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Spreading of floating microplastics in a tidal inlet system

Bachelor Thesis

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April 2021

Abstract

On the night of 1^{st} and 2^{nd} of January 2019, the container ship MSC Zoe lost 342 containers in the North Sea above the Wadden Islands. Most of the cargo of the containers was filled with grains of plastic granulate which are hard to clean up. To make sure the cleanups of the plastic grains can be started up quickly and efficiently, it is important to understand the dynamics of the Wadden Sea. Therefore a computational model, Delft3D, is used to simulate the hydrodynamics of a tidal inlet, where the Wadden Sea consists of multiple. Simulations were done over 16 days where 15 days the particles were tracked. Different scenarios were used for the simulations to understand the sensitivity of the plastic particles to the vertical structure of currents when tides and/or wind-driven currents are accounted for. Another part of the simulations was done to understand the difference in the spreading of the particles when waves are accounted for and Stokes drift is implemented. The results for a 3D simulation under influence of only tides are that 37% of the particles can potentially beach and for a 2DH simulation that is 34%. For a 2DH simulation under influence from tides and wind from the west 19.33% of the particles can potentially beach and for a 3D simulation under the same circumstances this is 7.67%. The results for a 3D simulation under the influence from tides and waves and/or wind no difference occur in the spreading of the particles, calculated by the Delft3D module *Drogues* when Stokes drift is implemented.

Contents

1 Introduction

On the night of 1^{st} and 2^{nd} of January 2019, the container ship MSC Zoe lost 342 containers in the North Sea above the Wadden Islands. The content of these containers was for the most part washed up in the Frisian Wadden Islands and the coast of Friesland and Groningen, see Figure 1a[1].[2] Most of the cargo of the containers was filled with grains of plastic granulate (see Figure 1b[3]), which are hard to clean up. This can be seen due to the fact that even after a year there are still plastic grains spotted on one of the Wadden Island, Schiermonnikoog.[4]

To make sure the cleanups of the plastic grains can be started up quickly and efficiently, it is important to understand the dynamics of the Wadden Sea. Those dynamics are hard to model due to the different effects (tides, topography, waves, wind, etc) which have a great influence in the Wadden Sea, and in particular, in a tidal inlet where this thesis is focusing on. When simulations are made, predictions can be made where this plastic will end up in certain situations, like the MSC Zoe event. This thesis will deal with simulations of trajectories for buoyant marine plastic debris, in this thesis (plastic) particles to be called from now on. Further, the dynamics of the simulation will be discussed in this particular area, the Wadden Sea. These trajectories will come out of the simulations made where the dynamics of the Wadden Sea are used as an input.

There are a lot of studies done about plastic spreading simulation, like van Sebille et al. (2020) and Zhang (2017). But those are about global spreading and near shelf seas spreading of those plastics. There are not a lot of studies done for the North Sea and/or the Wadden Sea. Two which can be mentioned are Janssen (2019) and van Hee and Pauw (2020). This study will follow van Hee and Pauw (2020) closely and will work further on what was established in their thesis. Both of these studies had some shortcomings.

In Janssen (2019) an ocean-based circulation model was used for the entire North Sea, so the small scale dynamics, especially near coastlines, coarse resolution (roughly 10 km), whereas it is known that in areas like the Wadden Sea the joint action of tides and residual currents around sandbanks (scales of several km or less) are important for dispersion of particles (Ridderinkhof and Zimmerman, 1992). The prediction of Janssen (2019) is that the plastic of the MSC Zoe will mainly be transported along the coasts of Germany and Denmark to Skagerrak.

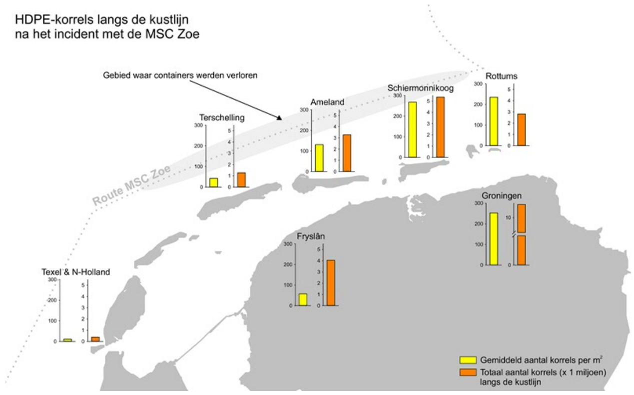
In van Hee and Pauw (2020) a 2D model is used and in their results, the Stokes drift of the particles is not accounted for. Stokes drift is the Lagrangian velocity due to the wave average of the water particle trajectory in the wave propagation(Myrhuag et al., 2018). This can be only simulated in a 3D model where Eurelian velocities are used and this stokes drift has an

[1]Groningen University 2019: First Waddenplastic.nl research outcomes, https://www.rug.nl/news/2019/03/eerste-onderzoeksresultaat-waddenplastic.nl_-schiermonnikoog-hotspot-van-aangespoelde-plastic-ko?lang=en

[2]Overboord geslagen containers: https://www.veiligheidsregiofryslan.nl/intern/overboordgeslagen-containers/

[3]Plastic granulate MSC Zoe spread til Denmark beaches: https://www.rtvnoord.nl/nieuws/219155/Plastic-korrels-MSC-Zoe-liggen-tot-in-Denemarken-op-de-kusten

[4]Wadden nog bezaaid met plastic na containerramp, Kamer wil dat reder dit betaalt: https://www.rtlnieuws.nl/nieuws/nederland/artikel/4933516/ramp-met-msc-zoe-de-bolletjes-zijn-klein-wadden



(a) The HDPE granule count (x 1 million) along the shores of the eastern Wadden area. Arrow marks location incident. Yellow = mean per m2; orange = total count.

(b) The beach of Schier lit with grains of plastic granulate.

Figure 1: The consequences of the MSC Zoe container disaster due to the spread of plastics

important role in the spreading of plastic as discussed in Onink et al. (2019). Results of van Hee and Pauw (2020) mainly showed differences in the spreading time (time for particles to reach the tidal inlet) and direction, and beaching quantity.

Taking these limitations in previous studies into account, the objectives for this thesis are:

- How sensitive are modelled trajectories of plastic particles to the vertical structure of currents when tides and/or wind-driven currents are accounted for?
- What will be the difference in the spreading of the plastic particles when waves are accounted for in a simulation (like in the situation of the MSC Zoe event) and stokes drift is implemented in the output data of the simulation?

These objectives will be achieved by using a numerical hydrodynamic model that is coupled to a particle trajectory model. The model is applied to a domain that resembles the area where plastics originating from the MSC ZOE spread in the North Sea and the Wadden Sea, further enlightened in section 3 *Methodology*.

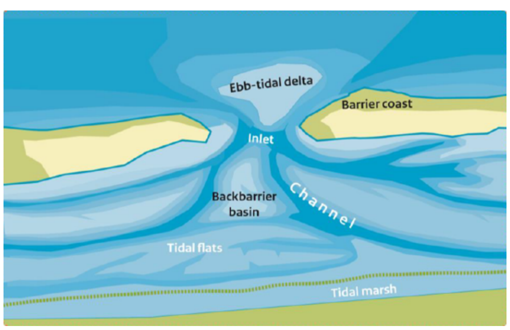
Before the *Methodology* is discussed, first there will be taken a short look at the *Theoretical Background* of this thesis in the next section. After the *Methodology* section, the results of the simulations will be displayed. The final two sections, *Discussions* and *Conclusions* will be discussed.

2 Theoretical Background

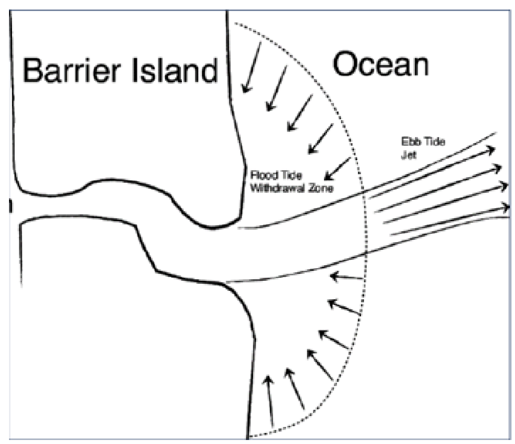
In this chapter, the following subjects are going to be discussed: tidal inlet, the tides, wind-driven currents, swell, residual velocity, model description and the hydrodynamic equations.

2.1 Tidal Inlet

A definition of a tidal inlet is that it is a breach through a coastal barrier, which connects an ocean or sea with a back-barrier basin and which is maintained by tides seaward of the inlet. The morphology of the back-barrier basin consists of a complex pattern of channels, tidal flats and marshes. (Fitzgerald et al., 2002) This can be seen in Figure 2a.



(a) Graphical depiction of a tidal inlet with its mentioned characteristics(Oost et al., 2014).



(b) Schematic overview of the ebb-tide jet occurring as the tide is falling (Rhynne, 2016).

Figure 2: Tidal inlet characteristics

In a tidal inlet when the tides come in, water gradually flows into the tidal inlet from all directions. When the tides turn, the outflow of water is pushed through the narrow tidal inlet with a high velocity, resulting in a so-called "ebb-tidal jet", see Figure 2b.(van Hee and Pauw, 2020)

In section 3.1 *Study Area* more specifics about the tidal inlet, that is used in this research, are mentioned.

2.2 The tides

Tides are generated by the difference between gravitational forces due to the Moon and Sun and the centrifugal forces that result from the revolution of Earth-Moon and Earth-Sun about their common centres of mass. The tides generated by the attraction of Earth and Moon are called M2 sine waves. These have a period of 12 hours and 25 minutes. The tides generated by the attraction of Earth and the Sun are called S2 sine waves, which have a period of 12 hours. Nevertheless, these tides are half as weak as the M2 if we look at the amplitude of those waves. This is because the tidal force is proportional to the inverse cubed distance between the celestial bodies (Haigh, 2017).

2.3 Wind-driven currents

Besides the tides, the wind is a very important factor that influences the currents in the coastal range. It matters greatly from which direction it comes and with what speed. The flow will directly follow the pattern of the wind in the shallower areas, like a tidal inlet system. Further, the wind causes wind stress on the ocean surface. There an Ekman Surface will be created where Ekman transport will occur. Ekman transport is not in the same direction as the wind, due to the Coriolis effect. This can be seen in figure 3 for the Northern Hemisphere (Cushman-Roisin and Beckers (2011)).

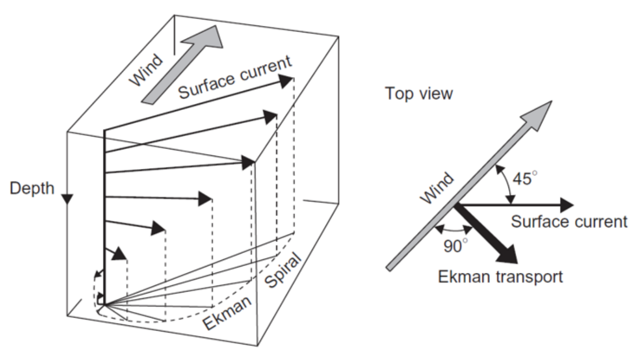


Figure 3: Graphical depiction of the structure of the Ekman layer in the Northern Hemisphere and the deflection is to the right of the surface stress (Cushman-Roisin and Beckers (2011)).

However, this applies to a situation in which the Ekman depth is way smaller than the water depth. So here the effect is less pronounced (no 45-degree angle etc). There's still some veering of the current, but not that pronounced. Figure 4 shows wind-driven circulations for part of the Wadden Sea.

2.4 Swell

A third process that can influence the hydrodynamics of the sea is swell. Swell are long waves, which means that these waves have a very long wavelength concerning wavelengths

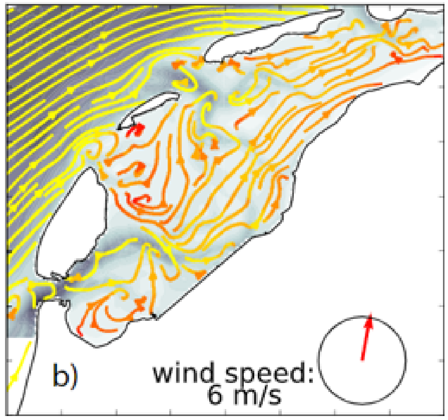


Figure 4: Residual circulation for six tidal periods with a southwesterly wind of 6 m/s. The colour denotes the magnitude of the transport (yellow stronger, red weaker). The grey scale in the background represents the bathymetry (Duran-Matute et al. (2016)).

of waves that are under direct action of the wind and have travelled far from a source. The amplitude of those waves is small compared to their wavelength and compared to the water depth. A possible source of swell is storms (University, 1999). From now on of waves are mentioned that will mean the swell waves generated by a distant storm.

Because we work in an Eulerian framework u and v are defined as the Eurelian velocity components. So u is the alongshore velocity and v is the cross velocity and both are velocities averaged over several wave cycles. But due to Stokes drift (which generates from the swell), there is a need to talk about the Generalized Lagrangian Mean, or from now on GLM. Stokes drift is the Lagrangian velocity due to the wave average of the water particle trajectory in the wave propagation(Myrhuag et al., 2018). This can be only simulated in a 3D model where Eurelian velocities are used and this stokes drift has an important role in the spreading of plastic as discussed in Onink et al. (2019). In simulations including waves, the hydrodynamic equations are written and solved in a GLM frame where there is talked about GLM velocities. These have the following definitions:

$$U = u + u_s \qquad\qquad V = v + v_s$$

Here u_s and v_s are the Stokes drift components due to the waves in a Lagrangian framework (Lesser et al. (2004)). It is thus important that Stokes drift is implemented because they play an important part in the spreading of particles (Alsina et al., 2020).

2.5 Residual velocity

The definition of residual velocities is that the residual velocities are the averaged velocities at a fixed location over multiple tidal periods. Residual velocity is widely more used to explain the mass transport in shallow seas, like the tidal inlets (Wang et al. (2013)). For the rest of this thesis, we will work in an Eulerian framework.

2.6 Model description

In this subsection, the tools for solving the hydrodynamic equations and particle trajectories and the ways of analysing the data are explained.

Delft3D is a computational model used to simulate the hydrodynamics of fluvial, estuarine and coastal environments where the particles which are going to observed can be put in the simulation.
Delft3D consists of two different modules: Delft3D-FLOW, Delft3D-WAVE (or SWAN) and Delft3D-Mor. For this thesis, only FLOW and WAVE will be considered. The hydrodynamic equations mentioned in section 2.8 of this thesis will be solved using the modules FLOW and WAVE.[5]
The FLOW module is the hydrodynamic simulation programme where WAVE will be coupled with FLOW for waves to be Incorporated in the simulation.

MATLAB is a programming and numeric computing platform used by millions of engineers and scientist to analyse data, develop algorithms and create models.[6]
In this thesis, MATLAB is used to analyse the data coming out of Delft3D. This will be in a similar way done as in van Hee and Pauw (2020).

2.7 Hydrodynamic equations

In this section, the hydrodynamic equations, which are being solved in the Delft3D model, are discussed. Further, there will be some boundary conditions mentioned which will make this set of equations a complete system. All the information mentioned in this section can be found in Lesser et al. (2004), but some slight modulations are made for this research. These will be explicitly mentioned.

At first, the coordinate system will be talked about, the equations will be given in the Cartesian form but the Delft3D model works in the sigma coordinate system, which only has repercussions for the vertical axis. The x-coordinate will be positive towards the east in the west-east direction and also its derivative u (alongshore velocity). The y-coordinate will be positive towards the north in the north-south direction and also its derivative v (cross-shore velocity). The vertical velocity ω will be positive upwards and negative downwards at location (x, y, σ) and is defined as $\omega = h\frac{d\sigma}{dt}$.

The vertical σ-coordinate system is defined by the following equation:

$$\sigma = \frac{z - \zeta}{h} \tag{1}$$

σ is scaled so $\sigma = 0$ is the free surface and $\sigma = -1$ is the bottom. Here z is the depth-coordinate, ζ is the elevation and the h is the depth.

[5]Delft3D `https://oss.deltares.nl/nl/web/delft3d/about`
[6]MATLAB `https://nl.mathworks.com/products/matlab.html`

Also the following horizontal momentum equations will be solved by the model:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + v\frac{\partial U}{\partial y} + \frac{\omega}{h}\frac{\partial U}{\partial \sigma} - fV = -g\frac{\partial \zeta}{\partial x} + F_x + M_x + \frac{1}{h^2}\frac{\partial}{\partial \sigma}(\nu_V \frac{\partial u}{\partial \sigma}) \tag{2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + \frac{\omega}{h}\frac{\partial V}{\partial \sigma} - fU = -g\frac{\partial \zeta}{\partial y} + F_y + M_y + \frac{1}{h^2}\frac{\partial}{\partial \sigma}(\nu_V \frac{\partial v}{\partial \sigma}) \tag{3}$$

Here ν_V is the vertical eddy viscosity coefficient. The value of it is calculated using a Delft3D linked turbulence model. In this research, k-epsilon will be used.

Here F_x and F_y are the components of the horizontal friction coefficient which have the following definitions:

$$F_x = \nu_H(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}) \qquad F_y = \nu_H(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2})$$

Here ν_H is the horizontal eddy viscosity coefficient. The last things which are not yet defined in the horizontal momentum equations are M_x and M_y. These are the components of the wave forces. These components are computed out of the output generated by the linked wave model of Delft3D-FLOW, Delft3D-WAVES.

The continuity equation reads:

$$\frac{\partial h}{\partial t} + \frac{\partial [hU]}{\partial x} + \frac{\partial [hV]}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0 \tag{4}$$

For the waves the following equation will be solved:

$$\vec{M} = \frac{D}{\omega}\vec{k} \tag{5}$$

Here $\vec{M}$ is the forcing due to radiation stress gradients (N/m^2), D is the dissipation due to wave breaking (W/m^2), ω is the angular frequency (rad/s) and $\vec{k}$ is the wavenumber vector (rad/m).

Next, boundary conditions are specified. At the bottom and the free surface, the kinematic conditions are respectively:

$$\omega(-1) = 0 \qquad \omega(0) = 0$$

Furthermore, at the bottom dynamic boundary conditions are imposed::

$$\frac{\nu_V}{h}\frac{\partial u}{\partial \sigma}\bigg|_{\sigma=-1} = \frac{\tau_{bx}}{\rho} \qquad \frac{\nu_V}{h}\frac{\partial v}{\partial \sigma}\bigg|_{\sigma=-1} = \frac{\tau_{by}}{\rho}$$

Here τ_{bx} and τ_{by} are wave-averaged bed shear stresses excerpted by in the x- and y-direction, which contain contributions due to currents and waves.
At the free surface boundary conditions are:

$$\frac{\nu_V}{h}\frac{\partial u}{\partial \sigma}\bigg|_{\sigma=0} = \frac{\tau_{wx}}{\rho} \qquad \frac{\nu_V}{h}\frac{\partial v}{\partial \sigma}\bigg|_{\sigma=0} = \frac{\tau_{wy}}{\rho}$$

Some more boundary conditions apply to the open and closed (coast) boundaries.
At open boundaries tides and waves. These will be mentioned in Section *3.2 Model configuration* because it is a model setting specific for this research.
For the closed boundary, the following boundary condition holds: free slip (=dynamic) and no normal flow (=kinematic).

3 Methodology

This chapter describes the study area, the model configuration, the experiments that were conducted to address the objectives and methodology to analyse the model output.

3.1 Study Area

The Vlie tidal inlet was chosen as a study area. This inlet is located between the Wadden Islands Vlieland and Terschelling, see Figure 5[7]. The bathymetry depicted in Figure 5 will be converted into the tidal inlet, which will be schematised sea-inlet-bay system. The coastlines will be straight and a rectangular basin will be the back-barrier basin, see Figure 6.
In real life, this means a tidal inlet system with a size of roughly 60 x 50 kilometers and a depth of 45 meters. The open sea is, in this case, is roughly 60 x 27 kilometers, the tidal basin is 14 x 20 kilometers.

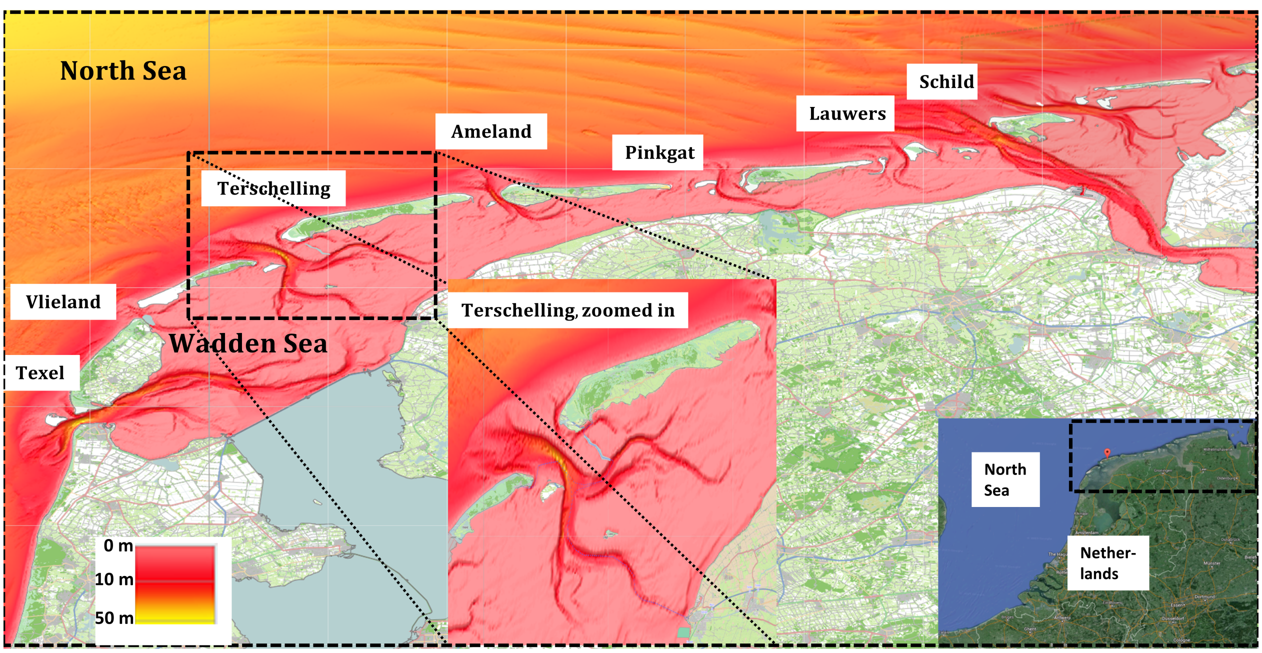


Figure 5: A map of the Dutch Wadden Sea with the tidal inlet between Vlieland and Terschelling exposed as the area to study. The colour bar at the bottom left side indicates the bathymetry of this region.

[7]Source: Emodnet bathymetry data portal http://portal.emodnet-bathymetry.eu/

The water motion in this domain is forced by tidal elevations at the open boundaries (red lines in Figure 6) and incoming sea waves. Characteristics of tides, waves, the wind will be representative for the Vlie inlet (and retrieved from field data and output of a large scale tidal model of the North Sea).

3.2 Model configuration

The dimensions of the model, which is used to represent the Vlie tidal inlet, are 296 by 229 grid cells with 1 or 10 layers depending on the nature of the experiment, see Figure 6. For every grid point, the hydrodynamic equations will be solved and the outcomes like the velocities will be saved at that grid point. If 10 layers are used in the experiment, the percentage per layer covering the depth of the grid cell, the layer thickness, is recommended in the *Delft3D FLOW User Manual*[8].

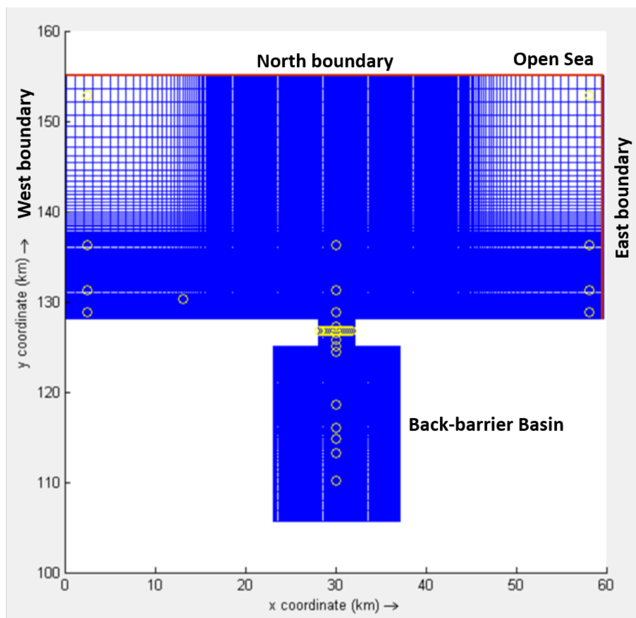


Figure 6: The grid of the physical domain used in the mode Delft3D FLOW. The red lines indicate boundaries where specific conditions are set.

The total running time of the simulations will be 16 days. The time step is 2 min for solving those hydrodynamic equations and the reference date is 31-12-2018, the night when the disaster of MSC Zoe happened. Every half an hour the solutions of the equations will be saved. Further two computational grids were used. One is used for Delft3D FLOW and the other for Delft3D WAVES, with the one for FLOW as mentioned before (Figure 6).
The grid used for Delft3D WAVES is slightly different because the swell (waves) needs to be generated outside of the experiment domain. In this grid there are 90 by 58 grid cells, see Figure 7.

[8]https://oss.deltares.nl/nl/web/delft3d/manuals

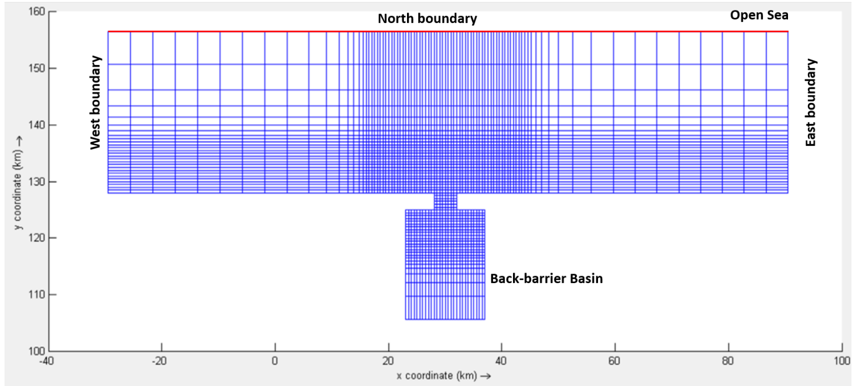


Figure 7: The wave grid used in the simulations where the mode Delft3D WAVES is used. The red line indicates a boundary where certain conditions are set.

An overview of the model parameters is presented in Table 1.

Parameters	Value
Latitude	53°
Gravity	9.81 m/s^2
Water density	1024 kg/m^3
Air density	1 kg/m^3
Wind drag coefficient	0.00723
Horizontal eddy viscosity	1 m^2/s
Horizontal eddy diffusivity	1 m^2/s
Significant wave height	2 m
Peak period waves	5.75 s
Nautical direction waves	335°
Directional spreading waves	4°

Table 1: Overview of the model parameters in Delft3D

The bathymetry seaward of the tidal inlet is schematised as in Figure 8. In this case, there is made use of exponential bathymetry for the coast/open sea part and the tidal inlet it is a result from a model output like in Ridderinkhof et al. (2014).

Next the different forcings used in the simulations which can be seen depicted in Figure 8 will be discussed: tidal, waves (swell) and wind.
When wind forcing is enabled for a simulation, the strength of the wind will be 4 m/s. There are two options here for the direction, namely wind from the west or wind from the north. This is displayed in Figure 8. The default setting for wind will be off.
Regarding tidal motion, it is forced by imposing free surface elevations at the open boundaries of the domain. Free surface elevations are such that they represent a tidal wave that

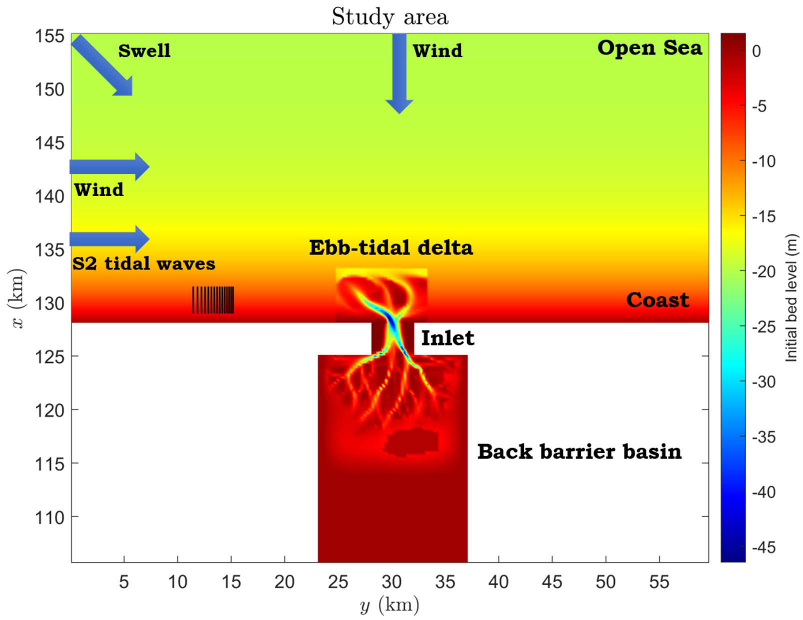


Figure 8: The bathymetry of the modelled system. The colours indicate the bathymetry. Black dots indicate the initial release location of the particles. Arrows represent the different kind of forcings used with their direction in this research.

propagates from east to west. At the western and eastern boundaries Neumann conditions are imposed. The amplitude and phase on the western boundary are 9.7924×10^{-6} and 65°. The amplitude and phase on the eastern are 9.7924×10^{-6} and 102°. More specifics on this can be found in the *Appendix A*. The default setting for tides will be on.
Waves are imposed at the seaward boundary, see Table 1 for the specifics. The default setting for waves will be off. One setting that makes a difference when the wave setting is turned on is stokes drift. The only thing that needs to be done so that this setting is on, is the put a certain line in the *mdf-file*, the file which is used in the Delft3D FLOW mode. This line is $SMvelo = glm$. See Section 2 *Theory* for more information about stokes drift. Stokes drift velocity will now be referenced as GLM from now on. The default setting for GLM will be on.

An important part of the model experiments that were conduced for this research will be the settings for the plastic particles.

The mode FLOW of Delft3D has the function of adding particles into the simulation. The number of particles used is 300, which will be released on the grid cells 15.5-29.5 by 129.5-148.5 with equal spacing between them (see Figure 8). In this case, the plastic particles are called drogues in Delft3D. Drogues are floats that move with the flow. Drogues are only transported due to the velocities in the surface layers (see

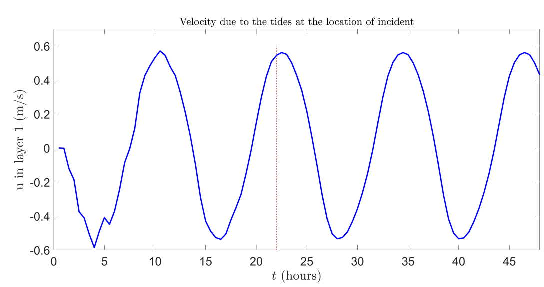


Figure 9: The x-component of the velocity (direction of the tides) in the surface layer of the default case. Reference time of 00:00 at 31/12/2018. The red striped line indicates 22 hours, the release time of the particles, which corresponds to the flood phase.

Delft3D FLOW User Manual[9]). These particles will be released 22 hours after the simulation starts (see Figure 9) so that these particles are set loose during the flood time and the simulation so has enough time to generate reasonable tides and waves.

3.3 Experiments

In this research, nine simulations will be used to answer the objectives earlier mentioned in the *Introduction*, which will be computed by Delft3D. The first simulation will be a default case. This case will be called Run1 in this thesis.
The specifics of Run1 is the same as mentioned in the subchapter *Model configuration* stated as the default setting, but now 10 layers are chosen for the vertical structure of the research domain.

The settings of the other 8 simulations are shown in Table 2.

Simulation	Number of layers	Tides	Wind (270°)	Wind (0°)	Waves	GLM
Run1	10	On	Off	Off	Off	On
Run2	1	On	Off	Off	Off	On
Run3	10	On	On	Off	Off	On
Run4	10	On	Off	On	Off	On
Run5	1	On	On	Off	Off	On
Run6	10	On	Off	Off	On	On
Run7	10	On	Off	Off	On	Off
Run8	10	On	On	Off	On	On
Run9	10	On	On	Off	On	Off

Table 2: The settings of every simulation.

Run1, Run2, Run3, Run4 and Run5 are used to answer the question of how sensitive the modelled trajectories of plastic particles are to the vertical structure of currents when tides and/or wind-driven currents are accounted for.
Run6, Run7, Run8 and Run9 are used to answer the question of what the difference will be in the spreading of the plastic particles when waves and/or wind-driven currents are accounted for and stokes drift is implemented in the output data of the simulation.

3.4 Analysis

In this subchapter, the way of analysing these 9 different simulations will be discussed in different sections. These different ways to analyse the data outputted by Delft3D will be done in MATLAB through different scripts.

[9] `https://oss.deltares.nl/nl/web/delft3d/manuals`

3.4.1 Mean location particles

This quantity will show us the mean location of the particles over time and thus also at the end of the simulation. This quantity provides an indication of the spreading of the cloud of particles. With the mean location (or mean pathway later called) it is easy to compare different simulations. The mean location can be analysed by standard deviation, see next section, and the x- and y-coordinate of the mean pathway. The latter will be only done for the default case, Run1.

3.4.2 Particle spreading

Here the dispersion of the particles will be calculated in the form of a standard deviation. This standard deviation indicates the distance of individual particles relative to the mean and shows thus a range.
Further, the number of particles inside the tidal inlet (y¡128 km) and the number of particles in the coastal area/ebb-tidal delta (y¿128 km) are calculated for each simulation. The 128 km in the y-direction is where the coast lays (see Figure 8). For the coastal area/ebb-tidal delta the number of particles is also the number of particles beached in that area. When the number of particles inside the tidal inlet reaches an equilibrium then it also means that those particles are possibly beached.

3.4.3 Residual velocities

To explain the results of the mean location and the spreading of the particles, a look at the residual velocities explained in chapter 2.5 will be taken. This is done due to the fact that the particles move with the flow, or the velocities, of the surface layer or the depth-averaged velocity. The velocities coming out of the simulations are being averaged over 3 Tidal periods (12 hours), which are then called the residual velocities of every grid point of the domain for every simulation.
The displaying of the residual velocities will be done in the research domain where per grid cell an arrow will be put. There will be for the residual velocities of Run6, Run7, Run8 and Run9 extra results (in a cross-shore direction plot) to compare these two because GLM will be an important factor there. For Run1, Run2, Run3, Run4 and Run5 the residual velocities of the surface layer of the depth-averaged velocity will be compared, so that the difference between a 3D model and a depth-averaged model can be assessed.
For the horizontal and vertical grids and their velocities, not the entire area will be shown, but a zoom at the tidal inlet. For the vertical grids (cross-shore direction) the x location will be away from the tidal inlet so only a coast situation can occur. The x-coordinate is on grid cell 87, which is at roughly 22.5 km.

4 Results

In this chapter, the results of all the simulations will be shown. First Run1 will be talked about because it is the default case for this study. Then in the other sections comparisons will be made between two or three runs for each type of scenario (3D vs. 2DH, 3D wind 270°

vs. 3D wind 0° vs. 2DH wind 270°, GLM on vs. GLM off and GLM on vs. GLM off with wind 270°). At the end of this chapter, an overview will be given for the particle spreading for every simulation. The way for analysing the different simulations is mentioned in the previous subchapter.

4.1 Default case

As mentioned before, the default case will be Run1 (see Table 2 for the specifics). Here the following results will be depicted: the mean pathway for the particles for all of the simulation time (Figure 10) and the spreading of the particles defined by certain quantities (Figure 11).

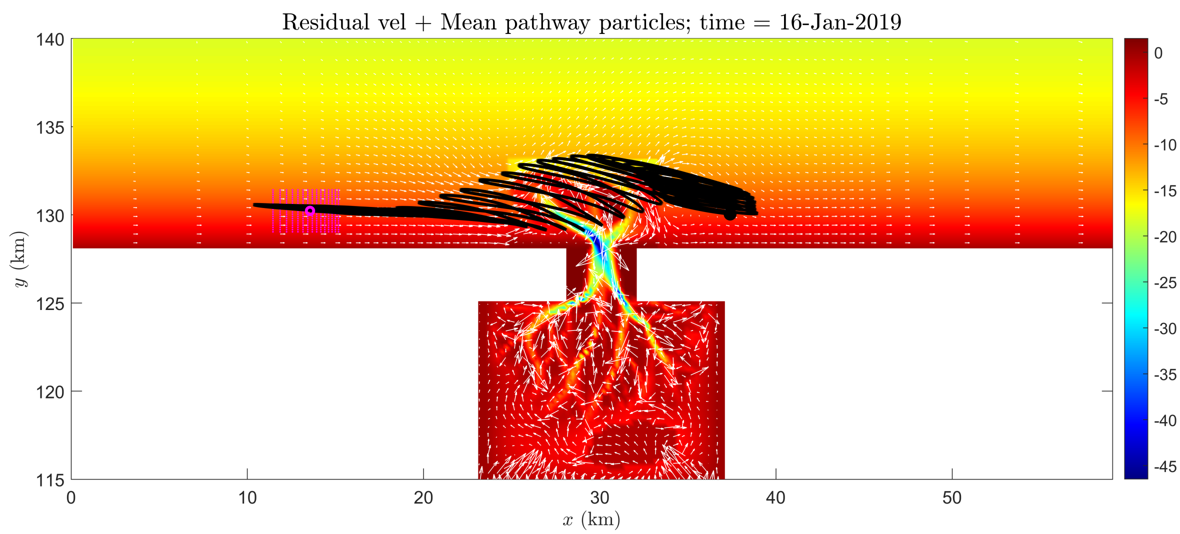


Figure 10: The mean pathway of the particles for Run1 (black line). The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The white arrows show the residual velocity (direction and relative strength) at that place. The colour bar indicates the bathymetry of the area in meters.

From Figure 10 it can be seen that the particles drift eastward and then when it reaches the ebb-tidal inlet, they will slowly drift northward all in an oscillating way. This is due to the tidal forcing. The oscillating becomes greater because of the ebb-tidal jet which ensures the particles will move larger distances. After the particle cloud passes the ebb-tidal inlet the particle cloud is way more oscillating at the same place until the simulation time is over. This is since the residual velocities after the tidal inlet are much smaller than in the tidal inlet and the ebb-tidal delta (white arrows in Figure 10).

From Figure 11 in panels a) and b) it can be seen that indeed the cloud of particles is oscillating over time, with Y_p having more variation than X_p in the oscillating when the mean reaches the ebb-tidal inlet area. This comes from the result that the residual velocities in the ebb-tidal area are way larger and more in the north-south direction than in the rest of the domain. Panel a) in Figure 11 shows a growing standard deviation, which means the cloud

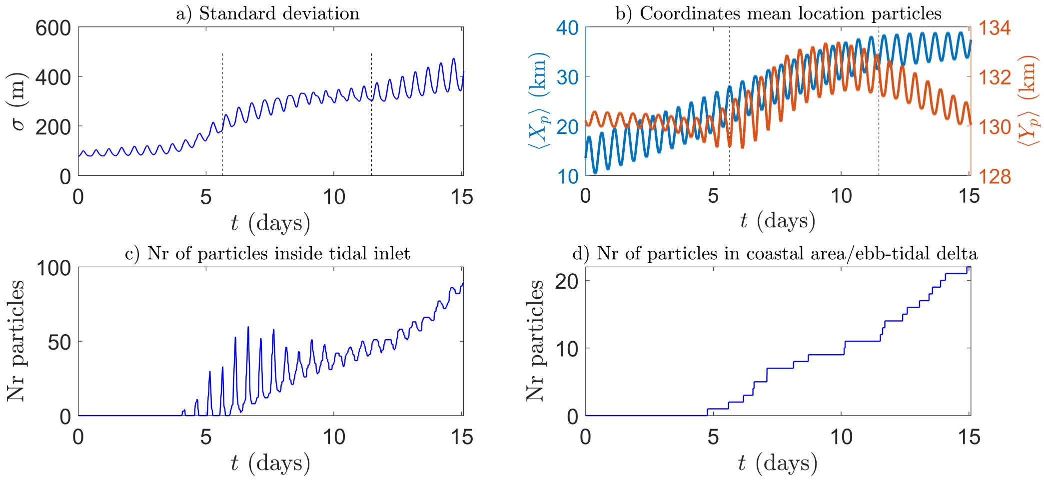


Figure 11: The spreading of the particles depicted in four different quantities as a function of time: (a) the standard deviation, in meters; (b) the x- and y-coordinate of the mean location of the particle; (c) the number of particles inside of the tidal inlet; (d) the number of particles in the coastal area and/or ebb-tidal delta. In (a) and (b) the area between the vertical dotted black lines represent the time the mean particles are in or above the tidal inlet.

of particles will grow larger and larger over time. Also seen in panel a) and b) it can be seen that the mean of the particles is trapped inside the tidal inlet for roughly 5 days (time between the two black dotted lines).

From Figure 11 in panels c) and d) it is clear that the number of particles steadily increases over time. The number of particles inside the tidal inlet oscillates while the number of particles in the coastal area/ebb-tidal delta is increasing step by step it is seen. This is due to the definition of the number of particles in coastal area/ebb-tidal delta because these numbers are the particles beached in that area! For the number of particles inside the tidal inlet, it oscillates because this quantity counts the number of particles of that time and due to the tides which are large here (big residual velocities in the north-south direction) so that is why it varies so much.

At the end of the simulation time, 89 particles (29.67% of the total number of particles) are inside the tidal inlet and 22 particles (7.33% of the total number of particles) are beached in the coastal area/ebb-tidal delta.

4.2 3D vs. 2DH

Here the results of Run1 and Run2 will be shown in the next figures. Figure 12 shows the mean pathway of the particles.

From Figure 12 it is visible that for Run1 the cloud of particles travels further east than Run2 at the same time. This can be explained in the difference in the residual velocities between Run1 and Run2, see Figure 13.

There it can be seen that especially at the north part of the ebb-tidal delta the residual velocities of Run1 are greater and more directed to the east than the residual velocities of Run2. It can be seen that the residual velocities of Run2 are larger and more directed to-

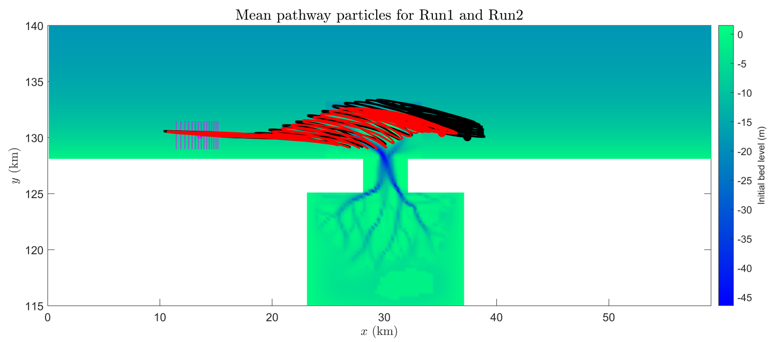


Figure 12: The mean pathways for Run1 (3D, black) and Run2 (2DH, red). The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The big black and red dot represent the end location of Run1 and Run2 respectively.

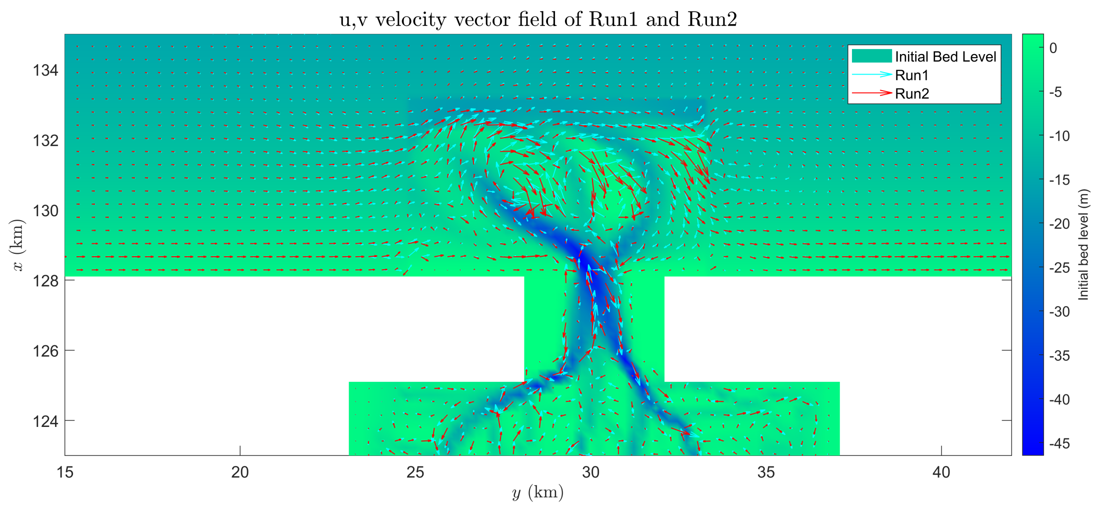
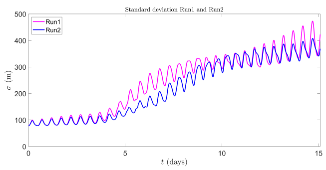


Figure 13: The residual velocities for Run1 (3D) and Run2 (2DH) in the horizontal plane.

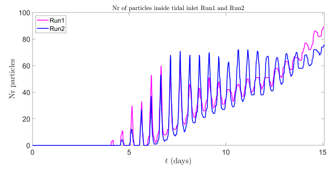
wards the tidal inlet in the ebb-tidal area and the residual velocities of Run2 inside the tidal inlet are larger and more directed towards the exit. So the particles will stay longer at the ebb-tidal delta so they oscillate there more due to the residual velocities of the tides. But these differences between Run1 and Run2 in the ebb-tidal delta and tidal inlet are not that great so the endpoints of the cloud of the particles lay close to each other.

To see even clearer the difference in the particle spreading between Run1 and Run2, a look at Figure 14 can be taken.

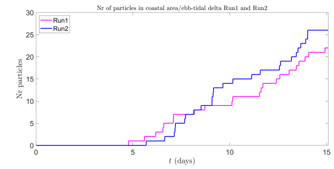
In Figure 14a it can be seen that the cloud of particles of Run1 will reach the tidal inlet earlier than Run2 since the standard deviation will be bigger earlier, which means that the cloud of particles will be more stretched out and cover a bigger area. This comes from the



(a) Standard deviation



(b) Number of particles inside the tidal inlet



(c) Number of particles in coastal area/ebb-tidal delta

Figure 14: Particle spreading defined by 3 different quantities for Run1 (3D) and Run2 (2DH).

ebb-tidal jet. Further, it can be seen that the particles of Run1 will beach earlier in the coastal area/ebb-tidal delta and also will earlier arrive in the tidal inlet, see Figure 14c and 14b. The difference between panel b) and c) for the form of the graphs have the same origin explained as in the previous section.
At the end of the simulation time, for Run1 there will be 89 particles inside the tidal inlet, which is 29.67% of the total number of particles. For Run2 that will be 76 particles, so 25.33% of the total number of particles. (see Figure 14b)
For Run1 22 particles beached in the coastal area/ebb-tidal delta, which is 7.33% of the total number of particles. For Run2 26 particles beached, which is 8.67% of the total number of particles. (see Figure 14c)

So for a 3D simulation under influence of only tides 111 particles can potentially beach, which is 37% of the total number of particles. This is higher than for a 2DH simulation under influence of only tides where 102 particles can potentially beach, which is 34% of the total number of particles.

4.3 3D wind 270° vs. 3D wind 0° vs. 2DH wind 270°

Here the results of Run3, Run4 and Run5 will be shown, where direct comparisons between Run3 and Run5 and Run3 and Run4 will be made.

First a comparison between Run3 (3D, wind 270°) and Run5 (2DH, wind 270°) will be made for the mean pathway of the particles, see Figure 15.

Here the same difference happens as in the subchapter before, only now the influence of wind of 4 m/s can be seen. The cloud of particles will almost reach the east end of the domain at the end of the simulation time with Run3 just ahead of Run5. It can also be seen that the oscillation frequency becomes less when the wind is enabled, but the cloud of particles will also reach down more inside the tidal inlet. The difference between Run3 and Run5 in the mean pathway is not that big, they quite follow the same pattern. This all can be explained with Figure 16.

Here it can be seen that indeed the differences between the residual velocities in direction and strength are small for Run3 and Run5. This is due to the wind, which has a great influence on the residual velocities at the surface, where the particle spreading happens. At the north and east part of the ebb-tidal delta, it can be seen that Run3 has slightly larger

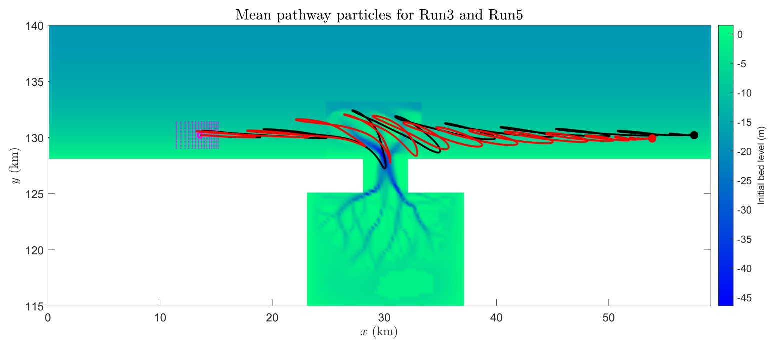


Figure 15: The mean pathways for Run3 (3D, black) and Run5 (2DH, red) with wind 270°. The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The big black and red dot represent the end location of Run3 and Run5 respectively.

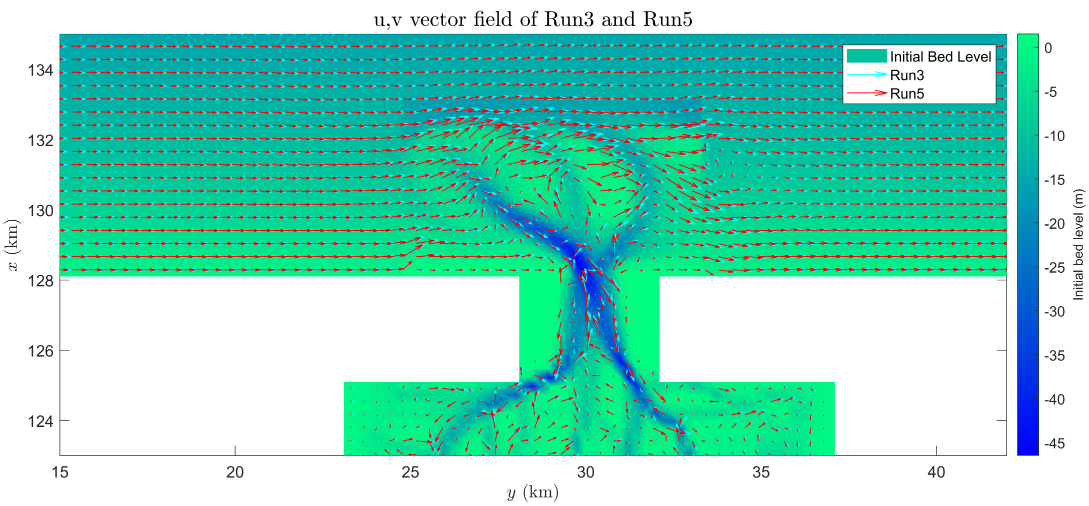


Figure 16: The residual velocities for Run3 (3D, surface layer velocity) and Run5 (2DH, depth-averaged velocity) in the horizontal plane where wind forcing from the west is also on.

residual velocities (indicating larger arrows in 16).

Now a comparison between Run3(3D, wind 270°) and Run4 (3D, wind 0°) will be made for the mean pathway of the particles, see Figure 17.

Here the difference of the cloud of particles where a wind from the north or northwest can be seen. It takes for Run4 all of the simulation time for the cloud of particles to even arrive at the ebb-tidal delta, whereas Run5 is at the east end of the domain. It looks for Run4 that the particles are trapped between the coast and the north boundary of roughly 131 km. Maybe a look at the residual velocities will explain this behaviour, see Figure 18.

Overall it can be seen that the residual velocities for Run3 are greater (bigger arrow) than

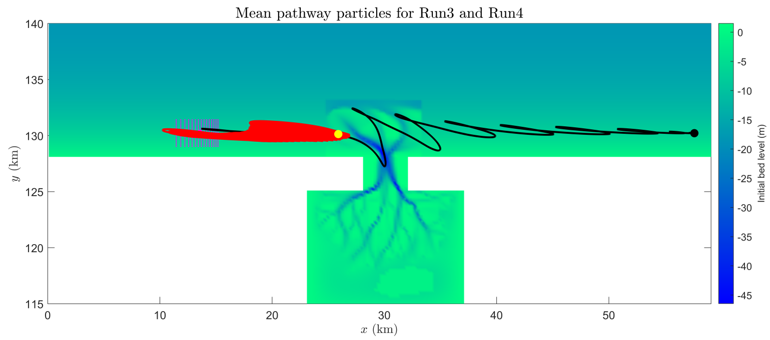


Figure 17: The mean pathways for Run3 (wind 270°, black) and Run4 (wind 0°, red). The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The big black and the yellow dot represent the end location of Run3 and Run4 respectively.

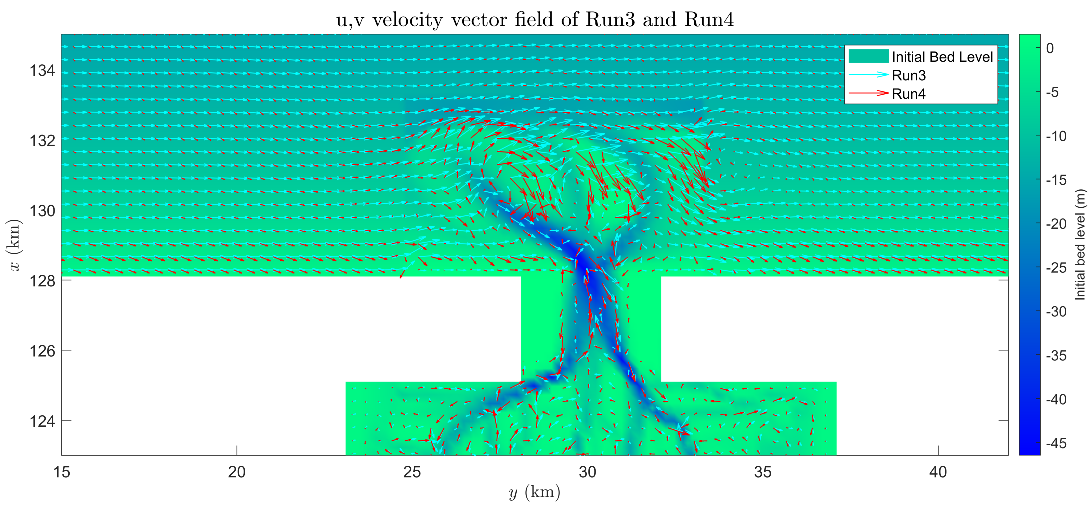
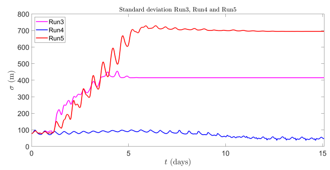


Figure 18: The residual velocities for Run3 (wind from the north) and Run4 (wind from the west) in the horizontal plane.

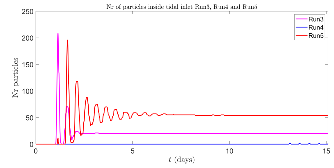
Run4 outside the tidal inlet and ebb-tidal delta. Further away from the coast the residual velocities of Run4 are small and the direction is not that clear to see, it looks towards the south with a very small strength but mostly in the eastward direction. This means that far from the coast the tides are more of an influence in this case at 134 km. Near the coast however you can see that the direction of the residual velocities is clearly towards the coast, thus southward.

To see the difference in the particle spreading between Run3, Run4 and Run5, a look at Figure 19 can be taken.

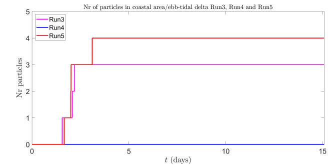
In Figure 19a it can be seen that for Run4 the stretching of the cloud of particles stays



(a) Standard deviation



(b) Number of particles inside the tidal inlet



(c) Number of particles in coastal area/ebb-tidal delta

Figure 19: Particle spreading defined by 3 different quantities for Run3 (3D, wind 270°), Run4 (3D, wind 0° and Run5 (2DH, wind 270°)

small, so the cluster of particles more or less stays the same. This is because the particles do not reach the tidal inlet yet. The dispersion of Run3 and Run5 on the other hand does become greater over time, where eventually for both simulations an equilibrium is reached. Further Run5 has a bigger dispersion than Run3. That the difference between dispersion is so clear probably occurs due to the wind and that the particles of Run5 are longer in the tidal inlet area so the cloud of particles can be longer more stretched out with each tidal cycle. This is also visible in Figure 19b because for Run5 the number of particles inside the tidal inlet will be largest, but actually, the particles of Run3 arrive just a little bit earlier at the tidal inlet. Eventually, for Run3 and Run5 an equilibrium will be reached, which means a high chance that the particles inside the tidal inlet are beached there. Also, the first beached particle in the coastal area/ebb-tidal delta occurs for Run3, but eventually, Run5 has the most particles beached. For Run4 it becomes clear that no particles arrive in the tidal inlet (barely) or beach in the coastal area/ebb-tidal area, see Figure 19b and 19c.

At the end of the simulation time, for Run3 there will be 20 particles inside the tidal inlet, which is 6.67% of the total number of particles. For Run4 there will be 1 particle, which is 0.33% of the total number of particles. For Run5 there will be 54 particles, which is 18% of the total number of particles.
For Run3 3 particles beached in the coastal area/ebb-tidal delta, which is 1.00% of the total number of particles. For Run4 0 particles beached. For Run5 4 particles beached, which is 1.33% of the total number of particles.

Thus for a 2DH simulation under influence from tides and wind from the west 58 particles can potentially beach, which is 19.33% of the total number of particles. This is higher than for a 3D simulation under the influence of tides and wind from the west where 23 particles can potentially beach, which is 7.67% of the total number of particles. The lowest number of potentially beached particles comes from Run4, which is 1 (0.33%).

4.4 GLM on vs. GLM off

Here the results of Run6 and Run7 will be shown for the mean pathway of the particles, see Figure 20.

It seems like only Run7 is plotted in Figure 22, but that is not the case. Run6 and Run7 give the same result. Further, the mean pathway shows an oscillating motion towards the

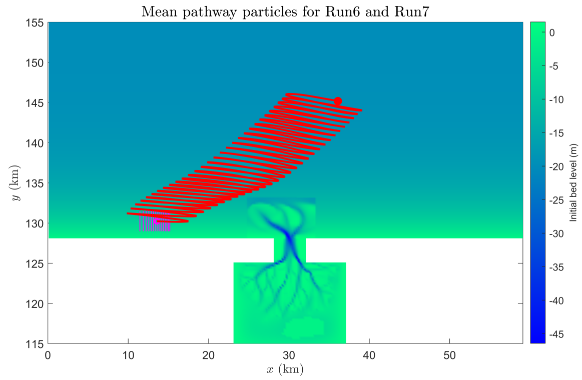


Figure 20: The mean pathways for Run6 (GLM on, black) and Run7 (GLM off, red) with wave forcing. The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The big black and the red dot represent the end location of Run6 and Run7 respectively.

northeast. To see if the residual velocities do differ between Run6 and Run7, a closer look at Figures 21 and 22 can be taken.

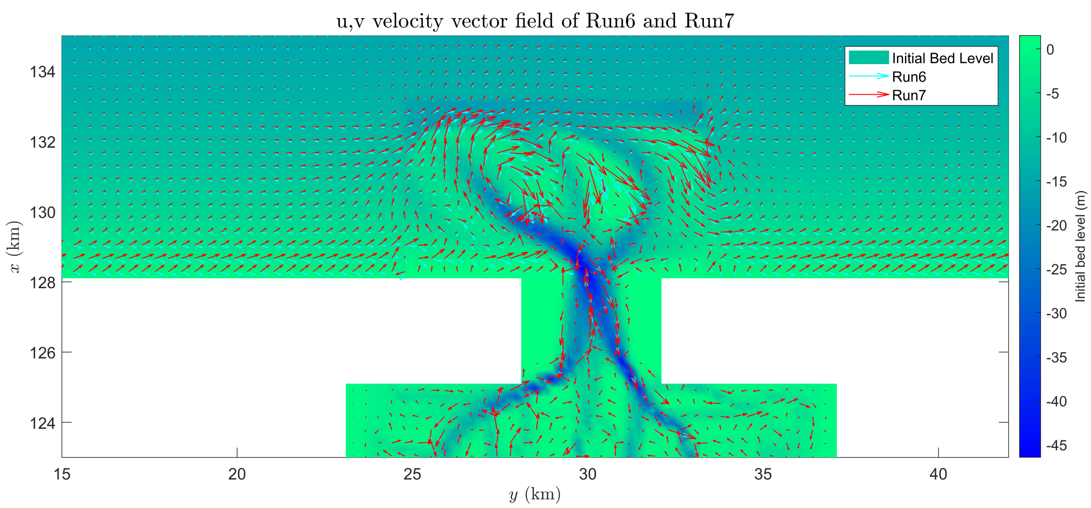


Figure 21: The residual velocities for Run6 (GLM on) and Run7 (GLM off) in the horizontal plane where wave forcing are on.

Immediately it is clear to see that the residual velocities are not the same, in the x,y-grid and they,z-grid. For the x,y-grid the difference in strength and direction of the residual velocities can be best seen near the coast, there is the difference largest. In the tidal inlet, the difference in strength and direction becomes small.
This would mean you have to see a difference in the spreading of the particles, so the mean pathway for both simulation should also differ. The implication of this result will be later addressed in the discussion section.

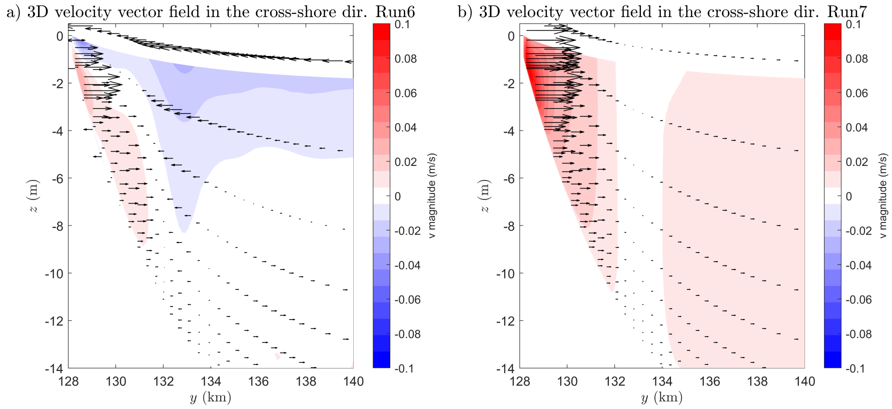
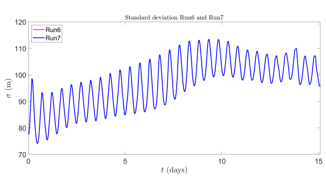


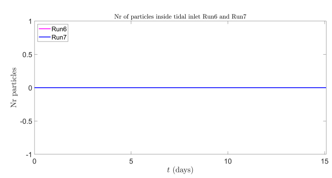
Figure 22: The residual velocities for a) Run6 (GLM on) and b) Run7 (GLM off) in the vertical plane with the cross-shore velocity v as a contour. Wave forcing is also on.

One more thing to notice is the circulation pattern that occurs in panel a) of Figure 22. This means an onshore flow at the surface and an offshore flow at the bottom (undertow). From this figure it is also visible that the velocities of Run7 (panel a)) are way more offshore (positive v) than Run6 (panel b)), where we only have offshore velocities in the deeper layers. In the surface layer and offshore of the coast over deeper layers, it can be seen that the velocities of Run6 are negative and thus towards the coast.

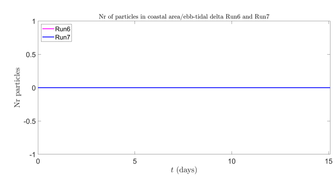
Also for the spreading of the particles, Run6 and Run7 give the same results, which can be seen in Figure 23.



(a) Standard deviation



(b) Number of particles inside the tidal inlet



(c) Number of particles in coastal area/ebb-tidal delta

Figure 23: Particle spreading defined by 3 different quantities for Run6 (GLM on) and Run7 (GLM off)

It becomes clear that no particles reach the tidal inlet and no particles beached at the coastal area/ebb-tidal delta.

4.5 GLM on vs. GLM off with wind 270°

Here the results of Run8 and Run9 will be shown where wind forcing will be on in the eastward direction. The same problem occurs for Run8 and Run9 as in Run6 and Run7, which can be seen in Figure 24 and Figure 25. This problem also will be more addressed in the discussion section.

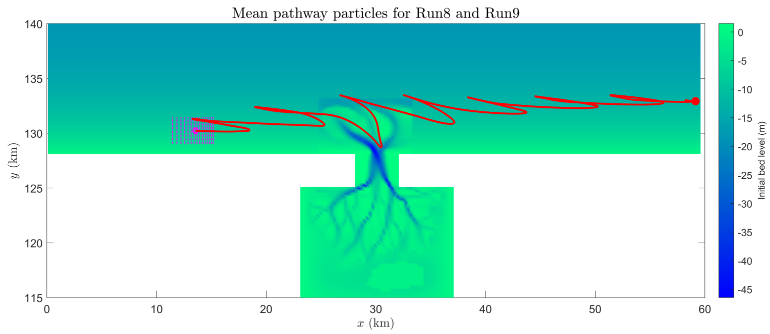
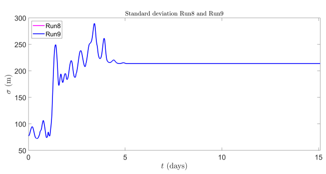
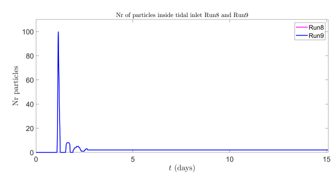


Figure 24: The mean pathways for Run8 (GLM on, black) and Run9 (GLM off, red) with wave forcing. The pink dots indicate the release location of each particle and the bigger pink circle indicates the mean of the particles at release. The big black and red dot represent the end location of Run8 and Run9 respectively.

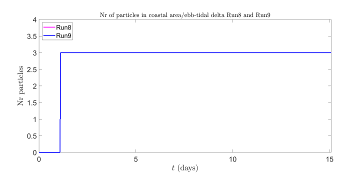
The same oscillating pattern due to tides and wind can be seen in Figure 24. Here it looks that the contribution of wind and tides masks the contribution of the waves.



(a) Standard deviation



(b) Number of particles inside the tidal inlet



(c) Number of particles in coastal area/ebb-tidal delta

Figure 25: Particle spreading defined by 3 different quantities for Run8 (GLM on) and Run9 (GLM off) with wind forcing 270°

Nevertheless, for Run6 and Run7 few particles are inside the tidal inlet (2 particles, 0.67% of the total) and there are a few particles that even beach at the coastal area/ebb-tidal delta (3 particles, 1.00% of the total), see Figure 25 This is probably due to the wind influence in this case, which is larger influence than the waves.

Looking at the residual velocities (Figure 26 and 27), there should be a difference expected between Run8 and Run9 in the particle spreading.

In Figure 26 it is visible that near the coast, in the ebb-tidal delta and even in the tidal inlet and basin the differences between Run8 and Run9 are large. Especially near the coast, the direction differs much, Run8 is directed to the coast and Run9 away from the coast. Further off the coast, the differences in velocities become small. The direction outside of the tidal inlet is mostly to the east, which confirms the direction the cloud of particles has taken.

In Figure 27 the same circulation pattern happens in panel a) as for Run6 earlier. From Figure 27 the difference between off- and onshore flow is only confirmed looking at the surface flow. In Figure 27 panel b) there are only positive cross-shore velocities overall depth. In panel a) there are negative velocities near the surface but further down the velocities become

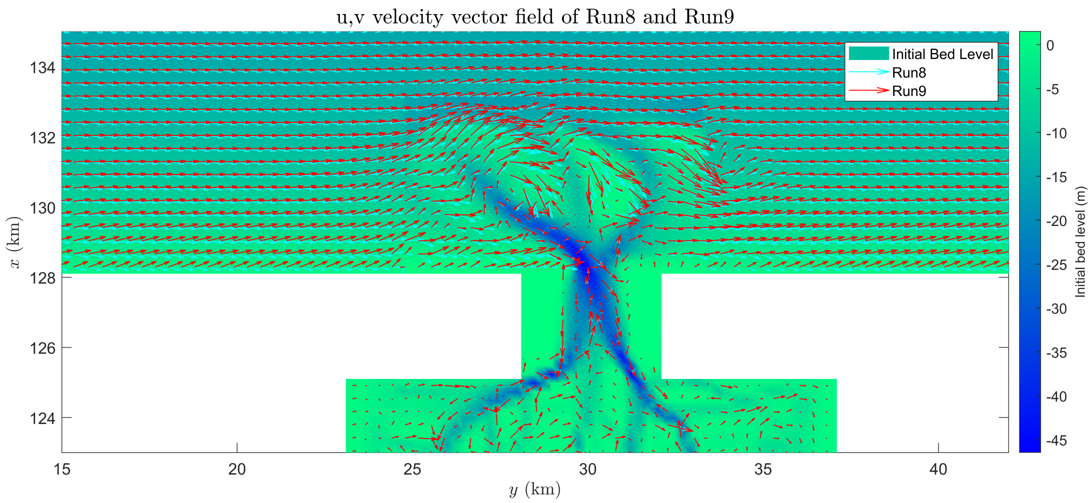


Figure 26: The residual velocities for Run8 (GLM on) and Run9 (GLM off) in the horizontal plane where wave forcing and wind forcing from the west is on.

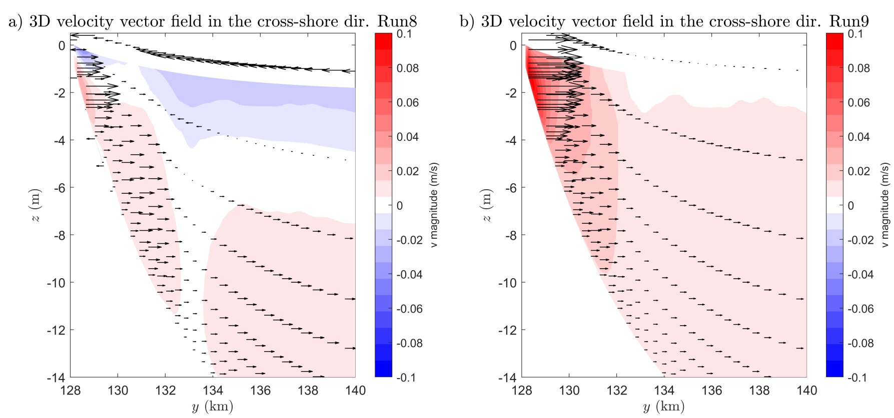


Figure 27: The residual velocities for Run8 (GLM on) and Run9 (GLM off) in the vertical plane with the cross-shore velocity v as a contour. Wave forcing and wind forcing from the west is also on.

positive. Looking at the arrows shown in Figure 27, the strength of the velocities for Run9 is much larger than for Run8.

4.6 Summary

Here is an overview of the results of the particle spreading, see Table 3.

Some findings of these results will be discussed in the next section.

Simulation	Tidal inlet nr.	Percentage %	Coastal area/ebb-tidal delta nr.	Percentage %
Run1	89	29.67	22	7.33
Run2	76	25.33	26	8.67
Run3	20	6.67	3	1.00
Run4	1	0.33	0	0
Run5	54	18.00	4	1.33
Run6	0	0	0	0
Run7	0	0	0	0
Run8	2	0.67	3	1.00
Run9	2	0.67	3	1.00

Table 3: Overview of the results regarding particle spreading in terms of the number of particles inside the tidal inlet and the number of particles in coastal area/ebb-tidal delta with their respective percentages of the total number of particles for every simulation.

5 Discussion

This chapter describes highlights, particle spreading for 3D simulations vs. 2DH simulations, current velocities vs. Generalised Lagrangian Mean, Limitations and Future Research in the following subchapters.

5.1 Highlights

Looking back at Table 3, the most interesting thing to notice is the fact that Run6 and Run7 give the same results for the particle spreading. The same holds for Run8 and Run9. This will be further discussed in the subchapter *Current velocities vs. Generalised Lagrangian Mean.*

Next, the differences in particle spreading for Run1 and Run2 are interesting to notice, because this will lead to an answer for one of the objectives of this Thesis. Namely what the difference is between a 3D simulation and a depth-averaged simulation. The results of Run3 and Run5 will further support the differences, only it is a slightly different circumstance (wind forcing is on). This will be further discussed in the subchapter *Particle Spreading 3D vs. 2DH.*

The last highlight is for Run4, the 3D simulation with wind from the north. Here it is interesting to see that due to the wind the majority of the particles (the particle cloud) will not reach the tidal inlet by the end of the simulation time. Only 1 particle is in the tidal inlet at the end time. So to make further conclusions from these simulations, a longer simulation time is needed. It would be interesting to see what the influence of the wind is when the cloud of particles reaches the tidal inlet, will they be more trapped in the tidal basin eventually? Now nothing can be concluded for sure.

5.2 Particle Spreading 3D vs. 2DH

In this subchapter, the differences between 3D simulations and 2DH simulations will be highlighted. Also, a look for an explanation for these results will be taken.

Looking back at Table 3, for a 3D simulation, the total number of possibly beached particles is higher than for a 2DH simulation. But when the wind is forced from the west the opposite occurs. How can this be explained?
The residual velocities play a part in that explanation because the particles follow the flow on the surface, which the residual velocities represent. It is expected that there would be a difference between the depth-averaged flow and the surface layer flow because of the way of solving the velocities here. It looks like for a 3D simulation, at the north part of the ebb-tidal inlet, the residual velocities are greater and more directed towards the east (see Figure 13). The same thing happens but then amplified for a 3D simulation with wind from the west (see Figure 16).
The other part of the explanation will be the simulation time. When there is no wind from the west, for the 3D simulation and the 2DH simulation the majority of the particles (particle cloud) just left the tidal inlet, while wind enabled the majority of the particles to reach the end of the eastern boundary of the domain (see Figures 12 and 15). So for the simulations where there is no wind, the particles can move in and out of the tidal inlet still and thus change the result for the particle spreading. The simulation time must be 40 days for the cloud of particles to reach the end of the domain (van Hee and Pauw, 2020).
Thus to conclude the possibly beached particles for the 3D and 2DH simulation without wind, there first has to be a longer simulation time so that the majority of the particles has reached the end of the domain. So for the simulations with wind, it seems like the conclusion is that more possibly beached particles there are for a 2DH simulation than a 3D simulation.

To make a last remark on the 3D versus 2DH simulation, a look at the difference between particles inside the tidal inlet and particles beached in the coastal area/ebb-tidal delta. For all the simulations regarding this scenario (Run1, Run2, Run3 and Run5) more particles are at the tidal inlet than in the other region, which means more particles can move to the back-barrier basin and thus drift towards the mainland, where a lot of particles arrived from the MSC Zoe event (see Figure 1a).

5.3 Current velocities vs. Generalised Lagrangian Mean

As mentioned in the previous chapter, something strange happens when a simulation is made with 10 layers and the wave forcing is on.

There is no difference between the particle spreading when *Generalised Lagrangian Mean* (GLM, the contribution of Stokes drift) is on or off and the direction of the mean of the particles is not as expected, see Figure 20. Why is this not expected? Well, the wave forcing and the tide forcing direction is from the northwest and west, respectively, whereas the direction of the particles is towards the north. Nevertheless, in Figure 22 it can be seen in panel b) that all of the residual velocities is towards the north, so that can explain why the particles follow that direction.
Looking back at the definition of the particles, the *Delft3D FLOW Manual*[10] states: Drogues

[10] `https://oss.deltares.nl/nl/web/delft3d/manuals`

are only transported due to the velocities in the surface layer. So look at Figure 21, which shows that the residual velocities of the surface layer are different for GLM on and off, therefor there should have been at least two mean pathway of the particles instead of one (see Figure 20). Now it seems that the particles only follow the residual velocities where GLM is off, so there is a flaw that Delft3D has in regards to particle (drogues) tracking. The GLM velocities are not used for the particle tracking while this is most important, because those velocities represent better flows in the presence of surface waves. As can be seen from Figure 22, there are clear flow circulation patterns, with the onshore directed flow at the surface (Stokes drift) and offshore directed flow at the bottom (undertow). Delft3D implements particle tracking based on Eulerian flow and not on mass transport flow (Eulerian + Stokes drift). This works only in the absence of waves!
When the wind is switched on, particles seem to properly follow the wind-induced surface currents (from west to east), despite the presence of waves, which tend to advert the particles in the offshore direction (see Figures 24 and 26). The latter does not happen because the wind-induced surface currents are more dominant.

These model outcomes thus indicate that the module Drogues of Delft3D should not be used to perform particle tracking when dealing with waves. Other particle tracking models (e.g. *OceanParcels*[11]) should be considered.

5.4 Limitations

This thesis used an idealised model to gain the hydrodynamic output of the tidal inlet. Here the limitations of that model are discussed.

At first, it is fair to say that a 12-hour tidal period is used which corresponds to an S2 wave which should represent the tides in this area. The M2 wave is usually more important but it falls in a fault march (van Hee and Pauw, 2020).

Secondly, there are for the 3D simulation only 10 layers used, but this was an assumption made due to the *Delft3D FLOW User Manual*[12].

Thirdly, the beaching of the particles in the coastal area/ebb-tidal delta was assumed to be their final locations, which in real life will not happen.

Fourthly, simulation time and the actual time to model these different simulations. Like earlier mentioned in the chapter *Discussion*, to see the difference between a 3D simulation and a 2DH simulation a longer simulation time is needed. But to perform these simulations, your computer already takes a long time to model. This has to do with the 10 layers and when you start multiple simulations at the same time, these simulations can need 4 days to complete. Of course, these things can be handled by better computers and by doing multiple simulations at the same time.

[11] `https://oceanparcels.org/`
[12] `https://oss.deltares.nl/nl/web/delft3d/manuals`

Lastly, the limitation of Delft3D for using the Eulerian velocities in the module Drogues to perform particle tracking in the case waves are deployed, which was earlier mentioned, is also a big limitation.

5.5 Future research

For future research, it will be interesting to see when the hydrodynamics coming out of Delft3D are implemented in an advanced particle tracking model (like the earlier mentioned *OceanParcels*). It is also possible to let the particles loose at different layers there. And so much more analysis can be done with *OceanParcels*.

Also, it is important to notice that this thesis only investigates one tidal inlet. It would be needed for understanding the particle spreading due to disasters like the MSC Zoe event that the whole Wadden Sea is modelled. Then you can have connecting back-barrier basins for every tidal inlet in that area which could be quite interesting to see what the outcome will be for the hydrodynamics. Only the time to model this will be very high probably.

6 Conclusions

The conclusions by answering the objectives mentioned in section 1 *Introduction* are:

1. How sensitive are modelled trajectories of plastic particles to the vertical structure of currents when tides and/or wind-driven currents are accounted for?

The cloud of particles will be further east for a 3D simulation than a 2DH simulation, so they will travel slightly faster.
For a 3D simulation under influence of only tides, 111 particles can potentially beach, which is 37% of the total number of particles. This is higher than for a 2DH simulation under influence of only tides where 102 particles can potentially beach, which is 34% of the total number of particles.
For a 2DH simulation under influence from tides and wind from the west 58 particles can potentially beach, which is 19.33% of the total number of particles. This is higher than for a 3D simulation under the influence of tides and wind from the west where 23 particles can potentially beach, which is 7.67% of the total number of particles.

2. What will be the difference in the spreading of the plastic particles when waves are accounted for in a simulation (like in the situation of the MSC Zoe event) and stokes drift is implemented in the output data of the simulation?

For 3D simulations where waves are accounted for, there is no difference when Stokes Drift is implemented while using Delft3D to track particles. There are no differences when using Delft3D because it uses Eulerian flow to advert the particles rather than the mass transport flow (Eulerian + Stokes drift).

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A Appendix: Tides specifics in Delft3D

Model settings to generate a S2 tidal forcing:

- Alongshore boundary: quantity = waterlevel, forcing type = harmonic, frequency = 30 °/h, amplitude begin = 0.68571 m, phase begin = 0°, amplitude end = 0.836697 m, phase end = 42° ;
- Cross-shore eastern boundary: quantity = Neumann, forcing type = harmonic, frequency = 30°, amplitude begin = 9.7924×10^{-6}, phase begin 102°, amplitude end = 9.7924×10^{-6}, phase end = 102°;
- Cross-shore western boundary:quantity = Neumann, forcing type = harmonic, frequency = 30°, amplitude begin = 9.7924×10^{-6}, phase begin 65°, amplitude end = 9.7924×10^{-6}, phase end = 65°;

B Appendix: extra results

The residual velocities for Run3 and Run4 in the crosshore direction (y,z-grid) at location x (which is roughly 22.5 km).

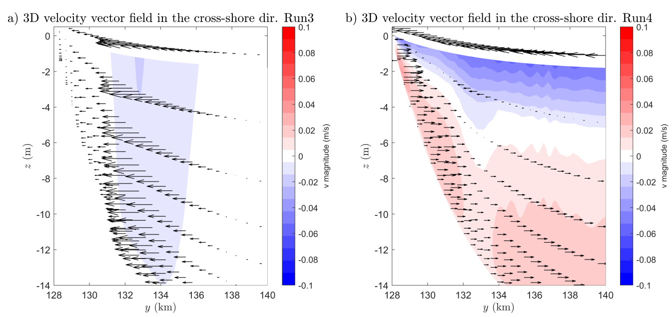

Figure 28: The residual velocities for a) Run3 (wind from the north) and b) Run4 (wind from the west), b), in the vertical plane with the cross-shore velocity v as a contour.