Modelling the transport and fate of buoyant macroplastics in coastal waters

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by

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Cover: Debris washed ashore on the beach of Schiermonnikoog after a container spill at sea

"The search for truth is on one hand painful, on the other simple. It is evident that no single individual can grasp it perfectly, but not everybody fails completely either. However, as each contributes something about nature that individually may be null or minimal, when all the contributions are compounded, a finite progress is made."

Aristotle, Book I, Chapter VII

Preface

November 2018: I am standing on a beach in Bali, Indonesia. After a night of heavy rainfall and stormy weather the beach has changed from a 'picture perfect' environment to a litter dumps site. On this day, together with my fellow team members of Pantai Project, I am doing a beach cleanup to collect data on the composition of the stranded debris. After analysing its composition it is found that over 90% of all collected items are plastics. For our research this is vital data, and confirms our hypothesis on the significance of plastic abundance in beach litter.

My experience with Pantai Project has motivated me to dive deeper into the plastic pollution issues. The understanding and modelling of plastics in the marine environment, particularly, sparked my interest. After reading many papers and discussions, I realised that this topic is still in its infancy. Motivated by the urgency to do something about the emerging plastic crisis, I wanted to focus my master thesis on this topic. Though, I realised this was going to be a 'rough ride' and this process has not always been easy. The complexity and scarcity of available data on the subject has provided a great challenge. Afterwards, when looking back on the track, I feel lucky that I have been able to graduate on a topic that kept me fascinating during the entire time I was working on it.

Acknowledgements

This thesis has been performed in collaboration with Deltares, an independent institute for applied research in the fields of water and subsurface. I am Deltares grateful for offering me this opportunity and their cooperation is hereby gratefully acknowledged. The enjoyable working environment has guided me through the graduation process with great pleasure. I would like to thank all people that showed interest in my work and for their support when needed.

I would like to take the opportunity to express special gratitude to my entire thesis committee. Their guidance throughout this research project is hereby gratefully acknowledged. First, I would like to thank Ad Reniers for chairing the committee. Your guidance has helped me to remain objective during the process. Moreover, I would like to express my gratitude to Frank Kleissen for supervising my research project at Deltares. Our mutual interest in the research topic has led to many interesting and, more than occasionally, extensive discussions, and sharing your expertise with Delft3D has been invaluable to this thesis. I would like to thank Tony Minns for supervising the project during Frank's absence and sharing the enthusiasm for research on plastic pollution. In addition, I would like to thank my other committee members. Wim Uijttewaal, thank you for your critical reflection during the meetings. Matthieu de Schipper, thank you for sharing your expertise in the field of scientific research and providing me with useful feedback.

I would also like to thank all my friends for the fun time I had during my whole study career, and distracting me from my work at the times I needed it. Last, but not least, I would like to thank my family for their unconditional support, especially in those weeks when progress was slow.

Enjoy reading!

E.J.F. van Utenhove

Delft, December 2019

SUMMARY

As a result of the unabated growth in plastic usage worldwide, their abundance in the marine environment has steadily increased over the last few decades. Nowadays, plastic litter is observed across all oceans and shores. Due to their wide spread and adverse effects on ecology, economy and potentially human health, plastic pollution has been recognized as a worldwide environmental and ecological threat. For these reasons, it is important to reduce and mitigate the abundance of plastic litter in the marine environment. As marine plastic litter predominately originates from near the coast, it is critical to study the plastic behaviour in coastal waters. However, there is considerable uncertainty regarding what factors are influencing the trajectories, distribution and deposition sites of plastic litter. Along with complex physical processes and scarcity of empirical data, there is currently little knowledge and understanding on the transport and fate of plastics in coastal waters.

With the aim of obtaining more insight into plastic behaviour, the present study intends to examine the most important processes, and quantify the effects of parameter uncertainty on modelling the transport and fate of buoyant macroplastic in coastal waters. The transport and fate of plastics is modelled by combining hydrodynamics with particle tracking concepts. For the simulations the Delft3D software Suite was used, where an Delft3D-FLOW model of the southern North Sea (ZUNO-DD) was coupled to Delft3d-PART. The model calculates how the position of plastic particles evolves in time from their release until the end of the simulation. In this study, model simulations are used as a numerical tool for exploring the relative influence of current uncertainties inherent in process parameters and data inputs on model results. A set of scenarios were defined by changing parameter values on at a time. By studying the changes in particle trajectories and shoreline deposition areas, a better understanding of their relative importance was obtained.

The modelling results imply that the effect of windage and release location are the most important parameters. Further, it is observed that dominating driving mechanisms may change with varying forcing conditions and object characteristics. Other factors such as small-scale processes and moment of release may also impact particle trajectories and fate. However, the relative influence of these processes is less significant and therefore considered less critical. Adopting the findings of this thesis into decision making policy can support emergency response operations and monitoring strategies.

The research on plastic behaviour in the coastal environment is still in its early stage, and much has yet to be revealed. Therefore, further improve understanding of buoyant macroplastic behaviour is required. Validation of the results presented in this study is limited due to the scarcity of empirical data. Thus, further research should be directed towards collecting more field data. Further, it is recommended that effort is put into parameterizing accurately the effect of windage. Moreover, numerical simulations should be expanded to a range of conditions and coastal environments so that trends can be compared and highlighted, but also allows for exploring new hypotheses.

Keywords: plastic litter, buoyant macroplastics, modelling, Delft3D, sensitivity, North Sea, coastal waters

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Introduction

1.1. Context

Since the start of the plastic industry in the 1950s worldwide production has grown exponentially up to 350 million tons per year in 2017 (PlasticEurope, 2018). Typical plastic properties such as low cost, versatility, durability and resistance to degradation make them superior to other materials in many applications. As a result, they are being used in innumerable products, applications and sectors and have become an indispensable component of modern life (Andrady and Neal, 2009). However, with these many benefits come challenges. As a result of the unabated growth in plastic usage worldwide, their abundance in the marine environment has steadily increased over the last few decades (Thompson et al., 2009b; Geyer et al., 2017). Here, they may survive for decades to centuries (Barnes et al., 2009).

Sources of marine plastic are varied and can be land based or marine (e.g. shipping vessels). The majority enters our oceans via land-based sources, dominated by river inputs (Lebreton et al., 2017). The emission of plastic waste from land into the marine environment was estimated to range between 4.8 and 12.7 million metric tons per year, and is predicted to increase by an order of magnitude by 2025 (Jambeck et al., 2015). Sea-based sources account for a smaller share of the global input, approximately 20% (Andrady, 2011). Nonetheless, activities such as fisheries and marine traffic may have a significant contribution to the abundance of marine plastic litter (Hinojosa and Thiel, 2009). Further, incidental events such as the 2011 Japanese Tsunami (Murray et al., 2018) or container spills at sea are an important source for marine debris.

Once plastics reach the marine environment they are distributed by various mechanism, including winds and ocean currents. Due to their buoyant character plastics can be transported over large distances and are globally distributed across all oceans and shores (Ryan, 2015a). Nowadays, plastic litter is even observed in the Arctic and Antarctic waters (Bergmann et al., 2016; Barnes et al., 2010) and remote island beaches (Duhec et al., 2015). From their release point, buoyant plastics may wash ashore or find their way to the open ocean, see

(a) Floating plastics at the ocean surface (McCormack, 2019) (b) Accumulating of plastic litter at the shoreline (Thompson, 2015)

Figure 1.1: Plastic accumulation in the marine environment

Figure 1.1.

Plastics compromise the majority of marine debris (Cózar et al., 2014). Their abundance in the marine environment is of particular concern since they impose negative impacts on ecology, economy and potentially human health. Impacts include the aesthetic degradation of the environment, entanglements or ingestion by marine organisms (see Figure 1.2), and human consumption of marine debris through seafood (Derraik, 2002; Thompson et al., 2009a; Cole et al., 2011; Van Cauwenberghe and Janssen, 2014; Gall and Thompson, 2015). For these reasons, marine plastic pollution has been recognized as a worldwide environmental and ecological threat, similarly to other issues such as climate change, ocean acidification and biodiversity loss (Sutherland et al., 2010; UNEP, 2014; G7, 2015). However, while the global plastic production continues unabated, so does the amount of marine plastic litter. Projections show that, if current trends continue, by 2050 the ocean will contain more tonnes of plastic than fish (Ellen MacArthur Foundation, 2016).

(a) Ingestion of plastics by birds (Jordan, 2009)

(b) Marine life entangled in plastic litter (Chiba et al., 2018)

Figure 1.2: Effects of plastic pollution on marine ecology

1.2. PROBLEM DEFINITION

There is a clear need to reduce and mitigate the abundance of plastic litter in the marine environment. To plan effective mitigation strategies and emergency response operations, it is vital to have advance knowledge on the factors influencing plastic distribution in the marine environment. Important questions regarding the release of plastic materials in the natural environment are: *'How does it spread?'* and *'Where does it accumulate?'* and particularly near sensitive ecosystems: *'What is the impact on ecosystems?'*. Answering these questions give policy and decision-makers critical guidance in how to best protect the environment, clean-up and identifying locations where mitigation strategies and monitoring are most efficient. This requires the identification of input pathways as well as knowledge and understanding of trajectories and deposition sites of plastic litter in the marine environment (Vegter et al., 2014; Veiga et al., 2016). However, this is a complex problem and much is still unknown about the behaviour of plastics in the marine environment (Ryan et al., 2009; Galgani et al., 2013).

Observations of the source, pathways, distributions and composition of marine plastics are sparse and inaccurate (Maximenko et al., 2019). Gathering of direct observational data is challenging given the vastness and complexity of the ocean. This is further hampered by the great variety of litter sources and large heterogeneity of plastic litter. Furthermore, consistent monitoring is costly and time consuming (Galgani et al., 2013). As a result there is a great scarcity of empirical data, limiting our knowledge on plastic behaviour.

Given these challenges and limitations, the use of numerical models can be a promising approach to gain better insights on the dynamics of plastic litter (Hardesty et al., 2017). Numerical simulation can be useful in extending the existing sparse observations, allowing to improve our understanding on the likely fate of debris from known sources or acute incidents such as tsunamis and container spills. Alternatively, models may be used in 'backward mode' to identify potential sources of debris from known deposition sites.

Most of the currently existing modelling studies are restricted to the distribution on global scale. These studies focused on the large scale features of surface plastic accumulation in subtropical gyres, where they are forming so-called 'garbage patches' (Kako et al., 2011; Lebreton et al., 2012; Maximenko et al., 2012; Cózar et al., 2014). Compared to the open ocean, coastal waters have received comparatively little attention to date. Since coastal and riverine input have been recognized as dominant sources, though, it is critical to study the plastic dispersion in coastal waters. Furthermore, field surveys and modelling studies have shown that most of the plastic released into the marine environment may stay near the coastline for many years or even decades (e.g. Lebreton et al., 2012), and that the shoreline might be a major sink in the plastic mass budget. Yet, the coastal region is characterized by complex physical processes often dominated by small scale features. Therefore, simulations are much more complicated and must take into account a large number of effects. For example, drifter experiments by Meyerjürgens et al. (2019) showed that the dispersion of floating litter in coastal waters may be highly variable and depending on local conditions.

Models require exact information on the environmental conditions such as winds, currents and turbulence for the accurate simulation of plastic movements. In practice this information is often not accurately known, therefore imposing uncertainties to model results. In addition, uncertainties arise with the paramterization of physical processes, often being based on simple empirical relations or rough estimates. Although some efforts are being made to establish better understanding on the behaviour of plastics in coastal waters (e.g. Critchell and Lambrechts, 2016; Isobe et al., 2014; Zhang, 2017), much is still unknown about the important processes. The aforementioned problems lead to the following problem statement:

> ***"In order to combat marine plastic pollution it is essential to improve current knowledge on the transport and fate of plastics in coastal waters. Insights into the sources, pathways and fate are important, yet, notoriously difficult to measure. To improve this, numerical modelling can be a promising tool. Accurate predictions, however, are hampered by both the complexity of the processes and uncertainty inherent in data inputs."***

1.3. RESEARCH OBJECTIVE AND QUESTIONS

The characteristics of plastic behaviour in coastal waters may be determined by a large number of effects, which in turn are driven by the physical properties of the object. Together with model parameters and assumptions, these processes determine the capability of predicting plastic transport and fate in the marine environment. Gaining more insight in these topics requires research on the drift and dispersion of plastics. As exact parameter values are often unknown it is desirable to study the influence of different parameter values on model results. This allows to gain more insight in the sensitivities of the various processes, which will improve emergency response operations and monitoring strategies, and to orient future research. This leads to the following research objective:

> ***"To examine the most important processes, and quantify the effects of parameter uncertainty on transport and fate modelling of buoyant macroplastic in coastal waters."***

To achieve the research objective three research questions are identified that together elucidate the main research objective within the scope of this thesis:

1. *What are the expected processes that drive the transport of floating plastics in coastal waters?*
2. *How can modelling techniques be used for simulating and examining the movement of floating plastic objects in the marine environment?*
3. *What are the most important parameters that influence the transport and fate of buoyant macroplastics in coastal waters, and what is their effect?*

1.4. RESEARCH SCOPE

In order to fulfil the objective of the research and ensure the quality and feasibility of the findings within the limited time available, a research scope has been determined.

1.4.1. SCOPE

This research focuses on the mechanisms that drive transport and fate of floating plastic litter in coastal waters and the effect of uncertainty parameters on modelling results. For this purpose, the relative impact of uncertainty factors on model results will be investigated. The type of uncertainties considered in this research encompass release and process parameters. Simulations will be performed in hindcast mode, using a validated hydrodynamic model. Therefore, uncertainties in environmental data are not considered here. To relate to the practical problem for emergency response operations, the study focuses on acute release events. In such applications interest is on the short term spreading. As such, the scope is limited to short term effects. Further, it should be noted that the emphasis of this research is on studying the relative importance of processes and parameters, rather than to predict actual trajectories and accumulation areas.

Plastic is an umbrella term that represents a large group of synthetic polymers, coming at a wide range of properties and applications. As different properties result in different behaviour, it would be very difficult to analyse all plastics, let alone model them. Therefore, the focus of this thesis is on a specific group of plastics that share similar characteristics. Since buoyant macroplastics are known to be a dominant polluter in the marine environment, these plastic types are the focus of this thesis. Other types are mentioned only briefly.

In this research, fate is defined as the final state of the particle at the end of simulations. Particles are subjected to beaching and surface drifting. Other states such as settling and suspended transport are not considered as our scope is limited to buoyant macroplastics. Consequently, vertical transport processes are not accounted for. Further, wave effects are disregarded in this study as waves are not included in the hydrodynamic model.

This study is carried out at Deltares. Given the tools and expertise available within Deltares, numerical simulations are carried out using the state-of-the-art Delft3D modelling software. This software has been tested and used for a wide range of applications and has been applied successfully to a large number of coastal areas.

1.4.2. STUDY AREA

The study area of this research is located in the southern North Sea and the adjacent Wadden Sea. An overview of the study site is shown in Figure 1.3. The motivation to study plastic dispersion in this area arose from a recent event where a containership lost part of its cargo[1], resulting in the beaching of a large amount of plastic litter along the shoreline of the Dutch Wadden islands. Since this area has great environmental importance – it is a UNESCO's World Heritage site and facilitates important nursery grounds for fish as well as central feeding grounds for birds and seals – such incidents can have severe impacts. Furthermore, major shipping routes that are among the busiest in the world are located in the area (Barry et al., 2006), creating high-risk for similar accidents. The study area selection is also based on the availability of a verified hydrodynamic model.

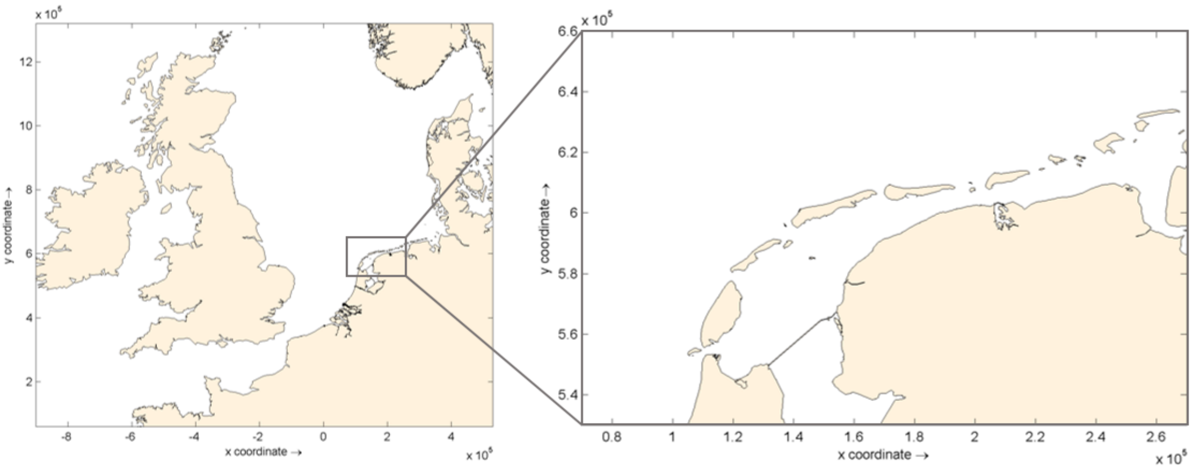


Figure 1.3: Study site localization: [left] Study site located in the North Sea; [right] Overview of the study site

[1]https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/waddenzee/opruimactie-containers-waddenzee-en-noordzee/index.aspx

1.5. APPROACH AND THESIS OUTLINE

In order to investigate the research problem, the first step is to identify important processes responsible for the transport of material in the coastal environment. A literature study was conducted to obtain an overview of the relevant processes. The characteristics of plastics were reviewed and related to their physical behaviour. Subsequently, transport mechanisms and the hydrodynamics of the study area were reviewed. Afterwards, numerical methods and models used in the field are elaborated on. With the findings in the literature study, research question 1 and 2 can be answered.

The outcomes of the literature study were used to set up a model for simulating the transport and fate of buoyant macroplastics. A modelling study followed in which the North Sea was used as a numerical laboratory for simulating hypothetical spill events. This model has been used to evaluate "what if" scenarios by varying conditions or parameters one at a time and observing the outcome. Numerical simulations are therefore used to gain insight into parameter sensitivities, rather than to predict actual trajectories. By studying the changes in the particle trajectories and shoreline accumulation areas, a better understanding of their relative importance in plastic transport modeling can be obtained. A set of indices have been defined that allow to assess and quantify changes between simulations. With the findings of the modelling study, research question 3 can be answered.

Based on this approach the structure of this report is as follows:

- **Chapter 1** ('Introduction') introduces the need for improving understanding on the behaviour of buoyant macroplastics in coastal waters. Next, the research objective, scope and approach are presented.
- **Chapter 2** (Literature study') discusses the general aspects of plastic properties and their behaviour in the marine environment. To understand what processes drive the movement of floating plastics in a coastal environment, hydrodynamic processes relevant for the Dutch coastal area are elaborated on. Further, modelling aspects used in current practice are discussed.
- **Chapter 3** ('Modelling methodology') elaborates the modelling methodology of this research. First the model framework, model setup and parameterization of key processes are discussed. Thereafter, simulation scenarios and evaluation methods to interpret the results are described.
- **Chapter 4** ('Results') investigates how the transport and fate of plastic particles are affected by input parameters. For this purpose, a set of scenarios were defined by changing parameter values on at a time. The particle distribution and coastline accumulation are compared and evaluated for all simulations.
- **Chapter 5** ('Discussion') evaluates the results and put findings into a broader perspective. This is followed by a discussion on the limitations of the research, where assumptions and model settings are critically reflected on.
- **Chapter 6** ('Conclusions and Recommendations') summarizes the conclusions of this research, and recommendations for further research are presented.

2

LITERATURE STUDY

In this literature study, 4 general aspects are discussed; in Section 2.1 **plastic characteristics** that influence their dynamic behaviour; in Section 2.2 **transport mechanisms** relevant for plastic transport; in Section 2.3 **hydrodynamics in the study area**; in Section 2.4 **numerical modelling** related to plastic transport.

2.1. PHYSICAL CHARACTERISTICS OF PLASTICS

Plastics comprise a large family of different materials with widely varying properties. They are being used in countless applications, all coming in a wide range of density, size and shape. In order to better understand the behaviour of plastic materials it is essential to review their characteristics. Given the large heterogeneity of plastics this may be a challenging task. In this section, an attempt is made to define behavioural assumptions by reviewing the main physical characteristics of plastics, i.e. density, size and shape, and relating their effects to buoyancy.

BUOYANCY

According to Archimedes' principle any object, completely or partially submerged in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object. This force is called the buoyancy and is opposed to the gravity force, as shown in Figure 2.1. The buoyancy force drives the vertical movement of particles and determines whether they will be floating on the surface or sink to the bottom. Generally, objects will tend to sink when they have density higher then the fluid density whereas objects with lower density will float at the surface. Though, objects with larger volume are more subjected to buoyancy effects as the weight of the fluid is proportional to the volume of the displaced fluid. Therefore, the size and shape of an object may also be of importance.

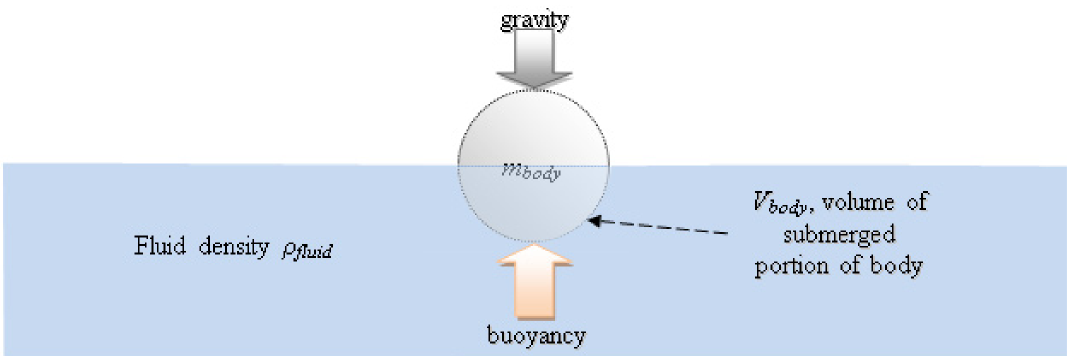


Figure 2.1: Buoyancy for a partially submerged body

2.1.1. PLASTIC DENSITIES

Density is considered a critical parameter determining the buoyancy and mobility of plastics in water. Depending upon resin type and manufacturing processes, plastic densities vary considerably. An overview of the specific density per plastic type and common applications is presented in Table 2.1. Since PP, PE and EPS have lower density than seawater they have positive buoyancy, therefore likely found at the surface and in the upper part of the water column. The other plastic resins are more dense than seawater, therefore non-buoyant and expected to sink to the bottom. Some plastic products, however, are compound with additives and trapped air. Accordingly, plastics such as PET bottles may also be observed at the sea surface. Field surveys and litter sampling demonstrate that Polyethylene (PE), Polypropylene (PP), and Polystyrene (PS) are among the most abundant materials in the marine environment and beach litter (Andrady, 2015; Erni-Cassola et al., 2019).

Resin type	Symbol	Demand [%]	Common application	Density [g/cm^3]
Polypropylene	PP	19%	Food packaging, wrappers, caps, automotive parts	0.90 – 0.92
Polyethylene, low density	PE-LD	18%	Carrier bags, trays and containers, food packaging film	0.91 – 0.94
Polyethylene, high density	PE-HD	12%	Toys, milk bottles, pipes, houseware	0.93 – 0.97
Expanded Polystyrene	EPS	3%	Packaging, building insulation	0.01 – 1.05
Seawater				**1.025**
Polystyrene	PS	4%	Plastic cups, utensils	1.04 – 1.09
Polyvinyl-chloride	PVC	10%	Window frames, profiles, pipes	1.16 – 1.30
Polyurethane	PUR	8%	Building insulation, furniture and bedding, footwear	1.20 – 1.27
Polyethylene Terephthalate	PET	7%	Beverage bottles, strapping	1.34 – 1.39
Others	-	19%	-	-

Table 2.1: Densities of plastics, common applications and their demand as percentage of the total plastic production (PlasticEurope, 2018)

2.1.2. SIZE CLASSES

Plastic litter can be categorized in different size classes. Nevertheless, there is a lack of consensus on how to define and categorize plastic litter and exact size limits are an ongoing debate (Hartmann et al., 2019). In scientific literature, different size categories for plastics are encountered, including terminology such as micro-, meso-, macro- and megaplastics (e.g. Lebreton et al., 2018), but also small, medium and large (e.g. Do Sul and Costa, 2013). In practice, size classes and limits are often chosen such that they correspond with sampling methods and vary relative to the aims of the study. For the sake of consistency, the categorization proposed by Technical Group of Marine Litter (LG-ML) is followed here (MSFD, 2013), defined as:

- **Microplastics**: all plastic particles <5 mm in diameter
- **Mesoplastics** or small fragments: particles that measures between 5 to <25 mm
- **Macroplastics** or large fragments: all particles > 25 mm

The behaviour and mobility of a particle in water is substantially dependant on its size. Macroplastics experience a relative strong buoyancy force and are therefore largely influenced by their size and density. Observations on the subsurface abundance of macroplastics are scarce, and it is generally assumed that macroplastics are either floating at the surface or sunken to the bottom. As particles become smaller the extracted buoyancy force reduces. As a result, buoyant microplastics can also be suspended in the water column. This may occur for particles that have density close to the density of water and are called neutrally buoyant. Very tiny plastic particles (<0.05 mm) exhibit behavior of colloidal particles and mainly exist as suspended particles in the water column, regardless of their density (Filella, 2015).

An overview of the transport pathways of plastics as a function of their size and density is presented in Table 2.2.

Size	Low density (ρ_p<ρ_w)	High density (ρ_p>ρ_w)
Macroplastics	Floatation	Sedimentation
Mesoplastics	Floatation Suspension	Suspension Sedimentation
Microplastics	Floatation Suspension Sedimentation	Suspension Sedimentation

Table 2.2: Transport pathways of plastics as a function of their size and density (adopted from (Zhang, 2017))

2.1.3. PARTICLE SHAPES

Plastic particles exist in various shapes, such as fiber, sheets, spherical or cylindrical. This may alter their vertical behaviour in the water column. Since buoyancy is governed by the positioning of an object in water, particles with different shape but same density and volume may differ in buoyancy. For spherical particles the alignment is identical over each axis. Particles with irregular shape, however, may experience different buoyancy effects depending on their orientation. For instance, horizontally aligned plastic films are subjected to a higher buoyancy force than spheres with the same density and volume. Classical theories developed to predict settling and rising velocities of objects in a fluid are mainly based on the assumption of spherical shapes. However, many different empirical shape factors exist to account for shape irregularities (Filella, 2015). For example, Stuparu et al. (2015) applied a shape factor (Corey Shape Factor) for modelling different microplastic objects. Yet, most shape factors presented in literature are validated for particles with much larger density than water (e.g. sediment) and one should carefully study their applicability to plastics. Recently, Waldschlager and Schuttrumpf (2019) established formulas to describe the vertical behaviour of microplastics for various shapes. Yet, the actual orientation remains difficult to predict, as also suggested by the experiment of Hofland and van der Mheen (2015). Furthermore, the effect for larger objects such as macroplastics remains mostly unexplored. However, shapes are expected to be of less importance concerning larger objects due to their strong buoyancy.

2.1.4. VARIATIONS OF PROPERTIES WITH TIME

During residence at sea, objects are being exposed to natural processes such as mechanical breakdown, degradation and fouling. Consequently, their physical properties may change over time (Morét-Ferguson et al., 2010; Zhang, 2017).

As a result of mechanical breakdown and degradation, items become more brittle and can break up into smaller fragments (Andrady, 2011). This is typically a slow process as conventional plastics are manufactured to withstand weathering during their lifetime. These time scales are much longer than the scales of transport (Barnes et al., 2009; Andrady, 2011). However, in the energetic coastal environment and with the presence of natural abrasives, such as sediment and rock, the breakdown into smaller fragments may occur on shorter timescales in the nearshore environment. Yet, actual fragmentation rates of different plastics in the marine environment are very hard to predict and field measurements are scarce.

Fouling is the attachment of organic material on the particle surface. This leads to an increase of its average density, reducing its buoyancy characteristic. Therefore, fouling can accelerate the sinking process. The rate at which this happens depend on the size and shape of the object (Ryan, 2015b). Since fouling is a function of surface area whereas buoyancy is a function of volume, small plastic items are more vulnerable to fouling as they have high surface to volume ratio. Yet, the timescales of fouling are also much larger than the transport scales (Ryan, 2015b). Given these findings, it can be assumed that the effects of natural processes are not important when being interested in the short term behaviour of plastics.

2.2. TRANSPORT MECHANISMS

Understanding flow and transport processes at the surface layer is important for a wide range of application and disciplines, including marine plastic pollution. In a fluid the transport of matter such as energy, mass or particles occurs through a combination of advection and diffusion. Advection is the transport by the mean motion of the fluid, while diffusion is transport associated with the random motion within the fluid. A general overview of both transport mechanisms and their length scales is shown in Figure 2.2. To obtain primary knowledge on the dynamics of coastal seas, the fundamental flow and transport processes are reviewed. Given the scope of the study, only horizontal transport mechanisms are discussed.

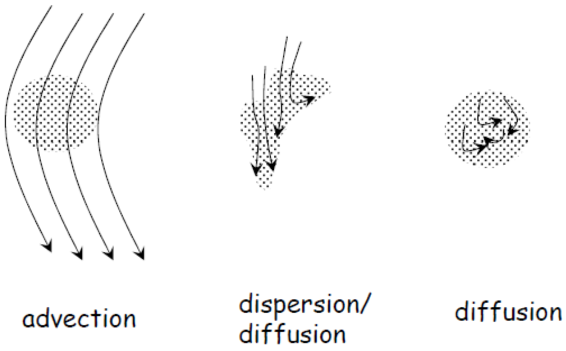


Figure 2.2: Effects of the different processes and their length scales (Uijttewaal, 2018)

OVERVIEW OF PROCESSES AND THEIR TIME AND SPACE SCALES

Coastal surface flows and the structure of velocity fields is influenced by a wide range of processes acting on different space and time scales, as shown in Figure 2.3. Some processes are local, such as the breaking of waves and turbulent eddies, with space and time scales of centimeters to meters and seconds to minutes, whereas others are global, such as wind and thermodynamically driven ocean currents (Stewart, 2008). In the context of this study, the main interest is on processes acting at submesoscales (time scales of minutes to days and spatial scales up to tens of kilometers). However, characteristics are depending on the dimensions and properties of the system, and may change over time and space due to varying meteorological conditions. Furthermore, the interaction of processes may impact one another.

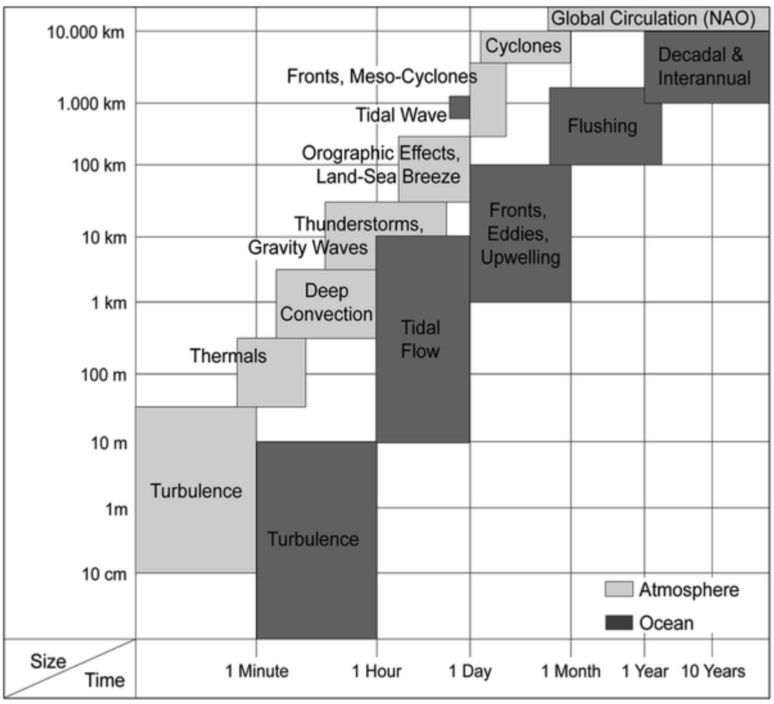


Figure 2.3: Oceanographic and atmospheric processes, from local turbulence that act on short term and small scales (meters) to global circulation patterns which act on much larger temporal and spatial scales (Ross, 1995)

2.2.1. ADVECTION

Advection is a mechanism capable of transporting material over large distances. Two main drivers for the advecion of buoyant macroplastics are identified: surface currents and winds. Winds affect the trajectory in two major ways, i.e. surface effects on the water and direct transport via wind drift.

SURFACE CURRENTS

Currents are the horizontal motion in a water body. Currents are influenced by many factors and may range in magnitude, from a few centimeters per second in open waters up to as much as 4 meters per second in specific straits and estuaries (Ross, 1995). The dominant influences that drive surface and sub-surface currents in our oceans and seas are gravity, wind friction and density variations (Stewart, 2008). Close to shore, waves may dominate the flow.

Tidal currents

Tides are the rise and fall of sea levels caused by the gravitational forces exerted by the Moon and Sun (Bosboom and Stive, 2012). The tide can be considered as a long wave propagating through the ocean. Due to the rotation of the earth the tidal wave is deflected to the right at the Northern Hemisphere and to the left at the Southern Hemisphere (Bosboom and Stive, 2012). Tidal ranges are affected by many factors including the different phases of the Moon, shape of the coastline and bathymetry. Different tidal cycles exist, depending on geographical location. Most coastal areas experience two high an low waters each day. When successive high and low tides are similar in height this pattern is called semi-diurnal. Mixed semi-diurnal patterns also exist, where the two high and low tides differ substantially. Further, some areas only have one high and low tide each day. This is referred to as diurnal tide.

The vertical movement of the water level due to the tide are often accompanied by a horizontal movement of water, called the tidal current. The speed and direction of tidal currents vary with location. Tidal currents are typically strongest before or near the time of highest or lowest water level. Weakest currents occur during flow reversal. Further, tides are strongest near the coast and relatively weak in open water. Near estuary entrances of narrow straits and inlets, the velocity of tidal currents can reach up to several kilometers per hour (Ross, 1995).

Due to depth variations and coastline interaction the tidal wave experiences non-linearities. This can create a significant difference in the ebb- and flood stages of the tidal current, referred to as tidal asymmetry (Bosboom and Stive, 2012). Such inequality gives rise to a net residual current. For example, when the rising tide is faster then the falling tide, flood currents are enhanced over ebb currents.

Wind-induced currents

Winds blowing across the sea surface transfers horizontal momentum to the sea (Stewart, 2008). This momentum transfer sets the surface water in motion in the direction of the wind. Depending on the magnitude and direction of the wind, they can have a significant effect on the surface currents. This holds particularly for shallow waters.

Density gradients

Horizontal gradient in density are due to differences in salinity or temperature. This causes variations in hydrostatic pressure along a horizontal plane and gives rise to currents, as the water flows from high to low pressure. These currents are mainly important for deep circulations in the water column and only have minimal effect on surface currents (Wright and Colling, 1995). However, freshwater discharges by rivers can generate fronts and redirect water flows (Wright and Colling, 1995). Furthermore, small water bodies, such as semi-enclosed basins, respond faster to heating and cooling by meteorological forcing. This may impose significant horizontal temperature gradients.

Wave-induced currents

As waves propagate into shallow water they are refracted and shoaled by features of the sea floor and will eventually break near the beach. Depth-induced breaking of oblique waves drive nearshore currents, including longshore currents and rip currents (Bosboom and Stive, 2012). Longshore currents may flow for relatively long distances parallel to the shore. A rip current is a strong and narrow jet flowing from near the shoreline to outside of the surfzone. Therefore, rip currents are a mechanism that enhance the cross shore exchange.

However, due to the irregularity of wave fields and local variations in the coastal profile, the distributions of wave-induced features will vary considerably. Beyond the breaker zone their effects are marginal.

WINDAGE

Wind also has a direct effect on the transport of floating particles by the force exerted on the surface above water. This effect is called windage, or sometimes also referred to as wind drift. Depending on the direction and speed of the wind, the windage can cause the motion of floating particles to diverge or accelerate from what one would expect based on surface currents alone (Breivik et al., 2011), as illustrated in Figure 2.4. The influence of windage depends on the local wind conditions as well as the buoyancy and shape of the object (Breivik et al., 2011). Since these processes come with many uncertainties, it is very challenging to accurately evaluate the average windage effects. However, it is likely that objects with strong buoyancy are more subjected to wind drift effect. For example, short term drift experiments showed that the movement of floating buoys, made of macroplastics, respond primarily to the velocity and direction of the wind while weighed down buoys follow surface currents (Astudillo et al., 2009).

Simplified approaches have been proposed, where the effect of windage is approximated empirically (e.g. Breivik et al., 2011). Such parameterizations make use of wind drift coefficients to express windage effects as a certain percentage of the wind speed. Wind drift coefficients have been used in many fields, such as marine search and rescue (SAR) models (e.g. Breivik and Allen, 2008) and for the tracking of oil spills (e.g. Jones et al., 2016). In modelling of floating litter, values encountered in literature are ranging from 1% to 6% (Kako et al., 2011; Maximenko et al., 2012; Liubartseva et al., 2016; Duhec et al., 2015).

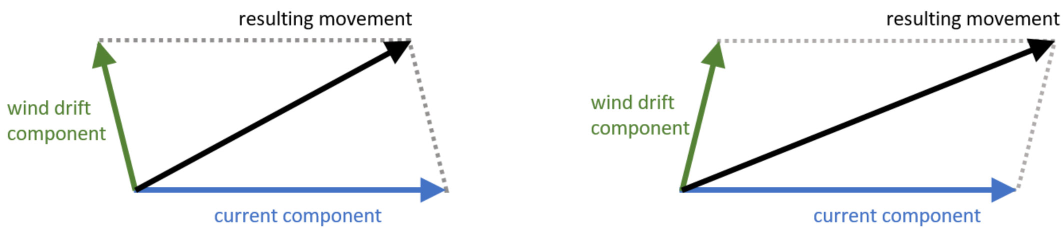


Figure 2.4: The effect of different wind and current directions on the resulting movement

2.2.2. DIFFUSION

Diffusion is the movement from a region of higher concentration to lower concentration. This is associated with a random movement and acts to even out inhomogeneities. This leads to mixing and results in the spreading over a wider area. In general, two kinds of random movements can be distinguished: one on the molecular scale, and one at macroscopic scale. Here, classical diffusion theories and observed dispersion at sea are reviewed.

CLASSICAL THEORY AND TERMINOLOGY

Molecular diffusion

The first type of diffusion is molecular diffusion. Molecular diffusion process is characterized by the movement of individual molecules or water parcels along the concentration gradient without bulk motion. Fick (1855) derived a mathematical formulation to describe this process. This formulation, Fick's Law, states that the mass flux of a tracer or particle through a unit area per unit time in x direction is proportional to the gradient of its concentration in the same direction. One dimensional Fickian transport is described by the diffusion equation:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \tag{2.1}$$

where c is the concentration of the diffusing substance and D is a constant called the diffusion coefficient (or diffusivity), with units of $m^2 s^{-1}$. Solving Equation 2.1 results in a Gaussian plume, as shown in Figure 2.5.
A suitable statistical measure for the size and spreading of a cloud of tracer is the standard deviation (σ) of the particles from a mean plane (Richardson and Stommel, 1948). From Equation 2.1 it can be derived that the second central moment of the distribution, i.e. the variance of the horizontal distribution, satisfy as:

$$\frac{\partial \sigma^2}{\partial t} = 2D \tag{2.2}$$

which says that the variance of the distribution (σ^2) grows linearly with time.

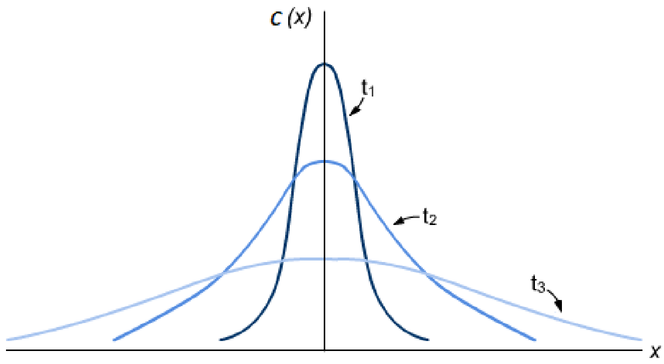


Figure 2.5: Diffusive spreading

Turbulent diffusion

A second type of diffusion is known as turbulent or eddy diffusion, acting on a macroscopic scale. In a chaotic system such as the sea surface, particles are subjected to turbulence. Turbulent motion in a fluid environment is characterized by chaotic fluctuations in flow velocity, which is contrary to laminar flow where the fluid moves in smooth paths. This results in the formation of eddies (or vortices), with different velocity and length scales. The length scales, or eddy sizes, can range from the smallest Kolmogorov scales up to to the largest integral scale. The turbulent diffusion is the scattering of particles due to these random and time dependent motions. The effects of turbulent diffusion are the same as for molecular diffusion, though acting on much faster and larger scales (Wright and Colling, 1995). However, the structure of turbulent transport is much more complicated as some properties are known to be dependant on the nature of the boundary conditions (**?**Fischer et al., 1979). Since most fluid motions in nature are turbulent, turbulent diffusion is a common and important feature.

Terminology

During the literature review on diffusion (modelling), it was found that terminology used to indicate diffusive processes and their effects on spreading is inconsistent. To avoid misunderstandings and anticipating on plastic transport modelling, which will be discussed in Section 2.4, it is important to use consistent terminology. The following terminology is used hereinafter:

- **Diffusion**: refers to the motion of particles causes by the turbulent flow.
- **Dispersion**: refers to the spreading of a cloud of particles. This is produced by a combination of the diffusion processes and the gradient of the mean velocity.
- **Subgrid dispersion**: refers to the spreading of particles as a result of unresolved diffusive motions, acting on scales smaller then the computation grid. In the modelling, a diffusion coefficient is used to account for subgrid-scale turbulent particle motion.

DISPERSION AT SEA

Mixing processes act to even out inhomogeneities in the ocean and seas and encompass both molecular diffusion and turbulent diffusion, of which the latter is much more important as it acts on much faster time scales (Wright and Colling, 1995; Fischer et al., 1979). The process of turbulent diffusion in coastal waters is very complex, and may be associated with a wide range of processes (Wright and Colling, 1995): wind-driven wave motions; convective overturn caused by density differences; vertical or lateral current shear (i.e. variations of velocity either with depth or across the flow); water movement over an irregular sea-bed or along an irregular coast; tidal currents, which vary with time as well as with position; and travelling eddies associated with currents.

Over the years, much experimental work has taken place to parameterize horizontal dispersion (or mixing) at sea. Experiments often include dye releases and observing their spread over time, from which a value for D was deduced. Okubo (1971) computed dispersion diagrams based on 20 sets of dye experiments, including empirical data of the North Sea, with releases close to instantaneous point sources. His study spanned a large range of horizontal scales (from 10m to 100km) and reported diffusion coefficients varying from 10^{-2} to 10^{-1} m^2/s at scales between 10 to 100 meters up to 10^2 m^2/s for length scales of 100km.

However, dye experiments are obtained for specific environmental conditions, often during relative calm weather conditions. It is not clear if such results also hold for other weather conditions. Further, various studies suggest that for dispersion at sea, the variance increases exponentially with time, indicating non-Fickian behaviour (Okubo, 1971; Elliott et al., 1997; LaCasce and Ohlmann, 2003). Yet, others suggest Fickian diffusive spreading (Elliott et al., 1997; LaCasce and Bower, 2000).

More recently, GPS drifters have been used to derive the turbulent characteristics of coastal surface currents. For example, Poje et al. (2014) studied the structure of submesoscale surface velocities in the Northern Gulf of Mexico with a large number of high-accuracy surface drifters. Such statistics can give useful insights into the role of turbulence. Nevertheless, although the basic concepts of turbulence theory are well established, the distribution of ambient mean velocity and turbulence are poorly known. Therefore, predicting the dispersion and horizontal mixing properties of coastal flows remains problematic and is still an area of active research.

2.3. HYDRODYNAMICS IN STUDY AREA

The dominant mechanisms vary with geographic location and is a function of the water body properties. Since these properties are location specific, the physical characteristics of the southern North Sea will be reviewed. First large-scale characteristics will be discussed. Subsequently, we zoom in to our focus area, located on the north(west) side of Dutch coast, to provide understanding of local and small-scale hydrodynamics.

GENERAL CHARACTERISTICS OF THE NORTH SEA

The North Sea is a typical shallow semi-enclosed continental shelf sea. It has a surface area of about 575 000 km^2 and volume of 42 000 km^3 (ICES, 1983). The small depths together with the continental borders determine largely the oceanographic dynamics within the North Sea. The average water depth is 80 m, with

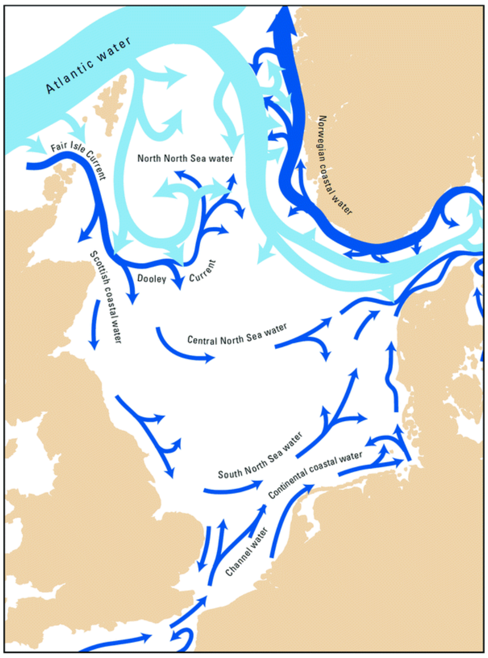


Figure 2.6: Main current patterns in the North Sea. The thickness of the lines indicate the magnitude of volume transport. (OSPAR, 2000)

Figure 2.7: Tidal currents along the Dutch coastline (Ecomare, 2013)

depths ranging between 20-40 *m* in the southern North Sea (below 54°N), after which it gradually increases to about 200 *m* at the edge of the continental shelf. Inflows of Atlantic water occur at the boundary with the Atlantic Ocean in the North and, to a smaller degree (<10%), via the English Channel (Lenhart and Pohlmann, 1997). The general flow pattern of the North Sea is characterized by a cyclonic circulation, as shown in Figure 2.6. Comprehensive reviews of the North Sea dynamics are provided in Otto et al. (1990), Charnock et al. (1994) and Rodhe (1998). From these studies it can be observed that the circulation is forced by the net tides, winds and density gradients.

Tide and tidal currents

The tidal motion is the most significant feature in the North Sea (Otto et al., 1990). The astronomic tide is characterized by the semi-diurnal M2 and S2 constituents. The tide enters the basin from the north and propagates like a Kelvin wave along the coastline of England towards the southern Dutch coastline, after which it propagates to the north and eventually exits the basin along the Norwegian coast. The tide also enters through the English Channel in the southwest.

The mean tidal amplitude is in the order of 2 *m* with with maximum flood and ebb velocities around high and low water (OSPAR, 2000). In the southern North Sea strong tidal currents are observed (OSPAR, 2000). Current amplitudes may reach up to 0.9 m/s during mean spring tides in the focus area (OSPAR, 2000). Due to tidal asymmetry flood currents are enhanced. This causes net horizontal transport directed northward along the Dutch coast, as shown in Figure 2.7.

Wind climate and wind-induced currents

The North Sea is altered by the prevailing westerlies wind belt (Weisse and von Storch, 2010). This wind belt causes a dominant west-to-east motion of the air in mid-latitudes. Furthermore, the North Sea region is under the influence of the North Atlantic storm track, resulting in the occurrence of large atmospheric pressure gradients and strong wind speeds in the region (Weisse and von Storch, 2010).

The water circulation in the North Sea is strongly controlled by the wind. In most of the region, wind-induced currents are responsible for the second largest current (Howarth, 2001). In the study area, the prevailing winds are directed from Southwest to West, as shown in Figure 2.9. The direction of the wind is an important factor controlling surface flow. Figure 2.8 shows the basic pattern of wind-driven circulations as a function of the wind direction. Westerly winds enhance the circulation whereas winds from the east weaken the circulation. Winds from other directions only have a marginal effect on the large scale circulation. However, on small-scale the meteorological variations may induce different current systems.

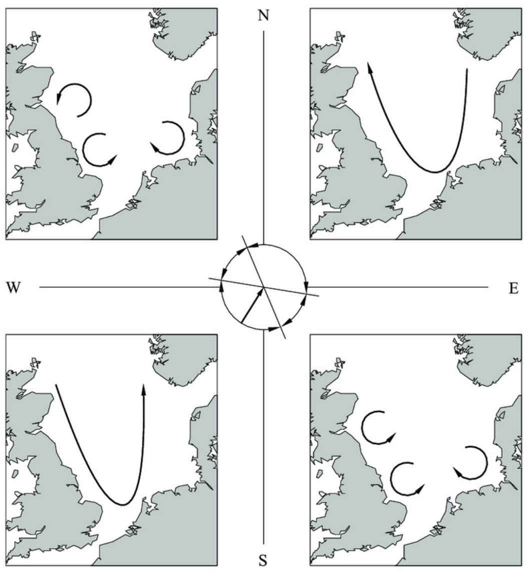


Figure 2.8: Wind-driven circulation as a function of prevailing winds (Sundermann, 2003)

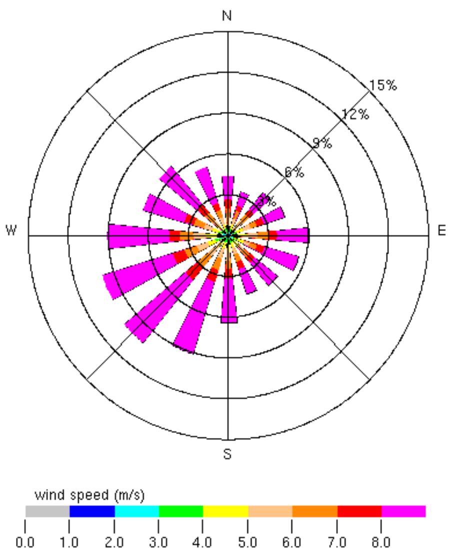


Figure 2.9: Wind rose showing long-term annual averaged wind conditions (retrieved from `waveclimate.com`)

DENSITY GRADIENTS

Spatial differences in temperature and salinity also affect the transport of water as they cause density gradients. Horizontal temperature gradients occur in shallow waters such as the Wadden Sea, which reacts faster to changes in meteorological conditions than deep(er) water (Gräwe et al., 2016). Furthermore, freshwater inflow of rivers causes cross-shore salinity gradients. In the coastal waters these gradients may become important for the residual current field and causes density driven flows.

LOCAL HYDRODYNAMICS AND WADDEN SEA

In the coastal zone the water depth is limited and nonlinear effects can become stronger. Many factors may contribute to small-scale effects, superimposed to the general circulation pattern. Consequently, nearshore circulation can significantly diverge from the general circulation pattern.
The exchange of water between the North Sea and Wadden Sea occurs through the tidal inlets and is primarily due to tides (Gräwe et al., 2016). However, as shown by observations and numerical simulations in Gräwe et al. (2016), residual fluxes are characterized by a strong temporal variability. Accordingly, short-term averages may show strong discrepancy to mean fluxes. Furthermore, this study highlights the presence of regional differences across the Wadden Sea. The flow in the Wadden Sea and exchange between channels and watersheds may strongly be influenced by the winds. Van Vledder and Adema (2007) show that the general characteristics of the flow pattern in the Wadden Sea under storm conditions is closely related to wind fields.

2.4. NUMERICAL MODELLING OF PLASTIC TRANSPORT

To simulate the transport of plastic one needs to solve the equations governing particle motion. This can be described as an advection-diffusion problem and is often represented by a set of differential equations. In practice, analytical solutions in coastal applications are difficult to obtain and require a numerical approach. This section reviews primary theoretical background on particle transport modelling in coastal application, with floating plastic particles being the main application.

2.4.1. ADVECTION-DIFFUSION EQUATION

In many transport models, the movement and spreading of a particle is described by the advection-diffusion equation. In coastal applications the molecular diffusion is negligible. However, one still has to account for velocity fluctuations due to turbulent mixing. This can be approximated by introducing the concept of 'eddy diffusivity', where it is assumed that turbulent fluxes in flow velocities can be described by analogy with molecular diffusion (Fischer et al., 1979). This can be formulated in a Eulerian or Lagrangian form. In Eulerian form (see Section 2.4.2), the advection-diffusion equation reads as:

$$\frac{\partial c}{\partial t} = -\nabla \cdot (Vc) + \nabla \cdot (D\nabla c) \tag{2.3}$$

where c is the tracer concentration at a specific location, V the velocity field, ∇ the gradient and D is the diffusion coefficient which parameterizes turbulence, often referred to as 'eddy diffusivity' or 'turbulent diffusion coefficient'. The left term of the equation describes the local change of concentration in time. The first term at the right is the advection part, whereas the second term describes the diffusion part.

The advection-diffusion Equation 2.3 can be transformed to the Lagrangian frame of reference, describing changes occurring at the particle motion (see Section 2.4.2), via the total derivative. The total derivative relates the acceleration of a particle to derivatives of the velocity field at a fixed point in the fluid. This transformation results in:

$$\frac{Dc}{Dt} = \nabla \cdot (D\nabla c) \tag{2.4}$$

where D/Dt is the operator indicating the Lagrangian frame of reference.

2.4.2. EULERIAN AND LAGRANGIAN APPROACH

A distinction between two methods can be made when modelling the transport of particles: Eulerian and Lagrangian method. Both methods differ in the frame of reference. The Eulerian approach is based on a description of the fluid properties in a reference frame that is fixed in space. This yields concentration values at fixed points on a predefined grid. As such, the particle concentration field is modelled as a continuum. The Lagrangian description, known as 'particle tracking', simulates particle transport by considering single particle motions. The individual particles are then tracked in time and space. This formulation is based on a moving frame of reference in which the change of momentum of a particle and its behaviour towards the environment is observed.

What method is preferred depends on the problem under consideration. Both approaches have their own advantages and disadvantages. A number of reasons exists why one might prefer the use of a particle tracking model instead of Eulerian models for applications related to contaminants, summarized by Dimou and Adams (1993) as follows:

- Sources of contaminates are more easily represented in the Lagrangian method, i.e. by means of particles, whereas the Eulerian approach cannot resolve processes on a spatial scale smaller than the Eulerian grid resolution.
- In particle tracking models, the computational effort is concentrated only in the region where most particles are located, unlike the Eulerian model, where all domain points are computed at each time step.
- Particle tracking models are very suitable for parallel computing techniques, contributing to an increase in the speed of calculations.
- If necessary, other dissipation mechanisms processes can be incorporated in particle tracking models in a straightforward matter, whereas Eulerian models have more numerical constraints.
- Particle tracking models may be a compulsory choice when interested in integrated properties of the concentration distribution (e.g. residence time and individual trajectories), rather than the concentration distribution itself.

Particle tracking models have been frequently used in coastal applications in a wide range of studies and disciplines. Studies range from simulating the dynamics of larvae (e.g Paris et al., 2005; Tiessen et al., 2014), sediment (e.g Krestenitis et al., 2007) or plastic (e.g Maximenko et al., 2012) to tracking water masses (e.g Mason et al., 2012) and oil spill modelling (e.g Mariano et al., 2011). Since particle tracking models provide more flexibility and tool to compute concentration distributions and statistical output at a particle level, in the context of this study the particle tracking approach is preferred.

2.4.3. PARTICLE TRACKING MODELS

In a Lagrangian particle tracking model the trajectories of a set of discrete particles are simulated. The concentration is then represented by the cloud of individual particles. The displacement of each Lagrangian particle is given by a sum of a deterministic and stochastic component. The deterministic component represents the displacement due to advection, while the stochastic component represents the chaotic nature of the flow field.

ADVECTION MODELLING

The movement due to advection can be described by the following ordinary differential equation:

$$\frac{dX_p}{dt} = V(X_p, t) \tag{2.5}$$

where $V(X_p, t)$ is the Lagrangian velocity in x, y, and z direction at a certain time point. The left term represents the particle displacement, where X_p stands for the location of the particle ($X_p = (X, Y, Z)$). The movement of the particles can be computed by applying a numerical integration scheme to the Equation 2.5.

Computing the particle movement requires the input of a deterministic velocity field. The surface currents used to drive particle tracking models can be derived using a number of different methods (NOAA, 2016):

- Currents can be computed from drifter data, which can be derived from ship drift data or satellite-tracked drifters.
- Currents can be calculated from satellite-derived measurements of wind stress and sea surface height.

- Currents can be inferred from long-term historical measurements of salinity, temperature, sea level pressure and depth.
- Currents can be derived from Eulerian circulation models. These models solve equations of motion in horizontal and vertical dimensions and include both physical and thermodynamic processes.

In practice, the velocity field is often derived from an external hydrodynamic model, i.e. a Eulerian circulation model. This gives an Eulerian velocity field at a series of fixed grid points and time instants, given by V = (u,v,w). The location of the particles are normally given at intermediate grid points, so spatial and temporal interpolation may be needed to obtain velocities at the particle location.

DIFFUSION MODELLING

Dispersion by large turbulent structures in the flow field, i.e. large eddies, are resolved by the hydrodynamic model, while processes acting on scales smaller than the hydrodynamic grid are not resolved. To account for the computational resolution restrictions, subgrid processes can be represented by adding a stochastic component to the advection equation. Principally, this means adding a random component to the particle motion to compensate for smoothing. This also allows to account for the variability in windage effects due to atmospheric turbulence. The displacement of each Lagrangian particle is then given by a sum of a deterministic and stochastic component. This results in a stochastic differential equation (SDE). When modelling these effects, it is assumed that the subgrid movement of particles due to the turbulent part of the flow field and unresolved eddies behaves as a Brownian motion. The Langevin equation forms the basis of these particle models (Van den Boogaard et al., 1993), which reads as:

$$dX_p(t) = V(X_p, t)dt + D(X_p, t)dW(t) \tag{2.6}$$

where the first term represent the displacement due to the deterministic velocity field. The second term represents the stochastic part where a Wiener process, *W(t)*, is used to increment stochastic behaviour. In essence, this is a series of random variables with statistical properties that are normally distributed with mean 0 and standard deviation $\sqrt{t}$. This means that the distribution of the random variable increase with time. By simulating the trajectories of many particles, the advection-diffusion process can be described.

As reviewed by Van Sebille et al. (2018), different approaches exist for numerically solving the stochastic differential equation. One method is to use the Fokker-Plank equation. Another approach is to find an 'ad hoc' SDE that matches the eddy field statistics. In this method the stochastic behaviour is incremented with a random walk scheme (Griffa, 1996). From a mathematical point of view, the method based on the Fokker-Plank equation is more correct. Though, in settings with strong convergent flows this approach comes with difficulties therefore the latter method is considered a more suitable for practical applications (Van Sebille et al., 2018).

3

MODELLING METHODOLOGY

This chapter elaborates on the methodology used for the modelling study. The model setup is discussed in Section 3.1. Here, the hydrodynamic and particle tracking model are described in more detail. In Section 3.2 the model scenarios are described. The modelling of scenarios is described in Section 3.3. The methods used for interpreting model outputs are outlined in Section 3.4. An overview of the model framework is presented in Figure 3.1. It should be noted that the aim of the modelling study is to investigate the relative influence of current uncertainties inherent in process parameters and data inputs on model results. Therefore, the model is not used to represent observed distributions.

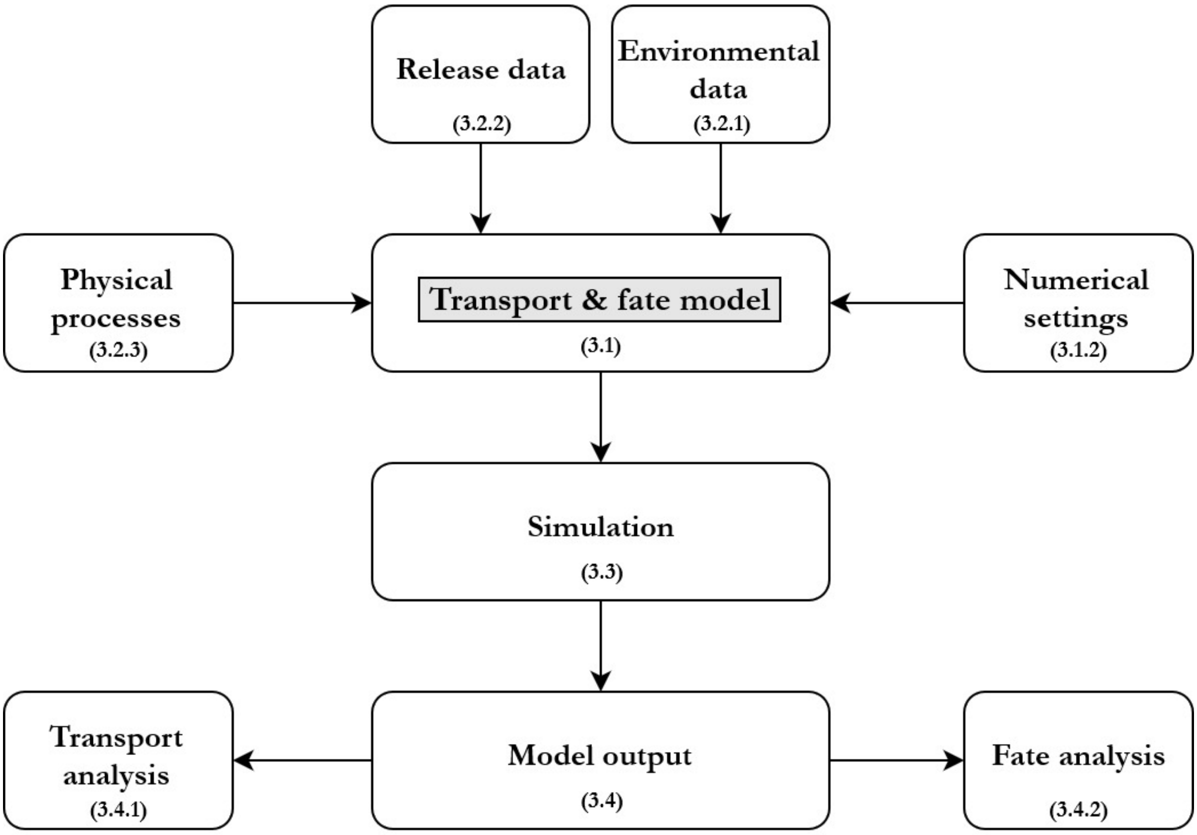


Figure 3.1: Overview of the model framework, including reference to the section where components are discussed

3.1. MODEL SETUP

In this study, numerical simulations were carried out using the Delft3D 4 (structured) modelling software suite for coastal areas. Delft3D is a process-based integrated modelling suite that can simulate flow, sediment transport and morphology, waves, water quality and ecological processes (Lesser et al., 2004). The Delft3D framework consist of several modules and are capable of handling interactions with one another. Delft3D-FLOW simulates multi-dimensional hydrodynamic flows and transport phenomena by solving the nonlinear shallow water equations derived from the Navier Stokes equations for incompressible free surface flow (Deltares, 2018b). This module was used for computing hydrodynamic conditions in the study area. The Delft3D-PART module simulates transport by means of a particle tracking method (Deltares, 2018a). In order to simulate the transport and fate of plastic litter, hydrodynamics and particle tracking concepts were combined. An overview of the model structure is depicted in Figure 3.2. In the model setup, the computed flow patterns from the hydrodynamic (Delft3D-FLOW) modelling results was used as input for the transport modelling of plastic litter (Delft3D-PART) by means of offline coupling. The position of every individual particle can be influenced by advection and diffusion. The trajectory of plastic particles are calculated from their release until the end of the simulation, allowing for the position of the particles to be described in a detailed spatial and temporal matter. Both models will be discussed in more detail in 3.1.1 (hydrodynamic model) and 3.1.2 (particle tracking model).

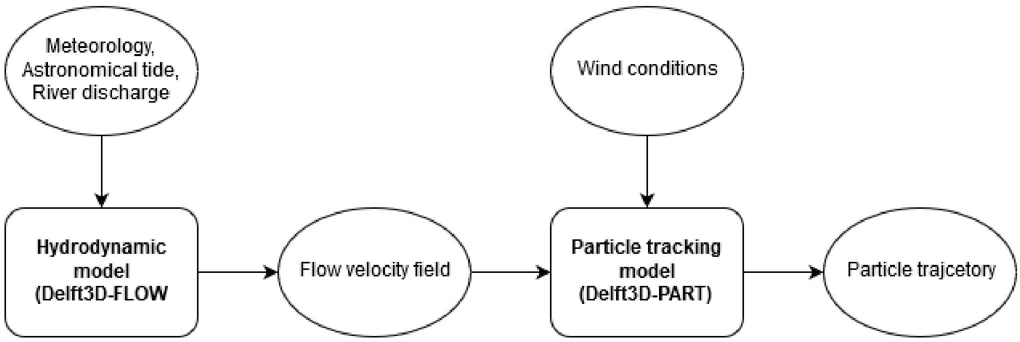


Figure 3.2: A schematic diagram showing the model structure and data flows

3.1.1. HYDRODYNAMIC MODEL

Hydrodynamic conditions were obtained from existing simulations of the southern North Sea computed by the ZUNO-DD (*"ZUidelijke NOordzee, Domein Decompositie"*) Delft3D-FLOW model. The ZUNO-DD model has originally been developed to study the impact of the Maasvlakte-2 construction, but has also been applied successfully to a variety of physical and ecological modelling studies including: fine sediment, fish larvae, floating debris, and water quality. An extensive description on the ZUNO-DD model setup is described in internal reports by Deltares (e.g. Cronin and Blaas, 2013; Blaas et al., 2012).

COMPUTATIONAL GRID AND BATHYMETRY

The domain of the model covers the southern North Sea (including the Wadden Sea) and spans from the Dover strait to the North of Denmark. It is characterized by two open boundary conditions, one located in the Channel (at 2° W) and the other in the North spanning from Denmark to England (at 57° N), see Figure 3.3. The model uses domain composition, a multi grid nesting approach, to combine three different grid resolutions of the North Sea. The area of highest resolution is found along the Dutch coast and decreases in offshore direction. The horizontal resolution of the three grids are presented in Table 3.1. Vertically, the model domain is discretized in 12 σ-layers with a thickness equal to a fixed percentage of the total water depth. The surface and bottom layer have a thickness of 4% of the total water depth, whereas the thickness of each middle layer is about 11%.

For the depth schematization bathymetric data from different sources are used. The bottom topography for the fine grid originated from surveys by Rijkswaterstaat. The bathymetry of the intermediate and course grids originate from NOOS. Figure 3.3 shows the lay out of the ZUNO-DD computational domain and the bathymetry in the area of interest.

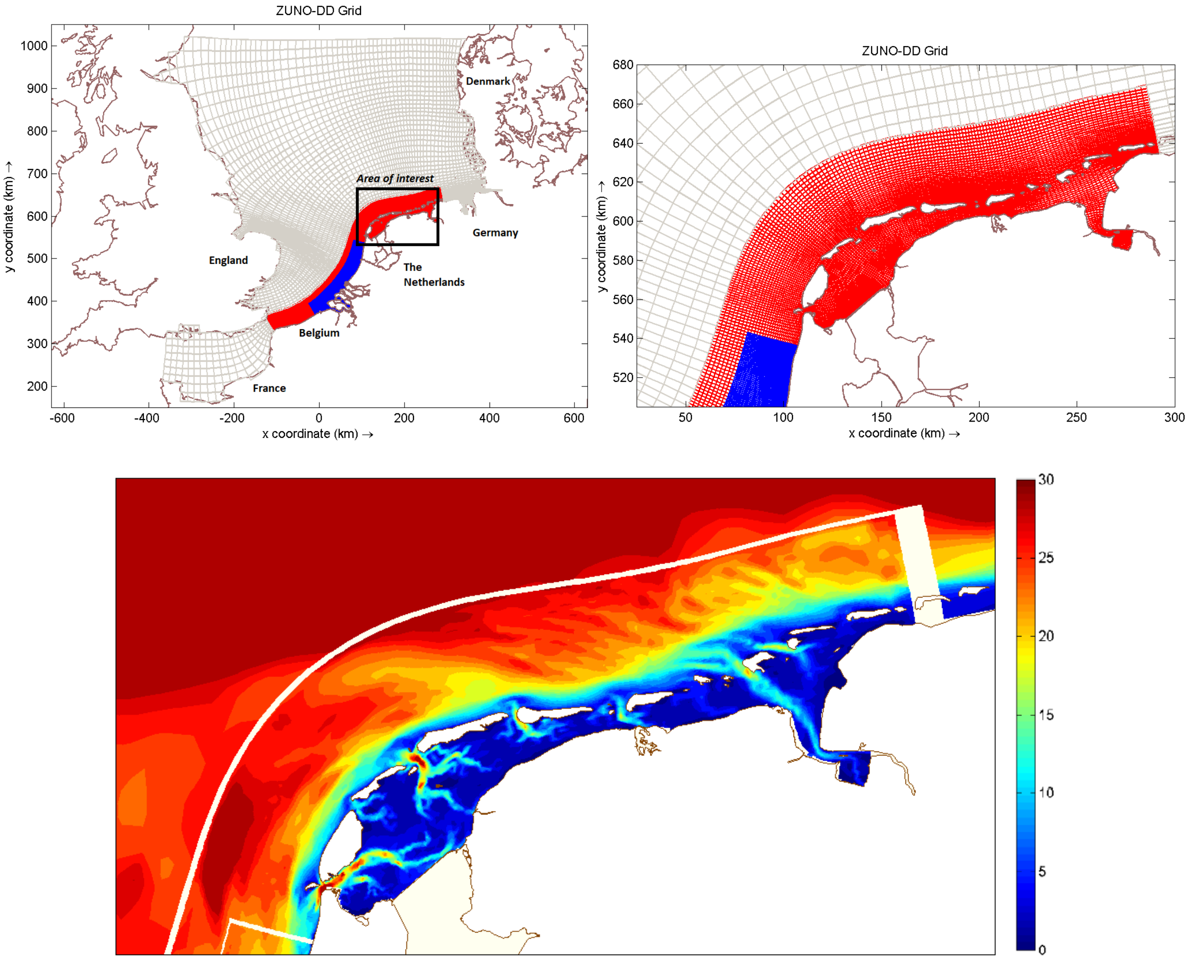


Figure 3.3: Overview of the ZUNO-DD computational grid and bathymetry: [top left] The ZUNO-DD computational domains with the coarse (grey), intermediate (red) and fine grid (blue); [top right] Overview of the computation grid in the study area; [bottom] Bathymetry in the area of interest. The white lines are plotting artefacts indicating the transition between two domain boundaries.

Grid	min (Δx, Δy)	max (Δx, Δy)	Refinement factor
Coarse	6 000, 5 000	20 000, 30 000	1:1
Intermediate	1 000, 2 000	2 500, 3 000	1:9
Fine	500, 1 000	1 000, 1500	1:36

Table 3.1: Horizontal resolution of the three computational grids in the ZUNO-DD model. The ranges are global, grid properties along catchment areas and coastal grids can have different shapes and sizes resulting in higher resolution.

FORCINGS

The forcings of the model consist of tide, wind, heat and freshwater fluxes at the surface. The data input comes from various data sets. Along the open sea boundaries, tidal harmonics for water level are imposed. The astronomic tidal motion is provided to the model by a set of 50 tidal constituents. The meteorological forcing is provided by space-time distributions of the winds and air pressure, using data from the High-Resolution Limited Area Model (HIRLAM) obtained from KNMI. The data were derived with a spatial resolution of ~10km and temporal resolution of 1 hour. It was then interpolated bi-linearly in space from the meteorological model grid and linearly in time to obtain the same resolution and time step as the hydrodynamic grid. From the same model temperature and cloudiness data are retrieved, used for the temperature forcing. Discharge points were defined in the model for all major rivers that discharge freshwater into the open sea. Discharges of Dutch rivers into the North Sea were retrieved from the DONAR Waterbase. Discharges for foreign rivers were taken from CEFAS or, in case of non-availability, estimated by assuming a seasonal uniform value. It should be noted that waves are not included in the model and therefore not accounted for in this study.

CALIBRATION AND VALIDATION

Model outputs have been extensively verified against field observations and in-situ measurements, described in Blaas et al. (2012); Cronin and Blaas (2013); Van der Kaaij et al. (2017). In these studies it is found that the accuracy of the model is generally high. Calibration is performed against water levels, whereas the hydrodynamic performance is checked against temperature, surface salinity and residual net flows through Marsdiep (entrance to Wadden Sea) and the English Channel. Generally, the sea water temperature and measured salinities are well reproduced. Comparison with a number of salinity and temperature observations shows good performance for near-shore stations, although salinity values further offshore are underestimated.

3.1.2. PARTICLE TRACKING MODEL

The particle tracking model used in this study is Delft3D-PART. In Delft3D-PART two type of models are available: Tracer model and Oil model. The Tracer model does not allow for particles to be subjected to additional advection due to wind drag. Therefore, the Oil model was used which — by neglecting all oil specific processes in the module — could be applied to simulate transport of plastic litter of different types. The values used for oil-specific parameters in Delft3D-PART are shown in Table 3.2.

Parameter	**Value**
Evaporation fraction per day	0
Oil dispersion	0
Sticky probability	[0,1]
Volatile fraction	0
Emulsification parameter	0
Maximum water content	1
Fraction at which emulsification starts	1

Table 3.2: Oil module settings for modelling macroplastics

In the model, plastic objects are represented by virtual passive particles floating on the water surface. Therefore, vertical movement of particles are neglected and transport is limited to 2DH. The position of every individual particle can be influenced by:

- Advection; transport by water flow and wind drag
- Diffusion; random displacement

The computation of particle transport in Delft3D-PART consists of two steps. For each time step, every individual particle is first transported by an advective step due to the shear stresses from currents and wind. This is the displacement according to the deterministic velocity field at its location. In the second step, particles are subjected to a diffusive displacement to account for unresolved processes. The governing equations of motion of the Lagrangian particle displacement has the following form:

$$dX(t) = dX_{adv}(t) + dX_{diff}(t) = u(x,y,t)dt + dX'(t) \tag{3.1}$$

$$dY(t) = dY_{adv}(t) + dY_{diff}(t) = v(x,y,t)dt + dY'(t) \tag{3.2}$$

In the following section the transport components and their model parameterization is described.

PHYSICAL PROCESSES

Advection

The advection displacement is given by the local current velocity field, provided to the model by the Eulerian velocity field from the hydrodynamic model. Additional advection due to windage can also be included and is superimposed to the flow velocity field. The velocity of the particle is therefore given as the vectorial sum of currents and windage velocities:

$$V_{adv} = V_{current} + V_{windage} \tag{3.3}$$

where V = (u,v).

Subgrid dispersion
Small-scale processes, not resolved by the hydrodynamic model, can be considered as dispersive mechanisms working on the general flow pattern. Horizontal dispersion due to unresolved turbulence is accounted for by means of a random walk method, modelled as:

$$dX'(t) = R_x\sqrt{2D\Delta t} \tag{3.4}$$

$$dY'(t) = R_y\sqrt{2D\Delta t} \tag{3.5}$$

where R represents a random number generated at each time step, with a value ranging between -1 and +1 that has uniformly distributed statistical properties with mean 0. The diffusivity is represented by D, and Δt stands for the Lagrangian time step. In this approximation, the diffusion coefficient accounts for all the random fluctuations caused by small scale deviations in wind and current velocity fields, occurring at subgrid scales. As such, the distance of the random displacement is a function of the subgrid diffusivity and the time step of the model. The diffusion coefficient is assumed to be isotropic, but the corresponding random displacements are computed for x- and y-direction separately.

Windage
Windage refers to the additional wind-induced drift on floating particles as a result of the direct wind force acting on the surface above water level. This effect is an addition to the overall wind effects applied in the hydrodynamics. In order to account for windage, wind conditions should be specified in Delft3D-PART (see Figure 3.1). The advection by windage is then represented as a percentage of the relative wind speed, specified as:

$$V_{windage} = C_{wd} * (V_w - V_{current}) \tag{3.6}$$

with C_{wd} the wind drag coefficient, V_w the wind speed at 10 m above sea level and $V_{current}$ the flow velocity. The wind drag coefficient is an empirical parameter related to object characteristics. As discussed in Section 2.2, the direct wind effect increases with increase in relative surface above water.

Beaching
A probabilistic approach is used to represent the effect of beaching, following a similar approach as in oil spill models. In Delft3D-PART the probability of beaching is represented by a value between 0 and 1, called the sticky probability (P_b). When a particle ends up at a land boundary it will be considered as beached, and consequently left out of further calculations, if a randomly generated number R[0,1] is smaller than the specified sticky probability. In case the random number is larger than the given beaching probability the particle displacement step will be reversed and reflected off the coastline. So when a particle comes in contact with the coastline, the following holds:

$$P_b \le R : beached$$

$$P_b > R : reflected$$

NUMERICAL SETTINGS

Numerical settings determine the resolution and computation time of the simulation. In order to set up a robust model, there should be a balance between the number of particles used in the simulation and the time step at which particle transport computations are performed. To test the effects of these numerical parameters several runs with different values have been performed, and used to determine the numerical settings.

The numerical settings for the hydrodynamic data are determined by the settings applied in the ZUNO-DD model. The hydrodynamic output of the ZUNO-DD model has a time step of 4 minutes. The data is not saved in one single file, but in multiple 'communication' files so that the files that need to be loaded into Delft3D-PART during simulations are smaller. The hydrodynamic output is stored in communication files that were computed every hour. The communication time step between the hydrodynamic and particle tracking model is therefore one hour.

The movement of particles are not restricted to the resolution of the hydrodynamics and a separate time step for particle tracking can be defined. The time step of PART is not limited to numerical conditions as is the case with Eulerian methods (e.g. CFL-condition), therefore its choice is determined by the computation time of the simulation and convergence behaviour of particles. The time step for particle tracking computations should be small enough in order to let particles follow the streamlines of hydrodynamic velocities, yet large enough to prevent long computation time. Test computations were performed in which particles are only subjected to advection by currents, so that the convergence behaviour of particles can be assessed. After several tests it was found that a time step of 10 minutes showed good results. Computations with this time step sufficiently describe convergence behaviour, i.e. particles are generally following the flow streamlines, and computation time is reasonable.

Another numerical setting is the number of particles used in the simulation. A large number of particles is desired for greater statistical certainty. In general, the accuracy varies with $\sqrt{N}$, where N is the total number of particles. Using a large number of particles, however, results in a longer computation time. Again, test simulations were carried out in order to find a good value. It was found that a release of 5000 particles per release location produces sufficient result resolution, yet keeping computation times reasonable.

Given the scope of the research, simulations are run for 7 days (168 hours). This allows for multiple tidal cycles and significant spreading. A summary of the numerical setting and parameters are given in Table 3.3.

Parameter	Value
Time step PART	10 minutes
Number of particles	5000 per location
Time step FLOW	4 minutes
Simulation time	7 days (168 hrs)

Table 3.3: Numerical settings used for simulations. Parameter values are fixed for all simulations

3.2. MODEL SCENARIOS

To test the effect of ambient, process and release parameters on plastic transport and fate several scenarios were developed. All simulated scenarios represent hypothetical spill events, and different scenarios were obtained by applying different parameter values. The two sources of uncertainties considered in this study were: release conditions and process parameters. In the following sections, the simulation period and parameter values used for the simulations are discussed.

3.2.1. FORCING CONDITIONS

Different hydrodynamic periods were considered for running the simulations, corresponding to different forcing conditions. The probability of acute accidents, such as container spills, is likely to be greater during "heavy" weather. Therefore, only periods with relatively high mean wind speeds and stormy peak wind conditions (>17.2 m/s) were taken into consideration. Furthermore, uniformity in wind direction over the simulation period is desired, since this enables to correlate spreading behaviour with characteristic forcing conditions. Simulations were carried out for the year 2010, motivated by wind and hydrodynamic data availability. Further, this year is in agreement to overall conditions, but also experiences storm activities (KNMI). Therefore, it is assumed that this is a representative year for the climate in the study site. Statistics on the (long-term) average wind conditions are included in Appendix A. Observational wind data time series, retrieved from the moored platform L9, have been used to analyse wind conditions for the year 2010. This station is located 25 km offshore the coast of Terschelling and near the main shipping lane, therefore considered a good representative for the study area. After a thorough analysis, two periods with different wind conditions were selected.

Period 1

Simulation period 1 spans from 1/3/2010 – 8/3/2010. This period is characterised by prevailing NW winds, reaching gale-force (up to 18.2 m/s). The mean wind velocity is 7.2 m/s. Statistics are presented in Table 3.4 and a wind rose is shown in Figure 3.4 (a).

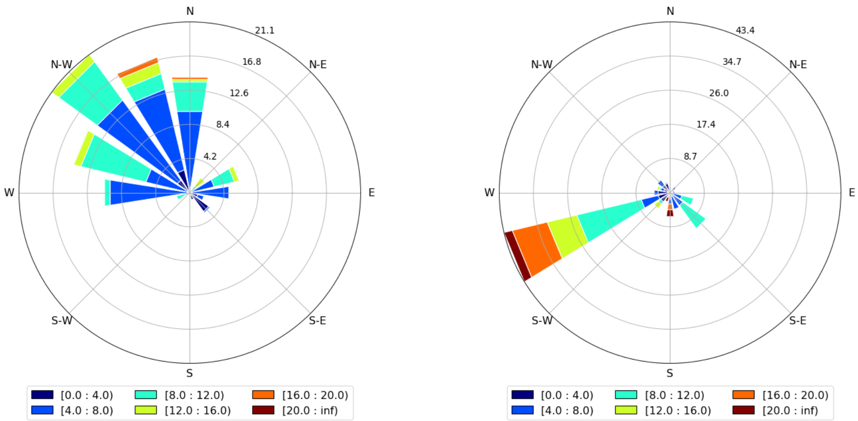
	mean	std	min	25%	50%	75%	peak
speed (m/s)	7.2	3.1	0.2	5.4	7.0	8.8	18.2
direction (°N)	320 (NW)	-	-	153	301	328	340[1]

Table 3.4: Statistics of wind speed during simulation period 1

Period 2
Simulation period 2 spans from 11/11/2010 – 18/11/2010. This period is characterised by an event with strong gale winds from SW, reaching up to 23.3 m/s. The average wind velocity is 9.0 m/s. Statistics are presented in Table 3.5 and a wind rose is shown in Figure 3.4 (b).

	mean	std	min	25%	50%	75%	peak
speed (m/s)	9.0	5.9	0.3	4.0	8.6	12.3	23.3
direction (°N)	220 (SW)	-	-	154	242	254	180[1]

Table 3.5: Statistics of wind speed during simulation period 2



(a) Period 1 (b) Period 2

Figure 3.4: Windrose for the simulations periods

WIND INPUT DELFT3D-PART

As indicated in Figure 3.2, wind conditions need to be specified in Delft3D-PART which are independently of the meteorological input in the Delft3D-FLOW model. With the aim of being as realistic as possible, the observed wind conditions from platform L9 have been adapted for the particle wind drift forcing instead of modelled conditions (from HIRLAM) that are used in the ZUNO-DD model. For model simulations spatially uniform wind conditions are assumed, as it is not possible to include spatially varying wind fields in Delft3D-PART. However, due to limited spatial extension of the study area the spatial variability of the wind field will generally be small.

FORCING ANALYSIS

In order to obtain insights in the model behaviour, the influence of hydrodynamic processes and wind effects on particles during both simulation periods are further analysed. The results are presented in Section 4.1. First, the wind conditions are analysed by dividing the wind in a x- and y-component (Section 4.1.1). Subsequently, hydrodynamic conditions are investigated by studying the residual currents (Section 4.1.2). The residual currents are calculated by averaging the Eulerian velocities over a number of tidal cycles. The mean current is obtained by averaging the values at each time step through a Fourier analysis performed during the

[1] corresponding to the direction during peak wind speed

Delft3D-FLOW calculation. Additional data on wind and hydrodynamic conditions during both simulation periods are included in Appendix A.

3.2.2. RELEASE PARAMETERS

Initial release parameters are relevant parameters for plastic transport modelling, but generally bring along large uncertainty. Therefore, it is important to obtain insight into their impact on model results. Two different types of release uncertainty were considered: release location and time of release. Due to time constrains, other release uncertainties such as type of release (instantaneous/continuous) or release radius are not taken into account and are beyond the scope of this thesis. All releases are modelled as an instantaneous release from point sources.

RELEASE LOCATION

Particles were released from specific release locations along the main commercial shipping route. The default release location was selected with a central orientation to the Wadden islands (location 1). To relate to the practical problem of the container spill accident that occurred in the study area, the influence of roughly knowing the release location is tested here. Hence, other release points were defined downwind and upwind from the default locations. Also, an offshore location is included. A comparable approach in testing the importance of source location is applied in various oil spill studies (e.g. Alves et al., 2015). An overview of the release locations is shown in Figure 3.5. Location 1–3 are referred to as the nearshore cluster, whereas location 4 is referred to as the offshore cluster. Due to time constrains the importance of accurately knowing the exact release location, thus differences at smaller space scales, are not accounted for in this study.

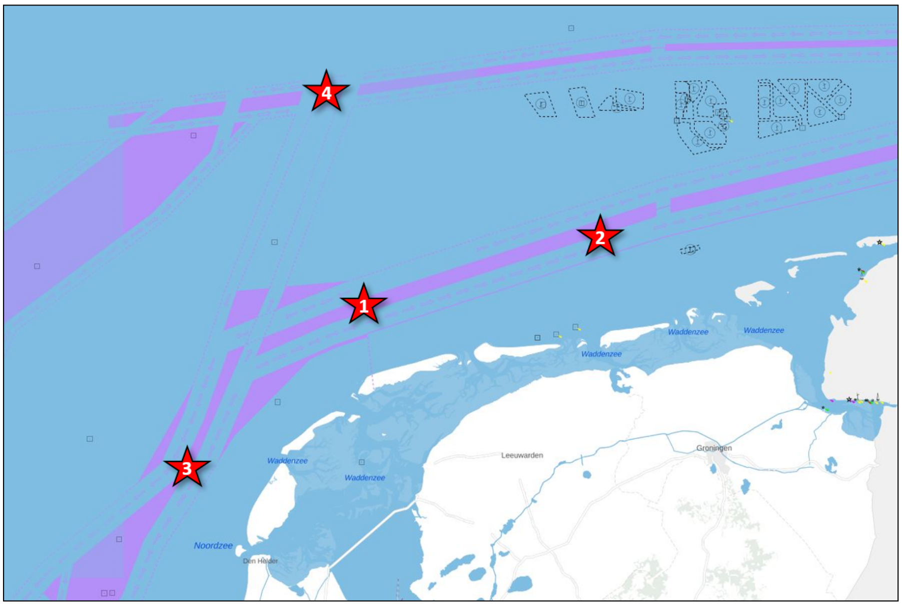


Figure 3.5: Map of the study area with hypothetical spill locations denoted by the red stars. The purple area indicates the main shipping route

TIME OF RELEASE

The time of release is at the beginning of the selected periods, i.e. the first day at 00:00 hr. To test the sensitivity of the results on uncertainties in release moment, simulations were also performed where the time of release is 6 hour after the start of the period (at 06:00 hr). In this scenario the simulation period is extended with 6 hours so that both scenarios are of the same duration. Releases are therefore defined during different instants in the tidal cycle. The water level during both periods is included in Appendix A. From Figure A.3 and A.5 it can be observed that both periods are in ebb tidal cycle at the start of the period (at 00:00 hr), and 6 hours later they are in a flood cycle.

3.2.3. PHYSICAL PROCESS PARAMETERS

The effect of uncertainties due to parameterization of physical processes were investigated by selecting different parameter values for all physical processes included in Delft3D-PART, i.e. windage, subgrid dispersion and beaching. As discussed in Section 2.2, the rate of these processes have yet to be quantified, so the real influence of the processes cannot be properly evaluated. However, a range of different values were used to identify its influence on plastic transport and fate. The proposed scenarios use idealized values for the model parameters. This standpoint allows for pragmatic choices when no accurate values are known. When possible, they were values from literature.

WIND DRIFT COEFFICIENT

The wind drift coefficient is directly linked to the object characteristics, and therefore the buoyancy of the object. This is challenging to predict and comes with high uncertainty. In order to achieve a relation, items are classified into groups with different windage coefficients, following Duhec et al. (2015):

- **Low windage items (0-1%)**;
  objects located (just) below the surface not or to a small degree subjected to direct wind forcing. Examples are plastic bags, fishing nets and bottle caps
- **Medium windage items (2-3%)**;
  objects with a significant part above the water surface, such as capped PET bottles partially filled with water, foam sheets
- **High windage items (4-5%)**;
  objects floating on the water surface, highly exposed to wind. Such items include empty capped bottles and fishing buoys.

For the simulations wind drift coefficient values corresonding to the upper value of the class are used, i.e. 1%, 3% and 5%. Further, a scenario without windage effects is defined by using a wind drift coefficient of 0%. As default a value of 1% is used.

TURBULENT DIFFUSION COEFFICIENT

During drift at the sea surface, particles are subjected to dispersive processes occurring at length and time scales not resolved by the hydrodynamic model. The diffusion coefficient represents the amount of random behavior added to the particle motion to account for subgrid dispersion. As default, a diffusion coefficient value of 5 $m^2 s^{-1}$ was used. This is a rather pragmatic choice, yet of same order as values applied in other plastic modelling studies (e.g. Critchell et al., 2015). The sensitivity of this process was tested by changing the value by 50%, i.e. using 2.5 and 7.5 $m^2 s^{-1}$. Further, it is of interest to see how the particles behave without the stochastic process. A value of 0 would result in all particles following the same track. Therefore, a scenario with very small diffusivity was simulated instead, allowing particles to propagate along different streamlines. For this scenario a diffusion coefficient of 10^{-2} $m^2 s^{-1}$ has been applied.

BEACHING PROBABILITY

As no further information concerning beaching behaviour of plastics or other marine litter is available, the beaching probability parameter is chosen to be a constant corresponding to the model default value of 0.5. The sensitivity is tested against sticky probability values of 0 (no beaching), 0.1 (low probability) and 1.0 (all contact with land results in beaching).

3.3. MODELLING SCENARIOS

Using the model described in Section 3.1 as a representation of plastic transport in coastal waters, "what if" scenarios were evaluated by varying conditions or parameters one at a time and observing the outcome. A total of 13 sensitivity scenarios were simulated for two different forcing conditions (see Table 4.1 for an overview of all scenarios) to evaluate the relative importance of release parameters (location, time) and physical process parameters (windage, diffusion, beaching). A summary of the simulations are presented in Table 3.6. The default values are shown in Table 3.7.

Category	Parameter	Value	Description
Forcing conditions	Simulation period	2 different periods	Periods with "heavy weather" conditions, characterized by stormy winds with average direction of NW and SW respectively.
Release parameters	Release location	4 different locations (see Figure 3.5)	Release sites defined near the coast, located at the commercial shipping lane. Locations are selected upwind, central and downwind of the Wadden islands. Also, a more offshore location is defined.
	Release time	0hrs (ebb), +6hrs (flood)	Release during different instants in the tidal cycle
Process parameters	Windage	0%, 1%, 3%, 5%	Object classification as in Duhec et al. (2015). Upper limit per object class selected for simulations, including a scenario without windage effects.
	Diffusion coefficient	10^{-2}, 2.5, 5, 7.5	Pragmatic choice, as actual values are unknown. The default diffusivity was set to 5 m/s^2. Sensitivity is tested against 50% deviations in parameter value, and a scenario with very low diffusion is included.
	Beaching probability	0, 0.1, 0.5, 1	This approach also requires a pragmatic choice, since no further information is available. Therefore, a range of values from 0 (exclude process) to 1 (all land contact results in beaching) is applied.

Table 3.6: Key parameters, sensitivity values and description

Initial release conditions		**Process parameters**		
location	release time	windage	diffusivity	beaching
location 1	0 hrs	1 %	5 m^2s^{-1}	0.5

Table 3.7: Default values

The experiment is divided in two stages. In the fist stage the control scenario was modelled using the default values mentioned in Table 3.7. As two different forcing scenarios are selected, two control scenarios are modelled. The control scenarios are analysed in detail by investigating the model behaviour and relate this to forcing conditions. Further, it serves as a benchmark to compare results. In the next stage, the actual influence of the parameters on transport and fate is investigated. First, simulations were carried out by changing release parameters one at a time and keeping all other parameters constant. Next, the same approach was carried out for all process parameters.

3.4. OUTPUT ANALYSIS METHODS

This section outlines the main tools and procedure used to post-process the Delft3D model results. As Delft3D does not provide tools to compute statistical key figures relevant for our application, a post-processing script is developed in Python. The script is included in Appendix D. Here, the raw particle trajectory output generated by Delft3D-PART, containing information on the location of every particle in the simulation at every time step, is further processed and analysed to help answer the scientific questions. The main post-processing procedure is illustrated in Figure 3.6.

The main analysis consists of sensitivity testing. Since this research focuses on both transport behaviour and the fate of particles, the post-processing procedure is split into two parts, i.e. transport and fate. The transport is analysed by looking at the trajectories of all particles at sea. The fate is analysed by studying the state of particles and examine the spatial distribution of beached particles at the end of the simulation. For each analysis a set of output parameters were defined to study particle behaviour. These indicators are computed at each time step to allow for a quantitative comparison between scenarios.

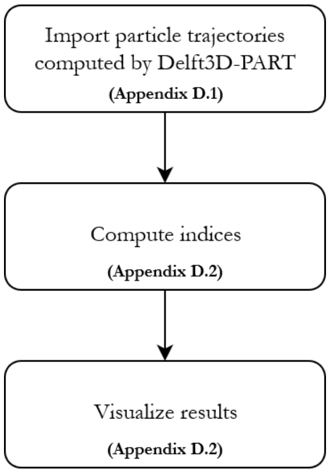


Figure 3.6: Overview of the main post-processing procedure

3.4.1. TRANSPORT

Considering the transport of the released virtual drifters as a cloud of particles, it is of interest to study how the cloud is moving and spreading over time. To describe (dis)similarities in transport patterns and quantify the effect of model parameters, post-processing was carried out to compute the following indices:

- **Travel distance** – distance travelled by the center of mass from the release location, indicating the rate of displacement.
- **Standard deviation** – mean distances from the center of mass, indicating the spreading of the particles. The standard deviation is computed as a collective where a radially symmetrical distribution is assumed.

Sensitivity index

The relative importance of each parameter on the transport behaviour was evaluated by comparing the model outputs of each scenario with those of the control scenario. To quantify the responsiveness of the model outputs to variations of model parameters a sensitivity index was used, formulated as:

$$S_p = 1 - \left| \frac{V_s - V_r}{V_r} \right| \tag{3.7}$$

where V is the value of the index variable, s stands for the scenario and r for the reference case. The sensitivity index is computed at every time step for all particles drifting at the surface. Once a particle has reached the coastline and becomes beached, they are left out of the transport analysis.

To compare behaviour over the full period, the mean value of the sensitivity index is compared. Although the sensitivity index value at the end of the simulation may be of most interest to address final differences, this comparison is found to be problematic since some simulations only have a small amount of particles in flotation. Therefore, this would results in low statistical quality.

3.4.2. FATE

Considering the fate of the particles, it is of interested to study the quantities and distribution of beached particles along the shoreline. Consequently, post-processing was carried out to compute the following output parameters:

- **State** – percentage of particles in either flotation or beached state, indicating the flux onto the coastline.
- **Shoreline distribution** – count of the number of beached particles per km shoreline, indicating the spatial distribution of beached particles.

3.4.3. VISUALIZATION

To elucidate on the results, the output parameters are visualised by generating plots. Here, and overview of the visualization methods and generated plots is presented.

Evolution of the patch
The evolution of the particle patch during the control scenario is tracked in time and space. This is visualised by plotting the trajectory and displacement of the particle patch, projected on a background map of the study area (Figure 4.3 and 4.5). The trajectory of the center of mass is computed, which is the mean position of the particles at a time step, is computed to represent the track of the particle patch. This shows how the patch is moving in its environment. The distribution of the particle cloud is computed using the *kdeplot* functionality from the *seaborn* plotting routine library, see Appendix D.3 (Listing D.12). Snapshots of the distribution are generated for day 1, day 3, day 5 and day 7. This gives more information on how particles spread out during the simulation.

Evolution of the indices
To put the effect of the parameter values into perspective, the evolution of indices for all scenarios defined for a parameter are plotted against another. By studying the (dis)similarities the effect on particle behaviour can be investigated. In all plots, the output parameter of the control scenario is indicated by a blue line.

Concerning the plots on the evolution of the standard deviation, the contribution of subgrid dispersion imposed by the initiated is included in the plot. This is indicated by a black dashed line. This component can be derived analytically and is computed using Equation 2.2. This allows for analysing what processes are dominating the spreading behaviour of the cloud.

Shoreline distribution
A plot is generated showing the accumulation of particles along the shoreline. This gives information on the distribution and quantity of beached particles. Plots are generated showing the shoreline distribution of all simulations for a parameter. Since the shoreline has a complex shape, the beached particles are counted per km shoreline using their x-coordinates (see Listing D.16). Therefore, beached particles are depicted along the same x-axis as in in 1.3.

Particle overview plots
To support interpretation of the results, overview plots of the particles are generates. This gives general information on how particles are migrating in the study area over time. Snapshots of day 1, day 4 and day 7 are computed. These plots are generated using the QUICKPLOT post-processing tool supplied with the Delft3D software. Overview plots of all simulations are included in Appendix C.

4

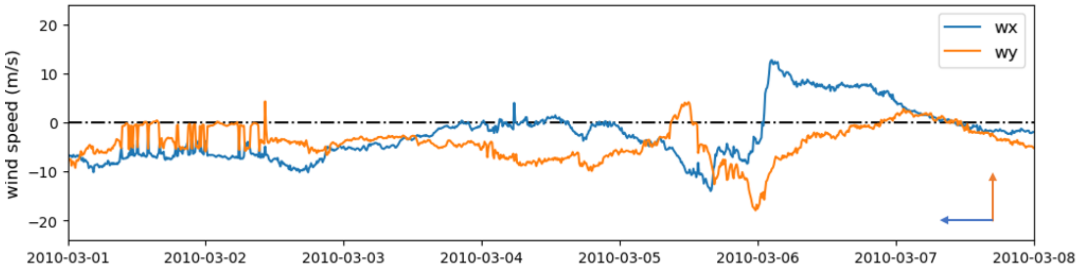
RESULTS

After analysing the forcing conditions in Section 4.1, the results of the modelling study are presented. First, the control scenario is presented in Section 4.2. Subsequently, the different scenarios are compared. In Section 4.3, the relative sensitivity on release conditions and different physical processes is quantified. Section 4.4 gives a detailed analysis on the effects of individual parameters on the fate and transport of plastic particles.

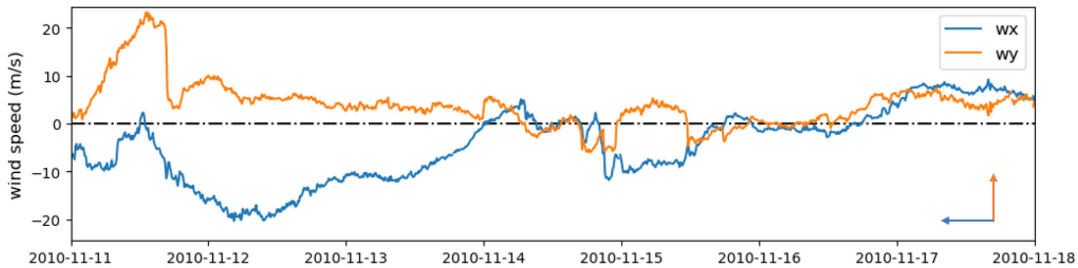
4.1. FORCING ANALYSIS

4.1.1. WINDS

To improve the interpretation of wind effects on the particle motion, wind velocities are split in x- and y-components. The y-component represents the south vector of the wind (wy), whereas the x-component represents the east vector of the wind (wx). For example, a positive wy vector represents south winds and initiates a northward movement of particles by windage effects. The wind vectors are presented in Figure 4.1. Period 1 is characterized by a continuous northern wind component (negative wy-value), therefore pushing particles towards the Dutch coast. Initially, the x-component is also negative, which causes transport towards the west. After 5 days, peak winds occur which initiates a strong south-east movement. Period 2 is characterized by both strong south and east wind components in the first 3 days. Such conditions will push particles away from the study area. A strong peak wind from the south is observed after 12 hours. After 3 days, the wind direction becomes more variable. Yet, as wind speeds decrease the wind effects are less significant.



(a) Simulation period 1

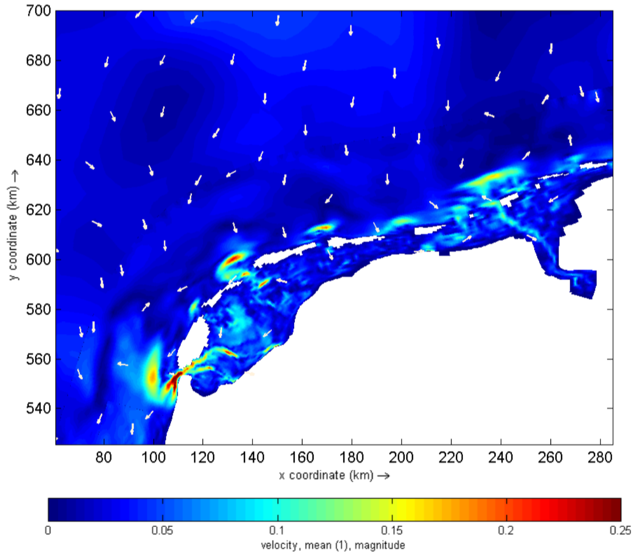


(b) Simulation period 2

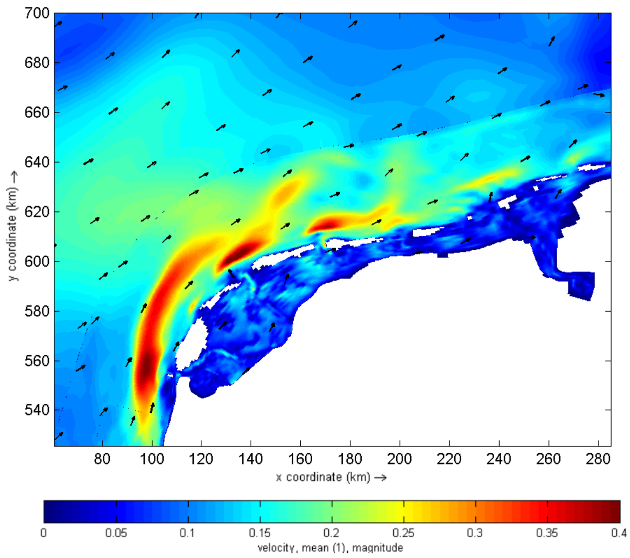
Figure 4.1: Wind velocities during the simulation periods. Velocities are split into an east (wx) and south (wy) component.

4.1.2. RESIDUAL CURRENTS

Looking at the residual surface currents during period 1, presented in Figure 4.2 (a), several remarks can be made. First, it is noticed that residual flow velocities are low at the open sea. Near tidal inlets, however, flow structures with significant velocities occur. The most significant feature is occurs near Marsdiep, which is the most western inlet. This inlet dominates the water exchange between the Wadden Sea and the North Sea. Here, residual currents exceeding 0.25 m/s are observed. Further, small features are present in shallow waters, i.e. close to shore and in the Wadden Sea. Looking at the residual surface currents during period 2, shown in Figure 4.2 (b), the most significant flow structures are observed relatively close to shore (at the North Sea side). These features are stretching along the coastline with length scales up to ~100 km. They also extend from the coastal zone further into the open water, yet at much smaller length scale (~ 15km). The highest residual currents occur in front of tidal inlets, with velocities up to 0.4 m/s. In Section 2.3 it was explained that winds from west to south are expected to cause water movement along the Dutch coastline in upward direction, enhancing the general circulation pattern. The modelled residual currents are in agreement with this theory. Given the strong winds, there are also significant residual velocities occurring in deeper waters. Further smaller and less energetic features are observed in the Wadden Sea.



(a) Period 1



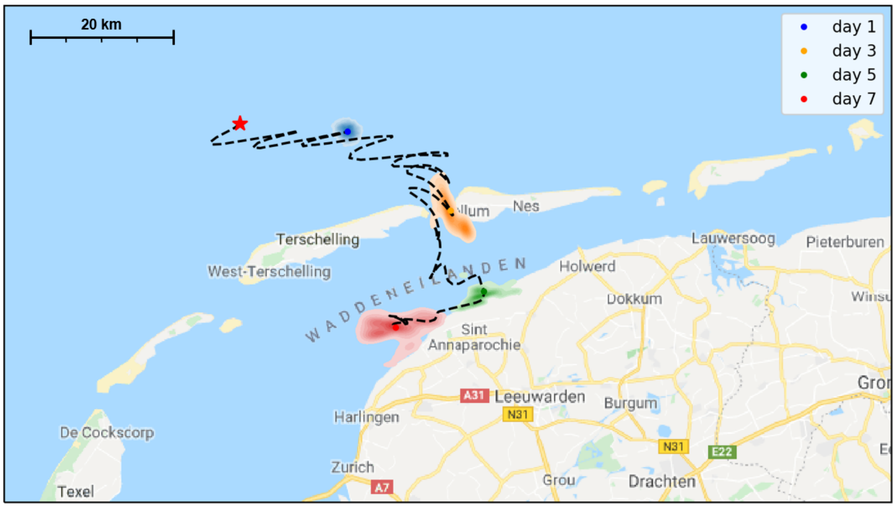
(b) Period 2

Figure 4.2: Residual surface flow patterns and magnitudes for the different simulation periods

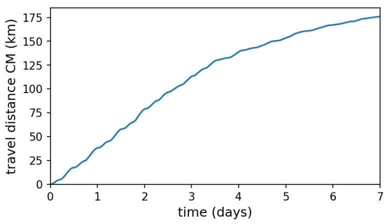
4.2. CONTROL SCENARIOS

In this section, the particle behavior during the control scenario is analysed in detail. First, the movement of the 'cloud' of particles, also referred to as 'patch', is analysed by examining the trajectory and displacement of the center of mass during the simulation. Subsequently, the distribution is investigated by studying the evolution of the standard deviation output parameter and snapshots of the patch distribution. Further, the beaching process is analysed by looking at the state of particles. The control scenario simulated during period 1 is discussed in Section 4.2.1, whereas period 2 is described in Section 4.2.2. In Section 4.2.3, both control scenarios are compared.

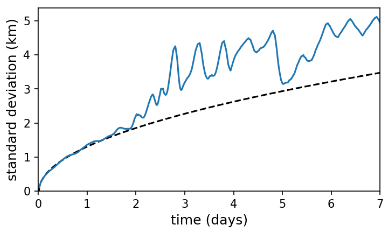
4.2.1. PERIOD 1



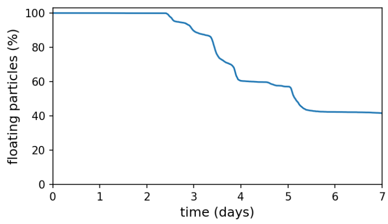
(a) Trajectory and distribution of the particle cloud



(b) travel distance



(c) standard deviation



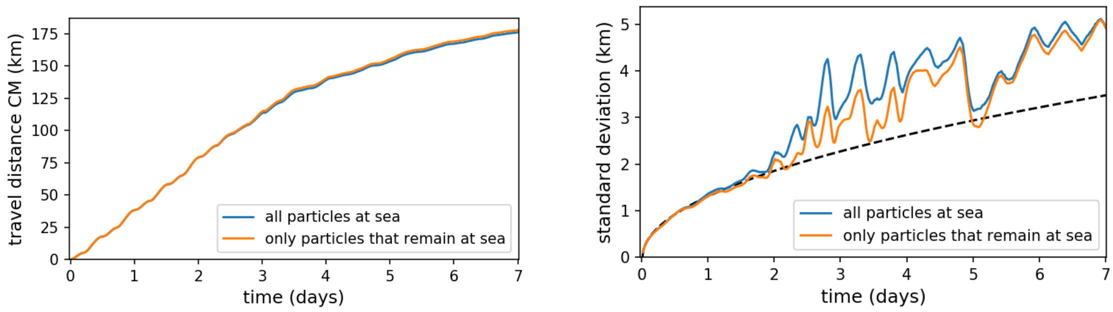
(d) floating particles (%)

Figure 4.3: Evolution of the particle cloud and output parameters for the control scenario during period 1

An overview of the trajectory and distribution of released particles for the control simulation during period 1 is shown in Figure 4.3 (a). The initial movement is directed towards the west, followed by a east-westward movement. This fluctuating behaviour occurs at a frequency of ~12 hours, similar to the tidal frequency. The net movement is towards the east. This corresponds with the tidal current pattern in the region, suggesting that the transport is to a large degree determined by the tide. Particles are also drifting towards the coast as a response to onshore winds. This allows for particles to become beached upon interaction with the coastline. Looking at the travel distance of the particle cloud, shown in Figure 4.3 (b), two different regimes are observed. In the first three days, particles are traveling relatively fast. This is indicated by the steep gradient in travel distance. During this time frame particles are located in the North Sea. The days thereupon, when particles are located in the Wadden Sea, the gradient becomes less steep so the particles are traveling slower.

Looking at the evolution of the standard deviation (Figure 4.3 (c)), several remarks can be made. The initial spread of the particle cloud is equal to the expected amount of dispersion initiated by the random walk model (black dashed line). After two days, the standard deviation starts to diverge from this pattern and becomes more variable. This indicates that other processes start to contribute to particle dispersion. In the initial period of time after the release, the cloud of particles is relatively small and the dispersion is only caused by the (parameterized) small-scale turbulence effects. Since particles are released as a point source, eddies of larger scales do not yet contribute to the spreading effect. However, after some time the cloud of particles will have spread sufficiently so that larger-scale eddies can contribute to the spreading effect. When the characteristic length of the velocity field structure is larger in one direction than another the distribution becomes asymmetric. Such developments are clearly observed (see snapshots of particle distribution in Figure 4.3 (a)). During day 2.5 – 4 the patch is located near the tidal inlet, where high variability in spreading occurs. During flood the tidal flow is directed into the Wadden Sea and causes contraction at the inlet, whereas during ebb the water is flowing from the Wadden Sea towards the North Sea. This is associated by flow divergence towards open waters. This phenomenon could be an explanation for the strong fluctuations observed in the standard deviation plot. Once in the Wadden Sea, particles are dispersed further. Water flows in the Wadden Sea are constantly changing with the tides and influenced by variations in wind conditions. Furthermore, as observed in 4.1.2 features in the Wadden Sea have relatively small scales. This may cause advective gradients over the width of the patch, which contributes to further (asymmetric) dispersion.

Looking at the fate of the particles, shown in Figure 4.3 (d), it is observed that 60% of all particles end up at the beach. As the patch travels from open sea into the Wadden Sea, it propagates along two barrier islands where a part of the patch comes in contact with the land boundaries. This results in beaching. It is observed that 40% of all particles end up at the shoreline during the migration from the North Sea towards the Wadden Sea. At day 5, further beaching occurs when the patch is located near the main land.



(a) travel distance

(b) standard deviation

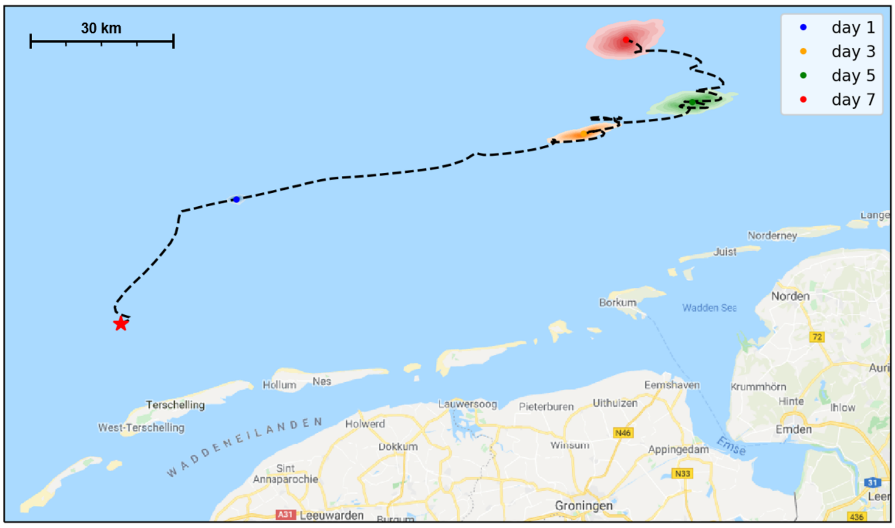
Figure 4.4: Difference in transport indices when considering only particles that remain at the sea surface at the end of the simulation

The beaching may affect statistical indices and therefore the representation of particle behaviour. This effect is investigated by comparing the 'normal' transport indices, computed with all particles at sea at a specific time point, with statistics considering only the particles that remain at sea during the entire simulation. In Figure 4.4 both indices are compared. They show similar behaviour, indicating that in this scenario the dispersion as a result of the dynamic system is similar for all particles.

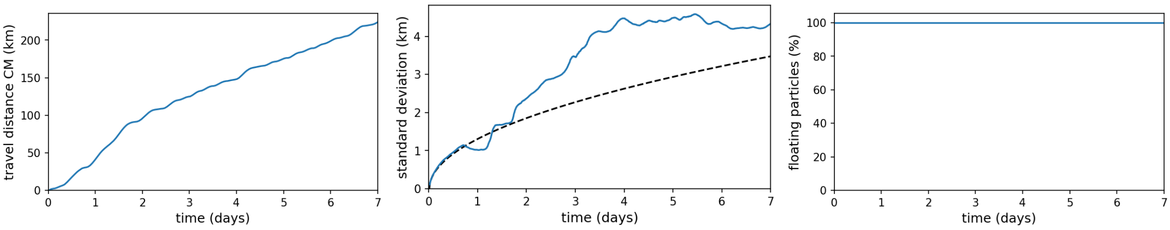
4.2.2. PERIOD 2

An overview of the trajectory and distribution of released particles for the control simulation during period 2 is shown in Figure 4.5 (a). At first, particles are drifting away from the coast in northeasterly direction, followed by a eastward movement after less then a day. At the last day of simulation the patch is drifting in northwesterly direction, when winds turn offshore. This is in line with the expected behaviour due to windage effects, as discussed in Section 4.1.1. Looking at the particle displacement in Figure 4.5 (b), it is observed that they are being transported quickly in the first two days. Here, nearly half of the total distance is covered. This window corresponds to the period with highest winds. After two days the displacement decreases, simultaneously with the decrease in wind speed. The mentioned relations imply that particle transport is dominated by wind effects.

Figure 4.5 (c) indicates the dispersive behaviour of the particle cloud. Again, the initial spreading follows the diffusive pattern imposed by the random walk. After 2 days the spreading gradually increases. As discussed in Section 4.1.2 significant features are present during this simulation period, also further offshore at open waters. These features are capable of increasing the spreading of the particle patch. Further, it is noted that all particles remain at sea during the simulation (Figure 4.5 (d)).



(a) Trajectory and distribution of the particle cloud

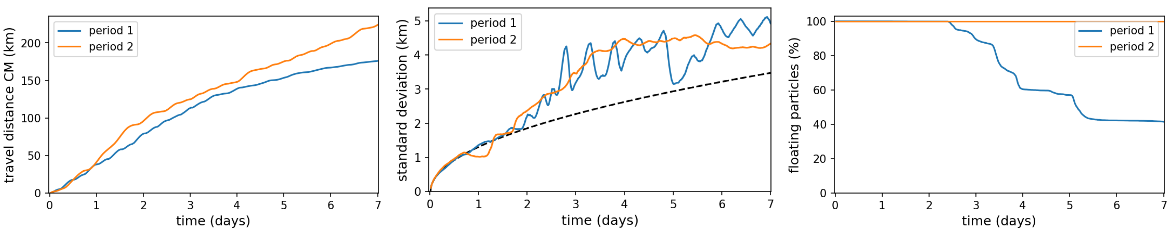


(b) travel distance (c) standard deviation (d) floating particles (%)

Figure 4.5: Evolution of the particle cloud and indices for the control scenario during period 2

4.2.3. DIFFERENCE BETWEEN BOTH PERIODS

To compare behaviour for both forcing conditions, the evolution of the indices during both control scenarios are plotted against each other. This is shown in Figure 4.6. Forcing conditions have a large effect on the speed and direction of the floating particles. During onshore winds (period 1), drift trajectories are directed towards the coast and being deposited on the shore or transported into the Wadden Sea, whereas particles are transported along the coast during SW winds (period 2). Although particles remain in deeper water during period 2, where flow velocities are expected to be smaller than areas closer to shore, the particles are being displaced remarkably faster compared to the simulation for period 1. As shown in Section 4.1 both winds and residual currents are higher for period 2, suggesting these two are important. Another remarkable difference is the varying dispersion patterns for both periods. Although the dispersion increases at the same time, approximately after two days, the evolution in standard deviation shows contrasting patterns. This implies that the driving factors differ under varying forcing conditions. The wiggling pattern at tidal frequency suggests that tides are the main factor during simulation period 1. Comparatively, the standard deviation is less variable



(a) travel distance (b) standard deviation (c) floating particles (%)

Figure 4.6: The behaviour of particles under varying forcing conditions

during period 2, indicating that the dispersion is dominated by other factors. Though, the overall pattern shows a same trend suggesting that the driving dispersive mechanisms act on similar spatial scales.

4.3. SENSITIVITY QUANTIFICATION

The relative importance of each parameter was evaluated by comparing differences in transport output parameters, using the sensitivity index defined in Section 3.4, and the fate of particles at the end of the simulation. For each scenario the sensitivity index is computed for the distance travelled by the center of mass and the standard deviation at each time step. The distance is a measure for advective transport, whereas standard deviation is a measure for the dispersion of the patch. As specified in Section 3.4, the sensitivity index quantifies the difference in calculated indices between the evaluated scenario and the control scenario. As each scenario represent the influence of one parameter value, a low sensitivity index value indicates a high dissimilarity to the evaluated parameter. Results on the sensitivity quantification and the final fate of particles are presented in Table 4.1. The average sensitivity of a parameter is evaluated by computing the ensemble mean and spread of the separate scenarios defined for a particular parameter. These results are presented in Table 4.2.

Parameter	**ID**	**Scenario**	**Period 1**				**Period 2**			
			dist	std	float (%)	beach (%)	dist	std	float (%)	beach (%)
location	Loc 1	Control	1	1	42	58	1	1	100	0
	Loc 2	1	0.92	0.98	74	26	0.91	0.90	100	0
	Loc 3	2	1.00	0.52	5	95	0.82	0.75	100	0
	Loc 4	3	0.75	0.72	100	0	0.80	0.74	100	0
release time	0hrs	Control	1	1	42	58	1	1	100	0
	6hrs	4	0.96	0.88	57	43	0.98	0.94	100	0
windage	wd0	5	0.83	0.80	100	0	0.85	0.79	100	0
	wd1	Control	1	1	42	58	1	1	100	0
	wd3	6	0.65	0.90	13	87	0.69	0.99	100	0
	wd5	7	0.62	0.83	1	99	0.30	0.86	100	0
diffusion	D0,01	8	0.97	0.55	59	41	0.99	0.53	100	0
	D2,5	9	1.00	0.83	53	47	1.00	0.81	100	0
	D5	Control	1	1	42	58	1	1	100	0
	D7,5	10	1.00	0.88	36	64	1.00	0.85	100	0
beaching	p=0	11	0.98	0.50	100	0	1.00	1.00	100	0
	p=0.1	12	0.99	0.90	51	49	1.00	1.00	100	0
	p=0.5	Control	1	1	42	58	1	1	100	0
	p=1	13	1.00	0.96	40	60	1.00	1.00	100	0

Table 4.1: Sensitivity table for simulation period 1 and simulation period 2. The sensitivity index for the travel distance (dist) and standard deviation (std) are calculated at all time steps and mean values are presented here. Only floating particles are used to calculate the statistics. Also, the final fate of particles are shown, which can be either floating at the surface (float) or beached at the shoreline (beach).

Parameter	**Scenario**	**advection**		**dispersion**		**fate** (% beach)	
		mean	std	mean	std	mean	std
location	1–3	0.87	0.09	0.77	0.16	20	38
windage	5–7	0.66	0.20	0.86	0.07	31	48
diffusion	8–10	0.99	0.01	0.74	0.16	25	29
beaching	11–13	1.00	0.01	0.89	0.20	18	28

Table 4.2: Ensemble mean and standard deviation of the sensitivity per parameter

Looking at Table 4.1 and Table 4.2, it is observed that all parameters affected the transport, but to a different degree. The impact of the parameters also varied between the two simulation periods. During period 2 all particles remained in flotation, whereas the fate of particles during period 1 differed in all the scenarios. In general, windage parameters as a whole exhibited the lowest sensitivity values and most variable results, therefore has the largest influence on model results. This is followed by the the release location. Overall, the beaching parameters had the smallest impact, highlighted by sensitivity values close to 1. However, neglecting this process results in a strong difference in spreading (scenario 11, period 1). The release time has only a minor impact on transport, although a significant difference in beaching quantity is observed during period 1. The diffusion coefficient has no effect on advection, yet, as per its definition, strongly controls the average amount of dispersion.

Looking at simulations for period 1, it is observed that particles released more offshore (scenario 3) and without windage effects (scenario 5) stayed in flotation. In the latter particles are only transported by the currents, which by definition can not result in beaching. Clearly, also no beaching occurred when the beaching processes is excluded (scenario 11). Most beaching occurs for simulations with medium and high windage effects and release location 3 (87–100%).

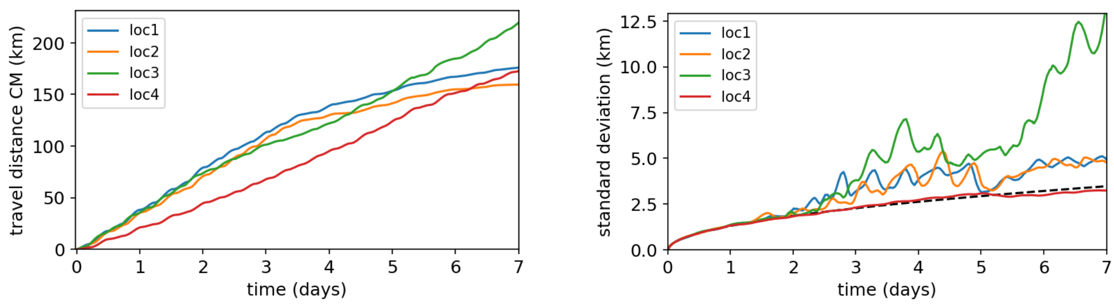
4.4. EFFECT OF PARAMETERS

The effects of individual parameters on the fate and transport of plastic particles was analysed by comparing the evolution of the indices for each investigated parameter. Furthermore, their effect on shoreline accumulation is analysed. This is evaluated by computing the shoreline distribution of beached particles. In Section 4.4.1 the release parameters are examined, whereas Section 4.4.2 elaborates on the process parameters. Supporting figures are included in Appendix C. Further, it should be noted that only period 1 is discussed. Since particles move away from the study site under the forcing conditions of period 2 these scenarios are not considered here, unless stated otherwise. The results of period 2 are included in Appendix B.

4.4.1. RELEASE PARAMETERS

EFFECT OF RELEASE LOCATION

The evolution of the transport indices are shown in Figure 4.7. Irrespective of where they are released, in the first two days the dispersion of the particle cloud is alike the dispersion due to the initiated random displacement by subgrid dispersion (Figure 4.7 (b)). After two days, particles released from the nearshore cluster (location 1–3) start to deviate from this trend and experience high spreading variability. Particles released from the offshore location (location 4), however, are solely dispersed by the initiated subscale dispersion during the entire simulation. This implies that in deep water particles are not experiencing advective gradients, therefore merely dispersed by small-scale turbulence. Looking at the distance traveled by particles, shown in Figure 4.7 (a), also large differences between the nearshore and offshore cluster are observed. In the first three days the particles from the nearshore cluster travel almost two times faster then the particles released form the offshore cluster. At the end of the simulation, however, location 4 has travelled a similar distance as location 1 and 2. This indicates that the particles are propagating significantly slower in the Wadden Sea. However, particles released from location 3 travel over 50 km more, which is equivalent to about 35% more distance. This

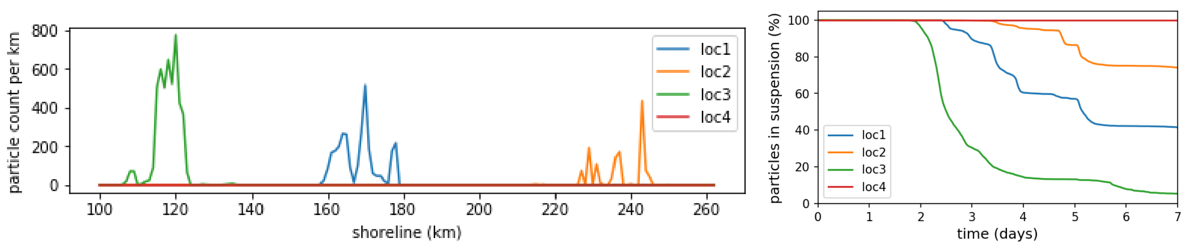


(a) travel distance (b) standard deviation

Figure 4.7: Evolution of transport indices for the various release location scenarios

shows that strong differences in transport rates may occur within the Wadden Sea. Release location 3 is located relatively near Marsdiep where, as identified in Section 4.1.2, the most significant residual currents occur. However, particle transport may also be affected by other processes such as local differences in topography. Though, it should be noted that the statistical quality of the transport indices for location 3 might be low due to the large amount of beaching. Since location 1 and 2 show very similar patterns, it is suggested that they are influenced by the same regime or similar features throughout the simulation period.

Looking at Figure 4.8, strong deviations in fate are observed. Since the release locations are relatively far from each other, they may be influenced by different features and land boundaries. Consequently, the statistics show strong deviations. For example, the particles released from location 3 are highly influenced by Texel (see also Figure C.1), resulting in high beaching. After three days already over 60% of all particles are beached, and at the end nearly all particles are beached. For the other nearshore release locations the beaching occurs more gradually. Particles released from the offshore location are not subjected to beaching as they do not get in contact with land boundaries during the simulation period.

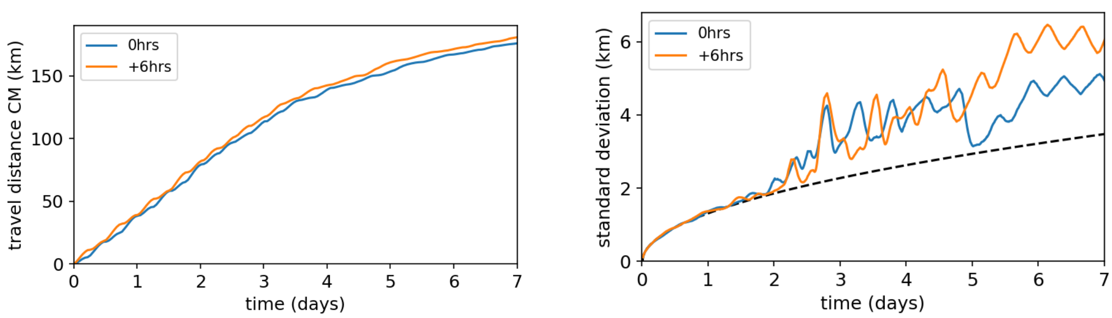


(a) shoreline distribution (b) floating particles (%)

Figure 4.8: Evolution of fate indices for the scenarios with different release location

EFFECT OF RELEASE TIME

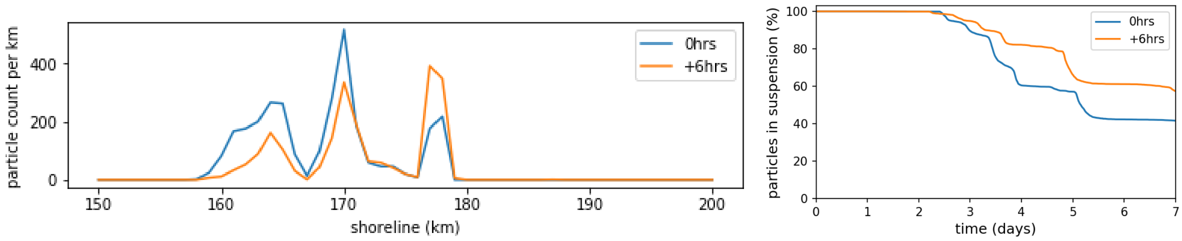
The initial direction of particle drift depend on the release time, as this is controlled by the tide. If particles are released with a difference of six hours, it means that the tidal conditions are opposed during both simulations. When particles are released during ebb tidal conditions they propagate towards the west, whereas their initial movement is towards the east during flood conditions (as described in Section 2.3). Since flood currents are stronger then ebb currents, the displacement is larger for particles during the flood cycle. This can be observed in Figure 4.9 (a), and is represented by the controverting step-wise increase in travel distance between both simulations. For example, the initial displacement of scenario +6hrs is larger then the control scenario (0hrs) in the first six hours of the simulation, whereas this is vice versa in the next six hours when the tidal current reverses. This is particularly observed in the first two days, when no beaching has occurred (Figure 4.10 (b)). When looking at Figure 4.9 (b), similar behaviour is observed in the first 5 days. This suggests that particles are dispersed by similar hydrodynamic features. Thereafter, discrepancy in the amount of spreading is observed.



(a) travel distance (b) standard deviation

Figure 4.9: Evolution of transport indices for the various release moment scenarios

Looking at the distribution of beached particles (Figure 4.10 (a)) it is observed that the accumulation density is shifted more eastward when particles are released 6 hours later, following the direction of the initial tidal currents. Furthermore, the amount of beaching differs between both scenarios by 20% (Figure 4.10 (b)).



(a) shoreline distribution

(b) floating particles (%)

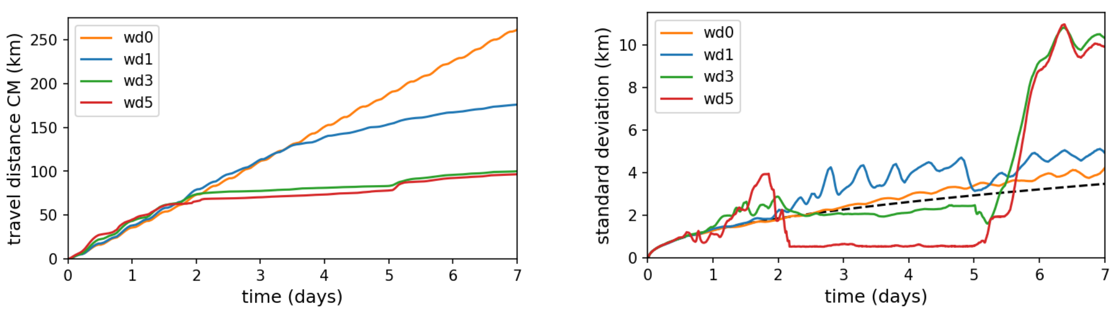
Figure 4.10: Evolution of fate indices for the scenarios with different release moments

4.4.2. PROCESS PARAMETERS

EFFECT OF WINDAGE

In Figure 4.11 the evolution of the transport indices for different windage coefficients are compared. An overview of the locations of particles in the study area for the different windage scenarios are shown in Figure C.4–C.7. Here, it is be observed that particles without additional wind advection (Figure C.4) are propagating parallel to the coastline, following the hydrodynamics. At the end of the simulation the bulk of the particles are still close to the release location, within a range of 20 km. This highlights that the net transport by currents is weak further at the region of release. When windage effects are added to the particle movement they are transported towards the coast by the onshore winds. The more windage is added, the faster the particles are propagating. This relation holds until the patch arrives at coastal boundaries which block particles from moving further. Therefore, the interaction with land boundaries makes it difficult to analyse the exact contribution of windage on the transport. In the absence of coastal boundaries and in open water, i.e. during period 2, the windage effect is more clearly observed (see Figure B.4). Adding a small amount of windage (i.e. applying a windage coefficient of 1%) results in a increase of 15% in travel distance, whereas objects with high windage effects (i.e. a windage coefficient of 5%) are transported 75% further. The increase in travel distance has a linear correlation to the windage coefficient. Yet, for all scenarios the currents have the largest contribution to the travel distance.

Looking at Figure 4.11 (b) it is observed that the variability in dispersion increases when windage is accounted for. The winds push the particles towards shallower waters, where more variability in the flow occurs. The scenario with higher windage coefficients (wd3 and wd5) show odd patterns, particularly after day 5 when the standard deviation increases with a factor 5. In both scenarios a large number of particles are subjected to beaching which affects the statistical representation.

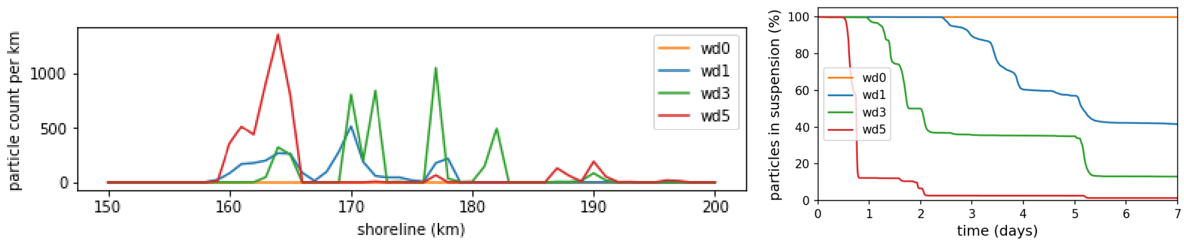


(a) travel distance

(b) standard deviation

Figure 4.11: Evolution of transport indices for the various windage scenarios

Large and inconsistent differences are observed in the location of highest accumulation when the windage coefficient is changed. Overall, the results in Figure 4.12 demonstrate that the total number of beached particles increases with windage coefficient. Particles with higher windage effects drift faster towards the coastline by the onshore winds and, consequently, will also beach faster. For example, in the scenario with high windage over 80% of all particles are already beached within the first day, whereas particles with low windage arrive at the coast after 3 days and beach relatively slow. Further, when no wind effect is applied all particles remain at sea.



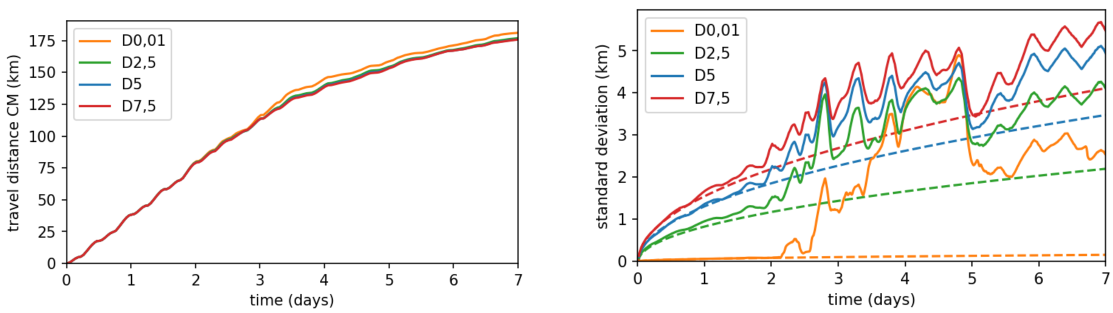
(a) shoreline distribution

(b) floating particles (%)

Figure 4.12: Evolution of fate indices for the scenarios with different windage coefficient

EFFECT OF SUBGRID DISPERSION

With increasing diffusion coefficients, the increase in spreading is in analogy to the rise in the initiated dispersion due to the random walk component (Figure 4.13 (b)). However, the spreading behaviour shows the same pattern in all simulations with significant diffusivity coefficients. This indicate that the overall behaviour is relative insensitive to exact diffusion coefficients. When looking at the scenario with a low diffusion coefficient, it is observed that still significant dispersion occurs during the simulation. A strong increase in spreading is observed after day 2. This indicates that advection gradients are dominating the spreading process in the shallow waters. This highlights the relative small impact of the diffusion coefficient on the transport.

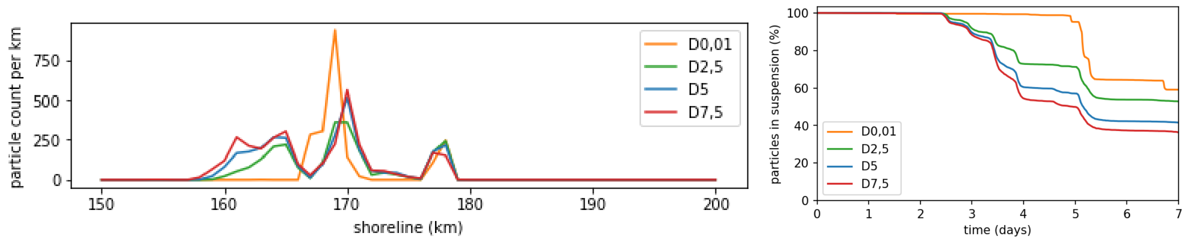


(a) travel distance

(b) standard deviation

Figure 4.13: Evolution of transport indices for the various diffusion coefficient scenarios

In Figure 4.14 the evolution of fate indices for different diffusion coefficients are compared. Varying the diffusion coefficient by 50% from the control scenario has almost no effect on the shoreline distribution (Figure 4.14 (a)), although a slight increase in the total amount of beaching occurs for higher values (Figure 4.12 (b)). Applying a very low diffusion coefficient results in a more concentrated shoreline accumulation as particles are less spread out. In this simulation, no beaching occurs below 168 km and a slight shift in the location of highest accumulations towards the west is observed.

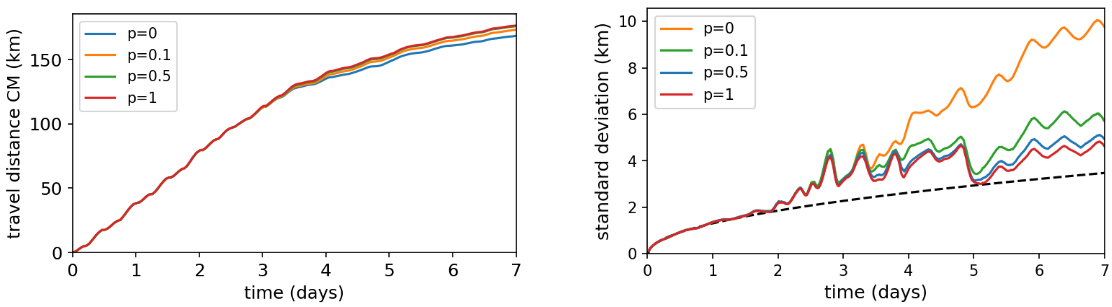


(a) shoreline distribution (b) floating particles (%)

Figure 4.14: Evolution of fate indices for the scenarios with different diffusion coefficients

EFFECT OF BEACHING

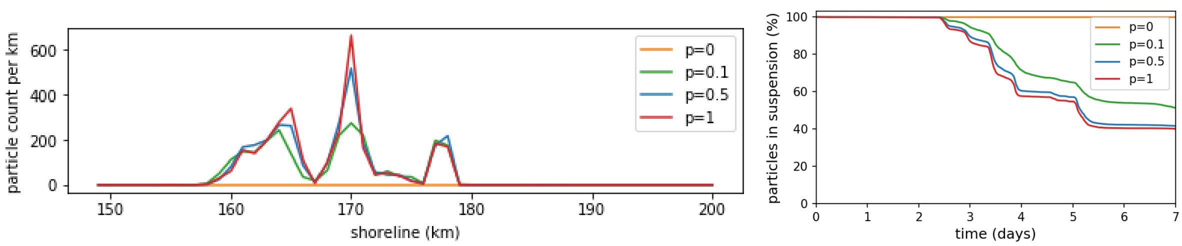
In Figure 4.15 the effect of different beaching probabilities on the transport indices are shown. The simulations that allow for beaching show only marginal differences, highlighting the insensitivity to actual beaching probability values. However, when beaching is not accounted for (p=0) the particles show a strong increase in dispersion from day 3.5 upon. This is the time when the cloud arrives at the Wadden islands. When particles can not beach they will be spread along the coastline. This is clearly observed in Figure C.12 and explains the strong increase in the standard deviation.



(a) travel distance (b) standard deviation

Figure 4.15: Evolution of transport indices for the various beaching probability scenarios

Remarkably, the location of the area with highest accumulation did not vary between the different scenarios that allow for beaching (Figure 4.16). The peak of accumulation was for all these simulations at 168 – 172 km. However, as one would expect, the rate of accumulation increased for higher beaching probabilities.



(a) shoreline distribution (b) floating particles (%)

Figure 4.16: Evolution of fate indices for the scenarios with different beaching probability

5

DISCUSSION

Before establishing the main conclusions, critical reflection on the conducted research is required. This chapter evaluates the relevance, applicability and quality of the research results, and how this fits into the current scientific knowledge. Furthermore, model limitations are reflected on.

5.1. RELEVANCE TO PRACTICE

To mitigate and reduce possible negative effects of marine plastic litter, being able to accurately predict its movement is essential. As information on the release and contribution of physical processes are often not accurately known, a better understanding of the relative importance of such parameters is required. In this respect, any contribution that is made to improve understanding on the processes that influence the transport and fate of plastics in the marine environment can be considered relevant.

This thesis has elaborated on the key parameters that drive the fate and transport of floating plastics, and explored a way to investigate their relative importance in a quantitative matter. For this, a set of indices were defined to enable statistical computations. This approach also allowed for studying how different parameter values affect the advection, dispersion and fate of simulated particles. The modelling results highlight the importance of key processes and emphasize what information is required to improve future predictions. Incorporating the findings from this study into policy decision making may support emergency response operations and monitoring strategies. For example, these findings may help prioritize data gathering, leading to more accurate modelling, and subsequently management in the future.

The practical relevance of the results is emphasized by an example. Lets consider a situation similar to the container spill event that occurred in the study area at the beginning of the year 2019 (see Section 1.4.2). For such acute spill events it is desired to minimize the environmental impact of the spill. In order to do so, emergency response operations should gather relevant data and analyse the release scenario to respond adequately. Using the results of this thesis, a prioritization of data gathering is presented. A first priority would be to analyse the characteristics of the system during and after the release. For example, during offshore wind condition it is less likely that objects travel towards the shore, whereas onshore winds may result in a quick migration towards the coastline. Such a scenario requires the responders to act quickly to minimize environmental impact. Further, the location of release should be identified. When the release occurs close to shore, it is expected that the objects are exposed to dynamic and chaotic velocity fields. Therefore, strong dispersion by turbulent mixing and differential advection may occur. If the release occurs more offshore, where the system is generally less dynamic, the transport and spreading of the patch occurs more gradually. Such a scenario give a larger time window for responders to act. In parallel, one should devote effort to find out what kind of objects are released. If the objects are buoyant, their trajectories can be significantly altered by the wind conditions. The modelling results imply that small changes in wind drift exposure can alter significant changes in trajectories and fate. They show that during onshore winds, especially highly buoyant particles end up at the beach. Further, the spatial variability in wind fields at the submesoscales may induce additional dispersion, resulting in a wider distribution. In contrast, objects with low buoyancy are less sensitive to direct wind effects and behave more as passive particles. So the potential impact is largest for nearshore releases, when onshore winds are present, and particles with high buoyancy. Such a scenario demands a quick response.

The other processes discussed in this study also contribute to determining the fate of plastics, however are considered less critical.

5.2. Applicability to other coastal waters

One must consider that coastal waters are a complex and chaotic system. On one hand, this aspect implies that the characteristics of the system can show large differences over relatively small temporal and spatial scales. This can cause relatively large changes to trajectories and fate of particles, as also highlighted by the simulations with varying release locations (Section 4.4.1) and the comparison between the control scenarios (Section 4.2). Furthermore, the transport mechanisms are to a large degree dependent on meteorological conditions. So, the driving processes may change over time. Therefore, different environmental conditions may cause quite a different movement of the patch. On the other hand, one must be aware that for other coastal waters with different characteristics, the outcomes may be different. Even cases that at first sight seem to be very similar might have a different response to the local hydrodynamics. Therefore, with regards to the generalization of the results of this research, these are now site specific and comparison with other coastal environments is required to formulate more general conclusions. However, the method of modelling used to simulate the short-term movement and fate of buoyant macroplastics can be applied to any coastal waters. All that is needed is a reliable hydrodynamic model and data on local wind fields. These data can then be used to compute the motion of particles using the particle tracking model.

As mentioned, this study did not aim to provide a fully validated model that can simulate the fate and transport of plastic particles with certainty. Validation data is required to assess the performance of the model. Due to the lack of empirical data the validation of computed particle trajectories remains problematic. Nonetheless, the model is valid with respect to its conformance to known theory and parameter constraints.

5.3. Scientific reflection

The behaviour of buoyant macroplastics in coastal waters has reveived little attention to date. Therefore, the direct comparison with previous studies is literature is limited. This study confirms that the wind coefficient is indeed an important process in the movement of buoyant macroplastics. The exposure to windage effects may have important consequences for the transport and fate of floating objects, as has been shown in this research (Section 4.4.2) as well as in literature (Breivik et al., 2011; Critchell and Lambrechts, 2016). Further, the release location has important consequences to the spreading and final fate of plastics, as it was shown that the model was sensitive to changes in release location. Remarkably, in Critchell et al. (2015) it is discussed that the release date, and therefore different weather conditions, does not affect the areas of accumulation along the shoreline. In this study, however, it is found that the fate is highly related to the forcing conditions. This discrepancy initiates that site specific conditions are indeed an important component. Moreover, the results show that the importance of dispersive processes are initially controlled by small-scale and local processes. After the initial distribution by small-scale turbulent mixing the particles are subjected to further dispersion and transport in the environment by mechanisms of larger scale. Such behaviour is also observed in field experiments Okubo (1971); LaCasce and Ohlmann (2003) and reported in literature Wright and Colling (1995); Fischer et al. (1979). On short time scales the effect of dispersion is limited, as the patch has a relative small spatial extend and is therefore dominantly transported by the bulk of the flow. However, on longer time scales (weeks to months, and lager) dispersion may result in differential gradients by large-scale eddies. This could lead to large spreading over different areas.

5.4. Model limitations

As in any model, numerical simulations require assumptions and simplifications of processes. Here, an overview of simplifying assumptions included in the model is presented, and some thoughts about their impact and validity are shared.

Delft3D-PART

Passive particle

In the model 'plastic particles' are assumed to behave as passive particles at the sea surface and do not have inertia. This is an incomplete model of real plastic particles and actual behaviour might be different from the findings presented here. For example, the geometry of an plastic object affects how it respond to the drag force induced by the flow. However, modelling realistic plastic particles is still one of the major challenges in the plastic community. Consequently, the use of passive particles was assumed to be sufficient for the purpose of this study.

Beaching and reflotation
Beaching is modelled using a probability and once particles were beached it was classed as its final destination. This is a mayor assumption. In reality, particles may undergo repeated episodes of stranding and release at the shoreline. Actual beaching is highly complex and depending on many processes including the structure of the coastline, winds, waves, tides and bathymetry. How these processes contribute to the actual beaching and reflotation is unknown.

Stokes drift
According to Stokes' theory, a particle floating on the free surface experiences a net drift velocity in the direction of the wave propagation. This net transport is known as Stokes drift. As buoyant particles are exposed to surface waves, this may be an important process for their movement. Since surface waves are formed by the friction between wind and surface water, wind waves are a function of the wind speed and generally propagating in the same direction. Therefore, the effect of Stokes drift may also be accounted for via the windage coefficient (Deltares, 2018a). This approach is commonly used in oil spill models. However, this relation only holds for certain sea states and in deeper water. For swell this relations does not hold as these waves are generated by distant weather systems and not, or only marginally, affected by local wind. Moreover, this relation does not necessarily holds in shallow waters. In this region, waves are refracted towards the coast. Given this property, though, Stokes drift results in an onshore transport component in shallow waters. Therefore, this effect may be of particular interest when studying shoreline accumulation. However, Stokes drift is a relative slow transport mechanism, therefore expected to be less relevant for short-term model simulations.

Horizontal mixing
The diffusion model has several simplifications including isotropy of the eddy diffusion, and stationary and homogeneous diffusivity. However, accurate parameterization of eddy diffusivity is problematic and an exact expression remains unknown. Such shortcomings may lead to a poor representation of particle motion due to turbulent mixing. Field measurements may reveal more insight on the diffusive structure, yet requires expensive equipment and is time consuming. However, for the relative short timescales considered in the simulations, subgrid dispersion only impose marginal effects on model results.

Vertical mixing
Plastic objects are represented by floating particles that remain at the surface. Due to this assumption vertical mixing is not taken into account. This process, however, may distribute floating particles within the mixing layer of the water column and lead to transport by subsurface currents. Yet, as the scope of this research is on buoyant macroplastics, which experience strong upward buoyancy, neglecting vertical transport seems to be a valid assumption. However, smaller particles or objects with density near water are more sensitive to vertical mixing. The effect of vertical mixing on micro- and mesoplastics in coastal waters has been addressed by Isobe et al. (2014). By combining field studies with numerical modelling, their study suggest that this mechanism is responsible for selective transport in coastal waters. Therefore, the application of this model is limited to plastics with strong buoyancy effects, i.e. macro-sized items with density lower then water, or smaller items with very low density.

HYDRODYNAMIC MODEL

The hydrodynamics used in this study are not forced by waves, so wave-induced currents are not included in the model. However, as discussed in Section 2.2, waves can induce very significant (and complex) currents and features in the surf zone. Hence, not including waves is a major limitation for transport close to shore and, consequently, to the ultimate deposition along the coastline. Taking into account wave effects would require (two-way) coupling to a wave model and high grid resolution in the nearshore. However, as the surfzone is a highly dynamic and complex system, accurately modelling the hydrodynamics in this area is challenging.

Another limitation is that the computational grid resolution is too course to accurately describe the complex bathymetry and tidal channels in the Wadden Sea. As such, it is likely that the flow and transport patterns are less accurately reproduced in this area. So, should one be interested in hindcasting or predicting actual trajectories it is important to be aware of the aforementioned limitations. This could result in discrepancy between the actual and modelled trajectories and deposition sites.

6

Conclusions and Recommendations

6.1. Conclusions

The main objective of this research is described as:

> *"To examine the most important processes, and quantify the effects of parameter uncertainty on transport and fate modelling of buoyant macroplastic in coastal waters."*

To meet this objective three research questions were proposed. The main findings of this research are illustrated below on the basis of the research questions outlined in Chapter 1.

1) What are the expected processes that drive the transport of floating plastics in coastal waters?

A literature study was conducted on the physical characteristics of plastics and transport mechanisms relevant to floating plastics in coastal waters. Following from literature, it is expected that transport of floating plastics is controlled by the physical properties of the object (density, size, and shape), conditions of the sea surface (currents, turbulence) and meteorological conditions (winds). The buoyancy of an object determines it position in the water column and therefore the exposure to external forcings. As buoyancy is a function of the density, size and shape of an object, it is determined by the characteristics of the object. The transport of floating particles are dominated by advective transport through the surface currents and winds. Wind effects the transport in two mayor ways, i.e. surface effects on the water and windage. Windage refers to the wind-induced drift on floating objects at the free surface due to the direct exposure to wind forcing. At the sea surface, particles are also subjected to horizontal turbulent mixing due to small scale processes such as shear in surface currents, wind and wave breaking. Mixing also occur due to eddies of larger scale, which can impose advective gradients over the patch. These processes impose chaotic behaviour to transport patterns and result in the spreading over a wider area.

The forcing condition during two different periods, corresponding to different wind and hydrodynamic conditions, have been investigated for the study area. Studying the residual currents in the study area showed the presence of significant hydrodynamic features, particularly in nearshore waters and close to tidal inlets. This highlights the discrepancy between transport in nearshore and open waters, where nearshore waters are much more dynamic. Further, it is observed that the residual currents are strongly influenced by wind conditions. Moreover, the importance of windage, parameterized as a function of the physical properties of an object, has been confirmed by the modelling study.

2) How can modelling techniques be used for simulating and examining the movement of floating plastic objects in the marine environment?

The movement of an object in a turbulent fluid system, such as the sea surface, can be represented by the advection-diffusion equation. From the literature review on particle transport modelling, it is found that the Lagrangian particle tracking approach is a suitable method to simulate the movement of plastic objects in the marine environment. In this approach, a large number of discrete particles floating on the water surface are used to simulate the movement of plastic objects from a release point. Such models are an effective tool to compute concentration distributions and statistical output at a particle level.

This study highlights the feasibility and utility of using a particle tracking model to simulate the movement of buoyant macroplastics in coastal waters, and to examine how they responds to the environment. In this study, the state-of-the-art Delft3D modelling software was used to carry out simulations, where Delft3D-PART allows for computing an output file that contains the coordinates of each particle at every time step. With this functionality it is possible to analyse particle behaviour in detail. In order to study their transport and fate, a set of indices were defined and computed at each time step. It was found that the travel distance and standard deviation of the floating particles propose an adequate method to study transport behaviour of the released particles. With these indices it is possible to examine the advection and dispersion of the particles throughout the simulated period. The fate was assessed by computing the state of particles (floating or beached) and the spatial distribution of beached particles. By comparing the indices, the relative importance of different processes can be studied and the effect of parameter uncertainty on the transport and fate of buoyant macroplastics can be tested.

3) What are the most important parameters that influence the transport and fate of buoyant macroplastics in coastal waters, and what is their effect?

To compute particle trajectories, the model requires input on release data and environmental data. Further, information is required for the parameterization of physical processes so that the numerical particles represent the behaviour of a buoyant macroplastic object. A control scenario was set by defining default parameter values. To put the importance of the parameters into perspective, several sensitivity scenarios were defined by varying parameter values one at a time. The importance of each parameter was assessed by a comparison with the control scenario. The effect was assessed by comparing the evolution of the indices for the set of scenarios defined for a parameter.

The parameter that influences the model results the most was the windage coefficient. Not only does windage largely control the transport and quantity of accumulation, but also the beaching time scale. For example, during onshore winds particles with high windage effects migrate quickly towards the coast. In this scenario, beaching already occurs within a day. Vice versa, particles with low windage effect travel slower towards the coast. In the simulation with high windage (5%), 99% of the particles end up at the beach in the simulations, whereas this is only 42% if a low windage (1%) is applied. Objects that are not subjected to windage effects remain all at sea and follow the hydrodynamics.

The second most important parameter was the release location. Along a complex shoreline the flow regime and, consequently, particle trajectories can differ considerably. Further, local differences in topography influences the interaction with the shoreline, which has an effect on the beaching of particles. Therefore, testing different release locations showed strong variations and is considered the second most important parameter. However, when particles are released more offshore, their behaviour becomes less variable. This indicates that the actual source location is of less critical importance in the open sea.

For the other investigated parameters (time of release, turbulent diffusion, beaching probability) the effect on model results is less critical, although they can still impact model results. For example, only marginal differences in shoreline distributions are observed between scenarios with different beaching probabilities, and this process is only important when particles drift towards the coastline and interact with land. Further, the inclusion of subgrid dispersion, used to account for the mixing processes missing in the forcing data, is found to be relevant. However, the overall behaviour is relatively insensitive to the applied diffusion coefficient.

6.2. RECOMMENDATIONS

The research on plastic behaviour in the coastal environment is still in its early stage, and much has yet to be revealed. Along with the complex nature of coastal waters, modelling plastic transport requires many simplifications. Therefore, further improve understanding of buoyant macroplastic behaviour is required. Based on the findings in this study, several recommendations for future research are presented.

Collection of more field data and model validation
The scarcity of field data on which to validate is one of the key limitations in plastic transport modelling, and therefore this thesis. Hence, additional data collection is essential for future work. To assess and improve the reliability of models validation data is required. At the very least, a comparison between observed and modelled trajectories should be made. This can be done by deploying surface drifters in the field and tracking their position, for example using drifters as in Meyerjürgens et al. (2019). Further, it is advised to put more effort in collecting useful data on plastic litter in the marine environment. The easiest and cheapest way to collect data are beach cleanups. Beach cleanup data provides insight into the flux of plastic litter. This information can also reveal better insight into the beaching process. However existing data lacks in consistency and monitoring frequency. Often, measurements have irregular frequencies or inconsistent description. This should be improved to obtain useful data. If the source and final deposition location is known, numerical tools can be used to examine the transport routes of the different types of plastic litter. Therefore, measurement campaigns should also be focused on source quantification. Together, these developments will help to work towards the ultimate goal of obtaining a valid model where one can simulate the transport and fate of different type of plastics accurately.

Carry out experiments and explore processes
To evaluate the role of the individual physical processes and how they affect the movement of buoyant macroplastics, experimental research is recommended. The same drifter experiments used to validate modelled trajectories, as stated above, can also be used investigate the influence of key processes. By comparing the drifter position data to local wind field observations and hydrodynamic data, one can assess how the drivers are contributing to the transport. Here, it is of interest to investigate different regions, such as the open sea and coastal waters. Further, experiments in controlled condition can aid to improve the parameterization of the key physical processes. For example, coupling the intrinsic physical properties of plastics with hydrodynamic processes under controlled conditions in the laboratory can reveal behavioural relations to the size, shape and density of plastics. Another important issue to solve would be to parameterizing accurately the effect of windage, as the results show that this is an critical processes. Whether the applied windage coefficients hold true in reality can be researched in future studies with experiments using different plastic objects. Further, it would be of interest to investigate to what degree waves contribute to the transport.

Effect of uncertainties in environmental data
Obtaining high quality data regarding the surface currents and the near-surface wind field in coastal waters remains a challenge. Fluctuations in the velocity field may cause different spreading behaviour. As this study highlights the importance of forcing conditions, it is recommendation for future research to be directed on identify the effect of uncertainties in the environmental data to the transport, dispersion and fate of surface particles.

Carry out more model simulations
In this study, a limited number of simulations are carried out. To obtain more comprehensive insight into the generality of the model results and the behaviour of buoyant macroplastics, more model simulations are required. Expanding the scenario analysis does not only allow for trends to be compared and highlighted, but also allows for exploring new hypotheses.

1. *Expand number of scenarios*
   In this study only a limited number of parameter values are used for the simulations. It would be of interest to expand the number of scenarios for the most important parameters. By carrying out more model simulations one can obtain more insight into correlations between the system behaviour and the parameter under consideration.

2. *Other forcing conditions*
   This study only focused on conditions with strong winds. It is of interest to investigate how the system behaves under other conditions, for example during weak wind conditions or winds from other directions.

3. *Different release sources*
   This study only accounts for marine input sources. It is recommended to also explore the transport and fate from other sources (e.g. rivers, coastal cities).

4. *Complete spatial mapping*
   Future research may also be directed to expanding the simulations to a greater area, where particles are released from a variety of sources. By performing many simulations with a large number of particles release locations allows for identifying areas of interest. For example, investigating what beaches are most likely to accumulate large quantities and relating this to topographic characteristics can provide relevant input to emergency response operations (e.g. to achieve maximum debris removal after a spill event) and aid to monitoring programs (e.g. to identify areas of interest for data collection).

5. *Comparison to other coastal areas*
   To obtain a more comprehensive insight into the applicability of the model results, it is recommended to carry out model simulation in different coastal areas and compare with trends highlighted in this study.

Expand model modalities
It is recommended to further develop the particle tracking model by including more model modalities:

1. *Include effect of waves*
   Waves can induce important transport features close to shore. To improve transport modelling near the coast, further research should be directed to assess the contribution of waves. Further, transport by Stokes drift enhances drift towards the coast in nearshore waters. Therefore, waves are expected to enhance beaching. By including the effect of waves in the model, simulations can be used to explore the relative contribution of waves.

2. *Probabilistic input*
   When accurate information in data input is not known, the model results may contain a great amount of uncertainty. To tackle this problem an ensemble simulation, consisting of many separate simulations with slightly different parameter values, could provide a method to indicate the level of confidence of model results. Implementing a tool that allows for defining stochastic input parameters, for example using Monte Carlo sampling techniques, can present an efficient method to take uncertainties into account in model results. This will aid to the usability of the model.

References

Alves, T. M., Kokinou, E., Zodiatis, G., Lardner, R., Panagiotakis, C., and Radhakrishnan, H. (2015). Modelling of oil spills in confined maritime basins: The case for early response in the eastern mediterranean sea. *Environmental Pollution*, 206:390–399.

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine pollution bulletin*, 62(8):1596–1605.

Andrady, A. L. (2015). Persistence of plastic litter in the oceans. In *Marine anthropogenic litter*, pages 57–72. Springer, Cham.

Andrady, A. L. and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):1977–1984.

Astudillo, J. C., Bravo, M., Dumont, C. P., and Thiel, M. (2009). Detached aquaculture buoys in the se pacific: potential dispersal vehicles for associated organisms. *Aquatic Biology*, 5(3):219–231.

Barnes, D. K., Galgani, F., Thompson, R. C., and Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 364(1526):1985–1998.

Barnes, D. K., Walters, A., and Gonçalves, L. (2010). Macroplastics at sea around antarctica. *Marine Environmental Research*, 70(2):250–252.

Barry, M., Elema, I., and Van Der Molen, P. (2006). Governing the north sea in the netherlands. *Administering Marine Spaces: International Issues*, page 64.

Bergmann, M., Sandhop, N., Schewe, I., and D'Hert, D. (2016). Observations of floating anthropogenic litter in the barents sea and fram strait, arctic. *Polar biology*, 39(3):553–560.

Blaas, M., Cronin, K., El Serafy, G., Friocourt, Y., Triana, I. G., Aguilar, S. G., and Keetels, G. (2012). Mos2: Model setup, data assimilation and skill assessment. Technical report, Deltares report.

Bosboom, J. and Stive, M. J. (2012). *Coastal Dynamics I: Lectures Notes CIE4305*. VSSD.

Breivik, Ø. and Allen, A. A. (2008). An operational search and rescue model for the norwegian sea and the north sea. *Journal of Marine Systems*, 69(1-2):99–113.

Breivik, Ø., Allen, A. A., Maisondieu, C., and Roth, J. C. (2011). Wind-induced drift of objects at sea: The leeway field method. *Applied Ocean Research*, 33(2):100–109.

Charnock, H., Dyer, K., Huthnance, J., Liss, P., and Simpson, B. (1994). *Understanding the North Sea System*. Springer Science & Business Media.

Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., and Fujikura, K. (2018). Human footprint in the abyss: 30 year records of deep-sea plastic debris. *Marine Policy*.

Cole, M., Lindeque, P., Halsband, C., and Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: a review. *Marine pollution bulletin*, 62(12):2588–2597.

Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á. T., Navarro, S., García-de Lomas, J., Ruiz, A., et al. (2014). Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences*, 111(28):10239–10244.

Critchell, K., Grech, A., Schlaefer, J., Andutta, F., Lambrechts, J., Wolanski, E., and Hamann, M. (2015). Modelling the fate of marine debris along a complex shoreline: Lessons from the great barrier reef. *Estuarine, Coastal and Shelf Science*, 167:414–426.

Critchell, K. and Lambrechts, J. (2016). Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical processes? *Estuarine, Coastal and Shelf Science*, 171:111–122.

Cronin, K. and Blaas, M. (2013). Mos2-ii determinisitic model calibration; updates of the hydrodynamic and spm model. Technical report, Deltares report.

Deltares (2018a). D-waq part, user manual. *Version: 2.15*.

Deltares (2018b). Delft3d-flow, user manual. *Version: 3.15*.

Derraik, J. G. (2002). The pollution of the marine environment by plastic debris: a review. *Marine pollution bulletin*, 44(9):842–852.

Dimou, K. N. and Adams, E. E. (1993). A random-walk, particle tracking model for well-mixed estuaries and coastal waters. *Estuarine, Coastal and Shelf Science*, 37(1):99–110.

Do Sul, J. A. I. and Costa, M. F. (2013). Plastic pollution risks in an estuarine conservation unit. *Journal of Coastal Research*, 65(sp1):48–54.

Duhec, A. V., Jeanne, R. F., Maximenko, N., and Hafner, J. (2015). Composition and potential origin of marine debris stranded in the western indian ocean on remote alphonse island, seychelles. *Marine pollution bulletin*, 96(1-2):76–86.

Ecomare (2013). *Sea currents*.

Ellen MacArthur Foundation (2016). The new plastics economy: rethinking the future of plastics. In *World Economic Forum*.

Elliott, A., Barr, A., and Kennan, D. (1997). Diffusion in irish coastal waters. *Estuarine, Coastal and Shelf Science*, 44:15–23.

Erni-Cassola, G., Zadjelovic, V., Gibson, M. I., and Christie-Oleza, J. A. (2019). Distribution of plastic polymer types in the marine environment; a meta-analysis. *Journal of hazardous materials*, 369:691–698.

Fick, A. (1855). On liquid diffusion. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 10(63):30–39.

Filella, M. (2015). Questions of size and numbers in environmental research on microplastics: methodological and conceptual aspects. *Environmental Chemistry*, 12(5):527–538.

Fischer, H. B., List, J. E., Koh, C. R., Imberger, J., and Brooks, N. H. (1979). *Mixing in inland and coastal waters*. Elsevier.

G7 (2015). *Leaders' declaration: G7 summit, 7–8 June 2015*.

Galgani, F., Hanke, G., Werner, S., and De Vrees, L. (2013). Marine litter within the european marine strategy framework directive. *ICES Journal of Marine Science*, 70(6):1055–1064.

Gall, S. C. and Thompson, R. C. (2015). The impact of debris on marine life. *Marine pollution bulletin*, 92(1-2):170–179.

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science advances*, 3(7):e1700782.

Gräwe, U., Flöser, G., Gerkema, T., Duran-Matute, M., Badewien, T. H., Schulz, E., and Burchard, H. (2016). A numerical model for the entire wadden sea: skill assessment and analysis of hydrodynamics. *Journal of Geophysical Research: Oceans*, 121(7):5231–5251.

Griffa, A. (1996). Applications of stochastic particle models to oceanographic problems. In *Stochastic modelling in physical oceanography*, pages 113–140. Springer.

Hardesty, B. D., Harari, J., Isobe, A., Lebreton, L., Maximenko, N., Potemra, J., van Sebille, E., Vethaak, A. D., and Wilcox, C. (2017). Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Frontiers in Marine Science*, 4:30.

Hartmann, N., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T. M., Brennholt, N., Cole, M., et al. (2019). Are we speaking the same language? recommendations for a definition and categorization framework for plastic debris. *Environmental science & technology*.

Hinojosa, I. A. and Thiel, M. (2009). Floating marine debris in fjords, gulfs and channels of southern chile. *Marine pollution bulletin*, 58(3):341–350.

Hofland, B. and van der Mheen, M. (2015). 2d physical model tests for the ocean cleanup.

Howarth, M. (2001). North sea circulation.

ICES (1983). Flushing times of the north sea.

Isobe, A., Kubo, K., Tamura, Y., Nakashima, E., Fujii, N., et al. (2014). Selective transport of microplastics and mesoplastics by drifting in coastal waters. *Marine pollution bulletin*, 89(1-2):324–330.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., and Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, 347(6223):768–771.

Jones, C. E., Dagestad, K.-F., Breivik, Ø., Holt, B., Röhrs, J., Christensen, K. H., Espeseth, M., Brekke, C., and Skrunes, S. (2016). Measurement and modeling of oil slick transport. *Journal of Geophysical Research: Oceans*, 121(10):7759–7775.

Jordan, C. (2009). *Message of the Gyre*.

Kako, S., Isobe, A., Magome, S., Hinata, H., Seino, S., and Kojima, A. (2011). Establishment of numerical beach-litter hindcast/forecast models: An application to goto islands, japan. *Marine pollution bulletin*, 62(2):293–302.

KNMI (n.d.). KNMI - Archief maand,seizoen en jaaroverzichten.
https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/.

Krestenitis, Y., Kombiadou, K., and Savvidis, Y. (2007). Modelling the cohesive sediment transport in the marine environment: the case of thermaikos gulf. *Ocean Science*, 3(1):91–104.

LaCasce, J. and Bower, A. (2000). Relative dispersion in the subsurface north atlantic. *Journal of marine research*, 58(6):863–894.

LaCasce, J. and Ohlmann, C. (2003). Relative dispersion at the surface of the gulf of mexico. *Journal of Marine Research*, 61(3):285–312.

Lebreton, L., Greer, S., and Borrero, J. C. (2012). Numerical modelling of floating debris in the world's oceans. *Marine Pollution Bulletin*, 64(3):653–661.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., et al. (2018). Evidence that the great pacific garbage patch is rapidly accumulating plastic. *Scientific reports*, 8(1):4666.

Lebreton, L. C., Van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature communications*, 8:15611.

Lenhart, H. and Pohlmann, T. (1997). The ices-boxes approach in relation to results of a north sea circulation model. *Tellus A*, 49(1):139–160.

Lesser, G. R., Roelvink, J. v., Van Kester, J., and Stelling, G. (2004). Development and validation of a three-dimensional morphological model. *Coastal engineering*, 51(8-9):883–915.

Liubartseva, S., Coppini, G., Lecci, R., and Creti, S. (2016). Regional approach to modeling the transport of floating plastic debris in the adriatic sea. *Marine pollution bulletin*, 103(1-2):115–127.

Mariano, A. J., Kourafalou, V. H., Srinivasan, A., Kang, H., Halliwell, G., Ryan, E., and Roffer, M. (2011). On the modeling of the 2010 gulf of mexico oil spill. *Dynamics of Atmospheres and Oceans*, 52(1-2):322–340.

Mason, E., Colas, F., and Pelegrí, J. L. (2012). A lagrangian study tracing water parcel origins in the canary upwelling system. *Scientia Marina*, 76(S1):79–94.

Maximenko, N., Corradi, P., Law, K. L., Van Sebille, E., Garaba, S. P., Lampitt, R. S., Galgani, F., Martinez-Vicente, V., Goddijn-Murphy, L., Veiga, J. M., et al. (2019). Toward the integrated marine debris observing system. *Frontiers in Marine Science*, 6.

Maximenko, N., Hafner, J., and Niiler, P. (2012). Pathways of marine debris derived from trajectories of lagrangian drifters. *Marine pollution bulletin*, 65(1-3):51–62.

McCormack, R. (2019). *Ocean Voyages Institute*.

Meyerjürgens, J., Badewien, T. H., Garaba, S. P., Wolff, J.-O., and Zielinski, O. (2019). A state-of-the-art compact surface drifter reveals pathways of floating marine litter in the german bight. *Frontiers in Marine Science*, 6:58.

Morét-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, E. K., Peacock, E. E., and Reddy, C. M. (2010). The size, mass, and composition of plastic debris in the western north atlantic ocean. *Marine Pollution Bulletin*, 60(10):1873–1878.

MSFD (2013). *Marine Strategy Framework Directive GES Technical Group on Marine Litter.* Guidance on monitoring of marine litter in European Seas, Technical Report EUR 26113 EN. Joint Research Commission (JRC).

Murray, C. C., Maximenko, N., and Lippiatt, S. (2018). The influx of marine debris from the great japan tsunami of 2011 to north american shorelines. *Marine pollution bulletin*, 132:26–32.

NOAA (2016). Modeling oceanic transport of floating marine debris. *Marine Debris Program Report.*

Okubo, A. (1971). Oceanic diffusion diagrams. In *Deep sea research and oceanographic abstracts*, volume 18, pages 789–802. Elsevier.

OSPAR (2000). Quality status report 2000 region ii greater north sea.

Otto, L., Zimmerman, J., Furnes, G., Mork, M., Saetre, R., and Becker, G. (1990). Review of the physical oceanography of the north sea. *Netherlands journal of sea research*, 26(2-4):161–238.

Paris, C. B., Cowen, R. K., Claro, R., and Lindeman, K. C. (2005). Larval transport pathways from cuban snapper (lutjanidae) spawning aggregations based on biophysical modeling. *Marine Ecology Progress Series*, 296:93–106.

PlasticEurope (2018). Plastics—the facts 2018.

Poje, A. C., Özgökmen, T. M., Lipphardt, B. L., Haus, B. K., Ryan, E. H., Haza, A. C., Jacobs, G. A., Reniers, A., Olascoaga, M. J., Novelli, G., et al. (2014). Submesoscale dispersion in the vicinity of the deepwater horizon spill. *Proceedings of the National Academy of Sciences*, 111(35):12693–12698.

Richardson, L. F. and Stommel, H. (1948). Note on eddy diffusion in the sea. *Journal of Meteorology*, 5(5):238–240.

Rodhe, J. (1998). The baltic and north seas: a process-oriented review of the physical oceanography. *The sea*, 11:699–732.

Ross, D. (1995). *Introduction to oceanography.* Harper Collins College Publisher.

Ryan, P. G. (2015a). A brief history of marine litter research. In *Marine anthropogenic litter*, pages 1–25. Springer.

Ryan, P. G. (2015b). Does size and buoyancy affect the long-distance transport of floating debris? *Environmental Research Letters*, 10(8):084019.

Ryan, P. G., Moore, C. J., van Franeker, J. A., and Moloney, C. L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):1999–2012.

Stewart, R. H. (2008). *Introduction to physical oceanography*. Texas A & M University College Station.

Stuparu, D., Van Der Meulen, M., Kleissen, F., Vethaak, D., and El Serafy, G. (2015). Developing a transport model for plastic distribution in the north sea. In *E-proceedings of the 36th IAHR World Congress*, volume 28.

Sundermann, J. (2003). The changing north sea: knowledge, speculation and new challenges. *Oceanologia*, 45(2).

Sutherland, W. J., Clout, M., Côté, I. M., Daszak, P., Depledge, M. H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D. W., Lurio, J. D., Impey, A. J., Lickorish, F., Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L. S., Pretty, J., Prior, S., Redford, K. H., Scharlemann, J. P., Spalding, M., and Watkinson, A. R. (2010). A horizon scan of global conservation issues for 2010. *Trends in Ecology Evolution*, 25(1):1 – 7.

Thompson, C. (2015). *Environmental Protection Agency*.

Thompson, R. C., Moore, C. J., Vom Saal, F. S., and Swan, S. H. (2009a). Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526):2153–2166.

Thompson, R. C., Swan, S. H., Moore, C. J., and Vom Saal, F. S. (2009b). Our plastic age.

Tiessen, M., Fernard, L., Gerkema, T., van Der Molen, J., Ruardij, P., and van Der Veer, H. (2014). Numerical modelling of physical processes governing larval transport in the southern north sea. *Ocean Science*, 10(3):357.

Uijttewaal, W. (2018). CIE5312: Turbulence in hydraulics [lecture slides].

UNEP (2014). *United Nations Environment Programme Year Book 2014: Emerging Issues in Our Global Environment*.

Van Cauwenberghe, L. and Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environmental pollution*, 193:65–70.

Van den Boogaard, H., Hoogkamer, M., and Heemink, A. (1993). Parameter identification in particle models. *Stochastic Hydrology and Hydraulics*, 7(2):109–130.

Van der Kaaij, T., van Kessel, T., Troost, T., Herman, P., van Duren, L., and Villars, N. (2017). *Modelondersteuning MER winning suppletie-en ophoogzand Noordzee 2018-2027: modelvalidatie*. Deltares.

Van Sebille, E., Griffies, S. M., Abernathey, R., Adams, T. P., Berloff, P., Biastoch, A., Blanke, B., Chassignet, E. P., Cheng, Y., Cotter, C. J., et al. (2018). Lagrangian ocean analysis: Fundamentals and practices. *Ocean Modelling*, 121:49–75.

Van Vledder, G. P. and Adema, J. (2007). Hydrodynamics in the wadden sea during storm conditions.

Vegter, A. C., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M. L., Costa, M. F., Eriksen, M., Eriksson, C., Estrades, A., et al. (2014). Global research priorities to mitigate plastic pollution impacts on marine wildlife. *Endangered Species Research*, 25(3):225–247.

Veiga, J. M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., Galgani, F., Thompson, R. C., Dagevos, J., Gago, J., et al. (2016). identifying sources of marine litter. msfd ges tg marine litter thematic report. In *JRC Technical Report*.

Waldschlager, K. and Schuttrumpf, H. (2019). Effects of particle properties on the settling and rise velocities of microplastics in freshwater under laboratory conditions. *Environmental science & technology*, 53(4):1958–1966.

Weisse, R. and von Storch, H. (2010). *Marine climate and climate change: storms, wind waves and storm surges*. Springer Science & Business Media.

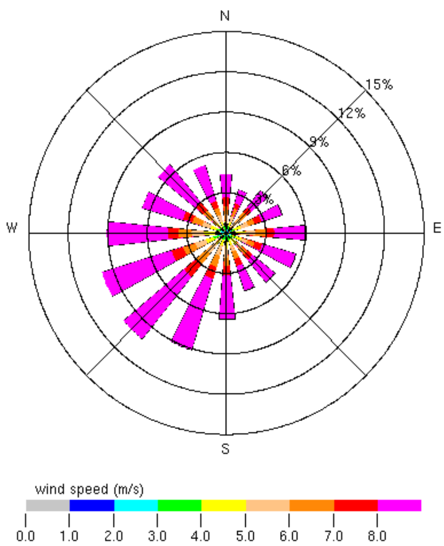
Wright, J. and Colling, A. (1995). *Seawater: its composition, properties, and behaviour*, volume 2. Pergamon.

Zhang, H. (2017). Transport of microplastics in coastal seas. *Estuarine, Coastal and Shelf Science*, 199:74–86.

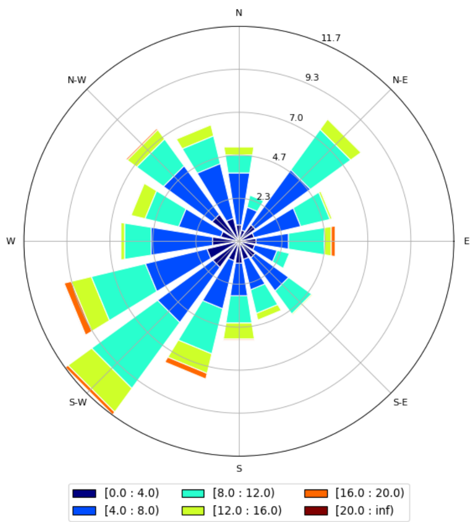
A

ADDITIONAL FORCING DATA

A.1. WIND CLIMATE



(a) Long-term annual averaged wind conditions (retrieved from waveclimate.com)



(b) Averaged wind conditions in 2010

Figure A.1: Wind roses for the study area

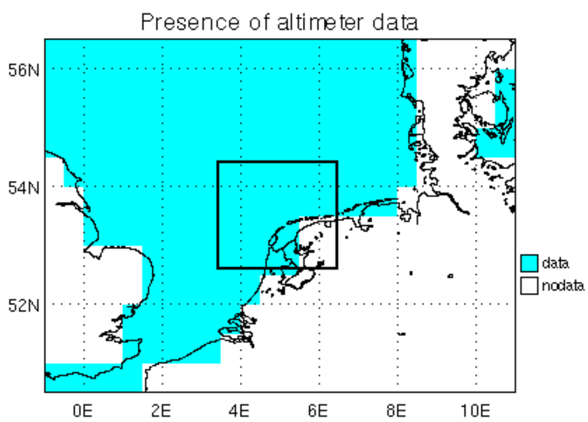


Figure A.2: Area used for retrieving the long-term annual averagerd wind conditions. Center of area is at 53° 30’N, 5° 36’E

A.2. CONDITIONS DURING PERIOD 1

WATERLEVEL

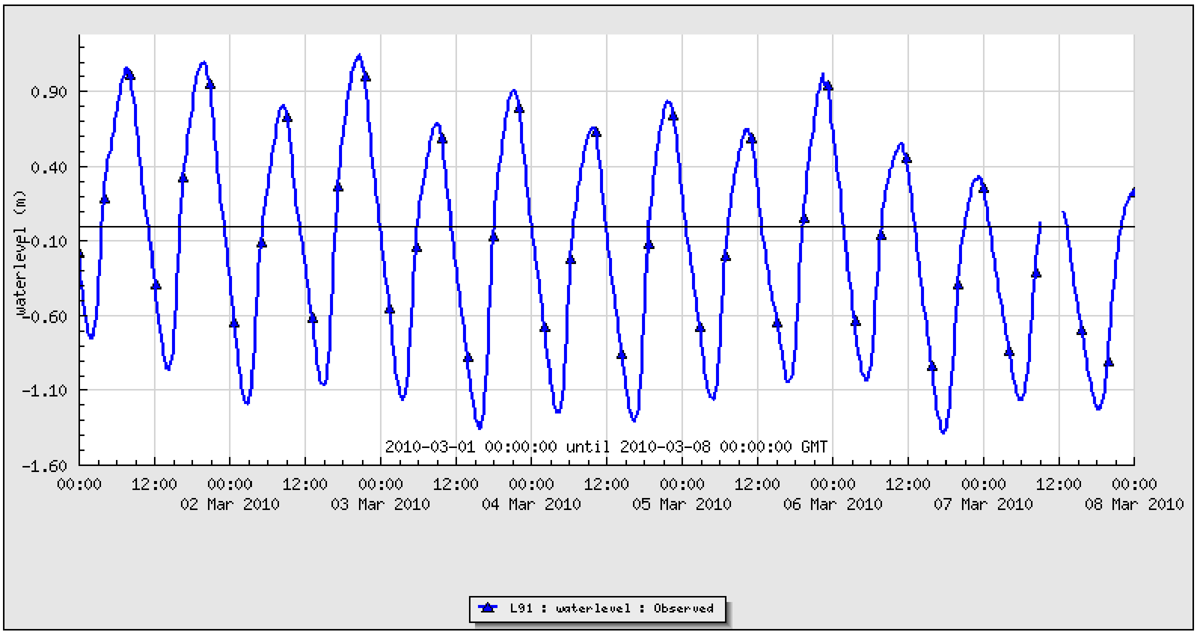


Figure A.3: Waterlevel

WIND CHARACTERISTICS

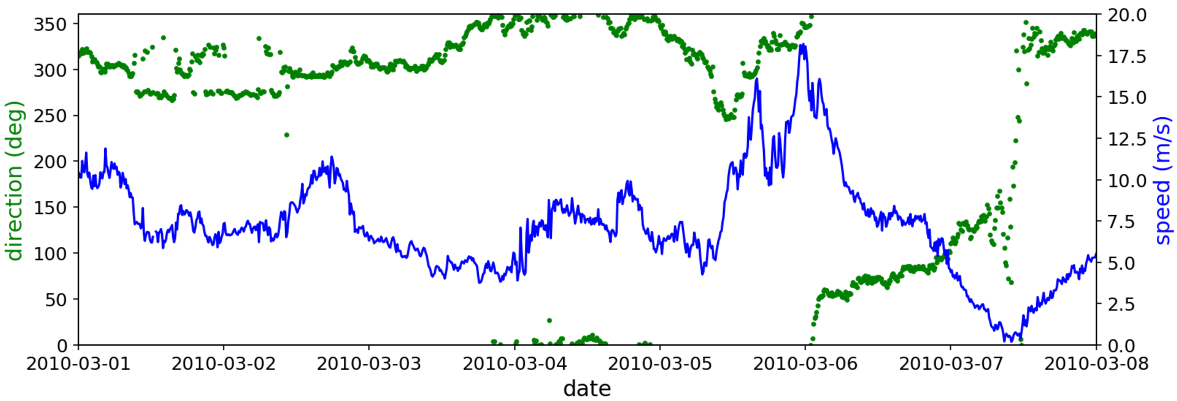


Figure A.4: Wind speed (blue) and direction (green) during simulation period 1

	mean	std	min	25%	50%	75%	peak
speed (m/s)	7.2	3.1	0.2	5.4	7.0	8.8	18.2
direction (°N)	320 (NW)	-	-	153	301	328	340

Table A.1: Statistics of wind speed during simulation period 1

A.3. CONDITIONS DURING PERIOD 2

WATERLEVEL

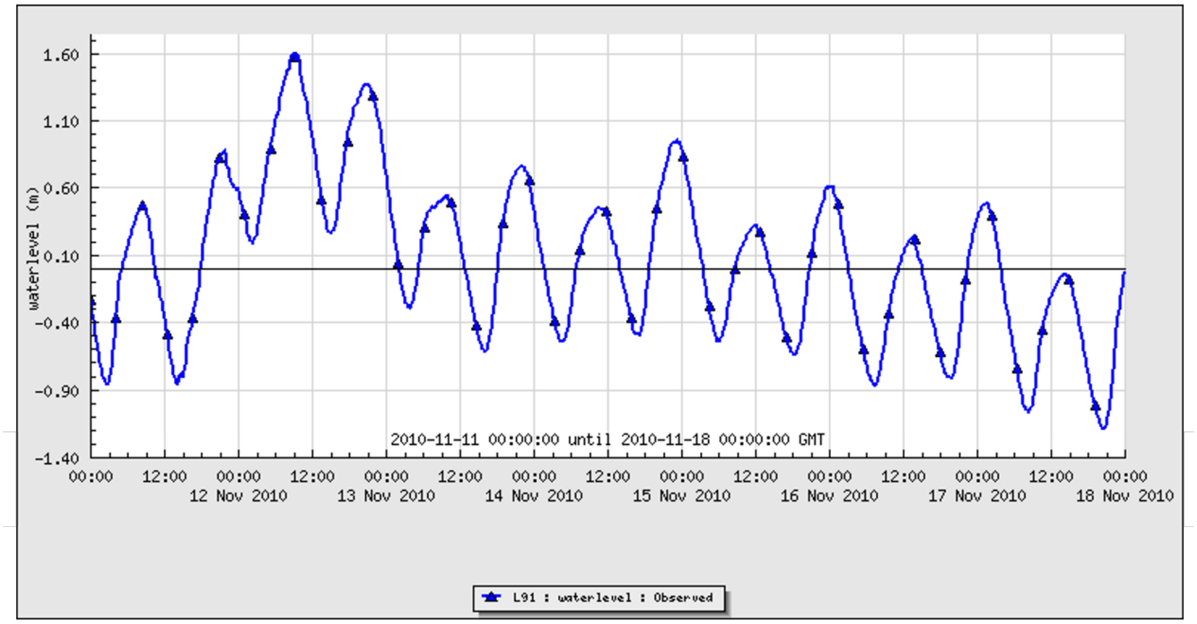


Figure A.5: Waterlevel

WIND CHARACTERISTICS

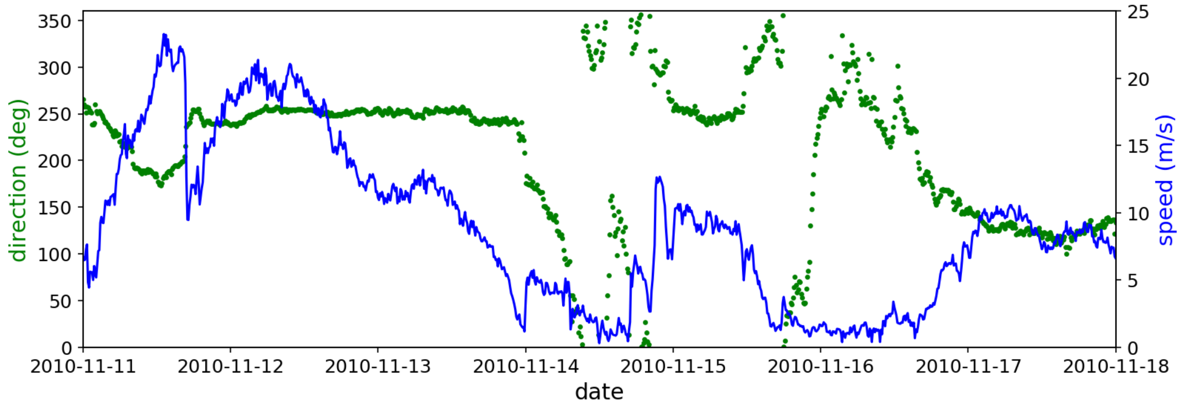


Figure A.6: Wind speed (blue) and direction (green) during simulation period 2

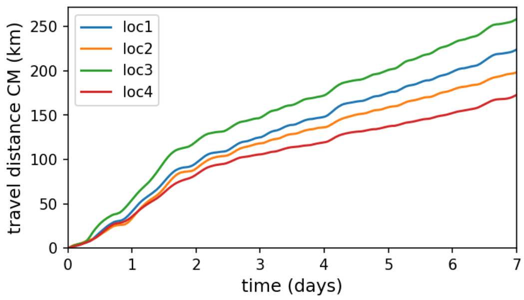
	mean	std	min	25%	50%	75%	peak
speed (m/s)	9.0	5.9	0.3	4.0	8.6	12.3	23.3
direction (°N)	220 (SW)	-	-	154	242	254	180

Table A.2: Statistics of wind speed during simulation period 2

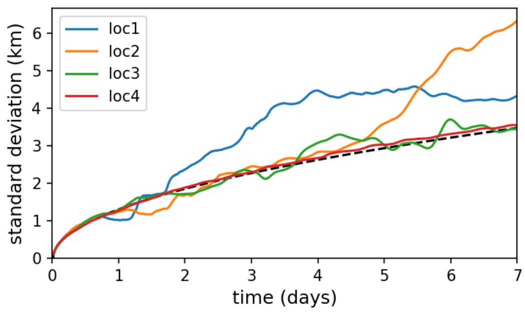
B

Output parameters for period 2

B.1. Release parameters

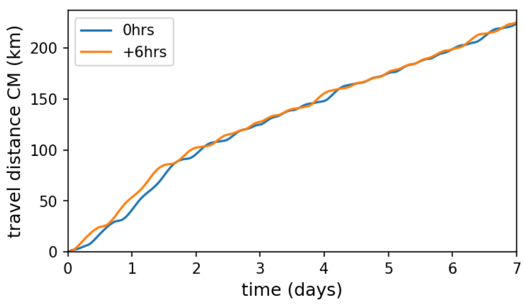


(a) travel distance

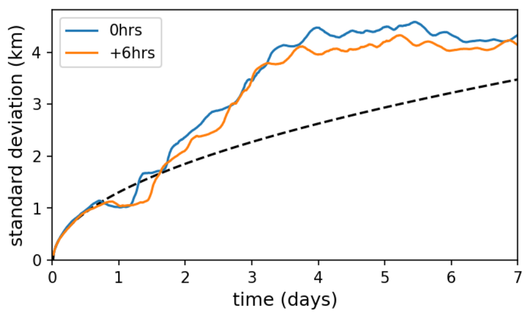


(b) standard deviation

Figure B.1: Evolution of transport indices for the various release location scenarios



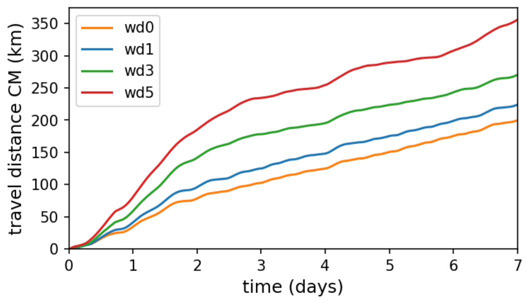
(a) travel distance



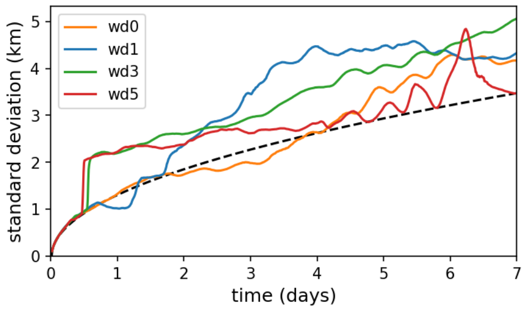
(b) standard deviation

Figure B.2: Evolution of transport indices for the various release moment scenarios

B.2. PROCESS PARAMETERS

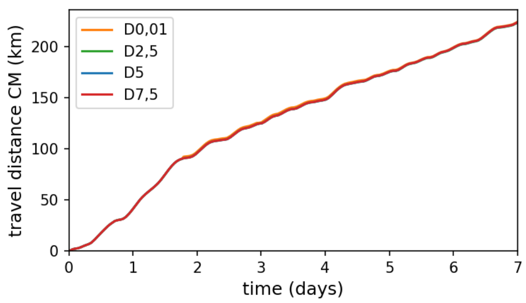


(a) travel distance

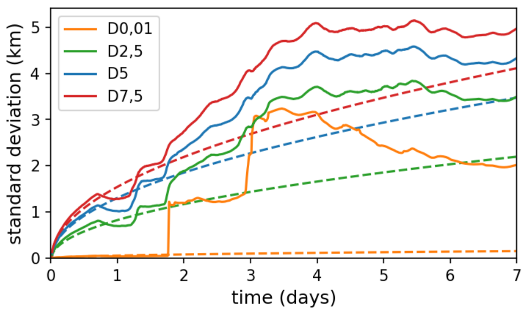


(b) standard deviation

Figure B.3: Evolution of transport indices for the various windage scenarios

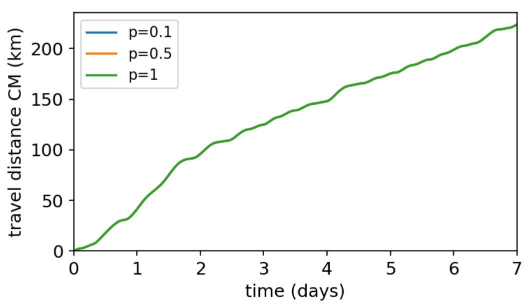


(a) travel distance

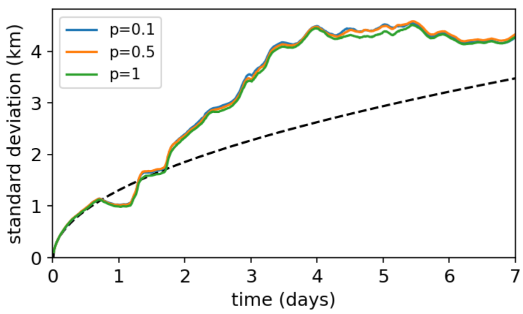


(b) standard deviation

Figure B.4: Evolution of transport indices for the various diffusion coefficient scenarios



(a) travel distance



(b) standard deviation

Figure B.5: Evolution of transport indices for the various beaching probability scenarios

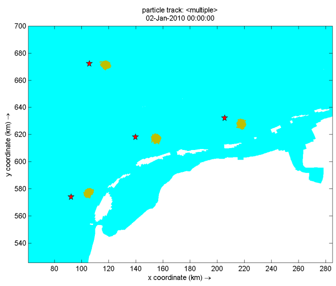
C

SUPPORTING FIGURES

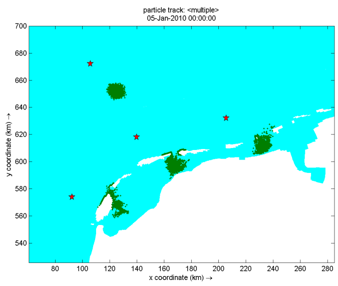
Snapshots of the particle distribution for different release locations. The red star marks the release location.

C.1. OVERVIEW PLOTS PERIOD 1

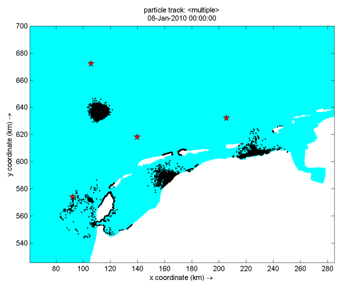
LOCATION



(a) t= 1day



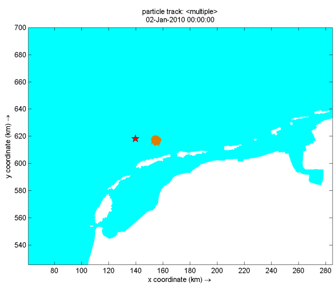
(b) t= 4day



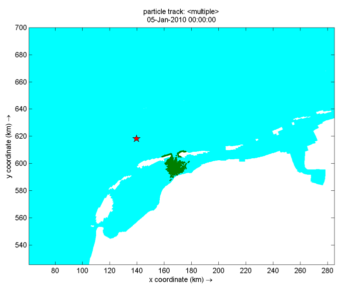
(c) t= 7day

Figure C.1: Release location scenarios

TIME OF RELEASE



(a) t= 1day



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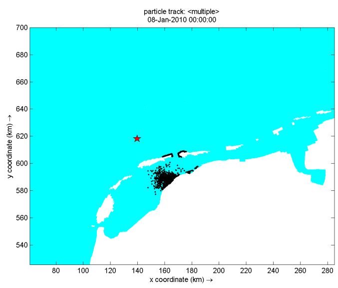
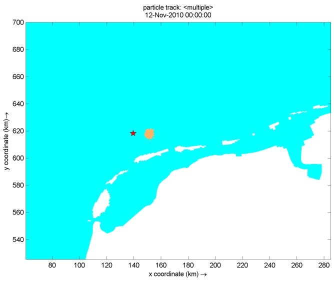
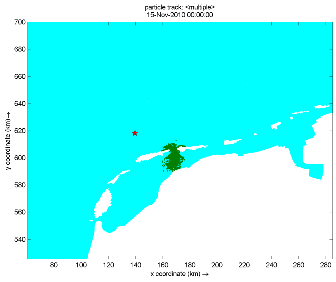


(c) t= 7day

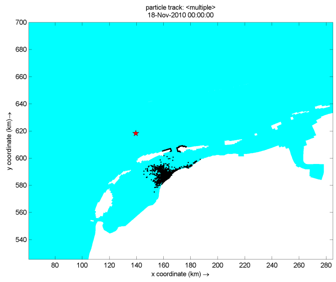
Figure C.2: 0hrs (control scenario)



(a) t= 1day



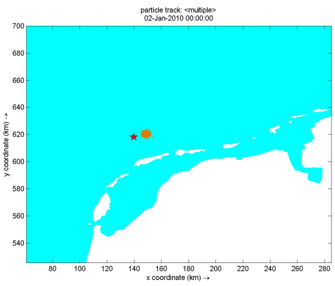
(b) t= 4day



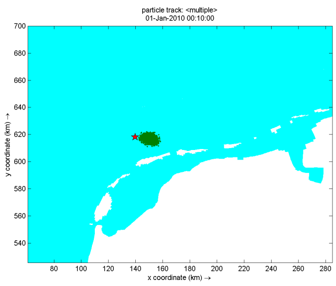
(c) t= 7day

Figure C.3: +6hrs

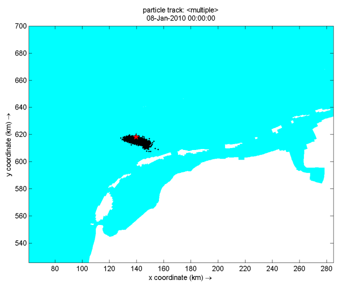
WINDAGE



(a) t= 1day

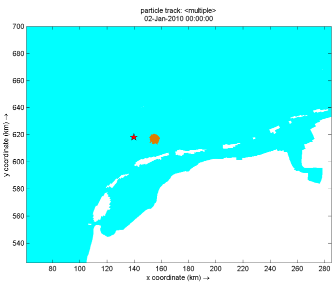


(b) t= 4day

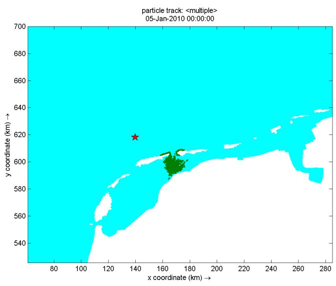


(c) t= 7day

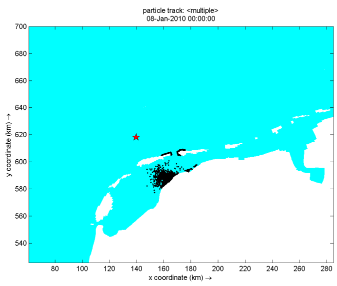
Figure C.4: wd = 0%



(a) t= 1day

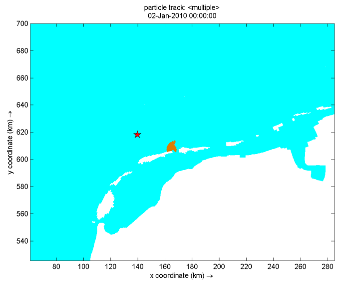


(b) t= 4day

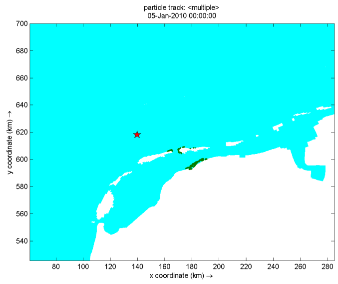


(c) t= 7day

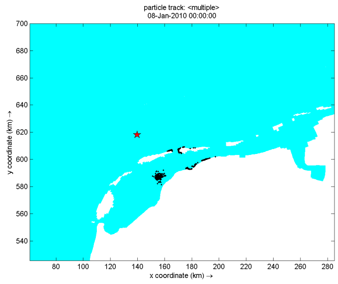
Figure C.5: wd = 1% (control scenario)



(a) t= 1day

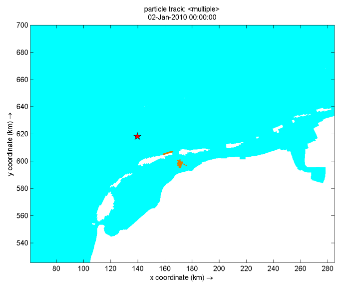


(b) t= 4day

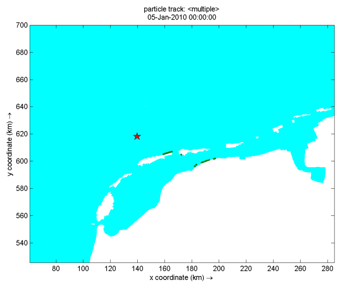


(c) t= 7day

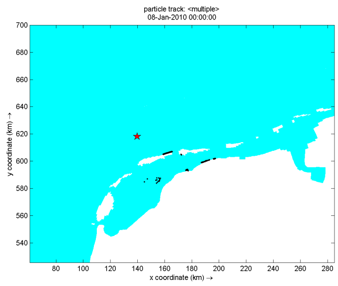
Figure C.6: wd = 3%



(a) t= 1day



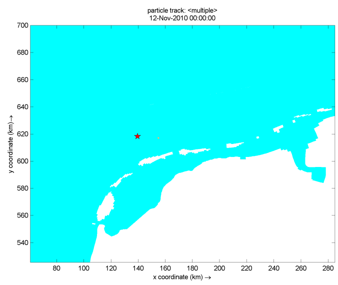
(b) t= 4day



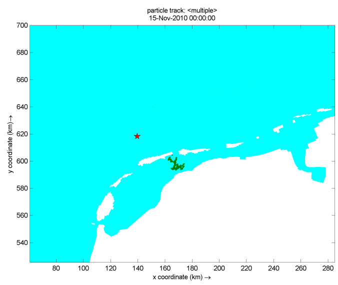
(c) t= 7day

Figure C.7: wd = 5%

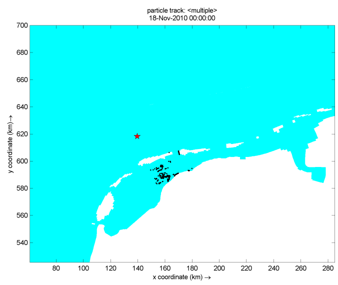
DIFFUSION COEFFICIENT



(a) t= 1day

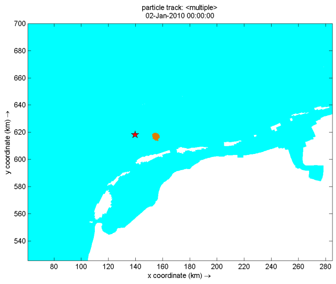


(b) t= 4day

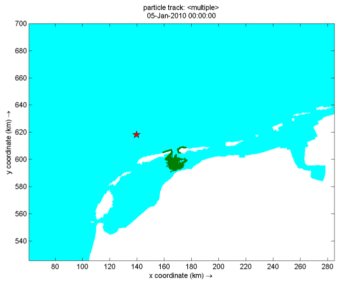


(c) t= 7day

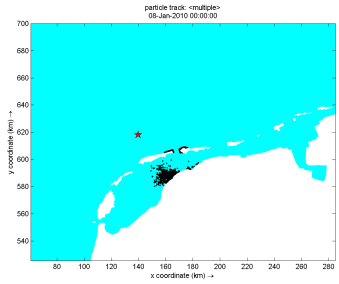
Figure C.8: D = 0.01



(a) t= 1day

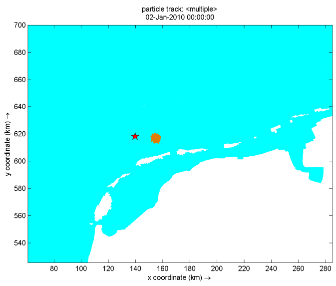


(b) t= 4day

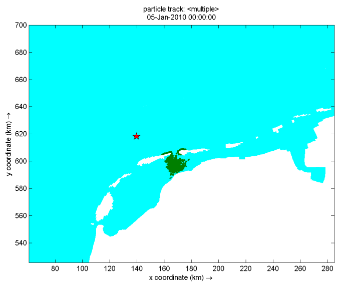


(c) t= 7day

Figure C.9: D = 2.5



(a) t= 1day



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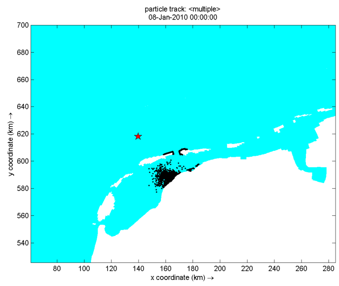
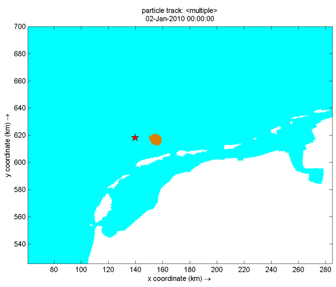
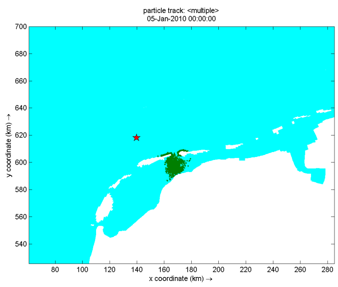


(c) t= 7day

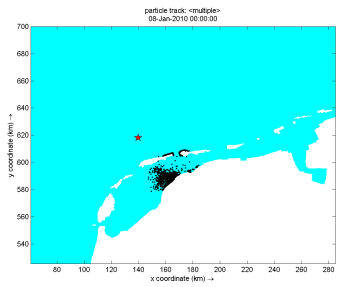
Figure C.10: D = 5 (control scenario)



(a) t= 1day



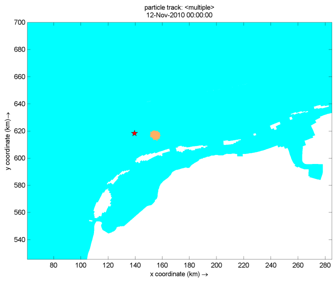
(b) t= 4day



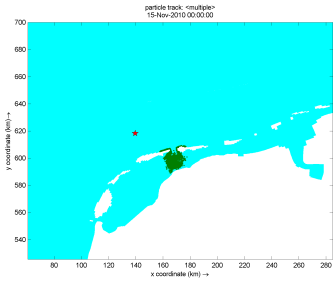
(c) t= 7day

Figure C.11: D = 7.5

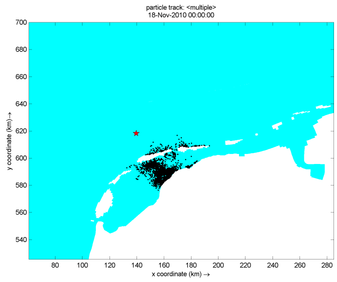
BEACHING



(a) t= 1day

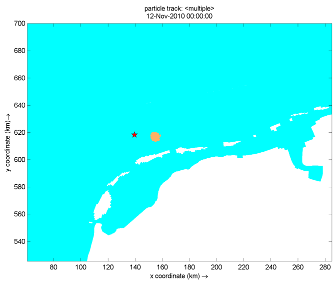


(b) t= 4day

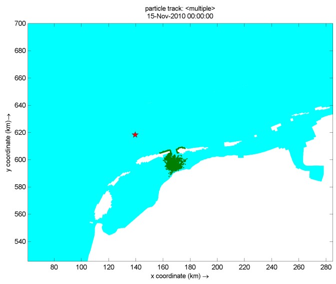


(c) t= 7day

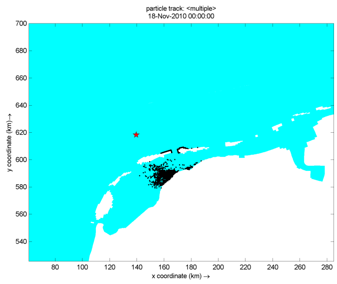
Figure C.12: Pb = 0 (no beaching)



(a) t= 1day

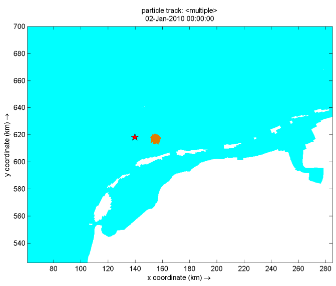


(b) t= 4day

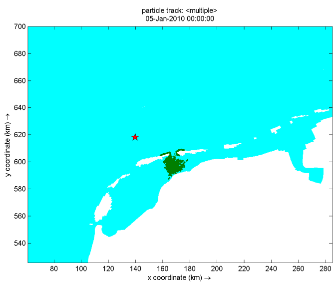


(c) t= 7day

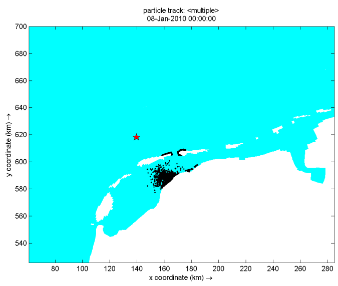
Figure C.13: Pb = 0.1



(a) t= 1day

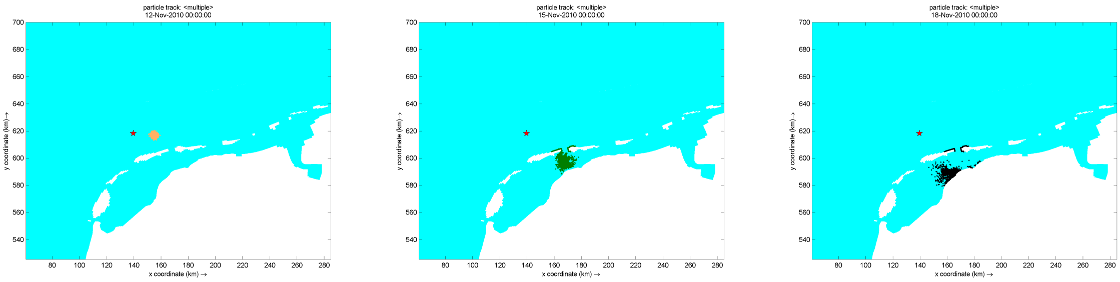


(b) t= 4day



(c) t= 7day

Figure C.14: Pb = 0.5 (control scenario)

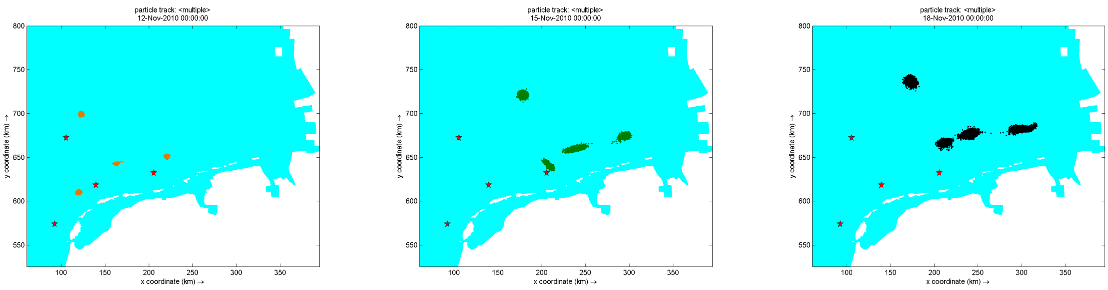


(a) t= 1day (b) t= 4day (c) t= 7day

Figure C.15: Pb = 1 (no beaching)

C.2. OVERVIEW PLOTS PERIOD 2

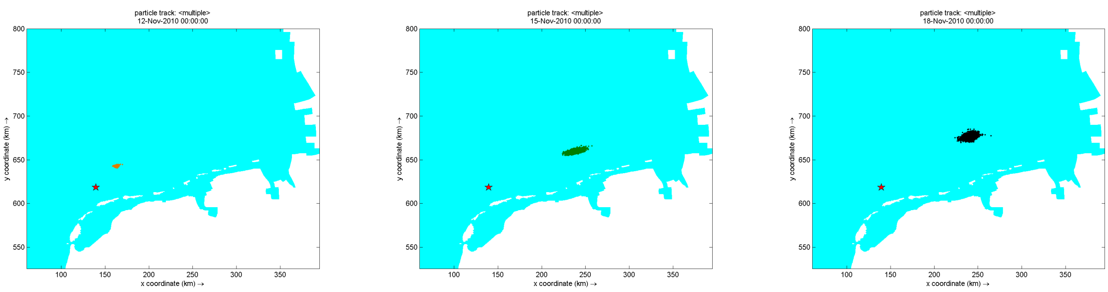
LOCATION



(a) t= 1day (b) t= 4day (c) t= 7day

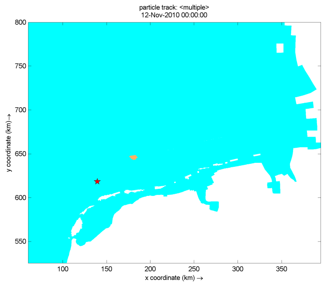
Figure C.16: Release location scenarios

TIME OF RELEASE

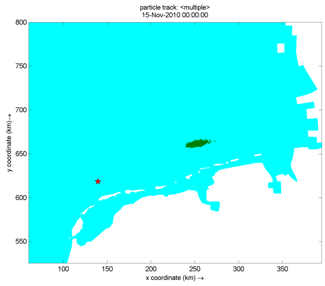


(a) t= 1day (b) t= 4day (c) t= 7day

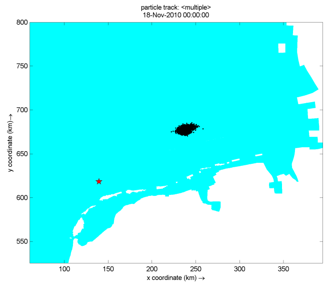
Figure C.17: 0hrs (control scenario)



(a) t= 1day



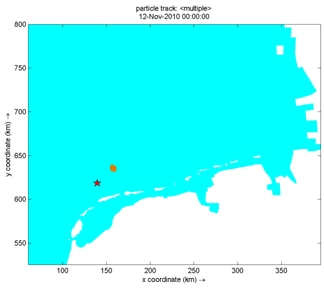
(b) t= 4day



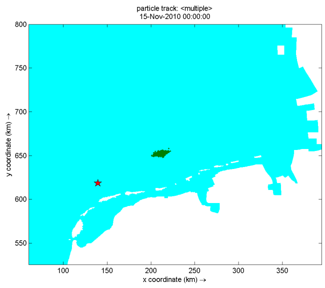
(c) t= 7day

Figure C.18: +6hrs

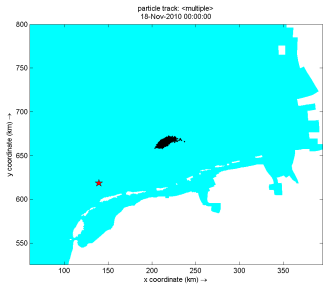
WINDAGE



(a) t= 1day

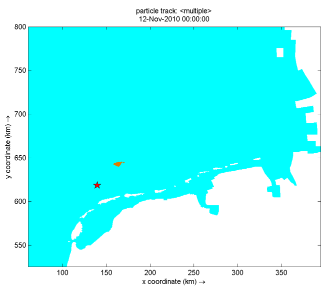


(b) t= 4day

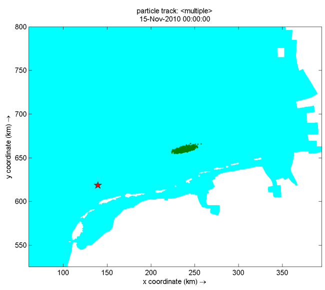


(c) t= 7day

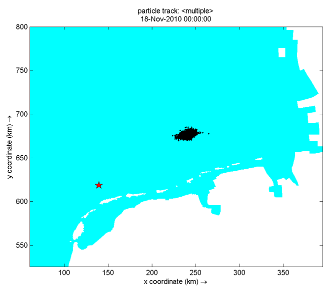
Figure C.19: wd = 0%



(a) t= 1day

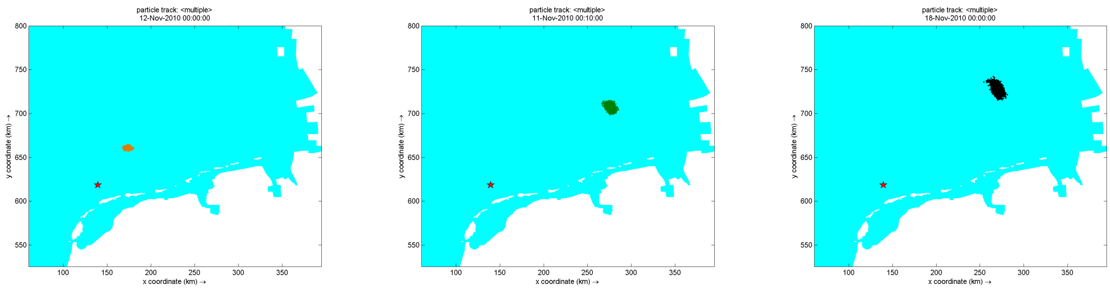


(b) t= 4day



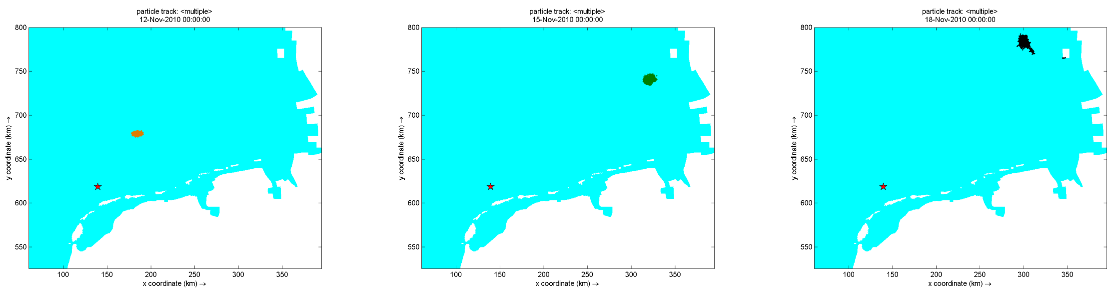
(c) t= 7day

Figure C.20: wd = 1% (control scenario)



(a) t= 1day (b) t= 4day (c) t= 7day

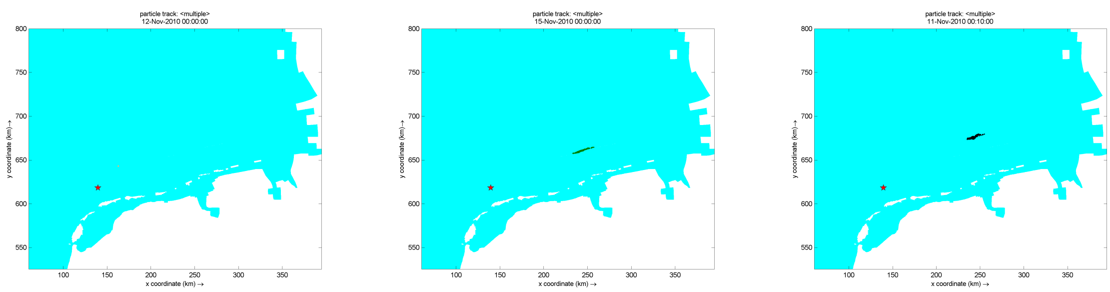
Figure C.21: wd = 3%



(a) t= 1day (b) t= 4day (c) t= 7day

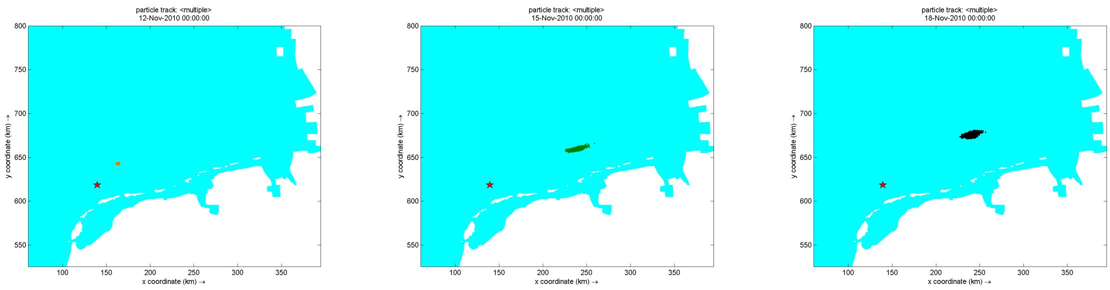
Figure C.22: wd = 5%

DIFFUSION COEFFICIENT



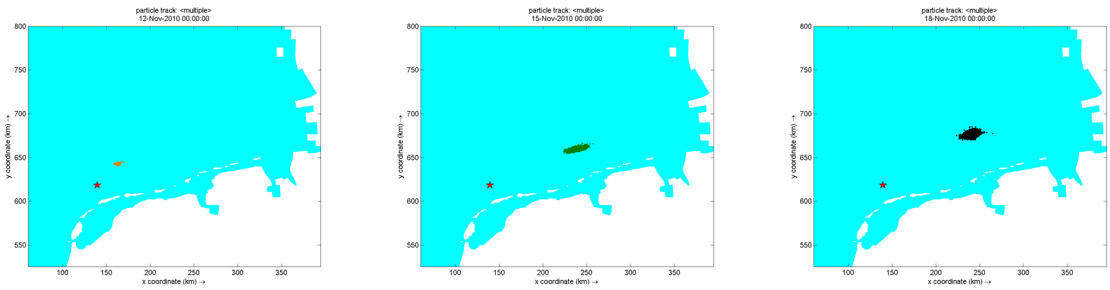
(a) t= 1day (b) t= 4day (c) t= 7day

Figure C.23: D = 0.01



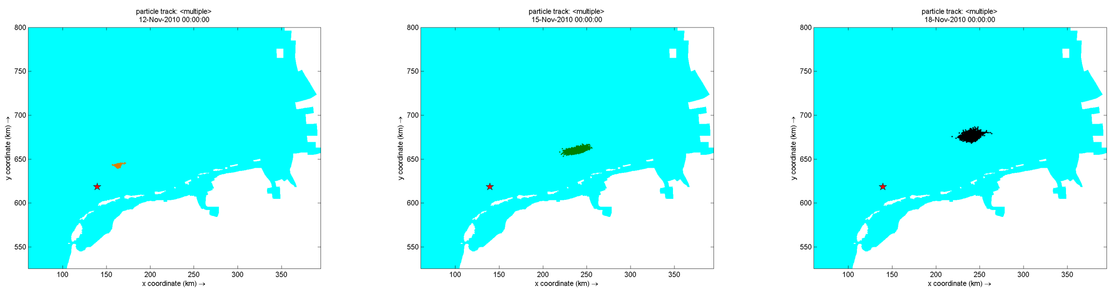
(a) t= 1day (b) t= 4day (c) t= 7day

Figure C.24: D = 2.5



(a) t= 1day (b) t= 4day (c) t= 7day

Figure C.25: D = 5 (control scenario)



(a) t= 1day (b) t= 4day (c) t= 7day

Figure C.26: D = 7.5

D
POST-PROCESSING SCRIPT

D.1. IMPORT DATA

Delft3D-PART computes an output file containing information about the position of every particle at every time step. The output of the 3D particle tracks results are written to the file:

- Delft3D | tracking file <trk*.dat>

This file can not be imported into python, therefore the first step is to convert this file to a different file format. For this, the QUICKPLOT tool, supplied with the Delft3D software, is used to convert the <trk*.dat> output file to a <.mat> file. The next step is to import the data to python and derive the x and y coordinate of the particles at every time step. This process is described below.

IMPORT LIBRARIES

```
import os
from scipy.io import loadmat
import pandas as pd
import numpy as np
```

Listing D.1: Import packages

SELECT THE PATH

```
path = r'C:\Users\utenhove\model\modelinput\part\results_period1' # select for period 1
path = r'C:\Users\utenhove\model\modelinput\part\results_period2' # select for period 2
```

Listing D.2: select the path

LOAD A DATASET

Release location scenarios

```
# import <*.mat> file
run_name = 'base_case'
data = loadmat(os.path.join(path,run_name+'.mat'))

# derive particle tracks from .mat file
ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]

# x and y coordinates of particles for timeserie
x = ptrack2['X']
y = ptrack2['Y']

# assign data of each release location to variable
x1 = x[1:,0:5000];       y1 = y[1:,0:5000]        # scenario Loc1
x2 = x[1:,5000:10000];   y2 = y[1:,5000:10000]    # scenario Loc2
x3 = x[1:,10000:15000];  y3 = y[1:,10000:15000]   # scenario Loc3
x4 = x[1:,15000:20000];  y4 = y[1:,15000:20000]   # scenario Loc4
```

Listing D.3: release location

Windage scenarios

```
# scenario wd0
run_name = 'wd0'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x1 = ptrack2['X']
y1 = ptrack2['Y']

# scenario wd1
run_name = 'base_case'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x2 = ptrack2['X']
y2 = ptrack2['Y']

# scenario wd3
run_name = 'wd3'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x3 = ptrack2['X']
y3 = ptrack2['Y']

# scenario wd5
run_name = 'wd5'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x4 = ptrack2['X']
y4 = ptrack2['Y']
```

Listing D.4: windage

Diffusion scenarios

```
# scenario D0,01
run_name = 'D0,01'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x1 = ptrack2['X']
y1 = ptrack2['Y']

# scenario D2,5
run_name = 'D2,5'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x2 = ptrack2['X']
y2 = ptrack2['Y']

# scenario D5
run_name = 'base_case'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
```

```
ptrack2=ptrack1[0]
x3 = ptrack2['X']
y3 = ptrack2['Y']

# scenario D7,5
run_name = 'D7,5'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x4 = ptrack2['X']
y4 = ptrack2['Y']
```

Listing D.5: diffusion

release moment scenarios

```
# scenario 0hrs
run_name = 'base_case'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x1 = ptrack2['X']
y1 = ptrack2['Y']

# scenario 6hrs
run_name = '+6hrs'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x2 = ptrack2['X']
y2 = ptrack2['Y']
```

Listing D.6: release time

Beaching probability scenarios

```
# scenario p=0
run_name = 'p=0'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x1 = ptrack2['X']
y1 = ptrack2['Y']

# scenario p=0.1
run_name = 'p=0,1'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x2 = ptrack2['X']
y2 = ptrack2['Y']

# scenario p=0.5
run_name = 'base_case'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x3 = ptrack2['X']
y3 = ptrack2['Y']

```

```
# scenario p=1
run_name = 'p=1'
data = loadmat(os.path.join(path,run_name+'.mat'))

ptrack = data['data']
ptrack1=ptrack[0]
ptrack2=ptrack1[0]
x4 = ptrack2['X']
y4 = ptrack2['Y']
```

Listing D.7: beaching

D.2. PARTICLE ANALYSIS

Now that the particle coordinates are obtained and stored to the variables x1–4 and y1–4, the next step is to compute the indices defined in Section 3.4.

DEFINE FUNCTIONS

```
# identify state of particles (floating/beached) and store in separate arrays
def fate_arrays(X,Y):
    #id beached particle
    Xp = np.where(X[-2,:]==X[-1,:])[0] #considered beached when position remains constant
    #time beach arrival
    p_min = np.nanargmin(abs(X[:-1]-X[1:]),0) #position of minimum difference
    Tp = p_min[Xp] #arrival time of beached particles
    #Array of beached particles
    dfb = np.zeros_like(x1) #to store
    dfb[Tp,Xp] = 1. #mark first beached particles
    dfb[dfb==0] = np.nan
    dfb = pd.DataFrame(dfb).fillna(method='ffill') #mark beached
    Xb = X*dfb #x-coordinates
    Yb = Y*dfb #y-coordinates
    #array of floating particles
    dfs = np.ones_like(X) #to store
    dfs = dfs - pd.DataFrame(dfb).fillna(0) #mark floating
    dfs[dfs==0] = np.nan
    Xs = X*dfs #x-coordinates
    Ys = Y*dfs #y-coordinates
    return Xs,Ys,Xb,Yb

# relative evolution of center of mass
def relative_distance(x,y):
    return np.sqrt((x-x.loc[0])**2+(y-y.loc[0])**2)

# travel distance of center of mass
def travel_distance_cm(x,y):
    x_cm = x.mean(1)
    y_cm = y.mean(1)
    step_dist = np.sqrt((x_cm[1:-1]-x_cm[0:-2].values)**2+
                        (y_cm[1:-1]-y_cm[0:-2].values)**2)
    travel_dist = step_dist.rolling(1008,min_periods=1).sum()
    return travel_dist

# standard deviation of random walk
def std_diff(D):
    t = np.linspace(0,1007,1008)*600
    return np.sqrt(4*D*t)
```

Listing D.8: funtions used to compute statistics

CALCULATE INDICES

```
# array with tracks of floating particles (x,y)
# array with position of beached particles (xb,yb)
x1,y1,xb1,yb1 = fate_arrays(x1,y1)
x2,y2,xb2,yb2 = fate_arrays(x2,y2)
x3,y3,xb3,yb3 = fate_arrays(x3,y3)
x4,y4,xb4,yb4 = fate_arrays(x4,y4)
```

Listing D.9: identify state and store in separate arrays

```
# create empty dataframe to store results
result = pd.DataFrame(columns = ['dist', 'SD', 'susp','beach', 'CM','SD_x','SD_y'])

# loop that calculates the statistical indices for each scenario
for i in range(4):
    if i==0:
        x = x1
        y = y1
    if i==1:
        x = x2
        y = y2
    if i==2:
        x = x3
        y = y3
    if i==3:
        x = x4
        y = y4
    # travel distance
    dist_cm = travel_distance_cm(x,y)
    #relative distance
    rel_dist = relative_distance(x,y).mean(axis=1) #1D
    # standar devation (relative, i.e. cm is reference frame)
    std_x = x.std(axis=1)
    std_y = y.std(axis=1)
    std = np.sqrt(std_x**2+std_y**2) #1D
    # percentage beached
    perc_beach = x.isna().sum(1)/5000*100

    #store results
    result['dist'] = dist_cm
    result['SD']=std
    result['beach']= perc_beach
    result['susp']= 100-result['beach']
    #other results (not using for final analysis)
    result['CM']= rel_dist
    result['SD_x']=std_x
    result['SD_y']=std_y

    #save results
    if i==0:
        result1 = result.copy()
    if i==1:
        result2 = result.copy()
    if i==2:
        result3 = result.copy()
    if i==3:
        result4 = result.copy()
```

Listing D.10: compute parameter output values for each scenarios

D.3. VISUALIZATION

IMPORT LIBRARIES

```
from matplotlib import pyplot as plt
import seaborn as sns
import cartopy.crs as ccrs
import cartopy.io.img_tiles as cimgt
```

Listing D.11: Import packages

EVOLUTION OF THE PATCH

```
# select background map style
request = cimgt.GoogleTiles()

# select domain
extent = [4.7, 7.6, 53, 54.3] #period 1
extent = [4.5, 7.1, 52.8, 53.7] #period 2

```

```
# plot background
fig, ax = plt.subplots(figsize=(10, 15),dpi=200)
ax = plt.axes(projection=request.crs)
ax.set_extent(extent)
ax.add_image(request, 9)

# select simulation data (data of floating particles for control scenario)
x = x1
y = y1

# coordinate conversion
xynps = ax.projection.transform_points(ccrs.epsg(28992), x.values, y.values)
x_ref = pd.DataFrame(xynps[:,:,0]) # x-coordinate in reference coordinates
y_ref = pd.DataFrame(xynps[:,:,1]) # y-coordinate in reference coordinates

# trajectory of center of mass
x_cm = x_ref.mean(1)
y_cm = y_ref.mean(1)
plt.plot(x_cm,y_cm,'--',color='black',label='_nolegend_') #plot trajectory
plt.plot(x_ref.iloc[0,0],y_ref.iloc[0,0], '*', markersize=10, color='red',
        label='_nolegend_') #mark release location

# density plots
for i in (143,429,715,1007):
    print(i)
    xr = x_ref.iloc[i].dropna().values
    yr = y_ref.iloc[i].dropna().values
    sns.kdeplot(xr,yr, shade=True, shade_lowest=False,alpha=1)

# mark location of CM for density plots
plt.plot(x_cm[143],y_cm[143],   'o', markersize=3, color='blue')
plt.plot(x_cm[429],y_cm[429],   'o', markersize=3, color='orange')
plt.plot(x_cm[715],y_cm[715],   'o', markersize=3, color='green')
plt.plot(x_cm[1007],y_cm[1007], 'o', markersize=3, color='red')

# layout axes
labels = ['day 1','day 3','day 5','day 7']
plt.legend(labels)
plt.show()
\label{daskl}
```

Listing D.12: Spatial and temporal evolution of the control scenario

EVOLUTION OF INDICES

Travel distance

```
# setup figure
fig = plt.figure(figsize=(12, 3), dpi=150)
ax = plt.subplot(121)

#plot data
plt.plot(result1['dist']/1000)
plt.plot(result2['dist']/1000)
plt.plot(result3['dist']/1000)
plt.plot(result4['dist']/1000)

# layout axes
ax.set_xlabel('time (days)', fontsize='large')
ax.set_ylabel('travel distance CM (km)', fontsize='large')
ax.set_ylim(0)
plt.legend()
```

Listing D.13: plot travel distance

Standard deviation

```
# setup figure
fig = plt.figure(figsize=(12, 3), dpi=150)
ax = plt.subplot(121)

# plot component initiated by random walk
plt.plot(std_diff(5)/1000,'--',color='black',label='_nolegend_')
```

```

#plot data
plt.plot(result1['SD']/1000)
plt.plot(result2['SD']/1000)
plt.plot(result3['SD']/1000)
plt.plot(result4['SD']/1000)

# layout axes
ax.set_xlabel('time (days)', fontsize='large')
ax.set_ylabel('standard deviation (km)', fontsize='large')
ax.set_ylim(0)
plt.legend()
```

Listing D.14: plot standard deviation

State of particles

```
# setup figure
fig = plt.figure(figsize=(12, 3), dpi=150)
ax = plt.subplot(121)

#plot data
plt.plot(result1['susp'])
plt.plot(result2['susp'])
plt.plot(result3['susp'])
plt.plot(result4['susp'])

# layout axes
ax.set_xlabel('time (days)', fontsize='large')
ax.set_ylabel('floating particles (%)', fontsize='large')
ax.set_ylim(0)
plt.legend()
```

Listing D.15: state of particles

SHORELINE DISTRIBUTION

```
fig = plt.figure(figsize=(8,2))

for i in range(4):
    #assign data
    if i==0:
        x = xb1
        y = yb1
    if i==1:
        x = xb2
        y = yb2
    if i==2:
        x = xb3
        y = yb3
    if i==3:
        x = xb4
        y = yb4
    #count nr of particles per km
    x = x.iloc[1007].dropna().round(-3)/1000 # aggregate per km
    xc = x.value_counts() #count nr of particles per km
    xc = xc.sort_index()

    #plot distribution
    xc2 = pd.Series(index=range(150,201))
    xc2 = xc2.fillna(0)
    xc2.loc[xc.index]=xc.values
    plt.plot(xc2)

# axis layout
plt.xlabel('shoreline (km)')
plt.ylabel('particle count per km')
plt.legend(labels)
plt.show()
```

Listing D.16: count nr of particles per km shoreline