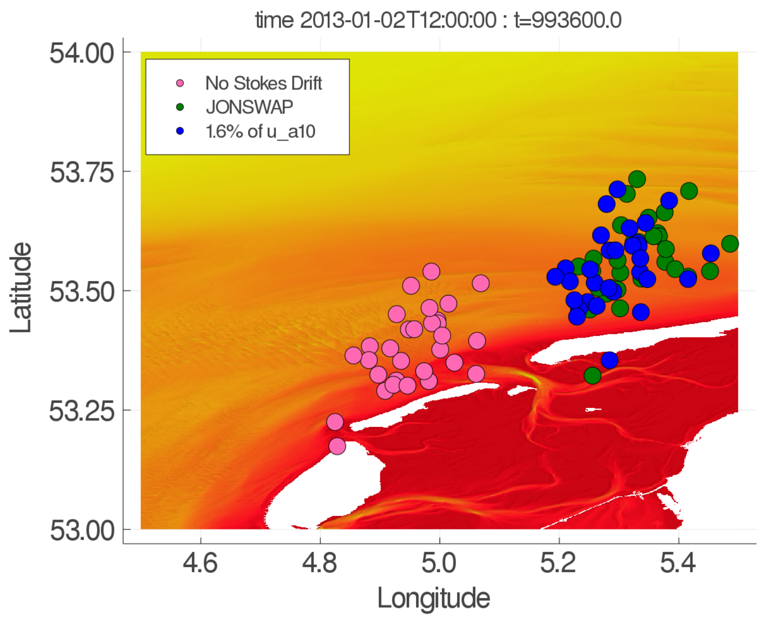
In the next step, besides the Stokes drift, also the water velocity was included. Because the accident with the MSC Zoe happened above the Dutch Wadden Islands, the water velocities of

2013 at that location were taken from the DCSM-FM model in 2D. For this set-up, two directions were considered: both the x-direction and the y-direction. The Bretschneider formula were again used to calculate the JONSWAP Stokes drift, with the wind velocity once more fixed at 10 m/s in only the x-direction.

Figure 7 shows that the particles without Stokes drift, in this model, have left their initial position as well, but they are still not far removed from this position. This is caused by the low water velocities and the fact that they are pulled back and forth by the tides. As expected by figure 5 for a wind velocity of 10 m/s, the JONSWAP again travelled faster than the particles modelled by taking 1.6% of the wind speed. Since the wind velocity is directed in only the positive x-direction, the particles move predominantly to the right following the shores of the Wadden Islands.



(a) Starting position.



(b) Position after 36 hours.

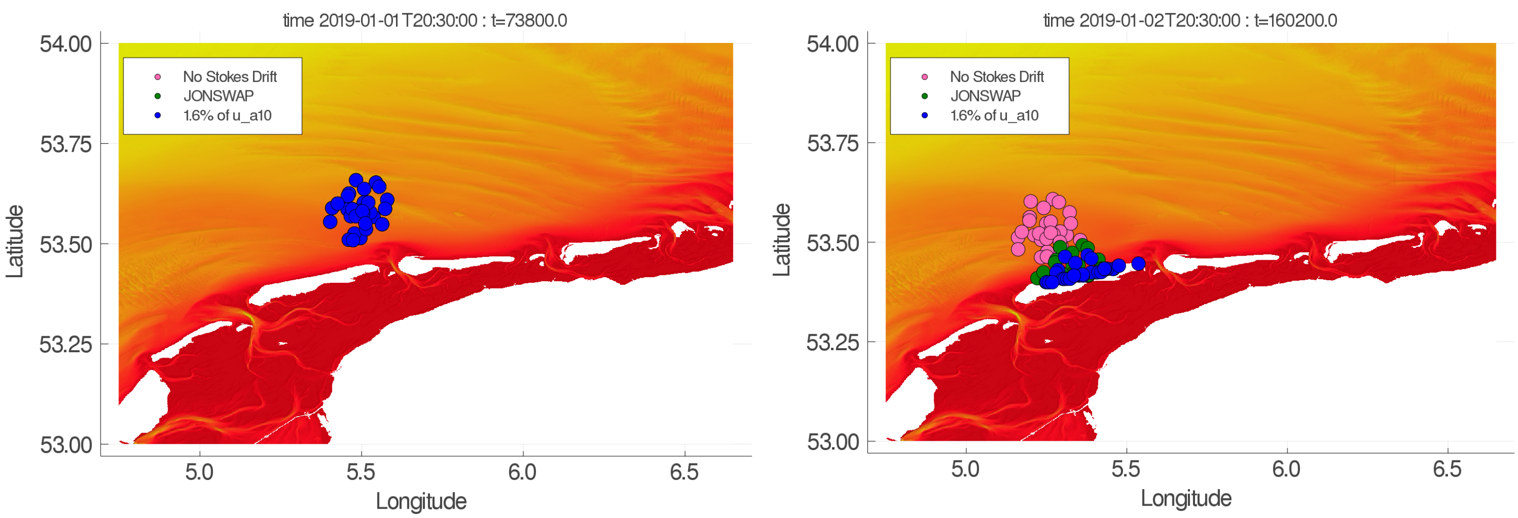
Figure 7: Plots of the three particle groups showing the effect of the Stokes drift above the Dutch Wadden Islands using DCSM-FM water velocity data of 2013. The pink markers represent the particles with no Stokes drift, the green markers represent the particles with the JONSWAP Stokes drift and the blue markers represent the particles with 1.6% of the wind Stokes drift.

5.5 DCSM-FM and observed data from 2019

In order to accurately simulate the conditions of the days after the accident of the MSC Zoe, we need wind, water and wave data of that same time. Therefore, in this simulation the wind, water and wave data from January 2019 was used. For the wind velocities, the significant wave height, H_s, and the mean wave period, H_m, the observed data from platform L91, which is located northeast of the islands, was considered. This means that the calculated JONSWAP Stokes drift no longer depends on the Bretschneider formula, but is rather established by actual data. Because, instead of the mean wave period, the peak period is needed for the JONSWAP Stokes drift, the observed

H_m values are multiplied by the factor $1/0.95$ [8]. The values of the water velocities were again retrieved from the DCSM-FM model.

Almost all JONSWAP Stokes drift and 1.6% wind Stokes drift particles washed ashore within 24 hours as can be seen in figure 8. In contrast to the previous models, in this model the particles with the Stokes drift computed by taking 1.6% of the wind velocity at 10 meter height are travelling faster than the JONSWAP Stokes drift particles. This behaviour can be explained by the fact that especially in the first 12 hours after the release of the particles, the wind blew very hard. At platform L91 an averaged value of 15.97 m/s was measured for the wind velocity during those first 12 hours. Looking at figure 5, this means that the particles of the 1.6% wind Stokes drift must have travelled faster for most of this time, which is also the reason why they stranded earlier in the model.



(a) Starting position.

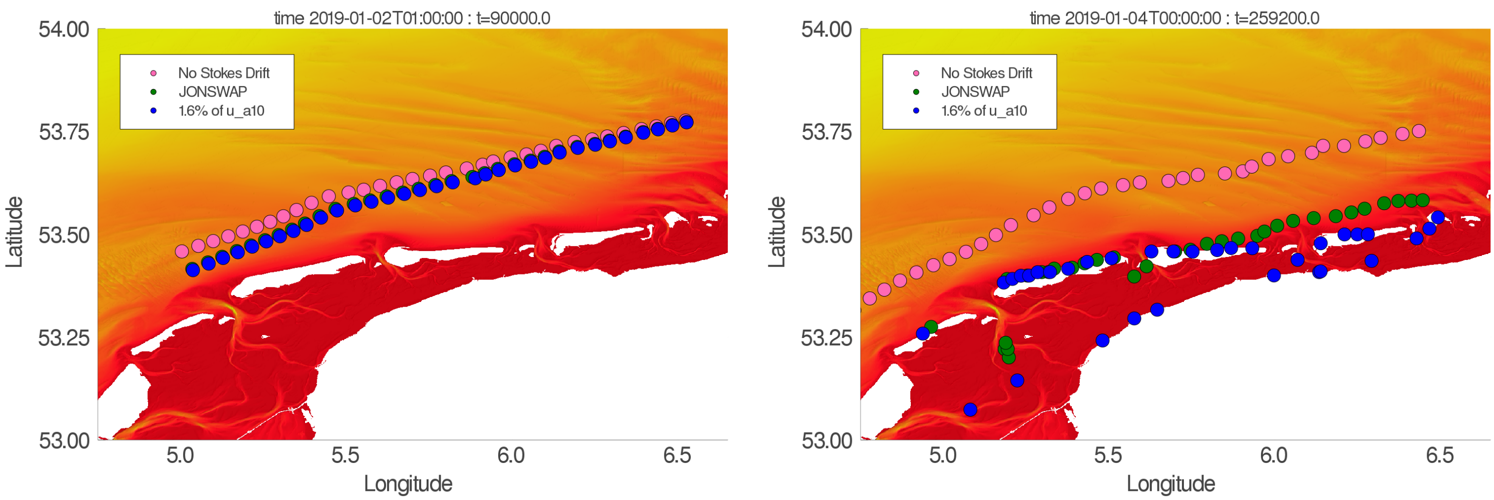
(b) Position after 24 hours.

Figure 8: Plots of the three particle groups showing the effect of the Stokes drift above the Dutch Wadden Islands using DCSM-FM and observed data from 2019. The pink markers represent the particles with no Stokes drift, the green markers represent the particles with the JONSWAP Stokes drift and the blue markers represent the particles with 1.6% of the wind Stokes drift.

5.6 Particles along the track of the MSC Zoe

Since it is not clear at which exact location the containers fell off from the MSC Zoe, it was decided to model the particles along the track of the MSC Zoe and see where they end up. This is done by releasing a particle every ten minutes along the GPS recorded track of the Zoe. In addition to this modification, the wind velocities are now taken from ERA5 by ECMWF. The observed values of the significant wave height and peak period were still used to calculate the JONSWAP Stokes drift and the water velocities were again taken from DCSM-FM.

Looking at figure 9 we see that most particles with Stokes drift ended up at the middle three islands, which is in agreement with the findings of the University of Groningen [27]. However, since we do not know anything about the time and location the HDPE granules left their bags and we do not know at what time the particles washed ashore, we can not say much more about the performance of the model. Therefore, it is hard to conclude whether the particles modelled by the JONSWAP Stokes drift predict the Stokes drift better than the Stokes drift modelled by taking 1.6% of the wind speed.



(a) Starting position.

(b) Position after 47 hours.

Figure 9: Plots of the three particle strings showing the effect of the Stokes drift above the Dutch Wadden Islands using DCSM-FM, ERA5 and observed data from 2019. The pink markers represent the particles with no Stokes drift, the green markers represent the particles with the JONSWAP Stokes drift and the blue markers represent the particles with 1.6% of the wind Stokes drift.

5.7 Lack of information

Although the model seems to roughly work, i.e. the particles move in the correct direction and wash ashore as also happened in the real case, it is still hard to verify if it works perfectly because a lot of information about the Zoe case is lacking. For a start, it is unclear when and at which location the containers fell off. The fact that the crew of the ship takes action after the location where many containers were found [16], suggests that the crew itself did not notice anything during the event of the container loss. If we look at the GPS data of the MSC Zoe of that night (figure 10), we see that there is some data missing on 1 January between 19:03:58 and 19:08:08. And after this missing data, the ship seems to lower its speed. In addition to this, experts say that the ship definitely should have hit the bottom of the sea [17]. The hitting of the floor might be the explanation for the gap in the GPS data and therefore also the moment at which the ship lost the first batch of containers. However, these are only speculations, not facts that we can use to verify our model with.

Furthermore, if it would be possible to track down at which position the containers fell off, we would also need to have the point at which they broke and the content started flowing out. This might be even harder to check, since the containers were tracked by no one. Moreover, this flowing out of the content is a gradual process, which means that the first particle and the last particle probably left the container at significant different times and places. In addition to all of this, in our case of the HDPE granules we also need to know when the bags that contained the microplastics ruptured open.

The answer to the above mentioned questions might be in hands of the Panamese Marine Authority (PMA), the German Bundesstelle für Seeunfalluntersuchung (BSU) and the Dutch Safety Board (DSB). Right after the incident with the MSC Zoe, these research teams started an investigation to determine the cause of the accident [28]. But the information they gather during the investigation has to be classified until the researchers have presented their final report. In December 2019 an intermediate report was presented by the teams, but it is unclear when the final report will be released. Due to time limitation of this study, there was no time to wait for the release of the final report, and it was decided to look further for another case that contained more data.

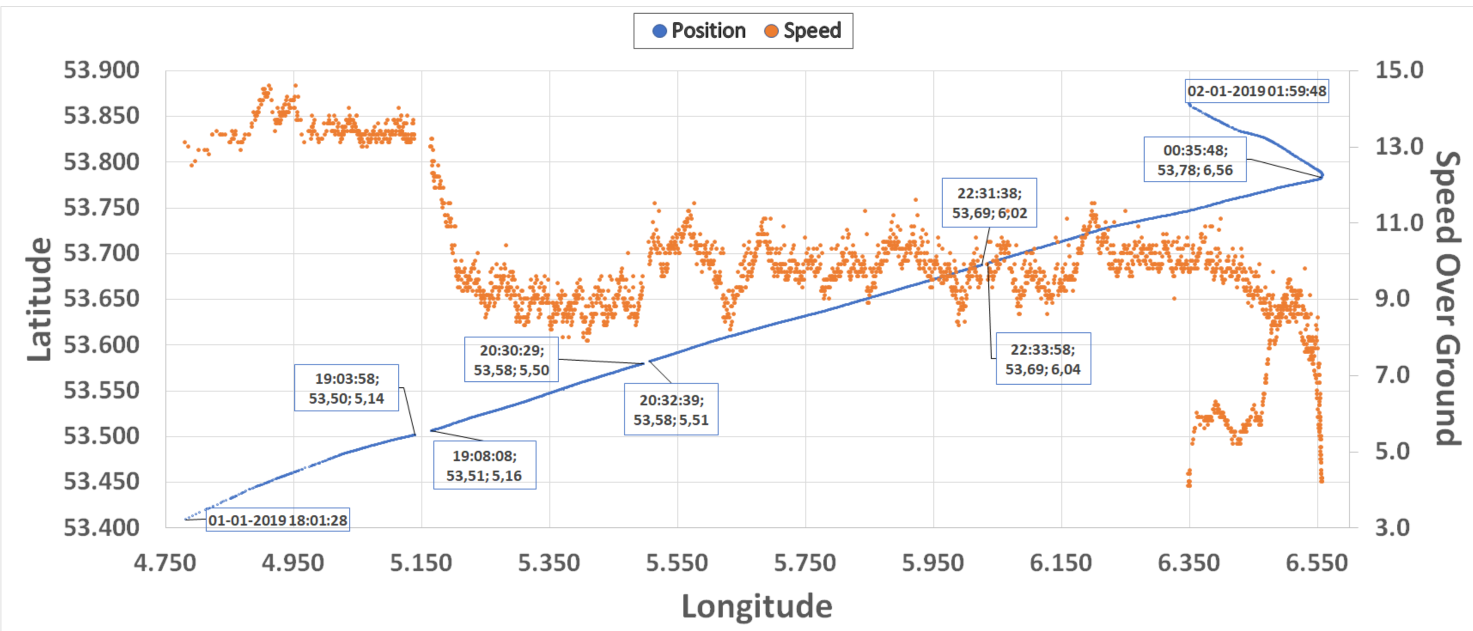


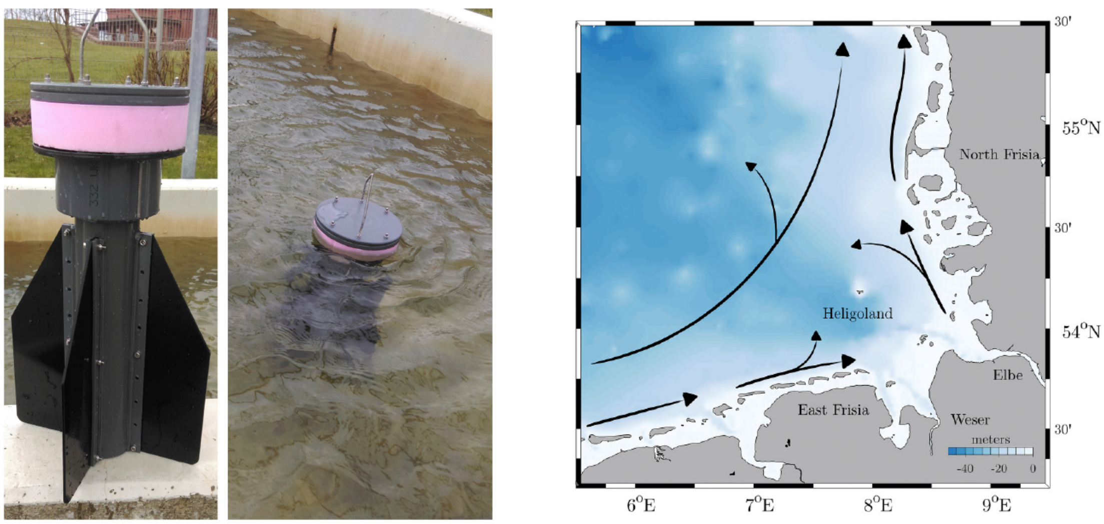
Figure 10: Graphs of the GPS data from Made Smart Group of the MSC Zoe during the accident [29]. The blue graph represents the coarse of the ship expressed in longitude and latitude coordinates, while the orange data shows its speed along its longitude.

6 German Bight Drifters

6.1 Case description

In [30] it was pointed out that there is a need for surface drifter data in the German Bight and North Sea to verify the performance of particle and hydrodynamical models. Therefore Meyerjürgens et al. developed a satellite-tracked drifter to study the pathways of floating litter. Their custom-made drifter consists of two parts: the upper half pink part and the lower part where the wings are attached to. The upper part contains the GPS unit and has a length of 136 mm and a diameter of 140 mm. The lower part contains the battery and has a length of 370 mm and a diameter of 90 mm. The four wings are made from polyethylene (PE) and function as a drogue. From figure 11a we can see that there is only a small part that protrudes from the water and therefore can be influenced by the wind.

The researchers released seven of their own designed drifters into the German Bight and followed their track by making use of the GPS unit (figure 11b). Four of them were deployed in March and the other three in October. This created a very extensive data set with the position and time of the drifters along their entire track. As a consequence, since this is also very valuable information to validate this paper's particle model in which the Stokes drift is included, it was decided to use this data to further verify the results.



(a) Drifter design [30].

(b) Study area: German Bight [30].

Figure 11: Drifter case.

6.2 Model specifications

As a last model step, the significant wave height, H_s, and the mean period, T_m, were retrieved from the SWAN DCSM model, where the wind velocities in this model are taken from HIRLAM by KNMI. In addition to this, also some particle properties were taken into account by including the wind drag into the model. For this, to obtain the particle velocity from equation 3, we needed additional information about the cross-sectional areas above and below the water surface, A_w and A_a, the drag coefficients of water and air, C_{D_w} and C_{D_a}, the density of water and air, ρ_w and ρ_a, and the protruding height to calculate the wind velocity (equation 4).

The cross-sectional areas have a value of 1194.6 cm^2 and 62.3 cm^2 respectively. Then the drag area ratio was used to derive a ratio for the drag coefficients [30]

$$R = \frac{C_{D_w} A_w}{C_{D_a} A_a} = 25.6.$$

From this and using the shape of the drifter, the drag coefficients were estimated to be 0.63 for water and 0.47 for air [13]. Assuming a temperature of 15°C and a salinity of 35 g/kg, we have that the water density is equal to 1026.0 kg/m^3 and the air density is equal to 1.217 kg/m^3. Lastly, the protruding height was estimated as 4.53 cm.

6.3 Results of drifters 1 and 2

Drifters 1 and 2 were with a distance of less than 1 meter between each other both released on 13 March 2017. The first drifter was deployed at 21:25 and the second at 21:24. In figures 13a and 13b we see the plots of drifter 1 and 2 after 42 hours. Here, the pink marker represents the particle without Stokes drift, the dark green marker represents the particle with the JONSWAP Stokes drift, the light green marker represents the particle with JONSWAP Stokes drift with wind drag included, the dark blue marker represents the particle with 1.6% wind Stokes drift and the light blue marker represents the 1.6% wind Stokes drift with wind drag included particle. The black path in the plots is the entire GPS-track of the drifter which is followed in time by the black marker.

After 42 hours we find all modelled Stokes drift particles to deviate from the actual drifter GPS data. While the GPS drifter went northeast, the four particles tend to go southeast, where the JONSWAP has an even stronger preference for the southern direction. From figures 13c and 13d it can be seen that after 24 days all Stokes drift particles have stranded. Both JONSWAP particles continued to propagate to the south and eventually ended up in washing ashore on an island in the South. The 1.6% wind particles managed to drift more to the east, but also these particles stranded in the end. Although the 1.6% wind particles roughly followed the track of the drifter for a longer time than the JONSWAP particles, both methods perform poorly in predicting the track of the GPS drifter. Furthermore, it can be seen from these figures that the effect of the inclusion of wind drag was minor as the particles with wind drag stay really close to the particles without wind drag along the entire path.

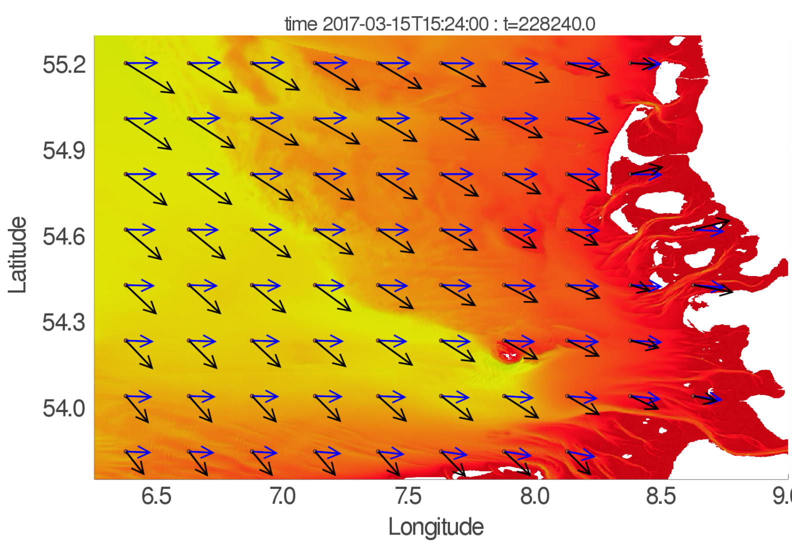
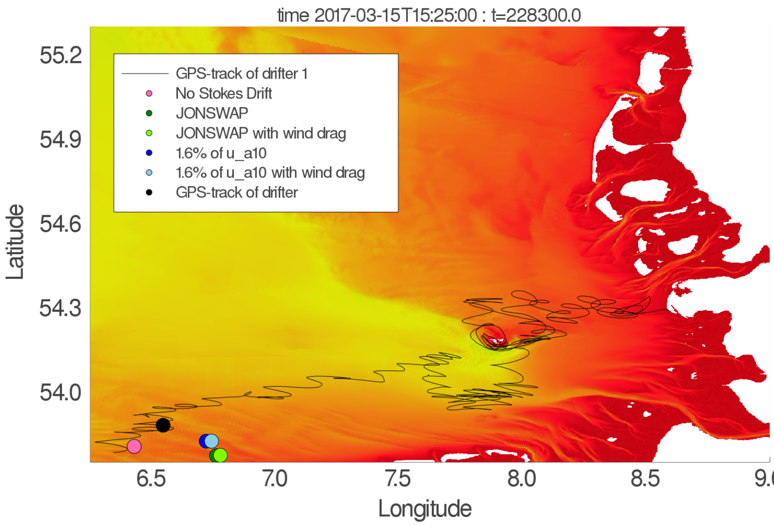
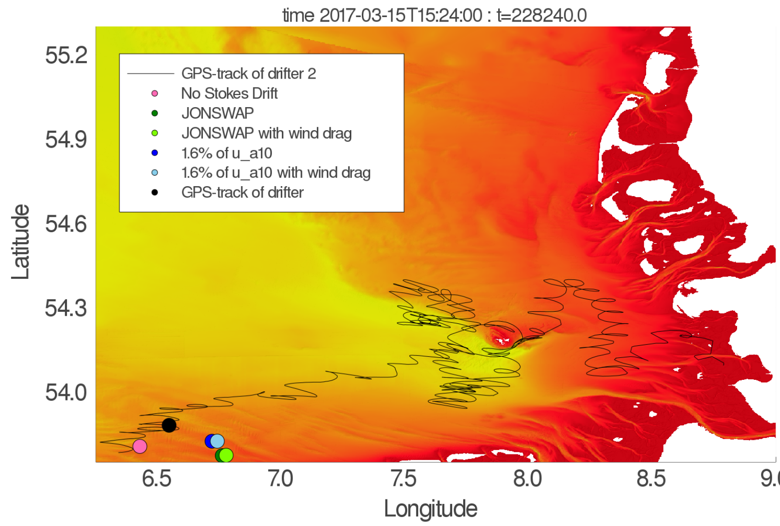


Figure 12: Wind (blue) and wave (black) direction in March.

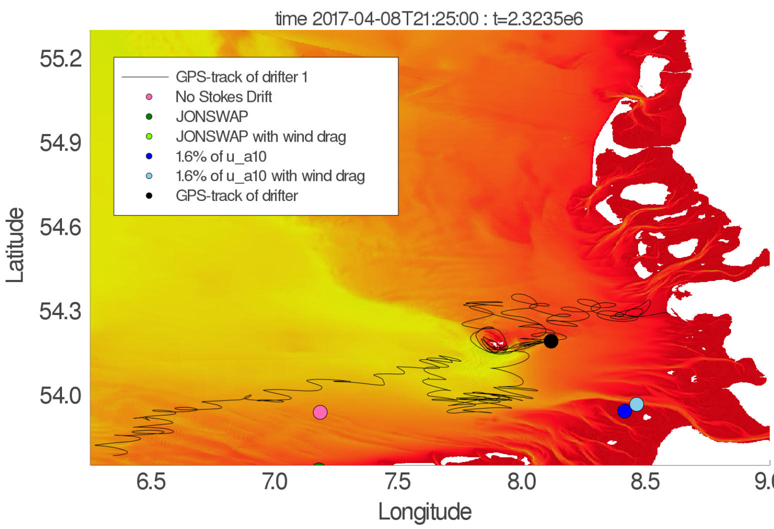
If we look at figure 12 we see that on 2017-03-15 15:24 the wind (blue) and waves (black) have the same directions as their corresponding particles are heading at: the wind in the eastern direction and the waves in the southeastern direction. Thus, the modelled Stokes drift particles are correctly following these directions, while the GPS drifter somehow took another path.



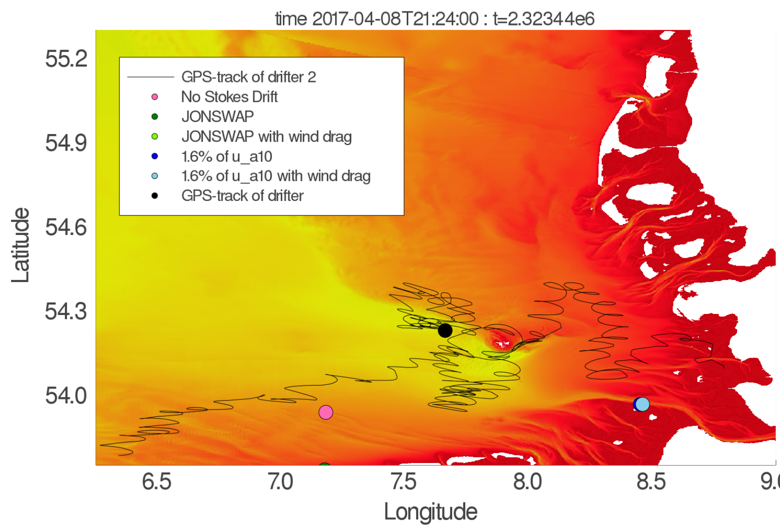
(a) Modelled particles of drifter 1 at 2017-03-15 15:25.



(b) Modelled particles of drifter 2 at 2017-03-15 15:24.



(c) Modelled particles of drifter 1 at 2017-04-08 21:25.

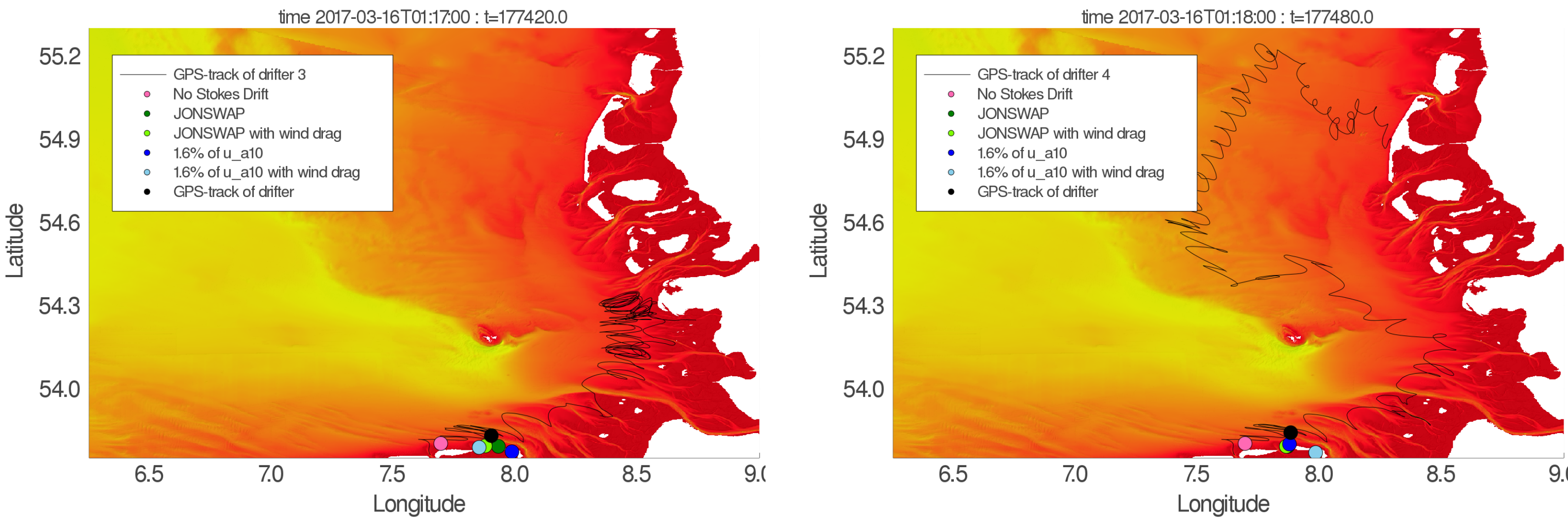


(d) Modelled particles of drifter 2 at 2017-04-08 21:24.

Figure 13: Particle tracks of drifter 1 and 2 in the German Bight. The pink marker represents the particle with no Stokes drift, the dark green marker represents JONSWAP Stokes drift, the light green marker represents JONSWAP Stokes drift with wind drag, the dark blue marker represents the 1.6% wind Stokes drift and the light blue marker represents the 1.6% wind Stokes drift with wind drag. The black marker is the GPS-track of the real drifter and will follow the black path, where this data was retrieved from [31] and [32].

6.4 Results of drifters 3 and 4

Both drifters 3 and 4 were deployed on 14 March around the same time, 13:17 and 13:18 respectively, with a distance of less than 1 meter between each other. Since the starting point of these drifters was very close to the coast (figures 14a and 14b) and because of the simplicity of the model the particles were not able to reenter the water, almost all Stokes drift particles very quickly washed ashore. For the simulation of drifter 3, only the 1.6% wind particle and the no Stokes drift particle did not strand after 36 hours. In the case of drifter 4 only the 1.6% wind with wind drag and no Stokes drift particles did not wash ashore. Therefore we can not say anything about the performance of the model in this situation.



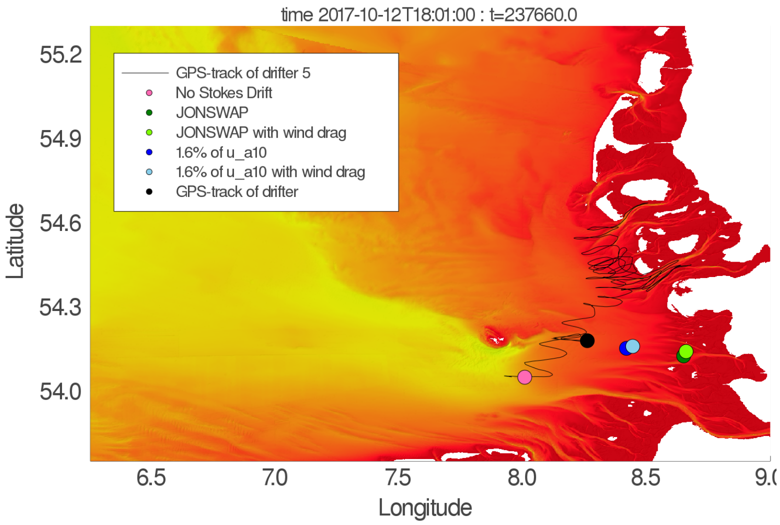
(a) Modelled particles of drifter 3 at 2017-03-16 01:17.

(b) Modelled particles of drifter 4 at 2017-03-16 01:18.

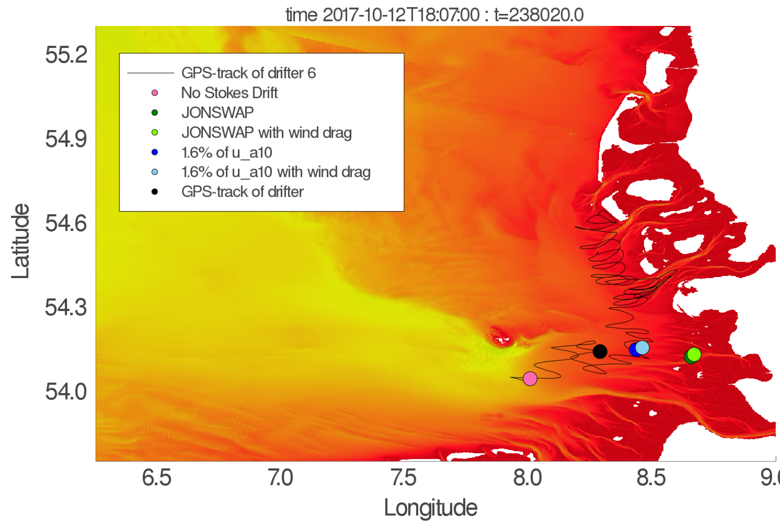
Figure 14: Particle tracks of drifter 3 and 4 in the German Bight. The pink marker represents the particle with no Stokes drift, the dark green marker represents JONSWAP Stokes drift, the light green marker represents JONSWAP Stokes drift with wind drag, the dark blue marker represents the 1.6% wind Stokes drift and the light blue marker represents the 1.6% wind Stokes drift with wind drag. The black marker is the GPS-track of the real drifter and will follow the black path, where this data was retrieved from [33] and [34].

6.5 Results of drifters 5 and 6

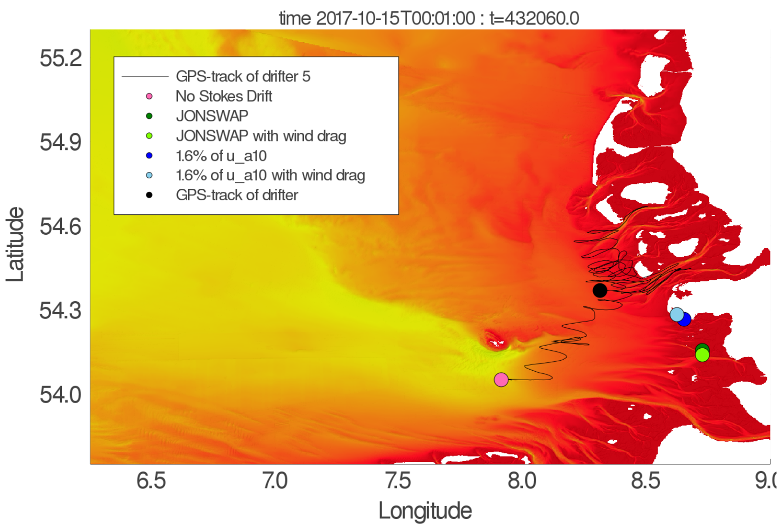
Drifters 5 and 6 started floating on 8 October at 09:29 and 09:31 respectively. However, because of a gap in the data of the H_s and H_m values on 10 October, the simulation was started after this gap at 19:01 and 18:02. Figures 15a and 15b show that after two days the Stokes particles again tend to head in another direction, to the east, than the GPS drifter which is drifting more to the northeast. When another 3 days have passed (figures 15c and 15d), the Stokes drift particles floated even more to the east and finally all washed ashore, but none of them close to the GPS drifter. Looking at figure 16 this behaviour once more can be explained by the wind and wave direction which were mainly pointed to the east during the time period of the simulation.



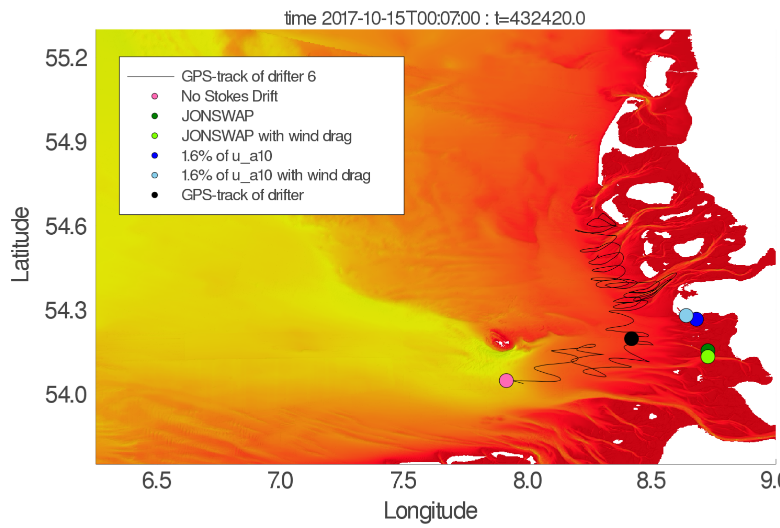
(a) Modelled particles of drifter 5 at 2017-10-12 18:01.



(b) Modelled particles of drifter 6 at 2017-10-12 18:07.



(c) Modelled particles of drifter 5 at 2017-10-15 00:01.



(d) Modelled particles of drifter 6 at 2017-10-15 00:07.

Figure 15: Particle tracks of drifter 5 and 6 in the German Bight. The pink marker represents the particle with no Stokes drift, the dark green marker represents JONSWAP Stokes drift, the light green marker represents JONSWAP Stokes drift with wind drag, the dark blue marker represents the 1.6% wind Stokes drift and the light blue marker represents the 1.6% wind Stokes drift with wind drag. The black marker is the GPS-track of the real drifter and will follow the black path, where this data was retrieved from [35] and [36].

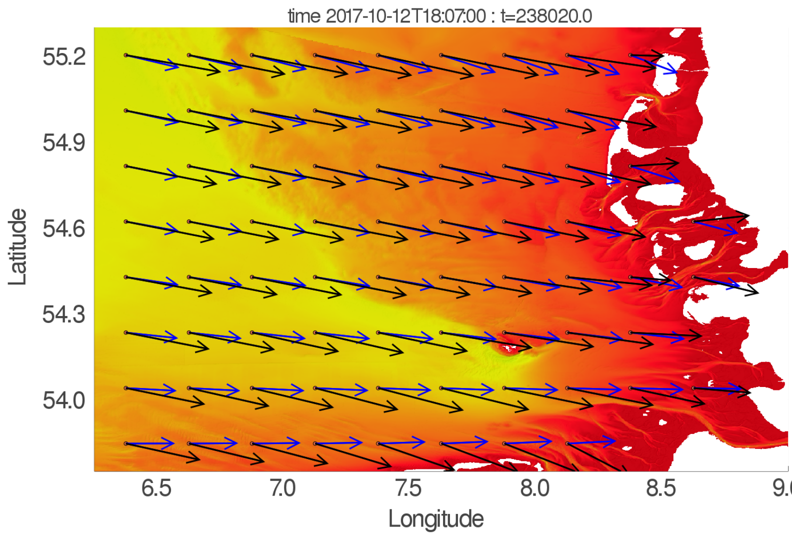
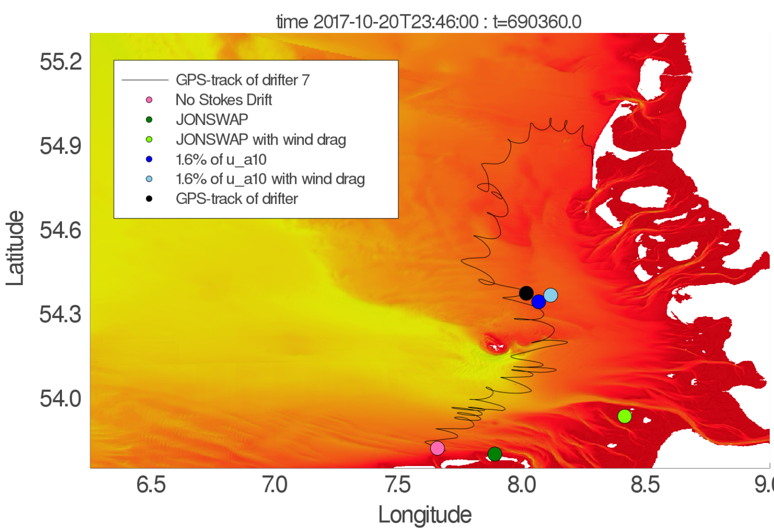
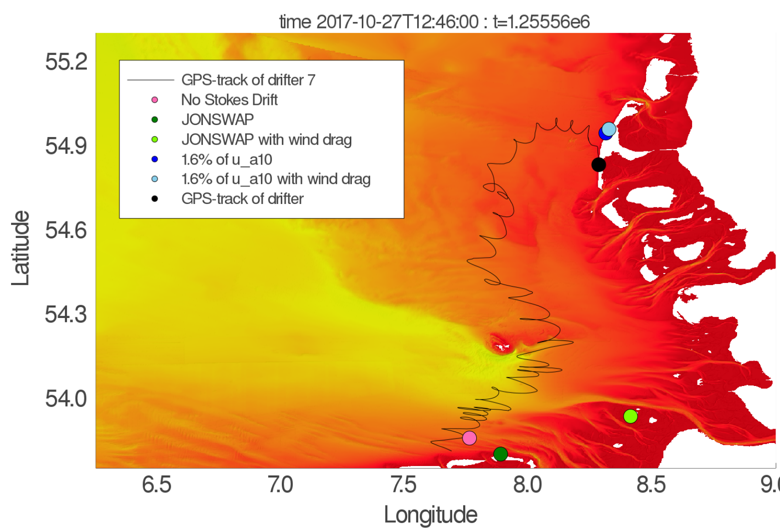


Figure 16: Wind (blue) and wave (black) direction in October.

6.6 Results of drifter 7



(a) Modelled particles of drifter 7 at 2017-10-20 23:46.



(b) Modelled particles of drifter 7 at 2017-10-27 12:46.

Figure 17: Particle track of drifter 7 in the German Bight. The pink marker represents the particle with no Stokes drift, the dark green marker represents JONSWAP Stokes drift, the light green marker represents JONSWAP Stokes drift with wind drag, the dark blue marker represents the 1.6% wind Stokes drift and the light blue marker represents the 1.6% wind Stokes drift with wind drag. The black marker is the GPS-track of the real drifter and will follow the black path, where this data was retrieved from [37].

The most successful simulation appeared to be the simulation for drifter 7 (deployed on 2017-10-13 at 05:46). As can be seen in figure 17, both the 1.6% wind and 1.6% wind with wind drag particles are following the track of the GPS drifter quite well and they eventually end up not very far from the end location of the GPS drifter. However, for the JONSWAP Stokes drift this simulation is not better than the simulations before, both particles did not follow the path of the GPS drifter and ended up far from the drifter's location.

7 Conclusion

In this report it was investigated whether the JONSWAP spectrum would be a better predictor for the Stokes drift than taking 1.6% of the wind speed measured at 10 meter height. It was expected that if particle properties were directly taken into account in stead of using a single coefficient to model the influence of wind and waves, it would be able to better model the Stokes drift.

In the MSC Zoe case we saw that the particles indeed end up washing ashore on the islands, where the HDPE granules in reality also stranded. However, since it is not known at which exact time the containers fell off, the containers broke and the bags ruptured open, the model could not be verified further. From the drifter case we saw that except for two particles, the 1.6% wind and 1.6% wind with wind drag particles, in only one drifter simulation none of the Stokes drift particle was able to predict the track of the GPS drifter sufficiently. As the wind and waves seem to have the same direction as the movement of the corresponding particles, it seems like the model works correctly. However, it does not resemble the track of the GPS drifter correctly. This might be the result of some simplifications that were made in the model.

Firstly, the currents were derived from a two-dimensional model. The surface currents in a three-dimensional model may deviate substantially from those of a two-dimensional model. Secondly, it was assumed that the temperature and salinity were constant in time and space. However, in reality this can be really different affecting the water and air density and therefore the flow pattern. Additionally, these effects are usually quite different in a three-dimensional model than in a two-dimensional model. Furthermore, by deriving a simplified expression for the Stokes drift (in section 2.1), deep water was assumed. But in both the MSC Zoe and drifter case, this assumption does not always hold, in particular when a particle is close to the shore. Lastly, the Stokes drift was simply added to the water velocity. This may be incorrect, especially near the coast where also other forces play a role and may have an influence on the Stokes drift.

Furthermore, the modelling of the particles' beaching process was simplified too much. Once a particle obtained zero velocity, it was stranded and could not reenter into the sea anymore. In reality the process of beaching is much more complicated. For instance, the tide can come in and pull the particle back into the water. This might have limited the modelling of for example the Stokes drift particle paths of the drifter 3 and 4 simulations, where the Stokes drift particles stranded after only 36 hours. If they would have given the chance to reenter the water, they might have ended up at a completely different location.

As a consequence, to overcome these limitations it is recommended to continue with the simulations using a three-dimensional model that is also able to resemble the complex beaching process more accurately. In addition to this, it would be interesting to explore also other ways of including the Stokes drift into the model, rather than just adding it to the flow.

Acknowledgements

I would like to thank Rijkswaterstaat and in particular Bert van Munster and Marlea Wagelmans for providing me with information about the MSC Zoe accident. I thank Firmijn Zijl for the supply of all of the DCSM-FM data and I thank Made Smart Group for the AIS data of the MSC Zoe. I would also like to show my gratitude to Jens Meyerjürgens for sharing their research drifter data with us. Lastly, I would like to thank Martin Verlaan, my supervisor, for his help and support during my internship.

A Derivation of the Stokes drift equation

The Stokes drift was derived by Kenyon [7] as

$$\mathbf{u}_s = g \int\int_{-\infty}^{\infty} F(\mathbf{k}) \frac{\mathbf{k}}{\omega} \left[\frac{2k\cosh(2k(z+d))}{\sinh(2kd)} \right] d\mathbf{k},$$

where g is the gravitational acceleration, $F(\mathbf{k})$ is the energy spectrum, $\mathbf{k}$ is the wavenumber vector, ω the radian frequency, $k = |\mathbf{k}|$ is the magnitude of the wavenumber vector, z is the vertical co-ordinate and d is the bottom depth. Now, since we are considering Stokes drift at the surface we can take $z = 0$, which leads to

$$\begin{aligned}
\mathbf{u}_s &= g \int\int_{-\infty}^{\infty} F(\mathbf{k}) \frac{\mathbf{k}}{\omega} \left[\frac{2k\cosh(2kd)}{\sinh(2kd)} \right] \mathrm{d}\mathbf{k} \\
&= \int\int_{-\infty}^{\infty} \left[\frac{2gk}{\omega \tanh(2kd)} \right] \mathbf{k}F(\mathbf{k}) d\mathbf{k} \\
&= \int\int_{-\infty}^{\infty} \left[\frac{2gk}{\omega} \right] \mathbf{k}F(\mathbf{k}) \mathrm{d}\mathbf{k} \\
&= \frac{2}{g} \int\int_{-\infty}^{\infty} \frac{g^2k^2}{\omega} \frac{\mathbf{k}}{k} F(\mathbf{k}) \mathrm{d}\mathbf{k} \\
&= \frac{2}{g} \int\int_{-\infty}^{\infty} \omega^3 \hat{\mathbf{k}} F(\mathbf{k}) \mathrm{d}\mathbf{k},
\end{aligned}$$

where in the second equality we assumed deep water, so for $kd \to \infty$ we have $\tanh(2kd) \to 1$ and $gk = \omega^2$ [8] and where in the last line $\hat{\mathbf{k}} = \frac{\mathbf{k}}{k}$ is the unit vector in the direction of the wave component. Then recasting the east and north components to the frequency-direction co-ordinates (f, θ) together with $f = \frac{\omega}{2\pi}$ [38], we get

$$\mathbf{u}_s = \frac{16\pi^3}{g} \int_0^{\infty} \int_0^{2\pi} f^3 \hat{\mathbf{k}} F(f, \theta) \mathrm{d}\theta \mathrm{d}f.$$

Since this expression is hard to evaluate, we will assume that the wave spectra are separable into the wave and direction components. Furthermore we will consider that the waves travel in the same direction. We split the wave spectra using

$$\int_0^\infty \int_0^{2\pi} F(f,\theta)\mathrm{d}\theta\mathrm{d}f = \int_0^\infty \int_0^{2\pi} \phi(f,\theta)F(f)\mathrm{d}\theta\mathrm{d}f = \int_0^\infty F(f)\mathrm{d}f$$

where ϕ is the directional distribution with $\int_0^{2\pi} \phi(f,\theta)\mathrm{d}\theta = 1$. As a consequence

$$\begin{aligned}\mathbf{u}_s &= \frac{16\pi^3}{g}\int_0^\infty \left[\int_0^{2\pi} \hat{\mathbf{k}}\phi(f,\theta)\mathrm{d}\theta\right] f^3 F(f)\mathrm{d}f \\ &= \frac{16\pi^3}{g}\int_0^\infty f^3 F(f)\mathrm{d}f\end{aligned}$$

where in last step we applied the unidirectionality assumption [9].

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