Modelling the Trajectory of Waveriders using 2D and 3D Velocity Flow of the North Sea and the Air Velocity.

Erik ten Hagen

Supervisor
Martin Verlaan

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1 Introduction

Particle models are a usefull tool for Search and Rescue (SAR). When trying to find people or objects lost at sea, these models can significantly reduce the area to be searched, potentially saving much time and increasing success rate. Before particle models can be used for such matter, they must be tested for a various of object to get a clear understanding of the math and the physics involved with it. In the past Ooms and Ruiter [1, 2] have worked on a particle model for drifters in the German Bight. These drifters where designed such that the vast majority of it is in water and are barely influenced by the wind. In their work they focussed on the stokes drift and the ocean current. As far as we are aware of there are no test done with drifters on the North Sea or with drifters with parts above water that can be caught by the wind, but we know there are numerous buoys in the North sea measuring current and waves of which some break off from their anchor and drift away. In this paper we research the influence of wind and test if these buoys can be used as drifters in the particle model. We use the wind velocity form ERA5 and the ocean currents from 3D DCSM-FM and 2D DCSM-FM.

2 The Buoy

Rijkswaterstaat (RWS) is a government agency responsible for the design, construction, management and maintenance of the infrastructure of the Netherlands. Among their responsibilities is monitoring the North Sea. They monitor the Sea by using buoys that can measure different variables. One of such buoys are the Waverider made by datawell. They have a diameter between 70 and 90 cm and an illustration is shown in Figure 1. They measure the wave height and wave direction on the locations they are placed. Most of the buoys used by RWS are placed around the dutch Wadden Islands or before the coast of the province Zeeland. To keep them in place they are connected to a heavy anchor, which again is connected to a rubber cord to keep them floating on the waves. This is Shown in Figure 2. Sometimes the rubber cord can snap and the buoy drift away. To recover them RWS can check their location since each of the buoys is equipped with a GPS unit. Since they record their location every thirty minutes we know exactly the trajectory it takes. For two of these buoys RWS has provided us with its trajectory. We can use those to formulate a theory about the influences of wind and check how well the particle model performs. The first buoy was located at 5.57 Longitude and 53.4 Latitude and broke free at 12:00 pm on 14 November 2016. This buoy drifted of to one of the island of Denmark at 6:00 am on 30 November 2016. The trajectory is shown in blue in Figure 3. In total this buoy drifted 15 days and 18 hours. The second buoy was located at 3.2 Longitude and 53.2 Latitude and broke free around 4:15 am on 10th of August 2016. This buoy drifted for a long time and we could only do the calculation until 11:15 am 23 September 2016 because that is where the calculations for the 3D DCSM-FM ended. Total time for this buoy is around 41 days. The trajectory of this buoy is shown in black in Figure 3.

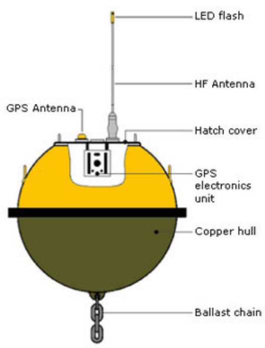


Figure 1: The basic design of a GPS Waverider buoy. [3]

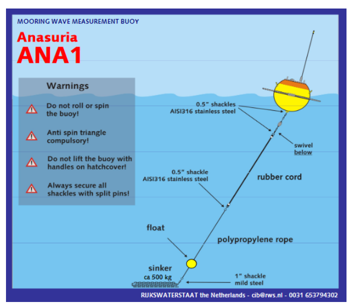


Figure 2: Waverider with anchor. Figure provided by RWS

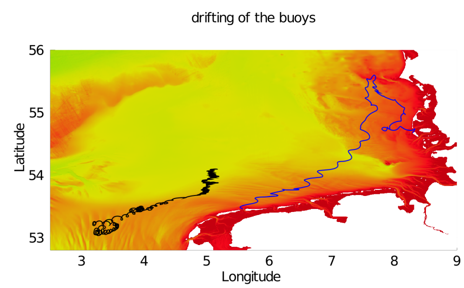


Figure 3: Drifting of the two buoys

3 ERA 5 and DCSM-FM

To use the particle model we need data of the wind velocity and the ocean current. We use ERA5 for the wind velocity and DCSM-FM for the 2D velocity of the ocean as well as the 3D velocity of the water current.

3.1 ERA5

In the past wind velocity is modelled with a range of different methods. Every now and then the models get improved or can be used on a finer grid. This makes it hard to compare data from previous models to data from now. To simplify this the European Centre for Medium-Range Weather Forecasts (ECMWF) started with reanalysing data of the past using one model for the whole period. The latest version is ERA5 and has a grid resolution of 31 km and covers the time between 1950 and the present [4]. it provides hourly estimates in 137 levels from the surface to a height of 80km [5]. Although they say 'surface' they mean at a height of 10 meters since meteorologist have standardized that as surface level. If one wants to know the height at a different height then a logarithmic wind profile is often used.

3.2 DCSM-FM

Deltares has already developed the sixth-generation of the DCSM-FM model. Previous versions focused on an optimal representation of the water levels, but this version can also be used for water quality, ecology studies, oil spills or Search and Rescues (SAR) [6]. It covers the North Sea as well as the shallow waters and estuaries of the Netherlands. From 15°W to 13°E and from 43°N to 64°N. This model does not have one spatial resolution, but uses a flexible mesh to give important areas a higher resolution. The DCSM-FM can be used for two and three dimensional modeling since it has been developed as an application of D-Flow Flexible Mesh of the D-HYDRO suite. All of this information and more about DCSM-FM can be found in the work of Zijl and Groenenboom [6].

4 Particle Model

This particle model models the movement of a particle in the ocean from the forces applied to it. From the forces it determines its velocity and direction. This particle model is called a Lagrangian particle model in fluid dynamics. In the past Ooms and Ruiter have worked on a particle model for the trajectory of a drifter, shown in Figure 4, using the currents and the stokes drift [1, 2]. The wind had barely any influence since the drifter was only a few centimeters above the water. In this paper we test if the buoys can be used as a drifter where the air force will be included and the stokes drift will be neglected.

Figure 4: Drifter used in the German Bight [7]

4.1 The Construction of the Particle Model

The particle model has been developed in different stages. It starts with the drifters only being influenced by the ocean current. The velocity of the particle is the velocity of the current at that location

$$u_p = u_w. \tag{1}$$

In the simplest form many forces are not included. To include those the particle velocity is determined from the use of Newton's second law. The derivation is covered in Modeling of leeway Drift [8]. The equation to work with is

$$M' \frac{\partial u_p}{\partial t} = F_a + F_w + F_c \tag{2}$$

with F_a, F_w and F_c respectively the air force, the wave force and the water force. $M' \frac{\partial u_t}{\partial t}$ is the inertial force in which M' is the total mass defined as

$$M' = m + km'. \tag{3}$$

m is the mass of the particle and km' the added mass when the particle drifts through the fluid. In km' the m' is the mass of the fluid displacement and k is a coefficient depending on the shape of the particle. The values for k has been empirically found over time for different objects.
For typical SAR objects, such as the waverider, the inertial force can be ignored[8].

$$F_a + F_w + F_c = 0$$

From this equation Ooms has already calculated the particle velocity, with neglecting the stokes drift the particle velocity is

$$u_p = \frac{\sqrt{C_{D_a} \rho_a A_a} u_a + \sqrt{C_{D_w} \rho_w A_w} u_w}{\sqrt{C_{D_a} \rho_a A_a} + \sqrt{C_{D_w} \rho_w A_w}}. \tag{4}$$

Since the waverider is close to a perfect sphere we assume for the physics it is. Then the projected area above water A_a and under water A_w are the same as well as both drag coefficients C_{D_a} and C_{D_w}. The particle velocity can be simplified to

$$u_p = \frac{\sqrt{C_D \rho_a A}\ u_a + \sqrt{C_D \rho_w A}\ u_w}{\sqrt{C_D \rho_a A} + \sqrt{C_D \rho_w A}} \tag{5}$$

Which is the same as

$$u_p = \frac{\sqrt{\rho_a} u_a + \sqrt{\rho_w} u_w}{\sqrt{\rho_a} + \sqrt{\rho_w}} \tag{6}$$

.

4.2 Extension with Air Factor

As mentioned before the wind velocity u_a applied to the buoy is not yet known, since the wind velocity at 'surface' level is still at 10 meters height as mentioned in Section 3.1. Using the logarithmic wind profile the velocity can be scaled to a height where it impacts the particle. Although we have to be cautious when the height is to close to the surface because there the viscosity must be taken into account and at surface level the waves can also distort the profile. In Figure 6 the logarithmic wind profile is shown and is given by the equation

$$u_a(z_a) = \frac{u_*}{k} \ln\left(\frac{z_a - z_d}{z_0}\right) \tag{7}$$

with $k = 0.4$ is the Von Kármán constant, z_d is the zero plane displacement, z_0 is the roughness length and u_* the friction velocity [9]. On open water there is no zero plane displacement and $z_0 = 0.0002$.
Because the air velocity at 10 meters height is known the friction velocity can be calculated with

$$u_* = u_a(10)\frac{0.4}{\ln(\frac{10}{0.0002})}, \tag{8}$$

thus Equation 7 can be rewritten as

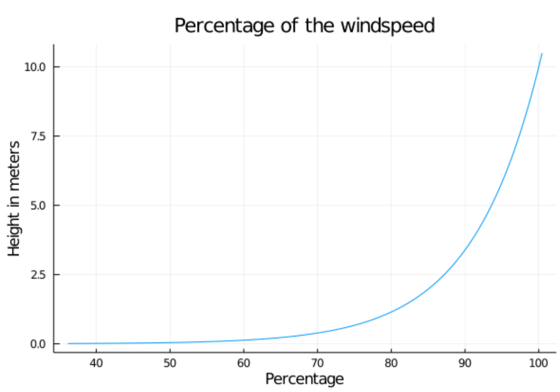
$$u_a(z_a) = u_a(10)\frac{\ln(\frac{z_a}{0.0002})}{\ln(\frac{10}{0.0002})}. \tag{9}$$

The effective height for the buoy is estimated somewhere between 35 and 45 cm, since the buoy has a diameter of 90 cm and only half of the sphere sticks above water. The percentage of the velocity at 10 meters that effects the buoy is

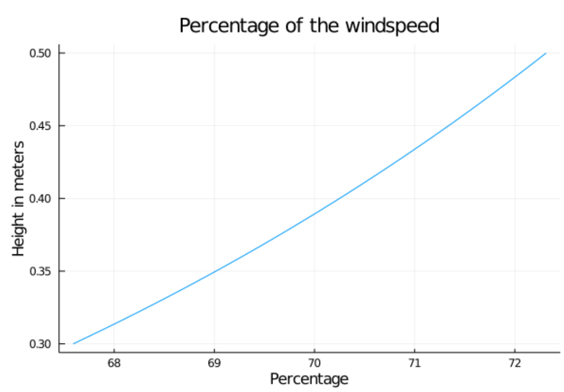
$$p_1(z_a) = \frac{\ln(\frac{z_a}{0.0002})}{\ln(\frac{10}{0.0002})}. \tag{10}$$

The change of the percentage depending on height is shown in Figure 5a and a close up of the relevant heights are shown in Figure 5b. The air velocity in Equation 6 can be replaced by the effective wind velocity $u_a(z_a) = p_1(z_a) \cdot u_a(10)$ in which z_a the height above water with values greater than zero. The particle model can now be described with

$$u_p = \frac{\sqrt{\rho_a}\ u_a(z_a) + \sqrt{\rho_w}u_w}{\sqrt{\rho_a} + \sqrt{\rho_w}} \tag{11}$$



(a) Overall change of percentage



(b) Close up percentages

Figure 5: Percentage of the wind velocity depending on the height.

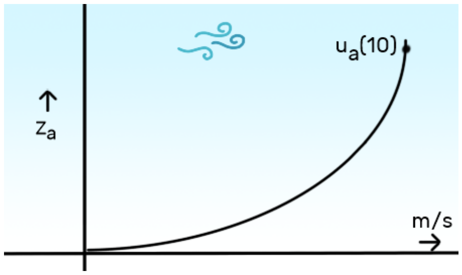


Figure 6: The logarithmic profile for the air velocity.

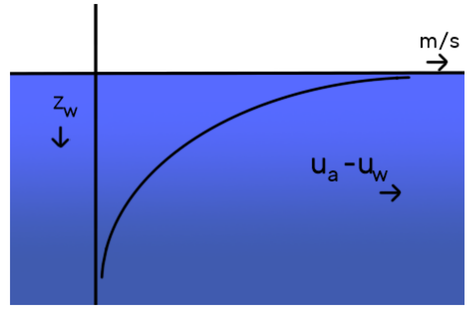


Figure 7: The logarithmic profile for the extra waterspeed

4.3 Extension with Water Factor for 2D Velocity Flow

The particle model works on a 2D and 3D model of the sea current. It needs the water velocity at the top layer of the water since that is where the buoy drifts. The 3D model describes this accurately because it is design to do that but the 2D is lacking there and describes more the velocity of the sea at some depth. It is assumed that the wind influences the water velocity near the surface and therefore an extra component of the wind is added to the water velocity to account for this phenomenon. To estimate this influence it is assumed that the extra water velocity follows the same logarithmic profile as the wind did in Equation 7

$$u_w(z_w) = \frac{u_{w*}}{k} \ln\left(\frac{z_w - z_d}{z_0}\right) \tag{12}$$

with

$$u_{w*} = \sqrt{\frac{\tau}{\rho_w}}. \tag{13}$$

This profile is shown in Figure 7. The shear stress τ in Equation 13 is defined as the force per unit area. Since the wind exerts a force per unit area on the sea then there is an opposite negative force per unit area from the sea to the wind, as a result of Newtons third law. Using the shear stress in Equation 7 the following equations can be derived

$$u_{w*} = \sqrt{\frac{-\tau}{\rho_w}} \tag{14}$$

$$u_{a*} = \sqrt{\frac{\tau}{\rho_a}} \tag{15}$$

$$u_{w*}^2 \rho_w = -u_{a*}^2 \rho_a \tag{16}$$

$$u_{w*} = -u_{a*}\sqrt{\frac{\rho_a}{\rho_w}} \approx u_{a*}\frac{1}{\sqrt{1000}} \tag{17}$$

applying Equation 8 results in

$$u_{w*} = -u_a(10)\frac{k}{\ln(\frac{10}{0.0002})}\frac{1}{\sqrt{1000}}. \tag{18}$$

The water log profile is

$$u_w(z_w) = \frac{-u_a(10)}{\ln(\frac{10}{0.0002})\sqrt{1000}} \ln\left(\frac{z_w}{z_0}\right). \tag{19}$$

Let h_0 be the depth at which wind has no influence anymore. Then the extra water velocity can be described with

$$u_{aw}(z_w) = u_w(z_w) - u_w(h_0) = \frac{-u_a(10)}{\ln(\frac{10}{0.0002})\sqrt{1000}} \ln\left(\frac{z_w}{z_0}\right) - \frac{-u_a(10)}{\ln(\frac{10}{0.0002})\sqrt{1000}} \ln\left(\frac{h_0}{z_0}\right) \tag{20}$$

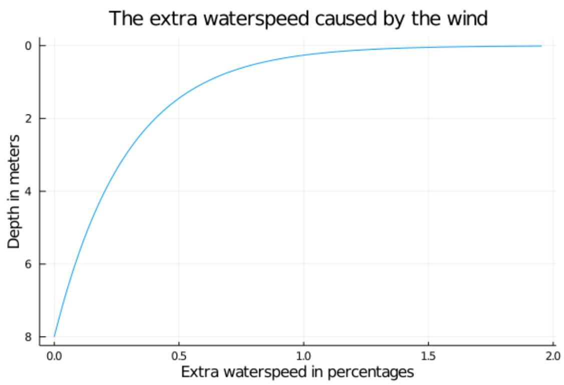
$$= -\frac{u_a(10)}{\ln(\frac{10}{0.0002})\sqrt{1000}} \ln\left(\frac{z_w}{h_0}\right). \tag{21}$$

$u_{aw}(z_w)$ can be rewritten as $p_2(z_w) \cdot u_a(10)$ with $p_2(z_w)$ a percentage function depending on the depth. In Figure 8 the percentage function is shown as well as a close up for the depth between 0.3 meter and 0.5 meter because of the size of the buoy. In Figure 8 it shows what percentage should be included in the particle model given Equation 21 with $h_0 = 8$. The improved particle model for the 2D current model will be

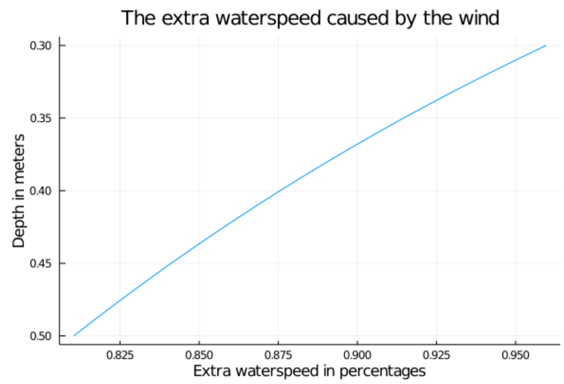
$$u_p = \frac{\sqrt{\rho_a}\ u_a(z_a) + \sqrt{\rho_w}(u_w + u_{aw}(z_w))}{\sqrt{\rho_a} + \sqrt{\rho_w}}. \tag{22}$$

or for objects that are almost entirely in water the particle model would be

$$u_p = u_w + u_{aw}(z_w). \tag{23}$$



(a) The change of the water velocity from 8 meters deep



(b) Close up of the extra water velocity for the relevant heights

Figure 8: percentages of the extra waterspeed caused by the wind depending on the depth

5 Results

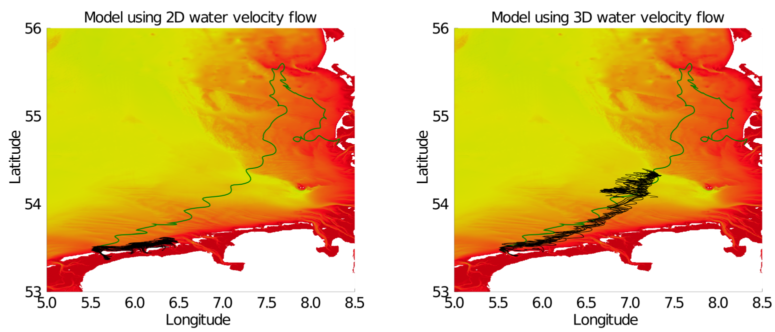
In this section various particles models are tested against the waveriders. First a buoy is discussed that follows the theory, secondly a buoy is discussed that had some unexpected behaviour. Then we test if this is a result of the starting point. The different particle models used are shown in Table 1.

	Model with only water velocity	Equation	Model with air	Equation
3D flow velocity 2D flow velocity	$u_p = u_w$	1	$u_p = \frac{\sqrt{\rho_a}\ u_a(z_a)+\sqrt{\rho_w}u_w}{\sqrt{\rho_a}+\sqrt{\rho_w}}$	11
	Model with extra waterspeed		Model with air and extra waterspeed	
3D flow velocity	$\times$	$\times$	$\times$	$\times$
2D flow velocity	$u_p = u_w + u_{aw}(z_w)$	23	$u_p = \frac{\sqrt{\rho_a}\ u_a(z_a)+\sqrt{\rho_w}(u_w+u_{aw}(z_w))}{\sqrt{\rho_a}+\sqrt{\rho_w}}$	22

Table 1: The four equations for the Particle Model

5.1 First Buoy

The first buoy started to drift around 12:00 pm on 14 November 2016 and ended around 6:00 am on 30 November 2016. All the tests done for this buoy are with 17 particles. One at Longitude 5.57 and Latitude 53.4, the exact location of the buoy, the other 16 are placed in a circle around this location. The model uses a forward time direction with timesteps of $\Delta t = 300$ seconds or 5 minutes.
The reason to improve the model is that with only using the water velocity for the particle model (Equation 1) the particles don't drift like the buoy did. This is shown in Figure 9 for both the 2D water velocity and the 3D water velocity. The particle model with the 3D velocity flow will be discussed first, since it is expected to be more accurate than the 2D velocity flow.



(a) Particle model with the 2D velocity flow

(b) Particle model with the 3D velocity flow

Figure 9: Only using the water velocity for the particle model

5.1.1 Particle Model using 3D Velocity Flow

In Section 4.2 the influence of the wind on the buoy was discussed. Because the buoy has a diameter of 0.9 meter the effective height z_a lies somewhere between 0.35 and 0.45 meter. Using Equation 10 the model (Equation 11) needs 69% to 71% of the wind speed.

Using 68% and 71% of the wind velocity results in a great trajectory that is close to the trajectory of the buoy. In Figure 10 the trajectory of the buoy and the particles are shown with a close up of the end position in Figure 11 both with the buoy in green and the particles in black. The figures show that using 69% and 70% of the wind velocity gives the closest trajectory of the particles to the buoy.

5.1.2 Particle Model using 2D Velocity Flow

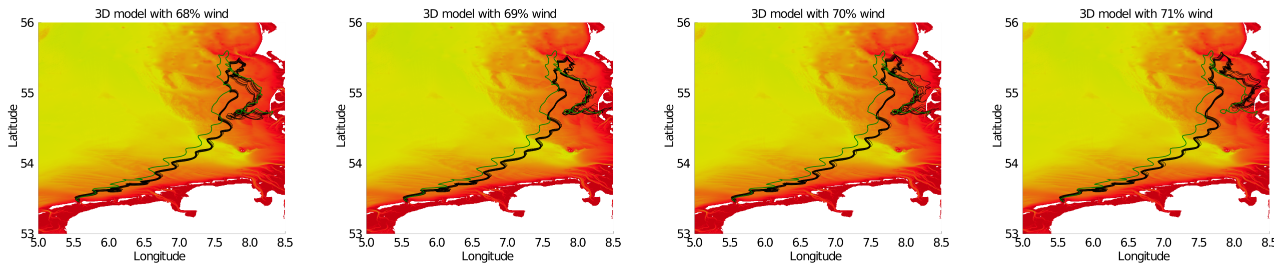


Figure 10: Buoy in green and the particles in black with different percentages of the windspeed

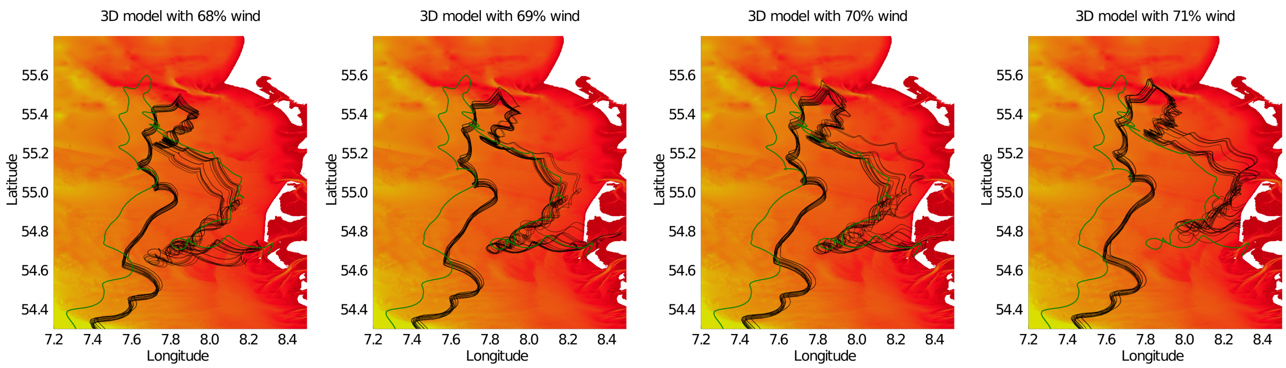


Figure 11: Close up of the end positions of Figure 10

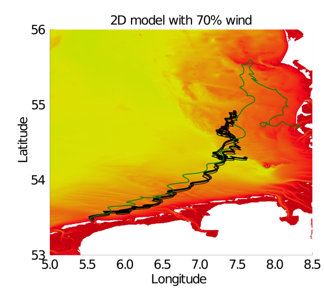


Figure 12: 2D water model with the particle model

Starting with the just found 70% the particle model (Equation 11) does not peform as well as the 3D counterpart, but there is already an improvement compared to not using the wind velocity. This difference can be seen between Figure 9a and Figure 12. In Section 4.3 this result was expected and discussed. The solution that was suggested is adding extra water velocity caused by the wind. Since the 3D velocity flow showed that using the wind gives a great improvement it was chosen to use Equation 22 for the particle model instead of Equation 23.
In the particle model there is now an extra component $uw(z)$. Depending on the effective depth a different percentage of the wind is used for the added water velocity. If the effective depth z_w is around 0.4 meter the extra water velocity is between 0.86% and 0.89% of the 'surface' wind velocity. In Figure 13 the trajectory of the particles are shown and they are closer to the 3D particles and the actual buoy than when the extra waterspeed was not included, i.e. using Equation 11 as the particle model. The best trajectory is when using 0.876% for the extra water velocity and using 69% of the wind velocity.

Noteworthy is that for both the 3D water velocity with particle model of Equation 11 and the 2D water velocity with particle model of Equation 22 all the particles are slightly more to the south east of the real trajectory of the buoy. Still they have all the same twist and turns as the buoy.

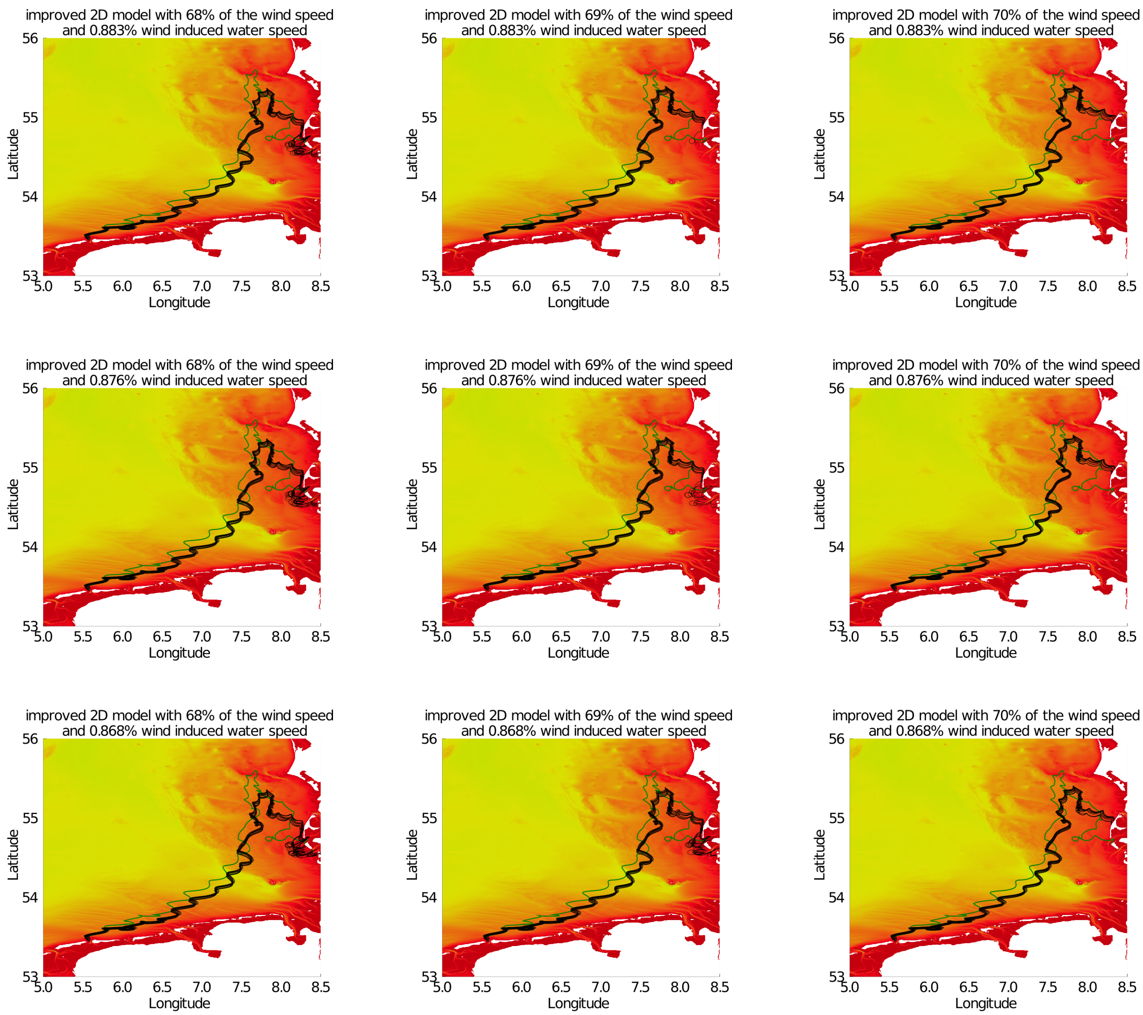


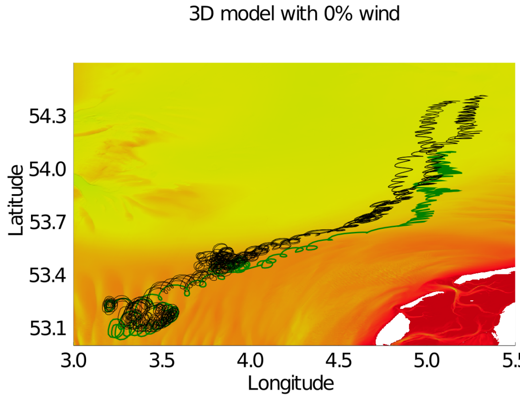
Figure 13: Improved 2D model

5.2 Second Buoy with 2D and 3D Velocity Flow

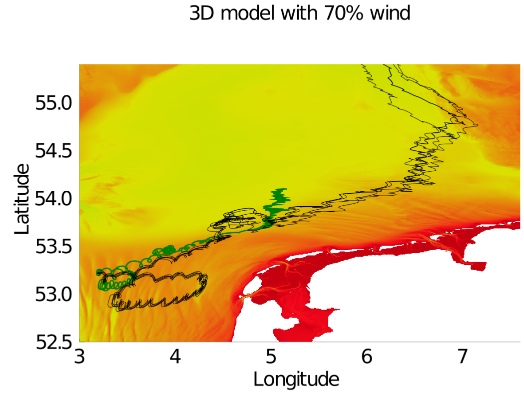
For the second buoy almost all of the parameters of the particle model are the same, expect for the time frame and the number of particles. This buoy was located at 3.2 Longitude and 53.2 Latitude and broke free around 4:15 am on 10th of August 2016. The simulations ended at 11:15 am 23 September 2016, because the data for the 3D velocity flow ended then. Because the buoy did not drift as far as for the first buoy and has a longer time period only 5 particles are used to get trajectories that are still distinguishable and to avoid getting one black blur for the particles. Just like the first buoy one particle starts at the exact location and the other 4 starts in a circle around it.

For the 3D velocity flow we started with using Equation 1 and Equation 11 with 70 % wind velocity for the particle model. Surprisingly the particle model without wind performs better than with wind, see Figure 14. An possible explanation is that this buoy still has part of the rubber cord hanging below the buoy. In Section 4.1 we assumed that the projected area of the buoy below water is the same as above water, but this can be wrong. In the case that the rubber cord is 20 meter long and 3.5 centimeters width the projected area below water is $\frac{1}{2}\pi 0.45^2 + 20 \cdot 0.0035 = 1.02m^2$ and above water is $\frac{1}{2}\pi 0.45^2 = 0.32m^2$. This means that the water force has a bigger influence than assumed before. For this buoy we can not test the wind velocity for the 3D velocity flow, but it is still possible to test if extra water velocity improves the 2D model compared to the 3D model using Equation 23 and Equation 1 respectively for the particle model.

Using only the water velocity for the particle model, the particles makes many loops, but the trajectory does not look like the buoy or the 3D trajectories, see Figure 15. The trajectory should exist of four parts as seen in the 3D



(a) Particle model using only 3D water velocity



(b) Particle model using 3D water velocity and 70 % of the wind velocity

Figure 14: 3D model of the second buoy

counterpart and the buoy itself. These are a big loop at the start around 3.4 Longitude, a much smaller loop/cluster around Longitude 4.0, rapid movement around Latitude 53.6 and a last part drifting mostly from West to East and back and slightly to the North. To use Equation 23 for the particle model we need to use some percentage of the wind, just like with the first buoy. The percentages used are 0.898,0.876 and 0.854. The effects are shown in Figure 16. With the use of extra water velocity the trajectory looks more like the real data of the buoy. Three of the four distinct parts of the trajectory are recognizable now. Only the rapid movement around Latitdue 53.6 is missing. Surprisingly in Figure 16 the different percentages do not have a big impact on the trajectory compared to the effects we saw for the first buoy in Figure 13.

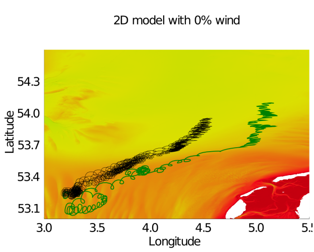
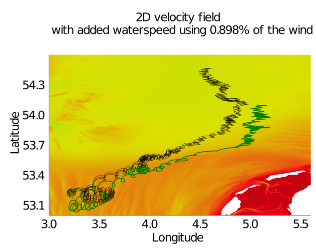
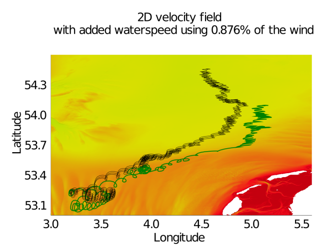


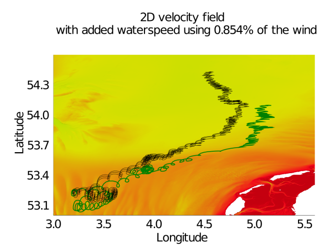
Figure 15: Particle model with the 2D current



(a) Using 0.898% of the wind



(b) Using 0.876% of the wind



(c) Using 0.854% of the wind

Figure 16: The improved particle model with the 2D current

5.3 Second Buoy with different Starting Times

As just mentioned the second buoy shows a complex trajectory consisting of four distinct segments and the particle model with 2D velocity flow and 3D velocity flow only shows three of them. To check what happens around Longitude 53.6 we started the particle model at different moments. For the 3D velocity flow Equation 1 is used and for the 2D velocity flow Equation 23 is used with 0.876% of the wind.

For the particle model using 2D velocity the trajectory is very stable, see Figure 17. It does not matter much when the simulation starts, the trajectory always has the same twist and loops. It also shows that the rapid movement of the buoy can not be simulated with using the 2D velocity flow. When the 3D velocity flow is used with different starting points the trajectories scatter more and the trajectory at the end depends mostly on where it crosses Latitude 53.6, shown in Figure 18. Still the rapid movement of the buoy can not be created. A possible explanation of this behaviour lies with the depth of the ocean. In every figure the background colors represent the depth of the sea and around Latitude 53.6 the sea changes from shallow water to deeper water. The phenomenon that happens when the buoy crosses this line can not be simulated yet. Second option is since there is a change this buoy still has a rubber cord attached that the cord drags over the ocean floor which influences the behaviour of the buoy.

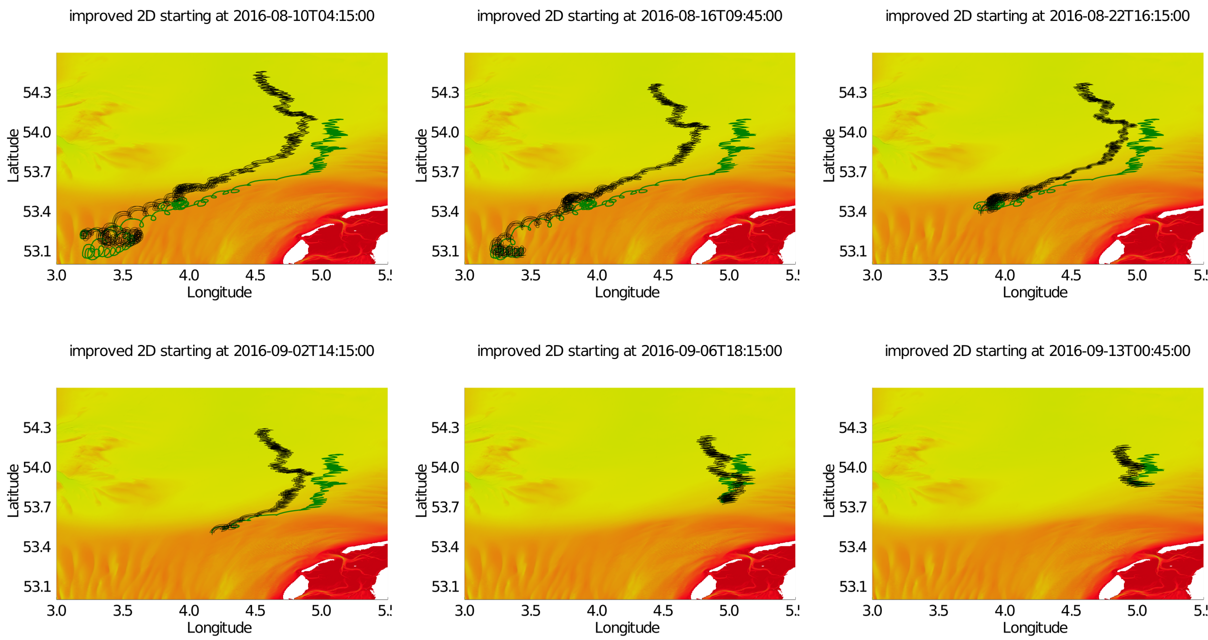


Figure 17: Particle model starting at different times with the 2D current

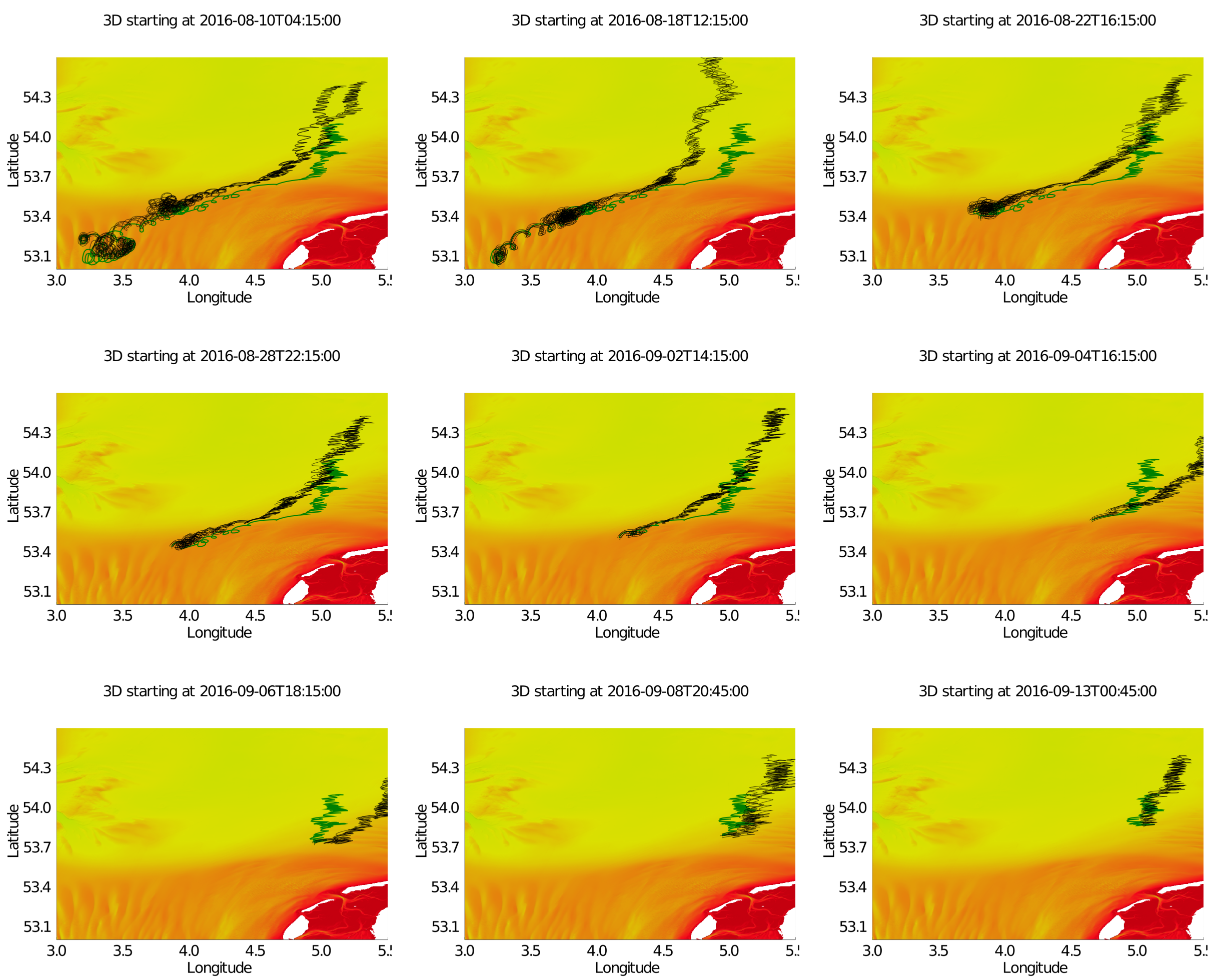


Figure 18: Particle model starting at different times with the 3D current

6 Conclusion and Discussion

The two additions to the particle model are the inclusion of the wind velocity for the 2D and 3D water velocity flow and the extra waterspeed for the 2D velocity flow caused by the wind. The inclusion of 69% and 70% of the wind velocity gave great results for the first buoy, which is in line with the theory. For the second buoy the inclusion of wind was a failure and it worked best for the particle model to only use the water velocity. For both buoys we saw that extra waterspeed for the 2D velocity flow improved the particle model greatly and the results looked similar to the trajectories using 3D velocity flow. For the second buoy there was rapid movement in the trajectory when it went from shallow water to deeper water of the sea. Although this could not be simulated when using different starting times it showed that the trajectories of particle model are stable.

If there was more time for this internship it would have been interesting to look deeper into some aspects of the particle model or to look at different datasets. An possible addition for the particle model would be the option to run the simulation with the rubber cord. Then you could test if 70% of the wind is an improvement for the second buoy. Also if the length of the rubber cord is unknown the simulation could be done with different lengths and using 70% of the wind velocity. Although it is easier to test this with more examples of drifted buoys. Lastly it would be interesting to test if the extra water velocity also works for the drifters in the German Bight and compare it with the results of Ooms and Ruiter where they used the stokes drift.

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