

# The impact of abiotic drivers on the dispersal of reef fish eggs near Bonaire

Modelling possible spawning grounds near Bachelor's Beach

L.S. (Lisa) Kleinveld





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by

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# Preface

Writing this thesis has been a challenging yet rewarding journey, marking the culmination of my Civil Engineering studies at Delft University of Technology. Over the past seven years, I have had the privilege of exploring my interests within the field of Civil Engineering and creating wonderful memories with the people I have met along the way. Experiences that I will treasure and look back on with fondness.

This master thesis would not have been possible without the support of many people. First and foremost, I would like to thank my supervisors for their guidance and advice throughout this process. Thank you to Matthijs, my daily supervisor, for your critical and practical thinking, which often helped me move forward, and for sharing my enthusiasm for this project. I would also like to thank your colleagues at HKV for making this an enriching experience. My gratitude goes to Sander, for introducing me to the world of coral reef fish and for helping me connect technical knowledge with real-world applications. Additionally, I would like to thank Ad for taking the time to discuss and advise on my model, helping steer me in the right direction. Many thanks as well to Ton and Matthieu, whose academic perspectives encouraged me to consider multiple angles of interpretation, ultimately deepening my understanding of the results.

Finally, I would like to thank all my friends for making studying so much more fun and being there for me. For the all joyful activities to keep our minds of studying, for just chatting away over a mandatory cup of coffee or pushing each other further when the exams came around. My thanks also go out to my family for continuously supporting and cheering me on through my studies. And thank you to my boyfriend, Bastiaan, for always believing in me.

*L.S. (Lisa) Kleinveld  
Delft, July 2025*

# Abstract

Coral reef ecosystems are declining due to climate change and other anthropogenic factors. Studies have shown that the presence and integration of reef fish are essential for the health and resilience of coral reefs. Consequently, RoffaReefs made them an integral part of their program to safeguard and improve the health of coral reef ecosystems. With this goal, they developed a floating breeding system designed to increase the survival rate of reef fish. Defining an optimal location for this breeding system requires knowledge of spawning locations and egg dispersal patterns in nearshore waters. However, spawning conditions are species specific and not known beforehand. Furthermore, current dispersal studies often opt for global or regional models, which do not resolve local scale abiotic drivers. The objective of this research is to identify possible spawning grounds near Bachelor's Beach based on the sampling data and varying abiotic drivers in nearshore conditions.

The sampled reef fish eggs are pelagic, exhibiting slight positive buoyancy, which keeps them within the surface layers. Given the focus on abiotic dispersal mechanisms, the eggs are modelled as passive Lagrangian particles that remain near the surface throughout the simulation. The literature review identifies tidal, wind-driven and wave-induced currents to be the key abiotic drivers near Bachelor's Beach. Through Delft3D-FLOW and -WAVE a hydrodynamic model is developed to simulate different scenarios, entailing the conditions of each abiotic driver and possible combinations. The obtained horizontal flow velocities and accompanying dispersal patterns indicate that wind-induced currents are the primary abiotic driver of dispersal near Bachelor's Beach, under both uniform and time-varying conditions. The impact of wave-induced currents only become significant under the presence of wind, whereas tidal forcing seems to play a limited role.

Using Delft3D-PART, dispersal patterns are simulated based on the hydrodynamic output. Under time-varying conditions, a consistent north to north west dispersal pattern was observed, moving eggs away from Bachelor's Beach. These results suggest that spawning grounds that cause eggs to pass Bachelor's Beach should be located within close proximity of the sampling area. It is recommended to RoffaReefs to position their breeding system in southern curve of Klein Bonaire, as many eggs tend to pass this location. Future research should prioritise local hydrodynamic measurements for model calibration and validation. To add to this a more detailed assessment of the spawning release conditions are advised to move from simplified to more biologically realistic scenarios.



# Contents

|                                                      |           |
|------------------------------------------------------|-----------|
| <b>Preface</b>                                       | <b>i</b>  |
| <b>Abstract</b>                                      | <b>ii</b> |
| <b>1 Introduction</b>                                | <b>1</b>  |
| 1.1 Background . . . . .                             | 1         |
| 1.2 Research problem . . . . .                       | 1         |
| 1.3 Scope and Objective . . . . .                    | 2         |
| 1.4 Research questions . . . . .                     | 3         |
| 1.5 Methodology and structure of report . . . . .    | 3         |
| <b>2 Literature review</b>                           | <b>4</b>  |
| 2.1 Biotic drivers . . . . .                         | 4         |
| 2.1.1 Pelagic fish eggs . . . . .                    | 4         |
| 2.1.2 Dispersal of pelagic eggs . . . . .            | 5         |
| 2.2 Abiotic drivers of dispersal . . . . .           | 5         |
| 2.2.1 Regional circulation . . . . .                 | 7         |
| 2.2.2 Wind-driven currents . . . . .                 | 7         |
| 2.2.3 Upwelling and downwelling . . . . .            | 9         |
| 2.2.4 Density-gradient driven currents . . . . .     | 10        |
| 2.2.5 Tidal propagation . . . . .                    | 11        |
| 2.2.6 Wave-induced currents . . . . .                | 12        |
| 2.3 Conclusion Literature review . . . . .           | 14        |
| <b>3 Modelling Methodology</b>                       | <b>16</b> |
| 3.1 Modelling approach . . . . .                     | 16        |
| 3.2 Model setup . . . . .                            | 16        |
| 3.2.1 Hydrodynamic model . . . . .                   | 17        |
| 3.2.2 Validation of the hydrodynamic model . . . . . | 20        |
| 3.2.3 Particle tracking model . . . . .              | 23        |
| 3.3 Model scenarios . . . . .                        | 25        |
| 3.3.1 Abiotic driver conditions . . . . .            | 26        |
| 3.3.2 Release conditions . . . . .                   | 29        |
| 3.3.3 Process parameters . . . . .                   | 31        |
| <b>4 Results</b>                                     | <b>32</b> |
| 4.1 Abiotic driver flows . . . . .                   | 32        |
| 4.1.1 Base scenarios . . . . .                       | 32        |
| 4.1.2 Interaction between abiotic drivers . . . . .  | 35        |
| 4.2 Dispersal per abiotic drivers . . . . .          | 38        |
| 4.3 Impact of release conditions . . . . .           | 41        |
| 4.3.1 Passage rates . . . . .                        | 43        |
| 4.4 Effect of parameters . . . . .                   | 45        |
| 4.4.1 Effect of Release radius . . . . .             | 46        |
| 4.4.2 Effect of diffusion coefficient . . . . .      | 46        |
| <b>5 Discussion</b>                                  | <b>48</b> |
| 5.1 Influence of the pelagic trait . . . . .         | 48        |
| 5.2 Model limitations . . . . .                      | 49        |
| 5.3 Broader implications . . . . .                   | 50        |

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|          |                                                            |           |
|----------|------------------------------------------------------------|-----------|
| <b>6</b> | <b>Conclusions and Recommendations</b>                     | <b>51</b> |
| 6.1      | Conclusions . . . . .                                      | 51        |
| 6.2      | Recommendations . . . . .                                  | 52        |
|          | <b>References</b>                                          | <b>54</b> |
| <b>A</b> | <b>Condition analysis</b>                                  | <b>59</b> |
| A.1      | Dispersion relationship - waves . . . . .                  | 59        |
| A.2      | Wave conditions in the Caribbean Sea . . . . .             | 59        |
| A.2.1    | Short-crested wind-generated waves . . . . .               | 60        |
| A.2.2    | Swell waves . . . . .                                      | 61        |
| A.3      | Time-varying wind and wave conditions . . . . .            | 62        |
| <b>B</b> | <b>Validation figures</b>                                  | <b>67</b> |
| B.1      | Comparison WUR measurements . . . . .                      | 67        |
| <b>C</b> | <b>Additional results</b>                                  | <b>69</b> |
| C.1      | Horizontal velocities - abiotic driver scenarios . . . . . | 69        |
| C.2      | Dispersal - abiotic driver scenarios . . . . .             | 72        |
| C.3      | Release conditions . . . . .                               | 74        |

# Introduction

## 1.1. Background

Coral reef ecosystems are inhabited by a very diverse group of species and approximately one-quarter of the ocean's marine life depends on the health of coral reefs (NOAA, 2019). Climate changes and other anthropogenic factors introduce systematic changes in the ocean. The stresses imposed by these changes have lasting effects on coral reef ecosystems (WUR, Wageningen University & Research, 2024). Furthermore, coral reef recovery occurs at a slower rate than the negative impacts of these changes. This instigated multiple coral restoration projects around the world to maintain the functionality of marine ecosystems, one of which is RoffaReefs. RoffaReefs is a program, founded and based in the Rotterdam Zoo 'Blijdorp', that aims to research and breed marine fish to safeguard and improve the health of coral reef ecosystems (RoffaReefs, 2024). Their focus is on reef fish since they are essential for the health and increased resilience of coral reefs.

Studies have shown that the diversity of reef fish communities has declined as the extent of coral reefs has decreased (Eddy et al., 2021). Reef fish know five stages in their life cycle and RoffaReefs focuses on the first three. A reef fish is namely the most vulnerable within these three stages, especially the first stage (Pineda et al., 2007). Reef fish start as eggs, which are simultaneously spawned into the sea. After approximately 24 hours the egg will transform into a hatchling, also known as the yolk-sac larva stage, the second stage (Colin and de Mitcheson, 2011). The third stage occurs after several days, depending on the fish species, when the hatchling will fully transition into a larva. To help with the survival rate of these reef fish, RoffaReefs has created a floating breeding system. This breeding system aims to catch fish eggs near the coast of Bonaire within the first stages and increase their survival rate.

In order for the breeding system to catch the fish eggs, knowledge about their dispersal within the water is required. Dispersal indicates the process of fish eggs being distributed in the water, influenced by both biotic and abiotic factors (Berenshtein et al., 2022, Leis et al., 2007, Pineda et al., 2007). Biotic factors typically depend on species specific traits, such as shape or buoyancy, while abiotic factors include environmental forces like currents and bathymetric features. The resulting transport mechanisms can be described by advection and dispersion processes. Advection describes transport due to the mean flow field, whereas dispersion accounts for the effects of unresolved small-scale turbulence or variability within that flow (van Utenhove, 2018). As a result, dispersal distances can range from several hundred meters to over several hundred kilometres, depending on these biotic and abiotic drivers (Siegel et al., 2003). Accurately capturing the different drivers is essential for optimizing the location of the breeding system. To initiate RoffaReefs' investigation into these drivers, they have structurally sampled eggs along the southwest coast of Bonaire throughout 2024.

## 1.2. Research problem

Reef fish egg dispersal begins with a spawning event, defined as the simultaneous release of sperm and eggs by multiple fish species at a specific site (DiBattista et al., 2025). The timing and location are species dependent (DiBattista et al., 2025, El-Regal et al., 2024). However, it is not known in advance which species will be sampled, limiting information on both the horizontal and vertical starting positions of egg dispersal. Furthermore, species specific traits further influence the vertical distribution of eggs. Abiotic

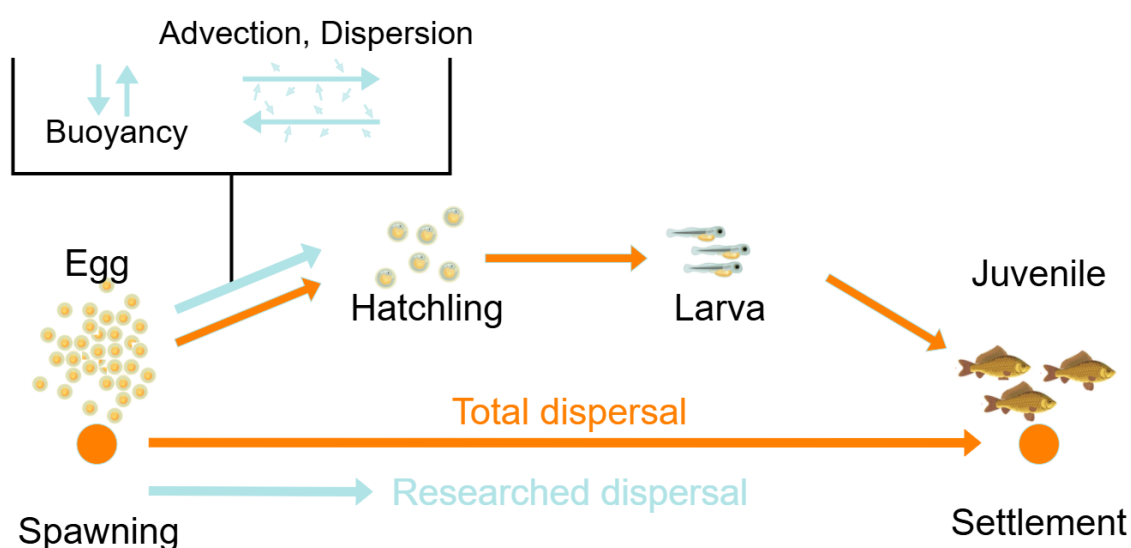


drivers distribute eggs in both horizontal and vertical directions, but the specific drivers responsible for nearshore accumulation along Bonaire's southwest coast remain unidentified. There are limited measurements of the conditions near Bonaire's southwest coast, that could provide these details.

Moreover, existing studies that focus on the biotic drivers often simplify the role of abiotic factors on the fish egg dispersal. Many therefore make use of Global Ocean Circulation Models, such as HYCOM, to account for the environmental conditions (McDonald, 2024, Chaput et al., 2022, Hernández et al., 2023). These models represent physical oceanographic circulation at global or regional domain scales. The applied grid cells range from one to hundred of kilometres. For the larger scaled drivers these cell ranges are sufficient, but smaller scaled abiotic drivers will not be resolved properly. To understand how the fish eggs retain in the nearshore region, the local abiotic drivers need to be resolved and quantified. Even when dispersal studies emphasize the influence of local abiotic drivers, there is little consensus regarding which factors are most relevant.

### 1.3. Scope and Objective

The goal of RoffaReefs is to acquire knowledge of the coral reef system near Bonaire to help sustain it in the future. Knowledge of this ecosystem will also help define the optimal location for their breeding system (RoffaReefs, 2024). Achieving this requires a thorough understanding of both biotic and abiotic drivers of fish egg dispersal in the region. While RoffaReefs is currently gathering data on biotic factors near Bonaire, knowledge of the abiotic drivers along the island's southwest coast remains limited. This study therefore focuses primarily on abiotic drivers, with an emphasis on local scale drivers affecting the egg dispersal. Figure 1.1 shows the components of the dispersal that are considered in this study in blue.



**Figure 1.1:** The total dispersal of the reef fish, shown in orange, contains both biotic and abiotic drivers. The researched dispersal in this study, shown in blue, focuses on the dispersal on fish eggs influenced by the abiotic drivers. Also the buoyancy of the eggs are considered, as it determines the vertical position in the water and influences which abiotic drivers are present.

In 2024, RoffaReefs sampled fish eggs along the southwest coast of Bonaire, recording sampling locations and dates. Due to the lack of in situ abiotic data, Bachelor's Beach is selected as the focal site for this research. It is located just south of Kralendijk, Bonaire's capital and previously studied in the literature with respect to abiotic drivers. To gain a understanding of the abiotic drivers in the region near Bachelor's Beach, a model-based analysis is selected for this study. Identifying suitable locations for RoffaReefs' breeding system requires prior knowledge of spawning grounds and associated dispersal patterns. Therefore, the objective of this research is to identify potential fish spawning grounds near Bachelor's Beach. This is achieved by simulating fish egg dispersal through the integration of nearshore sampling data and modelling of abiotic drivers.

## 1.4. Research questions

Based on the scope and objective, the main research question of this study is as follows.

*"How can spawning grounds near Bachelor's Beach be inferred using nearshore fish egg sampling data and varying abiotic drivers?"*

In order to find an answer to the main research question, several intermediate research questions are explored. These sub research questions are formulated below.

1. *"Can fish eggs be considered as Lagrangian particles when tracking their dispersal?"*
2. *"What are the dominant abiotic drivers influencing the dispersal of fish eggs near Bachelor's Beach?"*
3. *"Does the Delft3D Tracer model offer insights for inferring spawning grounds under varying abiotic drivers near Bonaire?"*

To start, an understanding is established of how fish egg dispersal can be represented within a modelling framework. This includes biotic as well as abiotic drivers. Secondly, a characterization of the dominant abiotic drivers in the Caribbean Sea, and specifically on the west coast of Bonaire, is required to support realistic parametrization. An abiotic driver is considered dominant if it exhibits the largest flow velocity over time within the region of interest. Sub research questions one and two will partially provide an answer to this. The resulting assumptions and parameters yield the possibility of setting up a model, which can simulate the abiotic drivers and the fish egg dispersal. The output of the chosen model contributes to the analysis if spawning grounds can be inferred, and if the chosen model is insightful for this objective.

## 1.5. Methodology and structure of report

The sub research question guide the approach taken in this research. The structure of the report reflects the approach and looks as follows.

- **Chapter 2** ("Literature review") explores how the biotic drivers of fish egg dispersal can be approached within a modelling framework. In addition, the abiotic drivers that drive the fish egg dispersal in nearshore regions are discussed and how they are included in current studies. The abiotic drivers surrounding Bonaire are further elaborated on and analysed on their flow velocities.
- **Chapter 3** ("Modelling Methodology") details the modelling approach of this research. The model framework, model setup and parametrization of key processes are discussed. The performance of these steps is analysed based on nesting results and validation through one measurement. Afterwards, simulation scenarios and evaluation methods are described to later interpret the results.
- **Chapter 4** ("Results") investigates the impact each abiotic driver has on the flow velocities near Bachelor's Beach, the dispersal of the fish eggs and for inferring spawning grounds. For this purpose, the proposed set of scenarios are used as guidelines for interpreting the results. The sampling data of RoffaReefs is compared to the realistic scenarios to see whether similar results are obtained.
- **Chapter 5** ("Discussion") reflects on the obtained results and the limitations of the research. This allows for the results to be put into a broader perspective.
- **Chapter 6** ("Conclusions and recommendations") summarizes the conclusions of this study, and presents recommendations for further research.

# 2

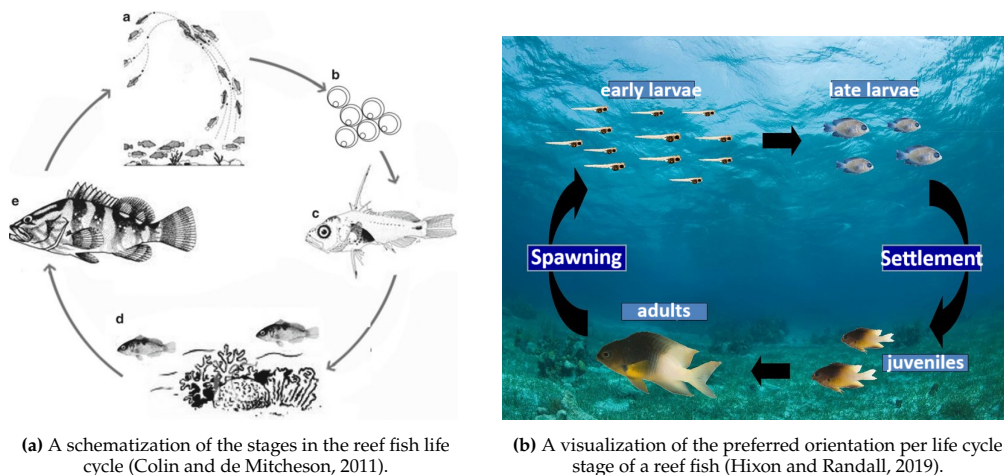
## Literature review

This chapter introduces the biotic and abiotic drivers of the fish egg dispersal and what knowledge is missing with respect to the drivers near Bachelor's Beach. To start, specific traits of fish eggs that influence the dispersal are detailed and what it means for considering the eggs as Lagrangian particles. This is followed by an elaboration on existing studies on dispersal of objects with similar traits as the fish eggs. Secondly, relevant local-scale abiotic drivers for fish egg dispersal are considered as well as dominant drivers near the coast of Bonaire based on existing literature. An overview of the abiotic drivers is made and the most relevant abiotic drivers will be used for the model scenarios later in this study.

### 2.1. Biotic drivers

#### 2.1.1. Pelagic fish eggs

The life cycle of bony reef fish consists of five stages; egg, hatchling, larva, juvenile and adult (Hixon and Randall, 2019, Murphy, 2024). In the first three stages, bony reef fish remain close to the water surface, which is referred to as pelagic. In the latter two stages, they become benthic (or demersal), which means they remain close to the sea floor. This orientation towards these preferred depths occurs not only with bony reef fish, but within the majority of marine fish families (Leis, 2021). This differs from fish families in freshwater environments, where the eggs are typically benthic (Sundby and Kristiansen, 2015). The different stages and preferred depths of marine fish are shown in Figure 2.1.



**Figure 2.1:** During spawning (2.1a, a) the fish eggs become fertilised. The eggs and larvae (2.1a, b and c) are pelagic and remain close to surface waters, also shown in 2.1b. From the moment that larvae transition to juvenile fish (2.1a, d), the fish will remain close to the sea floor for the rest of their life. The only exception is when adults, (2.1a, e), come to spawn and fertilize their eggs.

Whether a fish egg is defined as pelagic or benthic, has to do with their buoyancy. The buoyancy is related to the specific gravity of the egg and the ambient water (Leis, 2021). A pelagic fish egg typically

is (slightly) positively buoyant, while benthic eggs are negatively buoyant. The specific gravity of a fish egg can be expressed as a function of the temperature at depth, where the egg is located, and of the eggs salinity. The specific gravity of the ambient water can be described similarly, see Equation 2.3. The differences in thermal expansion between fish eggs and the ambient water are so small, it can be stated that the buoyancy for marine fish eggs is only dependent on salinity (Sundby and Kristiansen, 2015). The salinity concentration of the fish eggs are nearly constant over time, while that of the ambient water can change over depth and time. The differences in salinity lead to the pelagic egg to ascend towards the water surface, influencing its vertical location.

Pelagic eggs range from 0.5 to 1.2 millimetres in diameter and are generally smaller in size than benthic eggs (Colin and de Mitcheson, 2011). Their shape is typically nearly spherical, with exception of some species. For example, parrotfish eggs are spindle-shaped. Apart from their positive buoyancy, pelagic eggs tend to move passively, influenced primarily by external, abiotic factors. Existing studies on pelagic eggs often consider the eggs as passive particles (Nguyen et al., 2023, Grimaldi et al., 2022). Within 24 hours of spawning, the pelagic egg will transition into a hatchling, also known as egg yolk larva, followed by the larva stage. This is also the moment orientation behaviours and swimming abilities start to develop (Majoris et al., 2021). In a study by Paris and Cowen (2004), they showed that reef fish larvae influence their motion by using the vertical shear of the water column. Considering a fish larva to be passive, like the egg, would therefore not be valid.

### 2.1.2. Dispersal of pelagic eggs

In this study, dispersal refers to the process of particles being distributed in water. The resulting distribution is determined by environmental factors (abiotic) as well as the intrinsic characteristics of the particles themselves (biotic), i.e. fish eggs. Relatively few studies specifically address pelagic egg dispersal (Grimaldi et al., 2022, J. Graham et al., 2023), but it is known that both the abiotic and biotic drivers vary over time and space. The dispersal will therefore also vary over time and space. The fish species influences the spawning behaviour, like its moment in time as well as the duration. It is suggested that spawning occurs when conditions align with optimal abiotic factors. This is supposed to ensure the optimal survival of the eggs (Putri et al., 2024). The spatial scales of the dispersal can be separated into vertical and horizontal direction. In vertical direction, the eggs positive buoyancy cause the eggs to be near the water surface, see Section 2.1.1. As for the horizontal direction, the eggs are often considered as passive particles despite the positive buoyancy. The passive approach indicates that biotic factors of the egg do not influence the horizontal direction of their dispersal. In other words, the horizontal dispersal is governed by abiotic factors (Toschi and Bodenschatz, 2008).

Assuming the pelagic egg as passive Lagrangian particle is a simplification of reality. It would indicate that the eggs are neutrally buoyant and start close to the water surface in this case. The positive buoyancy leads to a more complex vertical dispersal. In comparison, studies on fish larvae dispersal highlight the influence of their biological traits on the dispersal, in both vertical and horizontal directions (Chaput et al., 2022, Hernández et al., 2023). Yet frequently the larvae are treated as passive particles, to generate initial predictions of dispersal patterns (James et al., 2002, Siegel et al., 2003). A similar approach is taken in this study, to provide initial insight in the dispersal of fish eggs. Therefore, the pelagic eggs are considered as passive, Lagrangian particles which are located within the surface layer of water.

## 2.2. Abiotic drivers of dispersal

Existing studies on the dispersal of fish eggs and larvae employ varying approaches in terms of how, and which, abiotic drivers are incorporated. The specific focus of each study often shapes this approach. For example, Hernández et al. (2023), Chaput et al. (2022) and Daudén-Bengoa et al. (2024) concentrate on biotic drivers of dispersal and population connectivity. Consequently, they employ global physical oceanographic circulation models, such as HYCOM (McDonald, 2024). The Connectivity Modelling System (CMS) developed by Paris et al. (2013), a multi-scale biophysical modelling system capable of simulating both complex larval migrations and abiotic particle dispersion, is also compatible with HYCOM. These circulation models are advantageous due to their wide-range applicability in resolving mesoscale abiotic drivers (Ross et al., 2020). For these type of studies this is often sufficient enough. The

resulting spatial scales of the drivers can span up to several hundred kilometres, which are reflected in the extent of larval dispersal (Leis, 2021). However, when the region of interest spans only tens of kilometres, global circulation models lack sufficient resolution. In such cases, especially when examining specific abiotic drivers, models that resolve meso- and local-scale conditions are preferable (Grimaldi et al., 2022, Fujimura et al., 2018, Onsri et al., 2024). Mesoscale drivers remain important, as they influence offshore-to-nearshore egg transport. The emphasis of this study, likewise, lies on localised nearshore environment where fish egg samples were collected. This necessitates a model that captures both meso- and local-scale abiotic drivers.

Assuming pelagic fish eggs are passive and within the surface layer, Lagrangian particle tracking indicates that abiotic factors primarily govern their dispersal. However, the specific abiotic drivers considered vary considerably across dispersal modelling studies. Notably, studies by Nguyen et al.(2023), Fujimura et al.(2013) and Siegel et al. (2003) include wind-driven currents while excluding tides. Conversely, Grimaldi et al. (2022) consider tidal forcing as a dominant driver in a reef-atoll system, while dismissing wind effects for regular conditions. Wind-driven and regional currents were concluded to have little impact on the flows near the studied reef atoll. Comparing this to the findings by Nguyen et al. (2023) provides a contrasting conclusion. Although the shallower waters of the West Florida Shelf (WFS) are of comparable depth with the reef atoll, the wind-driven flows are found to be influential for regular conditions at the WFS. These differences suggest that the relevance of each abiotic driver is site-specific.

A generic list of abiotic drivers is constructed based on existing literature. For this list, studies on dispersal of fish eggs and larvae are considered, as well as studies on particles close to the surface which are assumed to be passive, Lagrangian particles. For instance, microplastics and oil spills fit this description and have roughly the same size and shape as the pelagic fish eggs (Xu et al., 2024, Courteney-Jones et al., 2021, Drivdal et al., 2014). The resulting list is shown in Table 2.1. The accompanied effects of each driver is shortly explained and linked to their spatial scale at which the effects are noticeable. The dispersal studies that consider them as relevant are added as well. In the coming sections, each abiotic driver is detailed further and linked to the conditions found at Bonaire, especially focusing on the leeward side where Bachelor's Beach resides. Based on the estimated velocity magnitudes of each driver and their uncertainty, a hypothesis of the relevant abiotic drivers near Bonaire can be made.

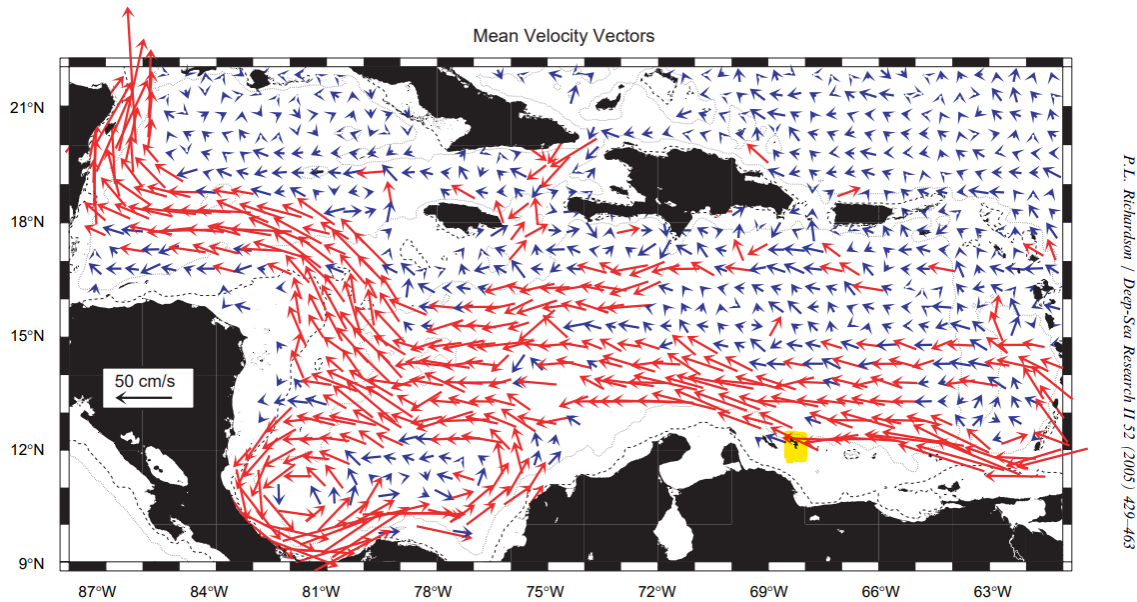
| Abiotic driver       | Associated processes             | Regional scale | Local scale | Supporting studies                                                                                |
|----------------------|----------------------------------|----------------|-------------|---------------------------------------------------------------------------------------------------|
| Regional circulation | - Boundary currents (gyres)      | X              | -           | Garcés-Ordóñez et al., 2021, Xu et al., 2024                                                      |
|                      | - Mesoscale eddies               | X              | -           |                                                                                                   |
| Wind                 | - Ekman transport                | X              | -           | Nguyen et al., 2023, Xu et al., 2024, Fujimura et al., 2018, Courteney-Jones et al., 2021         |
|                      | - Wind-driven shear turbulence   | -              | X           |                                                                                                   |
| Up- and downwelling  | - Surface divergence/convergence | X              | -           | Nguyen et al., 2023, Sundby and Kristiansen, 2015                                                 |
|                      | - Vertical velocity anomalies    | X              | -           |                                                                                                   |
| Density-gradients    | - Geostrophic currents           | X              | -           | Tracey et al., 2012, Erftemeijer et al., 2009, Van Duyl et al., 2024, Garcés-Ordóñez et al., 2021 |
|                      | - Baroclinic currents            | X              | X           |                                                                                                   |
| Tides                | - Flood and ebb currents         | -              | X           | Grimaldi et al., 2022, James et al., 2002                                                         |
| Wave action          | - Stokes drift velocity          | -              | X           | Fujimura et al., 2018, Drivdal et al., 2014                                                       |
|                      | - Wave breaking turbulence       | -              | X           |                                                                                                   |

**Table 2.1:** Abiotic drivers affecting pelagic fish egg dispersal, emphasizing scale-dependent mechanisms supported by existing literature. Associated processes per driver are linked and detailed further in sections below.



### 2.2.1. Regional circulation

Regional circulation refers to meso- to regional-scale movement of the ocean waters, driven by a combination of wind forcing, Earth's rotation (Coriolis effect), pressure gradients and boundary interactions (Pietrzak, 2021). It encompasses persistent flow features like boundary currents, mesoscale eddies and thermohaline structures. These currents are key components of the upper ocean circulation, facilitating horizontal transport of e.g. heat, nutrients and small particles across oceanic regions (Garcés-Ordóñez et al., 2021). Bonaire lies within the Caribbean Current System, which consists of the Caribbean Current that originates both in the subtropical gyre of the North Atlantic and in the upper limb of the thermohaline circulation from the tropical and South Atlantic (Xu et al., 2024). The total transport of the Caribbean Current can be divided into three passages, namely the Southern Islands, the Northern Islands and the Greater Antilles Islands (Richardson, 2005). Bonaire is located within the Southern Islands passage, highlighted in yellow in Figure 2.2. The velocity of the Caribbean Current through the Southern Islands passage can reach up to  $0.75 \text{ m/s}$  (Van Duyl et al., 2024). The flow within this passage seems to dominate the flow on the northern side of Bonaire, and in a northwest direction. Given the northwest direction and eastern origin of the flow, it seems unlikely that the current will have a similar magnitude on the southern side of Bonaire. If the Caribbean current is able to influence the dispersal of fish eggs on the leeward side of Bonaire, its magnitude is difficult to estimate but will most likely act in a north west direction.



**Figure 2.2:** The mean velocity vectors of the currents within the Caribbean Current, for which the swiftest velocities ( $> 25 \text{ cm/s}$ ) are shown within red (Richardson, 2005). Bonaire is highlighted in yellow, to illustrate its location within the velocity vectors.

In addition to this mean circulation, a strong mesoscale eddy field can be observed in the Caribbean. The characteristic motion of an eddy consists of a swirling velocity around its center, combined with its translational movement. They can be recognised as loops or cusps within a particle trajectory. Lin et al. (2011) analysed the Caribbean eddies and showed that they exhibit variability across temporal scales ranging from intra-seasonal to inter-annual periods. Although their velocities range from  $0.14 \text{ m/s}$  to  $0.70 \text{ m/s}$  within the different basins of the Caribbean Sea, their trajectories never reach (the leeward side of) Bonaire according to Lin et al. (2011) study. The possible impact of these eddies on the dispersal of fish eggs therefore is assumed to be limited.

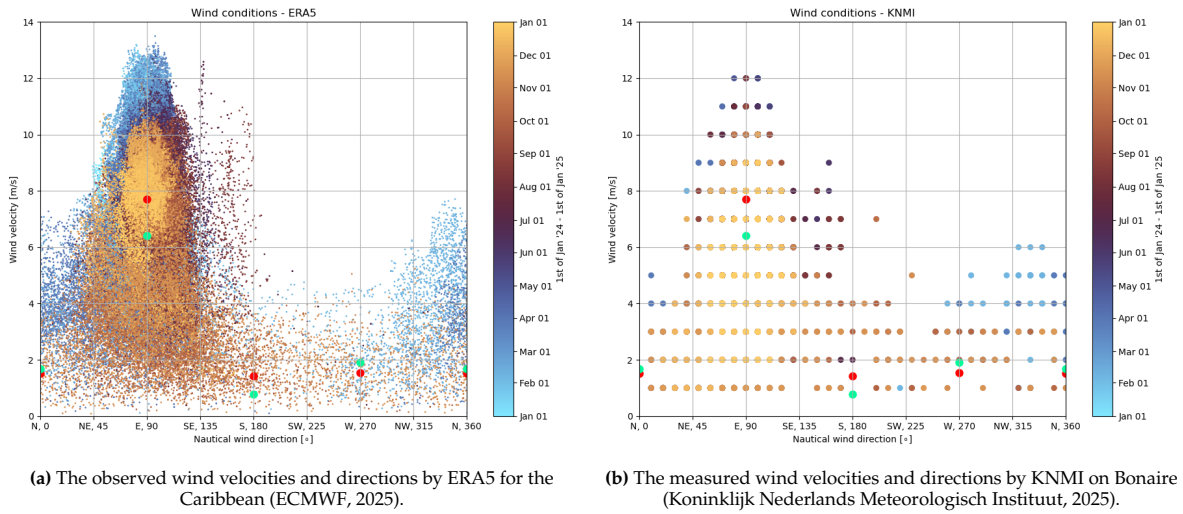
### 2.2.2. Wind-driven currents

As mentioned in the regional circulation, wind forcing is one of the main drivers. The shear stress exerted by wind ( $\tau_w$  in  $[N/m^2]$ ) on the water surface can start the formation of wind-driven currents. This can be modelled by a quadratic friction law, shown in Eq. 2.1 (Bosboom and Stive, 2023):

$$\tau_w = C_d \rho_a W^2 \quad (2.1)$$

$C_d$  [-] represents the drag coefficient depending on the wind velocity  $W$  [m/s], and  $\rho_a$  is the air density [ $kg/m^3$ ]. The drag coefficient  $C_d$  can be computed with  $(0.63 + 0.066W) \times 10^{-3}$ . Through the shear, momentum is transferred to the upper layers of the coastal waters resulting in a current. Wind-driven currents involve sustained directional flow and require time to develop. The most prominent currents are found in areas with persistent winds, such as trade winds (Pietrzak, 2021, Bosboom and Stive, 2023). Trade winds in turn are driven by the global atmospheric pressure system that cause circulation patterns. Bonaire, located within the Caribbean Sea near the Equator, experiences tropical Atlantic Trade Winds (Xu et al., 2024). These trade winds, driven by the North Atlantic High-pressure system, create a dominant air flow from the (north)east (Van Duyl, 1985, Van Leeuwen, 2022). The Coriolis effect deflects the resulting surface currents approximately  $45^\circ$  to the right of the wind direction. This interaction creates an Ekman spiral, where surface current velocity decreases exponentially with depth and forms a vertical structure of water movement. These currents promote an Ekman transport in the upper water layers, which is directed  $90^\circ$  to the right of the wind direction in the Northern Hemisphere. The transports within the Caribbean Sea were studied by Johns et al. (2002). They researched and modelled the total Caribbean Current System and its separate components. The component of the Caribbean Current driven only by wind results in a transport of roughly  $10 Sv$ , which is about  $0.20 m/s$ .

On a local scale, wind conditions play a role in shaping nearshore hydrodynamics. They operate over smaller spatial and temporal scales compared to the prevailing trade winds and interact with other forcing mechanisms, such as tides and waves. The effects of these interactions are often site-specific, and the relative contributions of each interaction can vary considerably depending on local conditions (Fujimura et al., 2013; Grimaldi et al., 2022). A broader trend in the Caribbean with respect to local wind conditions can be observed. Windward coasts (typically east- or northeast-facing) experience stronger, more persistent Trade Winds. In contrast, leeward sides (west- or southwest-facing) are sheltered, resulting in weaker and more variable winds (Slagter, 2023, Van Duyl, 1985). This aligns with Bonaire's wind conditions, as its topography and orientation reduce the effective fetch toward the southwest, limiting wind acceleration (Shimada et al., 2018). This further diminishes wind speed and consistency on the leeward side of Bonaire.



**Figure 2.3:** The observed Northing and Easting wind velocities during 2024. The red and greenish dots represent the mean velocity magnitudes of the wind coming from South, West, North and East direction based on ERA5 and KNMI data respectively. The colors of the color bar represent the direction from which the observed wind velocities come from.

| Data source | North dir.<br>$0$ or $360^\circ$ | East dir.<br>$90^\circ$ | South dir.<br>$180^\circ$ | West dir.<br>$270^\circ$ | Coloured dots in Fig. 2.3 |
|-------------|----------------------------------|-------------------------|---------------------------|--------------------------|---------------------------|
| ERA5        | 1.431 [m/s]                      | 7.703 [m/s]             | 1.527 [m/s]               | 1.534 [m/s]              | Red                       |
| KNMI        | 0.784 [m/s]                      | 6.403 [m/s]             | 1.906 [m/s]               | 1.672 [m/s]              | Green                     |

**Table 2.2:** A comparison of the mean velocities values of the observed wind conditions by ERA5 and KNMI in 2024.

This variation in wind exposure is supported by observational data from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) weather station on Bonaire and the ERA5 reanalysis for the Caribbean region by the European Centre of Medium-Range Weather Forecasts (ECMWF), illustrated in Figure 2.3). It should be noted, that the precise location of the KNMI station on Bonaire is not specified, which may introduce some uncertainty in the comparison. Nevertheless, Figure 2.3 and Table 2.2 illustrate that the magnitude of the tropical Atlantic trade winds from the east decreases over Bonaire compared to the open Caribbean Sea. Similarly, winds from the north also diminish, while those from the west and south exhibit increased magnitudes. The actual differences in wind magnitude and direction are dependent on the specific location on Bonaire, as local topography and land-sea interactions can create significant spatial variability.

Using Eq. 2.1, the wind stress magnitude from local wind conditions over Bonaire can be estimated. The resulting flow velocities induced by this wind stress are approximated using Eq. 2.2, following Roelvink and Reniers (2011).

$$v_{\infty} = \sqrt{\frac{\tau_w}{\rho_w C_f}} \quad (2.2)$$

$v_{\infty}$  is the equilibrium velocity as a result of wind stress  $\tau_w$ .  $\rho_w$  is the water density, which is equal to  $1023 \text{ kg/m}^3$  at Bonaire (Van Duyl et al., 2024). Lastly,  $C_f$  is the friction coefficient equal to 0.04 (Van Leeuwe, 2023). An air density of  $1.17 \text{ kg/m}^3$  is yielded through the ideal gas law (Wallace and Hobbs, 2006) and using the mean air pressure reported in the atmospheric data by Koninklijk Nederlands Meteorologisch Instituut (2025). The wind velocity from the east direction and the mean velocity of the other directions obtained by KNMI are used to first obtain a value for the wind shear stress  $\tau_w$  by applying Equation 2.1. Followed by Equation 2.2, the resulting values are shown in Table 2.3. The mean velocity of the other directions was used, as their magnitudes are relatively similar. This average provides a reasonable estimate of their influence. The estimated velocities are relatively low in magnitude with respect to the regional current magnitude. The magnitude difference between the wind directions indicates that the east wind will have more impact on the dispersal of the fish eggs, compared to the other wind directions.

| Wind direction   | Velocity $W$ - KNMI | Drag coefficient $C_d$ | Shear stress $\tau_w$ | Wind-driven current $v_{\infty}$ |
|------------------|---------------------|------------------------|-----------------------|----------------------------------|
| East             | 6.403 [m/s]         | 0.00105 [-]            | 0.0505 [ $N/m^2$ ]    | 0.0351 [m/s]                     |
| Other directions | 1.454 [m/s]         | 0.00073 [-]            | 0.0018 [ $N/m^2$ ]    | 0.0066 [m/s]                     |

**Table 2.3:** An approximation of the local wind-driven currents, based on data provided by Koninklijk Nederlands Meteorologisch Instituut (2025) and Equation 2.2.

### 2.2.3. Upwelling and downwelling

Wind-driven coastal upwelling or downwelling is an oceanic phenomenon resulting from the divergence or convergence, respectively, of surface waters at the coastal boundary (de Oliveira Júnior et al., 2024). These are driven by both alongshore winds and the Earth's rotation. Offshore displacement of surface water, typically through Ekman transport or divergent flow, is compensated by the upward movement of colder, nutrient-rich subsurface water, forming upwelling zones. Conversely, onshore displacement due to opposing wind conditions or surface water convergence along the same coastline leads to downwelling. Surface waters are forced downward as result (Webb, 2023). These mechanisms can significantly affect the dispersal and retention of fish eggs. Upwelling tends to transport eggs offshore, reducing nearshore retention rates. Downwelling, however, promotes retentions by directing eggs toward the coast.

In the Caribbean, Bertonecelj et al. (2024) reported the presence of upwelling along the windward coast and downwelling along the leeward coast of Curaçao. These are to be driven by the Caribbean Current and the Island Mass Effect (IME), which is explored by De Falco et al. (2022). The average velocity of the resulting surface current ranges between 0.1 and 0.3 m/s. Given Bonaire's geographic similarity and proximity to Curaçao, similar oceanographic patterns might be expected. However, Van Duyl et al. (2024) conducted measurements on salinity and nutrient concentrations of multiple stations around both islands. It was concluded that no differences in nutrient concentrations could be detected between wind- and leeward sides of Bonaire. In contrast, Curaçao exhibited more variability between stations on wind- and leeward sides in both salinity and nutrient profiles, aligning with Bertonecelj et al. (2024)

observations. These results suggest that upwelling and downwelling processes are minimal or absent along the leeward coast of Bonaire. A limited influence on the dispersal and retention of fish eggs near Bonaire is therefore implied.

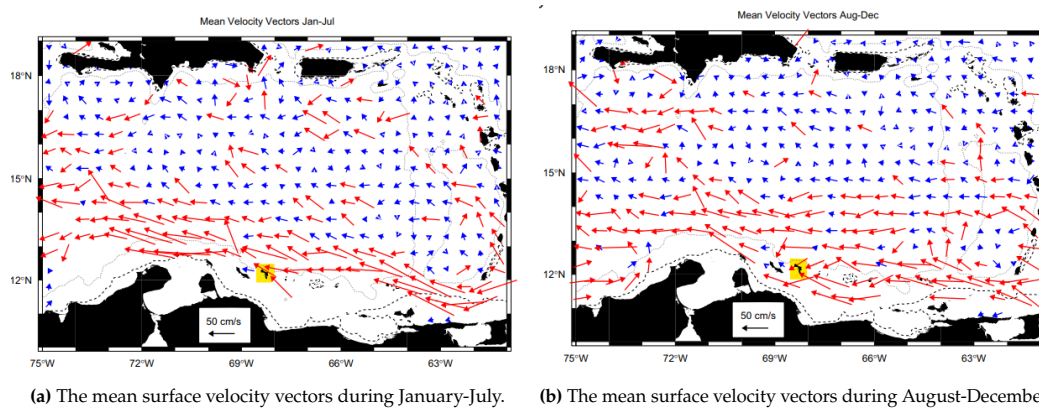
#### 2.2.4. Density-gradient driven currents

Another regional-scale abiotic driver of ocean circulation is the presence of density-gradient-driven currents. They arise from spatial variation in seawater density  $\rho$ , primarily controlled by temperature  $T$  and salinity  $S$  differences, with pressure playing a secondary role at depth (Pietrzak, 2021). This relation can be represented through Equation 2.3 by Pietrzak (2021):

$$\Delta\rho = \alpha\Delta T + \beta\Delta S \quad (2.3)$$

The values of  $\alpha$  and  $\beta$  are dependent on temperature, salinity and pressure, but are typically around  $0.2 \text{ kg/Cm}^3$  and  $0.8 \text{ kg/PSUm}^3$ , respectively (Cole and Quessenberry, 2025). Collectively they determine the stratification and baroclinic structure of the water column. The gradients create horizontal pressure differences, driving flow that adjusts under the Coriolis force into geostrophic currents (Gordon and Cenedese, 2025). The Caribbean Current, as described earlier, consists partially of the thermohaline circulation from the tropical and South Atlantic (Xu et al., 2024, Johns et al., 2002). The horizontal components of this circulation can be described as a geostrophic current. The transport of this geostrophic current is about  $14 \text{ Sv}$ , which can roughly be translated to  $0.28 \text{ m/s}$ . However, as mentioned, (the magnitude of) its impact on the dispersal of fish eggs on the leeward side of Bonaire is difficult to determine.

In addition to regional scale geostrophic flows, freshwater inputs from precipitation, river discharge, or localised evaporation-precipitation imbalances can generate baroclinic currents. The freshwater input reduces the surface salinity, creating vertical stratification and introducing a density gradient. The impact of the freshwater input can be of regional as well as local scale, depending on the source of freshwater. Large rivers like the Orinoco and the Amazon rivers seasonally exhibit extended plumes, particularly after the peak of seasonal rains. These seasonal rains occur during wet season from October to December in the Caribbean (Bertoncelj et al., 2024). The extended freshwater plumes enter the Caribbean Current in the Southern Caribbean and produce westward flowing jets which result in lower salinity values (Chérubin and Richardson, 2007). Figure 2.4 shows the resulting differences in mean surface velocity vectors within the dry and wet season, 2.4a and 2.4b respectively. The figures illustrate that north of Bonaire a strong surface current is observed for both seasons, and during the wet season also a surface current south of Bonaire and Curaçao becomes present. The currents during wet season are directed along the corner points of Bonaire, causing more water flow on the leeward side of Bonaire. However, the direction of the vectors do not seem to indicate flow towards the leeward side. If the dispersal of the fish eggs would start near these corner points, it would most likely result in an offshore dispersal instead of retention on the leeward side.



**Figure 2.4:** Mean surface velocity vectors of the currents within Caribbean Current, using the same bins as Richardson (2005) and shown in Fig. 2.2. Similarly, the swiftest velocities ( $> 25 \text{ cm/s}$ ) are shown within red and Bonaire's location is highlighted in yellow.

Taking a closer look at catchments on Bonaire, a few catchments on the leeward side of Bonaire can be observed (Slijkerman et al., 2019). West of Karpata and two close to Kralendijk provide freshwater plumes on the leeward side, which become most influential after similar peaks of seasonal rains. The magnitude of these plumes are highly dependent on the amount of precipitation. The average monthly precipitation during wet season can reach up to 100 mm (Bertoncelj et al., 2024). On a typical rainy day during wet season precipitation reaches 35 mm per square meter (Koninklijk Nederlands Meteorologisch Instituut, 2025). In order to estimate the resulting density-driven velocity, the effects on 1 cubic meter of sea water ( $V_{sea}$ ) is analysed. The resulting salinity change can be approximated with respect to the volume change resulting from the rainfall, using the following Equation (2.4):

$$\Delta S = \left| \frac{S_0 + V_{sea}}{V_{sea} + V_{rain}} - S_0 \right| \quad (2.4)$$

The initial salinity  $S_0$  surrounding Bonaire equals 35.5 PSU and  $V_{rain}$  equals  $0.035 m^3$ , which results in an absolute  $\Delta S$  of 1.200 PSU (Van Duyl et al., 2024). Assuming  $\Delta T$  is zero in this case, results in a density change  $\Delta \rho$  of  $0.960 kg/m^3$ , based on Equation 2.3. The velocity magnitude of the resulting flow  $U$  can be estimated with the following Equation (2.5) by Pietrzak (2021):

$$U = \sqrt{g \frac{\Delta \rho}{\rho_0} h} \quad (2.5)$$

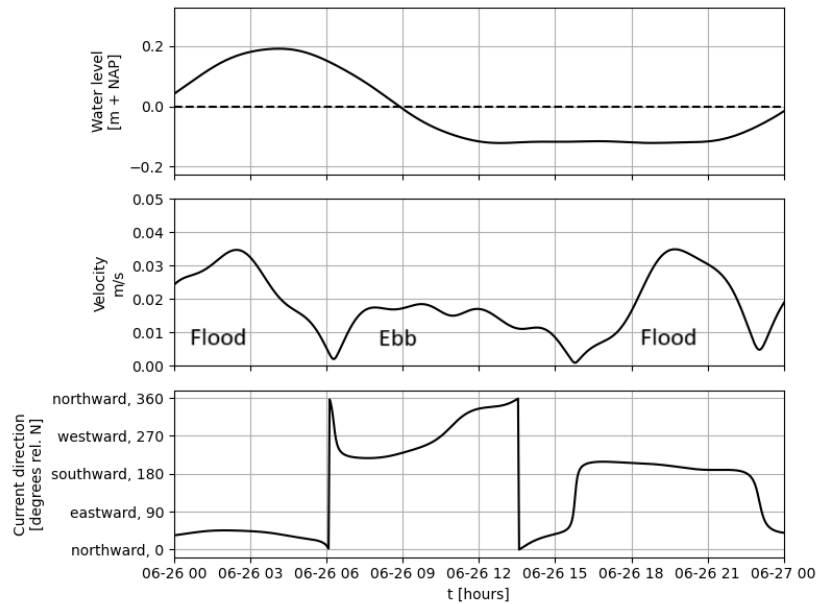
The gravitational acceleration  $g$  is equal to  $9.81 m/s$  and up to 50 meter depth the initial seawater density  $\rho_0$  is  $1023 kg/m^3$  surrounding Bonaire (Van Duyl et al., 2024). Rainfall-induced plumes are typically shallow, thus a plume thickness  $h$  of  $0.2 m$  is assumed (Anwar and Weller, 1981). The rainfall-induced plumes can result in a flow of approximately  $0.0429 m/s$  on the leeward side of Bonaire. However, the rest of the year almost no fresh rain water reaches the coastal region (STINAPA, 2018). Furthermore, a baroclinic current could also be driven by temperature. The seawater temperature is relatively constant throughout the year, ranging from 26 and 28 °C throughout the year (STINAPA, 2018). A gradual temperature change  $\Delta T$  of  $0.1 °C$  and no salinity change could lead to a baroclinic flow  $U$  of  $0.0062 m/s$ , based on the same approach as previous calculation. Overall, the effect of a density-driven currents on the leeward side of Bonaire are expected to be limited with respect to the dispersal of fish eggs.

### 2.2.5. Tidal propagation

Tide is generated by centrifugal forces, from the Sun-Earth and Moon-Earth systems, and tractive forces, from the Sun and Moon on Earth's surface (Pettersen, 1930). Tidal propagation involves both vertical and horizontal variations of water level, which are generated by the previously mentioned forces. The vertical variations are generally defined as slow, harmonic (sinusoidal), up and down motions of the sea surface. The vertical water level can be determined by a mean water level and the sum of cosine waves with varying frequencies, amplitudes and phases. Horizontal variations are often referred to as ebb and flood currents. The associated horizontal movement back and forth becomes more pronounced near coastal regions. Because the tide generating forces vary around the world, the tide is different for each coast and along that coast (Pietrzak, 2021). This also has to do with different bathymetries and the location of the amphidromic points (Bosboom and Stive, 2023). So although the tide is generated globally, the interest lies on the local scale effects.

Garcés-Ordóñez et al. (2021) and Grimaldi et al. (2022) identified tides as an important driver of small particle retention in coastal systems. Their studies highlighted how the phase relationship between vertical and horizontal tidal components can amplify tidal current. Figure 2.5 illustrates this through velocity peaks preceding the water level peaks. In their study areas, characterised by tidal ranges of approximately 3 m, prolonged velocity peaks produced strong currents. These currents had a significant impact on particle retention. Near Bachelor's Beach, however, the tidal regime differs considerably. While local tidal measurements are scarce, global tidal models such as the Finite Element Solution (FES) (AVISO+, 2024) and regional studies (Van Leeuwe, 2023) estimate a diurnal tidal range of roughly 0.4 m. This smaller range shortens the duration of the velocity peaks, resulting in weaker tidal currents. Van Leeuwe (2023) has measured the tidal currents at Bachelor's Beach and shows that they do not exceed 0.05 m/s. Consequently, tidal forcing likely plays a reduced role in particle retention compared

to systems with larger tidal ranges. While tidal forcing will be present, the impact of the tidal velocities near Bachelor's Beach is dependent on the magnitude of the other abiotic drivers in the region.



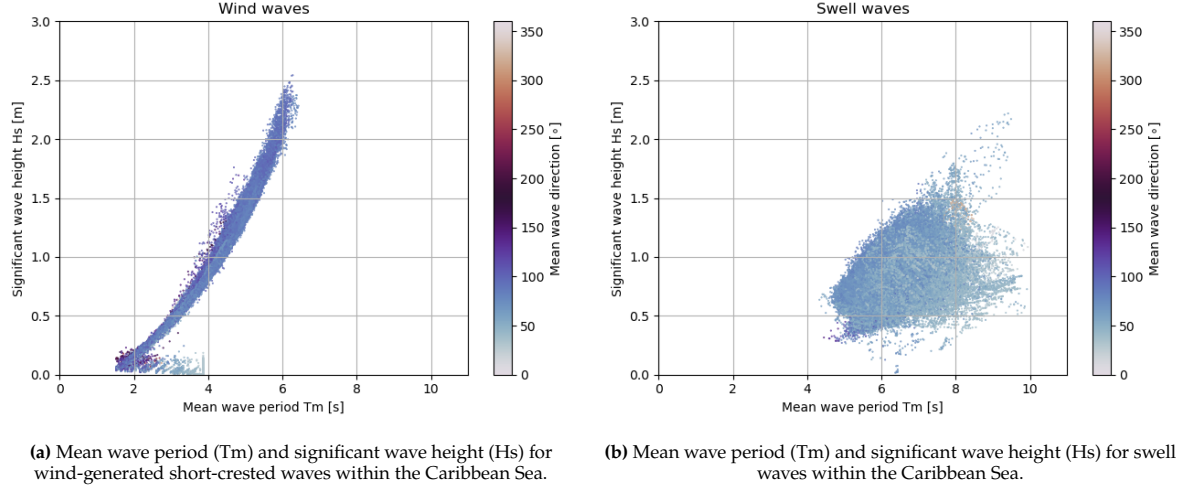
**Figure 2.5:** The water level (top), current velocity (middle) and current direction (bottom) within the Caribbean Sea on 26st of July 2024, based on the Finite Element Signal (FES) data (AVISO+, 2024). The figure illustrates the phase difference between vertical and horizontal tide.

### 2.2.6. Wave-induced currents

Waves can be classified based on their period, for instance storm surges, tsunamis and wind-generated waves. Given the study's scope, only frequent wave conditions near Bonaire will be considered. Frequent conditions include primarily wind waves and some swell waves. Local wind fields generate relatively short, random, and irregular waves with periods in the order of several seconds (Bosboom and Stive, 2023). Over long distances, these waves can evolve into longer, faster, lower, and more uniform swell waves, depending on their area of origin. Their periods can reach around ten seconds. Wave conditions within the Caribbean Sea is also modelled by ECMWF in ERA5 and exhibits a clear distinction between the swell and wind waves. Figure 2.6 illustrates the mean period and significant wave heights of the two wave types. It shows that wave heights of wind waves can reach up to 2.5 metres, while swell waves roughly stay below 2 metres. Van Duyl (1985) mapped the wave environment surrounding Bonaire, highlighting a clear contrast between the Northeast and Southwest coasts. The Northeast coast experiences high wave energy, with waves reaching up to 3.5 meters from the northwest. In contrast, the Southwest coast has a moderate to low wave energy environment, typically featuring smaller waves of around 50 centimetres in height.

This difference in wave energy between the Northeast and Southwest coasts can be attributed to the Southwest being sheltered from the Caribbean trade winds, as well as differences in local bathymetry. As discussed for the wind conditions and visible in Figure 2.3, the Northeast coast is directly exposed to persistent and strong easterly trade winds, which generate consistent wave activity from the east (Van Duyl, 1985). This exposure can result in elevated wave energy impacting the northeast shoreline, allowing for wave heights to occasionally reach up to 3.5 meters. In contrast, the Southwest coast is shielded from these winds, leading to reduced wave energy in this region. Additionally, the predominant wave directions in the Caribbean Sea are from the northeast to east, shown in Figure 2.6 through its colours. For such waves to reach the southwest coast, they must refract around the Bonaire. This process causes the waves to lose velocity and further reduction in wave heights (Holthuijsen, 2007).





**Figure 2.6:** Wave conditions of the two wave types observed within the Caribbean Sea based on the ERA5 reanalysis of ECMWF during 2024 (ECMWF, 2025). The color of a dot represents the nautical direction of that specific wave, so direction where the wave came from.

Bathymetric variations further contribute to these differences. The Northeast coast of Bonaire is characterised by a steeper underwater slope compared to the Southwest, which is visualised in Figure 3.2. This enables higher-energy waves to approach closer to the shore before breaking (Bosboom and Stive, 2023). It should be noted that the Southwest coast of Bonaire also includes fringing coral reef at a depth of 10 metres (STINAPA, 2025). The fringing coral reef introduces a high roughness resulting from the reef's structural complexity and coarse morphology of individual coral colonies (Monismith, 2007, Van Wiechen, 2020). This increased hydrodynamic roughness leads to higher rates of wave energy and velocity dissipation (N. Graham and Nash, 2013). Since 1985 this coverage has declined due to the impact of hurricanes, changing the bathymetry along the southwest shoreline (BonaireTax, 2023). This can indicate less dissipation of wave conditions. However, the observed wave environments by Van Duyl (1985) surrounding Bonaire remains overall representative of current wave environment (BonaireTax, 2023, Van Duyl et al., 2024).

In existing studies on pelagic fish egg dispersal, the secondary effects of waves near the surface are often considered to play a crucial role (Colin and de Mitcheson, 2011, Fujimura et al., 2013, Drivdal et al., 2014, Xu et al., 2024). These effects include wave-driven currents, such as those caused by Stokes drift and wave breaking. Stokes drift can be explained from a Lagrangian point of view. Consider a fluid particle as Lagrangian, then it represents the centre of mass of a fluid element and the particles follow an orbital motion (Siegel et al., 2003). In the crest of the wave their velocity increases, as the influence of the seabed is reduced compared to the region beneath the wave trough. This imbalance prevents the orbits from fully closing, resulting in a residual motion, known as Stokes drift. This drift acts in the direction of wave propagation. Stokes drift is proven to be important for a representative dispersal (Rühs et al., 2024, Cai et al., 2025). The Stokes drift can be expressed as drift velocity  $\bar{u}_l$  based on the following Equation (2.6) by Roelvink and Reniers (2011):

$$\bar{u}_l = \omega k a^2 \frac{\cosh 2k(h+z)}{2 \sinh^2 kh} \quad (2.6)$$

where the radian frequency  $\omega$  equals  $2\pi/T$ , with  $T$  being the wave period [s] and wave number  $k$  can be approached using Fenton's approximation, see Appendix A.1. The amplitude  $a$  is equal to half the wave height  $H$ ,  $h$  represents the total water depth and  $z$  the vertical location of a water particle. For the following approximation a water depth  $h$  of 30 meters, just outside fringing reef, and the particle is assumed to be in the mean water surface, so  $z$  equals 0 (Slagter, 2023). An estimation of the velocity is made for both short-crested wind-generated and swell waves, based on the 80th-percentile of the conditions shown in Figure 2.3 and Appendix A. The resulting velocities for the Stokes drift are presented in Table 2.4.

| Wave type                    | Wave height $H_s$ | Peak period $T_p$ | Wave number $k$     | Stokes drift velocity $\bar{u}_l$ |
|------------------------------|-------------------|-------------------|---------------------|-----------------------------------|
| Short-crested wind-generated | 1.175 [m]         | 5.291 [s]         | 0.1435 [ $m^{-1}$ ] | 0.0588 [m/s]                      |
| Swell                        | 0.965 [m]         | 7.944 [s]         | 0.0619 [ $m^{-1}$ ] | 0.0120 [m/s]                      |
| Estimation leeward wave env. | 0.500 [m]         | 3.200 [s]         | 0.3930 [ $m^{-1}$ ] | 0.0482 [m/s]                      |

**Table 2.4:** Overview of the variables necessary to approximate the Stokes drift velocity, based on Equation 2.6 and the 80<sup>th</sup> percentile of the wave conditions, shown in Appendix A.

Secondly, wave breaking occurs when waves become too high with respect to the depth below the wave. This typically occurs at a depth  $h_{br}$  equal to roughly 1/0.75 times the wave height  $H$  (Holthuijsen, 2007). During breaking, a layer of air-water mixture is generated, also known as surface roller. The surface roller converts the wave energy into turbulent kinetic energy and carries momentum shoreward. Since the roller rests on the front of the wave, the absolute mean velocity in the roller equals the propagation speed  $c$  of the wave (Svendsen, 1984). The propagation speed of a wave  $c$  in shallow water, where breaking occurs, can be approximated with the following Equation (2.7) by Holthuijsen (2007):

$$c = \sqrt{\frac{g}{k} \tanh kh} \quad (2.7)$$

The wave number  $k$  will again be approximated by Fenton's method using the breaker depth  $h_{br}$ . The resulting propagation speed for the surface roller of each wave type is presented in Table 2.5. In addition, Lenain et al. (2019) have shown that Stokes drift is enhanced for breaking waves. Both the surface roller and the enhanced Stokes drift of wave breaking contribute to a shoreward transport of surface particles.

| Wave type                     | Wave height $H_s$ | Breaker depth $h_{br}$ | Wave number $k$     | Roller velocity $c$ |
|-------------------------------|-------------------|------------------------|---------------------|---------------------|
| Short-crested wind-generated  | 1.175 [m]         | 1.567 [m]              | 0.4689 [ $m^{-1}$ ] | 3.6189 [m/s]        |
| Swell                         | 0.965 [m]         | 1.287 [m]              | 0.4953 [ $m^{-1}$ ] | 3.3398 [m/s]        |
| Estimation lee-ward wave env. | 0.500 [m]         | 0.6667 [m]             | 0.1797 [ $m^{-1}$ ] | 2.5513 [m/s]        |

**Table 2.5:** Overview of the relevant variables to approximate the propagation speed of waves, which equals to surface roller velocity, based on Equation 2.7.

The estimated velocities induced by short-crested wind-generated and swell waves are expected to occur primarily on the windward side of Bonaire. On the leeward side, these velocities are anticipated to be lower due to processes that reduce or limit wave energy and velocity. The exact extent of this reduction remains uncertain. However, based on wave height observations of approximately 50 cm by Van Duyl (1985), combined with wave period data shown in Figure 2.6a, an approximation of the leeward velocities was made. The calculated Stokes drift and surface roller velocities are presented in Tables 2.4 and 2.5. Although the wave height is reduced, the obtained flow velocities are in the same order of magnitude as the windward waves. This suggests that, regardless of wave type, these processes most likely influence the dispersal of fish eggs in the nearshore region of Bachelor's Beach.

## 2.3. Conclusion Literature review

In this literature review the biotic and abiotic factors of fish egg dispersal studies are considered and analysed, with respect to the condition surrounding Bonaire. The characteristics of marine fish, such as their shape, seize and density determine the biotic drivers in this study are related. Marine fish eggs are considered to be pelagic, which indicates a (slightly) positive buoyancy. While this does influence their vertical position in the water, most studies on pelagic fish egg dispersal consider the particles as passive. Also dispersal studies of larvae with an emphasis on initial dispersal predictions apply this approach, even though a larvae has more influence on its dispersal. Therefore in this study, the fish eggs will also be considered as passive, Lagrangian particles which are within the surface layer and thereby answering the first sub research question. This indicates that their dispersal is governed by abiotic drivers.

In existing dispersal studies different approaches to the considered abiotic drivers are taken, depending on their emphasis. If the emphasis lies on the biotic drivers, often global or regional scaled abiotic

models are considered, simplifying nearshore conditions. However, if the emphasis lies on the abiotic drivers, different drivers are considered dominant per study. This suggests that dominant abiotic drivers are site-specific and no direct conclusion on dominant abiotic drivers near Bachelor's Beach can be concluded. A list of possibly relevant abiotic drivers for the dispersal was constructed in Table 2.1 and the estimated velocity ranges of each abiotic driver are summarised below in Table 2.6. The table also estimates the uncertainty of each driver's impact. A "Low" uncertainty indicates that the presence of the driver is relatively certain. and therefore also it's estimated velocity magnitude. Based on a combination of the estimated velocities and the uncertainty, an expected relevance for the egg dispersal on the leeward side of Bonaire, where Bachelor's Beach resides, is constructed.

| Abiotic driver       | Approximated/associated velocity magnitude(s) | Uncertainty of impact | Expected relevance       | Included in this research |
|----------------------|-----------------------------------------------|-----------------------|--------------------------|---------------------------|
| Regional circulation | 0.140 - 0.750 [m/s]                           | Medium                | (Less) Relevant          | -                         |
| Wind                 | 0.007 - 0.200 [m/s]                           | Low                   | Relevant                 | X                         |
| Up- and down-welling | 0.000 [m/s]                                   | High                  | Most likely not relevant | -                         |
| Density-gradients    | 0.006 - 0.280 [m/s]                           | Medium                | Less relevant            | -                         |
| Tides                | 0.005 - 0.050 [m/s]                           | Low                   | Less relevant            | X                         |
| Wave action          | 0.012 - 3.619 [m/s]                           | Medium                | Relevant                 | X                         |

**Table 2.6:** An overview of the approximated or associated (surface) velocity ranges per abiotic driver near Bonaire are put in this Table, together with the expected uncertainty of the magnitudes. Based on these velocities, uncertainties and the gathered knowledge on the drivers a hypothesis of their expected relevance for the south west coast Bonaire is included, as well as which drivers are further investigated in this study.

Based on the approximated flow velocities and associated uncertainties, regional circulation, wind-driven, and wave-induced currents are expected to be the most relevant abiotic drivers. Ideally, all three would be incorporated; however, limitations in resolving regional circulation along Bonaire's southwest coast fall outside the scope of this study. As a result, only wind and wave forcing are included. To broaden the analysis, tides are also considered. Tidal forcing is reliably present, straightforward to implement, and does not require additional field data. In contrast, density-driven currents are more episodic and require site-specific measurements, which are currently unavailable. Similarly, while up- and downwelling may possibly influence dispersal, accurately representing these processes would require additional field data that are not presently available.

In brief, this study focuses on simulating the effects of tides, wind-generated, and wave-induced currents on egg dispersal. While estimated velocities presented here provide context, modelled outputs may differ depending on the physical formulations used.

## Modelling Methodology

### 3.1. Modelling approach

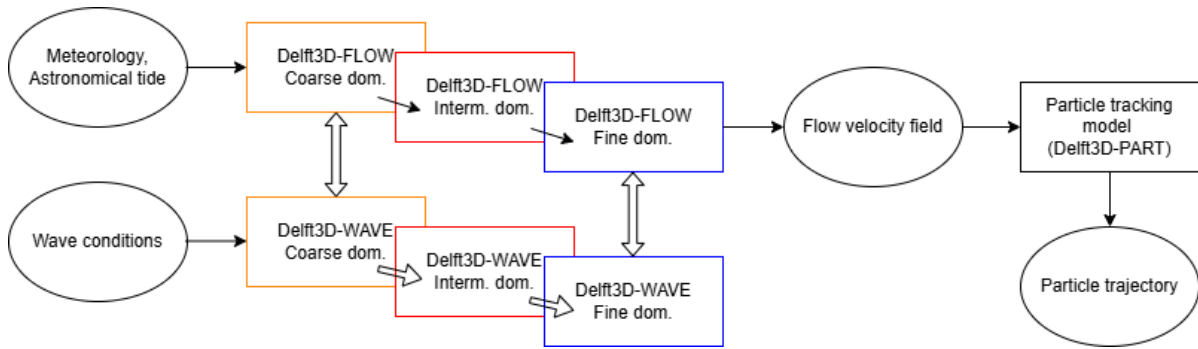
The (sub)research questions provide a framework for analysing abiotic drivers and their influence on egg dispersal. The second sub question focuses on identifying the dominant abiotic drivers near Bachelor's Beach. Due to limited local measurements, their effects are explored through hydrodynamic modelling. The applied model is detailed in Section 3.2.1. Scenario-based simulations allow for a structured assessment of how these abiotic drivers shape local velocity fields and dispersal patterns. The scenarios are based on the selected abiotic drivers in Section 2.3, and scenario specific conditions are outlined in Section 3.3.1.

The third sub question and the main research question, examines dispersal outcomes by simulating the movement of passive particles within these velocity fields, using a particle tracking model (Section 3.2.3). To infer likely spawning locations, the model applies time-varying scenarios aligned with RoffaReefs' sampling conditions. Various release locations and timings are tested (Section 3.3.2), and resulting passage rates at Bachelor's Beach are compared to the observed egg data. Agreement between modelled and observed data supports inferences of potential spawning origins. Finally, the model's sensitivity to selected process parameters is evaluated. Although this is not the primary focus, assessing their influence ensures that key uncertainties in the dispersal patterns are adequately considered.

### 3.2. Model setup

In this study, numerical simulations are carried out by using Delft3D version 4 (structured) modelling software. Delft3D is a modelling system that can simulate flows, waves, sediment transports, morphological developments and ecological processes and consists of several modules (Lesser et al., 2004). The Delft3D-FLOW is able to simulate multi-dimensional unsteady flow and transport phenomena resulting from tidal and meteorological forcing. The non-linear shallow water equations derived from the Navier-Stokes equations for incompressible free surface flow are solved by Delft3D-FLOW (Deltares, 2025a). This module is used to compute the hydrodynamic conditions surrounding Bonaire. To account for the flow phenomena resulting from waves, Delft3D-WAVE is online coupled to Delft3D-FLOW. Delft3D-WAVE is based on the third-generation SWAN model and allows for simulating the evolution of random, short-crested wind-generated waves in nearshore coastal regions (Deltares, 2025c, Holthuijsen et al., 1993). Together the modules are able to simulate the flow velocities in a specified domain, based on the applied boundary conditions.

Lastly, to simulate the dispersal of the fish eggs near the Southwest coast of Bonaire Delft3D-PART is used. Delft3D-PART is a random walk particle tracking model, which is able to calculate dynamic concentration distribution by following the tracks of thousands of particles with time (Deltares, 2025b). Delft3D-FLOW and -WAVE generate flow patterns that serve as input for Delft3D-PART. Using offline coupling, the model then calculates the trajectory of the fish eggs.

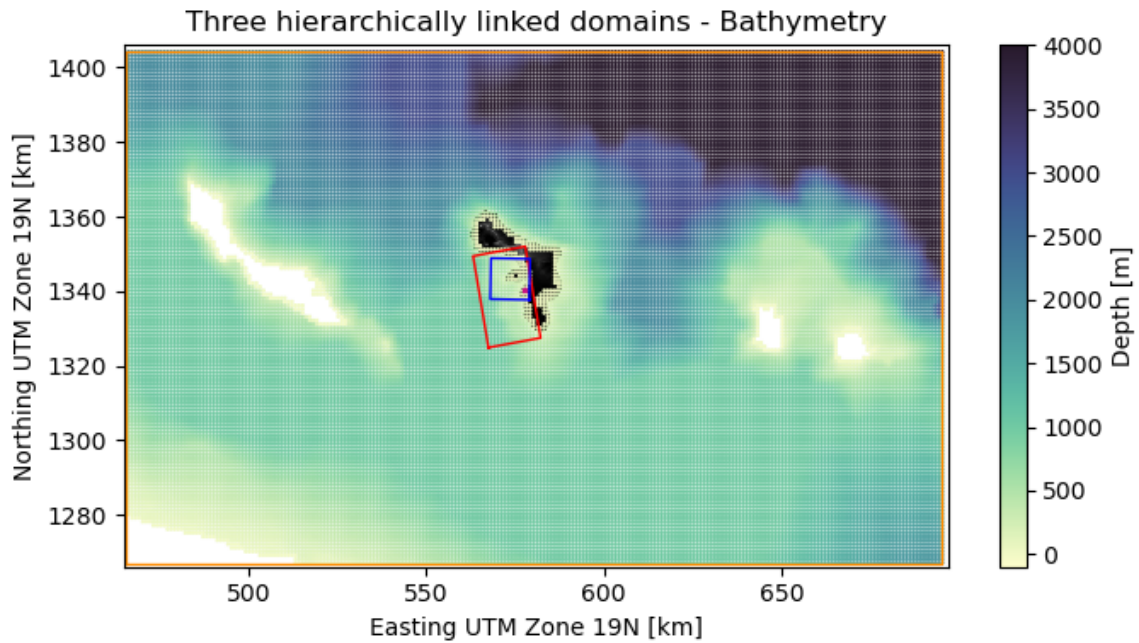


**Figure 3.1:** A simplified, schematic overview showing the model structure and data flows. The wider arrows represent the online coupling within the model structure, whereas the black arrows represent a successive, offline order in data flow.

An overview of the model structure is depicted in Figure 3.1. The settings for the hydrodynamic and particle tracking model are further detailed in sections 3.2.1 and 3.2.3 respectively. Section 3.2.1 and Figure 3.4 further details the approach to coupling and nesting between FLOW and WAVE modules.

### 3.2.1. Hydrodynamic model

A structured, three-dimensional hydrodynamic model is developed to simulate the hydrodynamics driven by abiotic factors near Bonaire. Multiple data sources are used to implement the forcings in the study area. The sources include large-scale processes within the Caribbean Sea, where observational data are spatially sparse. The station spacing typically has the order of several kilometres. To ensure accurate propagation of these forcings to local boundaries near Bachelor's Beach, a nested modelling approach is employed, which is further detailed below. This consists of three hierarchically linked computational domains. An overview of the three computational domains is provided in Figure 3.2 and 3.3 and Table 3.1.



**Figure 3.2:** The coarse domain is shown within the orange frame, the intermediate within the red frame and the fine domain within the blue frame. The coordinates on the axis are given within the Cartesian system. Bonaire is presented in the middle (shown in black), with Curaçao on the west of Bonaire (shown in white).

### Computational grid and bathymetry

Each computational domain in the model is equipped with its own structured grid to ensure numerical stability and accurate representation of physical processes. All domains are rectangular with grid resolutions not exceeding 500 cells in any direction, to limit computation time. For the coarse domain, the grid consists of 460 cells in the  $\xi$ -direction (u- and M-direction) and 276 in the  $\eta$ -direction (v- and N-direction) (Deltares, 2025a). The intermediate and fine domains use 150 by 250 and 440 by 440 cells in the  $\xi$ - and  $\eta$ -directions, respectively. Each shape is illustrated in Figure 3.2, and the grid cells are indicated in Figure 3.3a. These computational grids used in Delft3D-FLOW are also applied in Delft3D-WAVE. Table 3.1 provides an overview of each domain considered in this study.

| Domain       | Size             | Grid resolution | X,Y -Origin (UTM 19N) | Rotation | Vertical layers |
|--------------|------------------|-----------------|-----------------------|----------|-----------------|
| Coarse       | 230 km by 138 km | 500 m by 500 m  | 4657000, 1266700      | 0°       | 1               |
| Intermediate | 15 km by 25 km   | 100 m by 100 m  | 567500, 1324900       | 10°      | 12              |
| Fine         | 11 km by 11 km   | 25 m by 25 m    | 579000, 1337700       | 89°      | 12              |

**Table 3.1:** Overview of the three hierarchically linked computational domains. The Cartesian co-ordinate system is used to provide the values of X,Y -origin and rotation in degrees.

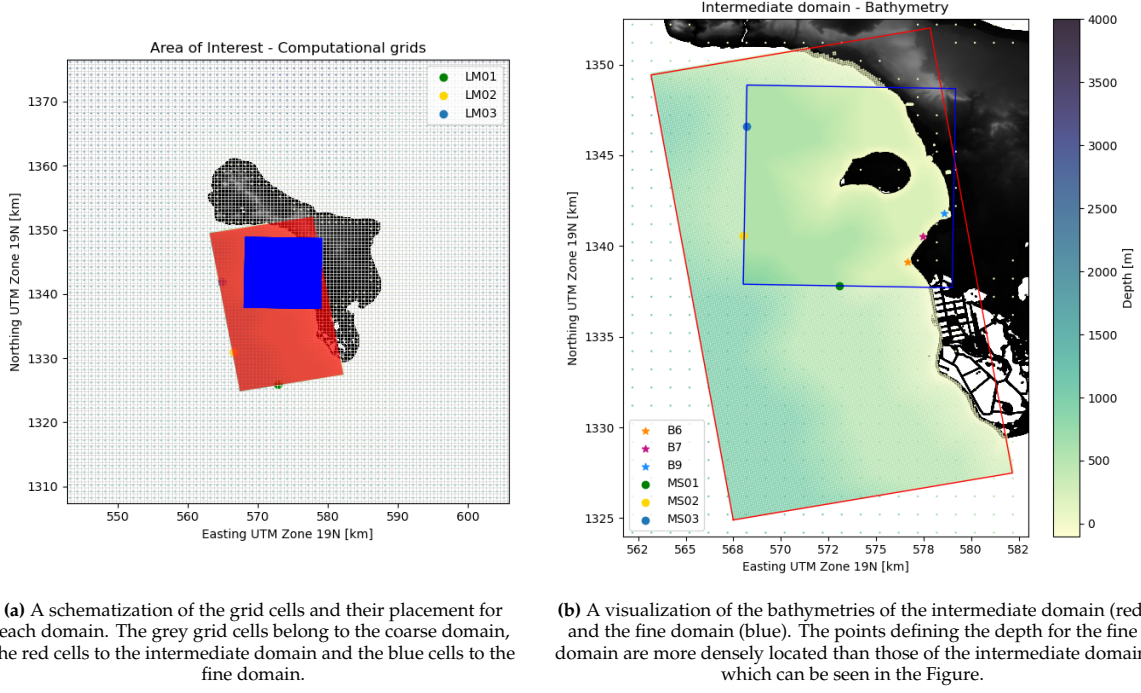
It was chosen to include a vertical structure into the intermediate and fine domain, achieving a three-dimensional model. This allows for the surface flows to be resolved. A 2DH model (horizontal, depth-averaged) would underestimate the flows that occur at the surface in the nearshore region of Bachelor's Beach. For the vertical discretisation, a  $\sigma$ -layer system is used. 12  $\sigma$ -layers are used and each layer has a height of 8.333% of the water column. As a result, in the nearshore region with depths around 7 to 10 metres, the surface layer will have a height of roughly 50 to 80 centimetres, which is where the pelagic eggs reside in reality.

To guarantee numerical stability, several grid quality criteria must be met (Deltares, 2025a). First, the aspect ratio, representing the ratio of cell length in the M-direction to that in the N-direction, should fall within the range of 1 to 2. Uniform grid spacing is applied in both directions within each domain, yielding an aspect ratio of 1. Thereby the criterion is satisfied. Grid smoothness, defined as the ratio of adjacent cell sizes, should not exceed 1:1.2 in the regions of interest. Within each domain, this condition is met. However, at the interface between domains during nesting, a cell size ratio of 1:5 or 1:4 is applied, potentially introducing boundary effects. To mitigate this, boundary cells of the intermediate and fine domains are carefully aligned and validated with those of their coarser domains, along the points LM01 to LM03 and MS01 to MS03 presented in Figure 3.3. Lastly, the criteria for the time step of each domain is based on the accuracy argument, which is dependent on the Courant-Friedrichs-Lewy number (CFL), described in Equation 3.1:

$$CFL = \frac{\Delta t \sqrt{gH}}{\min(\Delta x, \Delta y)} \quad (3.1)$$

where  $\Delta t$  is the time step in seconds,  $g$  the acceleration of gravity,  $H$  is the local water depth and  $\min(\Delta x, \Delta y)$  the minimal value of the grid spacing in either direction. The Courant number should remain below ten to ensure accuracy, preferably close to one. Based on the smallest water depths and corresponding grid sizes in each domain, time steps of 2.5 minutes, 1 minute, and 30 seconds were selected for the coarse, intermediate, and fine domains, respectively. These time steps keep the Courant number below the recommended threshold.





**Figure 3.3:** An overview of the computational grids and bathymetries for the different domains.

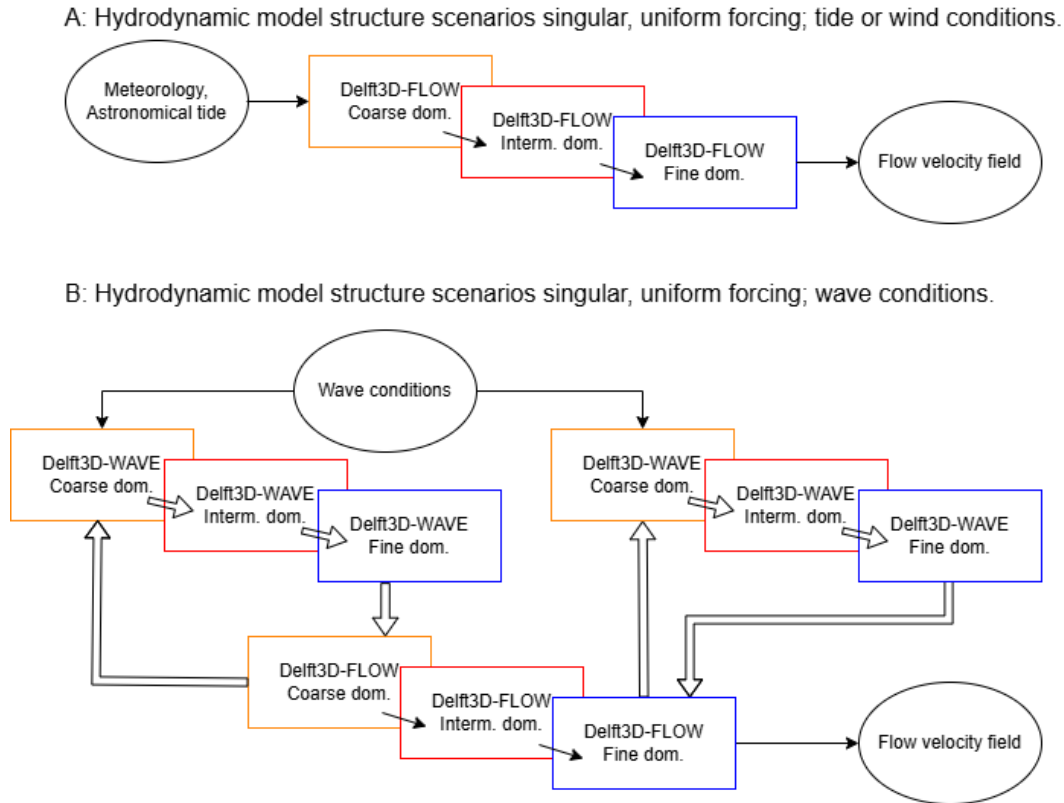
The model bathymetry is derived from two primary datasets: a high-resolution contour map surrounding Bonaire, and a coarser dataset encompassing the broader Caribbean Sea. The high-resolution bathymetry was developed by Slagter as part of his MSc thesis in 2023. The depth contours range from 4 to 20 meters and accurately captures the fringing reef along Bonaire's coastline. The broader dataset, obtained from EMODnet captures the seabed depths from 50 to 4000 meters across the Caribbean Sea. The datasets are integrated and interpolated to construct a continuous bathymetry for model input, as illustrated in Figure 3.2 and 3.3b.

#### Boundary conditions and forcings

The coarse domain is bounded by open ocean interfaces, requiring the application of open boundary conditions to represent the offshore interactions. Given the presence of multiple open boundaries, two complementary boundary condition types are implemented. Neumann time-series type for boundaries aligned with the  $\xi$ -direction, prescribing the water level gradient normal to the boundary. And, Riemann time-series type for boundaries aligned with the  $\eta$ -direction, which simulates weakly reflective wave behaviour to minimize artificial reflections (Deltares, 2025a). Both condition types are assigned zero values to emulate an idealised non-reflective ocean boundary. For Neumann this indicates  $\delta\xi/\delta\eta = 0$  and for Riemann non-reflective wave components. This configuration prevents the artificial reflection of outgoing hydrodynamic forcing at the model boundaries. As a result, the hydrodynamic integrity of the coarse model is preserved. For both the intermediate and fine domains, the boundary conditions are defined by water level time series for the West boundary and (water) current time series for the North and South boundaries, derived through nesting from the coarser domains.

In the Literature review it was concluded that the forcings of the model will consist of tide, wind and waves. Various datasets provide the input for these forcing mechanisms. Along the Northern and Eastern open boundaries of the coarse domain, tidal water levels are prescribed. These are based on 30 amplitudes and phases of harmonic constituents from the global tide model AVISO+ (Lyard et al., 2021). The meteorological forcing is derived from KNMI's weather station on Bonaire as well as the ERA5 reanalysis for the global climate and weather by the European Centre of Medium-Range Weather Forecasts (ECMWF). Koninklijk Nederlands Meteorologisch Instituut provides local conditions on Bonaire, such as the wind velocities and direction. It should be noted that the location of the weather station on Bonaire is unknown. ECMWF provides the similar information, but on sparser stations

within the Caribbean Sea. Information on wave conditions, such significant wave height, period and direction, is also obtained through ERA5 by ECMWF.



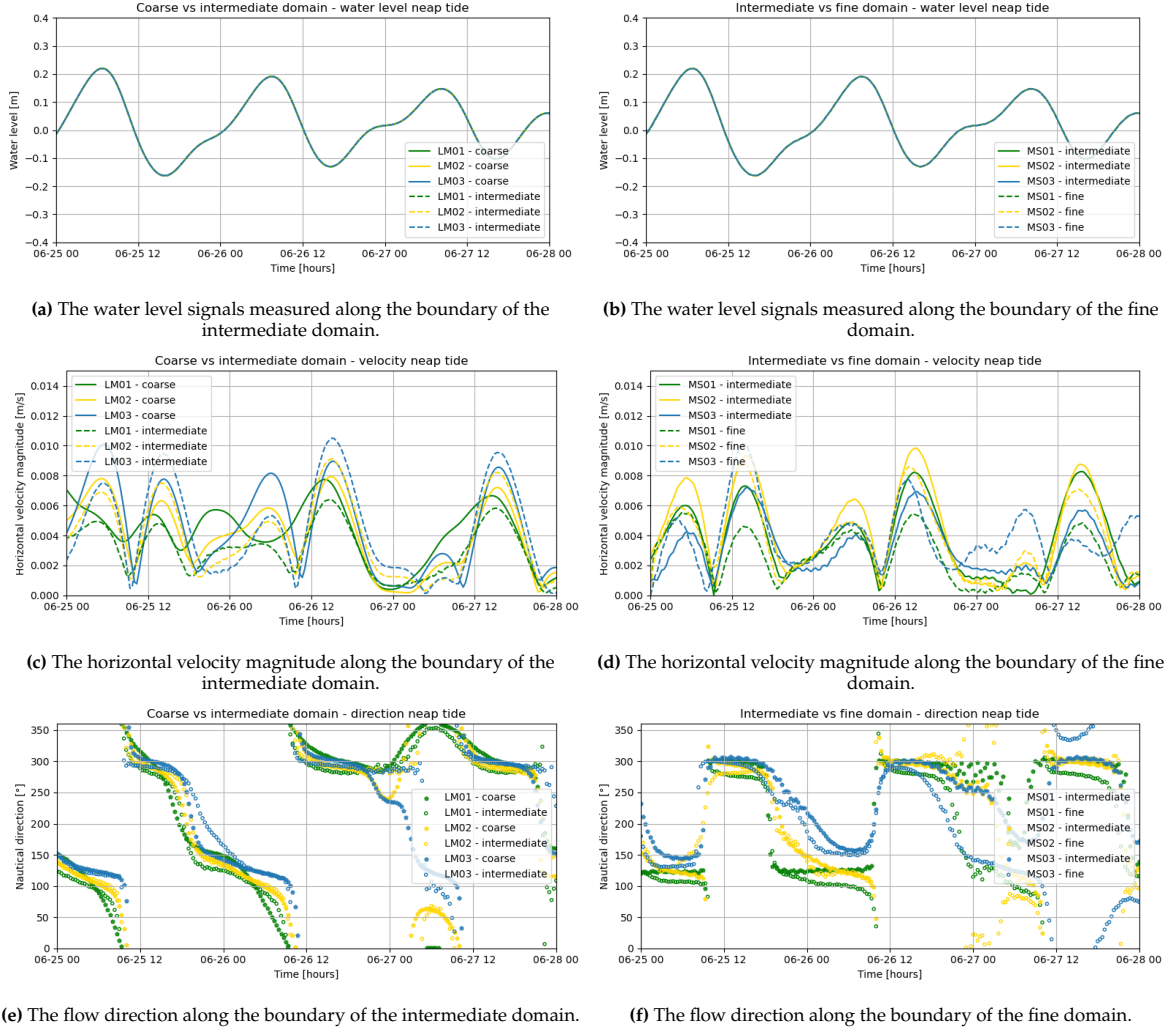
**Figure 3.4:** The approach to nesting boundary conditions dependent on the forcing applied. Part A exhibits the steps to offline nesting (black diagonal arrows) for forcing of tides or wind conditions. Part B shows the steps for online coupling and/or nesting (white hollow arrows) and offline nesting (black diagonal arrows) required for including wave forcing.

Due to the sparse distribution of forcing stations, nesting is required to define boundary conditions for the intermediate and fine domains. The nesting approach varies with the type of forcing applied. Figure 3.4 outlines the hydrodynamic modelling workflow based on these inputs and nesting procedures. In the upper section (A), forcings such as tides and wind are directly applied in the coarse domain using Delft3D-FLOW. The offline nesting tool then generates boundary conditions for the intermediate domain, and this process is repeated for the fine domain and results in the desired flow velocity field. Wave forcing, shown in the lower section (B), requires Delft3D-WAVE. Within this module, wave characteristics are defined for the coarse domain, and the intermediate and fine grids can be directly nested within it. The WAVE module is online coupled to the FLOW module, providing wave-driven flow and boundary conditions for the intermediate domain. The intermediate domain serves solely to determine FLOW boundary conditions for the fine domain and is therefore not coupled to the WAVE module. The fine domain receives these FLOW conditions along with wave forcing via the nested WAVE module, yielding the final wave-induced flow velocity field.

### 3.2.2. Validation of the hydrodynamic model

Due to the limited availability of nearshore measurements around Bachelor's Beach, model validation is constrained. As a result, nesting performance is assessed by comparing hydrodynamic conditions between nested domains along their boundaries. Points LM01–03 and MS01–03 are used for this purpose, see Figure 3.3 for their location in the domains. Figure 3.5 presents the comparison results under tidal forcing, including water levels, velocity magnitude, and flow direction. Tidal forcing was selected to demonstrate the model's ability to capture a temporally varying boundary condition. Table 3.2 summarizes the Root Mean Square Errors ( $RMSE$ ) and coefficients of determination ( $R^2$ ).  $RMSE$  reflects the average error magnitude, and  $R^2$  indicates the extent to which variability in the finer domain

is explained by the coarser one (Lanzafame et al., 2024).



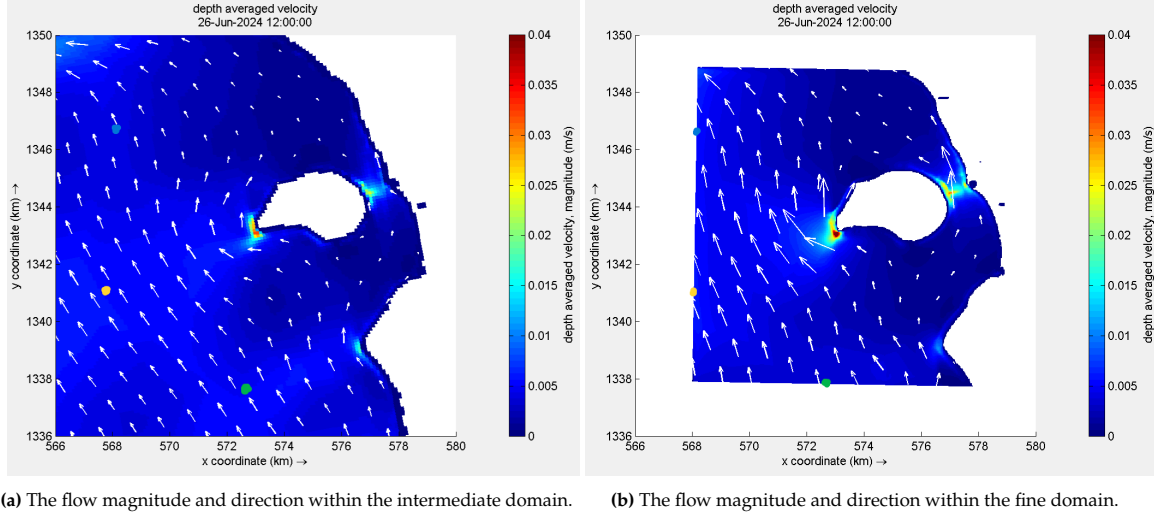
**Figure 3.5:** An overview of the Goodness of Fit between domains, comparing each point at the boundary of the intermediate (left) or fine (right) domain with the corresponding point in the coarse (left) or intermediate (right) domain.

| Variables                   |       | LM01    | LM02    | LM03    | MS01     | MS02    | MS03    |
|-----------------------------|-------|---------|---------|---------|----------|---------|---------|
| Water levels [m]            | RMSE  | 0.00089 | 0.00078 | 0.00079 | 0.00112  | 0.00108 | 0.00106 |
|                             | $R^2$ | 0.99995 | 0.99996 | 0.99996 | 0.99988  | 0.99989 | 0.99989 |
| Velocity magnitude [m/s]    | RMSE  | 0.00224 | 0.00096 | 0.00150 | 0.00170  | 0.00106 | 0.00185 |
|                             | $R^2$ | 0.15194 | 0.85112 | 0.78509 | 0.496553 | 0.86045 | 0.04882 |
| Nautical flow direction [°] | RMSE  | 25.23   | 21.22   | 34.95   | 65.63    | 42.99   | 61.50   |
|                             | $R^2$ | 0.88825 | 0.88344 | 0.75061 | 0.35982  | 0.60098 | 0.43619 |

**Table 3.2:** The RMSE and  $R^2$  of the points along the different domains, for the components shown in Figure 3.5

The water levels in Figure 3.5 show strong agreement across the model domains, supported by low RMSE and high  $R^2$  values. This indicates a clear correlation between water levels in the coarse, intermediate, and fine domains. In contrast, velocity magnitudes and flow directions show more variability between the domains. Between the coarse and intermediate domains,  $R^2$  values remain relatively high, except at point LM01. LM01 exhibits a lower  $R^2$  and higher RMSE. This is likely due to the low velocity magnitude at LM01 (roughly 0.01 m/s), where even small absolute errors significantly reduce correlation. For the comparison between the intermediate and fine domains,  $R^2$  values for

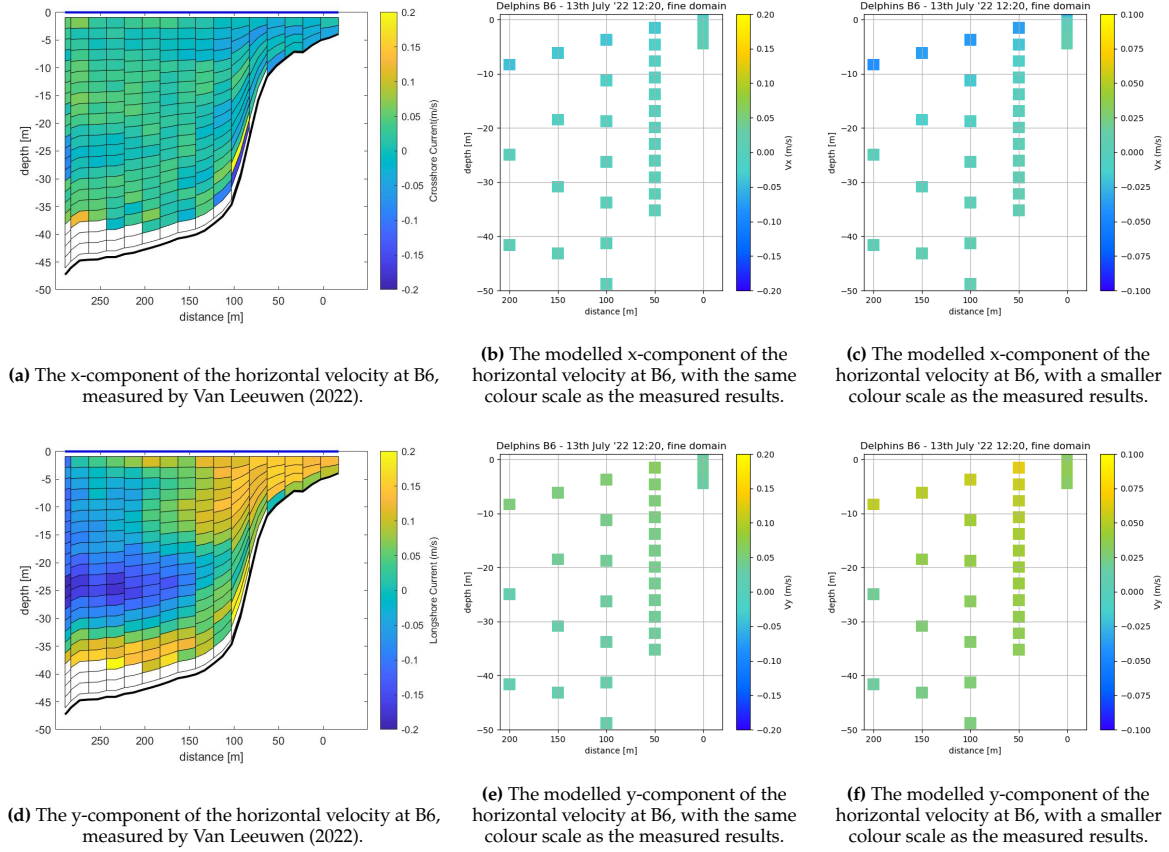
velocity and flow direction decrease further, particularly at MS03. This is partly influenced by the low velocity magnitudes relative to the error, but it also introduces potential nesting limitations. Ideally, it should not matter which points along the boundary are chosen for this comparison, however this is not the case for the hydrodynamic model. To fully assess the models nesting performance, the internal flow structures are qualitatively examined in Figure 3.6.



**Figure 3.6:** Qualitative comparison between the intermediate and fine domain with respect to nesting qualities. The points MS01 - 03 along the boundary of the fine domain are also present in their respective colours.

Figure 3.6 offers a closer, qualitative assessment of the overall flow patterns in the intermediate and fine domains. The Figure shows that flow magnitudes and directions are generally comparable across both domains. Some variation is expected, as grid refinement should capture additional detail. If this were not the case, refinement would have little purpose. Ideally, the choice of comparison points for the quantitative assessment should not influence a qualitative evaluation, but this is not entirely the case for the current model. Although the  $R^2$  values for velocity magnitude and flow direction between the intermediate and fine domains are not optimal, the overall flow structure and water levels remain consistent. Therefore, the nesting between these domains is considered valid and includes a known variability. It is important to reflect on this variability of the model with respect to the obtained results, and is discussed in Chapter 5.

A single dataset of water current measurements near Bachelor's Beach, which does exist, was available for this study. These measurements were conducted by Van Leeuwen (2022) for Wageningen University and Research (WUR). Using Acoustic Doppler Current Profilers (ADCP), the study recorded particle movement in three dimensions ( $x$ ,  $y$ , and  $z$ ). On July 13, 2022, measurements were taken near Delphins/Windhoek, Bachelor's Beach and Port Bonaire, points B6, B7 and B9 respectively in Figure 3.3b. Subsequently the measurements were converted into  $x$ - and  $y$ -components of the flow velocity. The corresponding wind, wave and tidal conditions during this period are provided as input into the model developed in this study. As only the results of the measurements are available, a qualitative comparison is made between the measured and modelled results. The comparison for Delphins/Windhoek (B6) is shown in Figure 3.7, with Bachelor's Beach (B7) and Port Bonaire (B9) included in Appendix B.1.



**Figure 3.7:** The measured (a, d) and modelled (b, c, e, and f) results for the horizontal velocity at Delphins/Windhoek, Bonaire, on July 13, 2022, at 12:20 h. The two figures on the right hand side exhibit a smaller colorbar, to better visualize the modelled flow directions.

Figures 3.7 (and Figures B.1, B.2) show that the measured horizontal velocities exhibit more variation in magnitude over depth, compared to the modelled results with the same colour scale. It should be noted that the ADCP measurements are the most reliable for first 5 up to 20 metres of depth. Afterwards it becomes difficult for the instrument to distinguish the correct directions. The direction of the flow in the upper layers are relatively similar between the measured and modelled results. Although the values of the flow velocity or not exactly the same, they flow towards the same direction. This similarity in flow direction is better visualised by the smaller colour scale for the modelled results in the two Figures on the right, 3.7f and 3.7c. Given that the measured values are a snapshot of the flow system near Bachelor's Beach, it remains difficult to fully validate the model based on this single comparison. Though the flow directions align, more measurement data is necessary to confidently evaluate the results and conclude if the velocity magnitudes are underestimated or correctly modelled.

### 3.2.3. Particle tracking model

Through Delft3D-PART the transport of particles is simulated by means of a particle tracking method using the flow data from the respective hydrodynamic modules. The model is best suited for mid-field range (200 m up to 15 km), which aligns with the (intermediate and) fine domain(s) of this study (Deltares, 2025b). Two type of modules are presented in Delft3D-PART, namely the Tracer and Oil module. The Tracer module allows for passive advection and diffusion without additional processes, such as buoyancy, degradation and more. The Oil module does allow for these type of settings, but does not fit the assumption of a passive Lagrangian particle, which is surface bound.

The location of a particle in the Tracer module consists of two elements, namely the advection step and a random walk step (Deltares, 2025b). First, the advection step is due to the shear stresses from water flow

and wind. Thereafter, the random walk step is related to the horizontal and vertical dispersion, which influence the size and the direction of the movement. Each step is shortly explained in the following sections.

#### Advection process

The path of a particle in a computational grid-cell is determined by analytical integration along the velocity field which is driven by currents, leading to mass-conservation of water. This aligns with the advection step. The analytical integration procedure is given by Equation 3.2:

$$x(t + \Delta t) = x(t) + \int_0^{\Delta t} \left(\frac{dx}{dt}\right) dt \quad (3.2)$$

where  $x$  is the distance depending on streamline distance function  $s(t)$ ,  $t$  is the time, and  $\frac{dx}{dt}$  is the velocity. The position of a particle at time  $(t + \Delta t)$  is calculated with this equation based on its position at time  $t$  and the velocity over the time interval  $\Delta t$ . The velocity  $\frac{dx}{dt}$  is given by Equation 3.3:

$$\frac{dx}{dt} = \frac{ds}{dt}(\alpha_x x(s) + \beta_x) \quad (3.3)$$

where  $\frac{ds}{dt}$  is the rate of change of the streamline distance and  $\alpha_x$  and  $\beta_x$  are constants that depend on the flow field. They are defined in Equations 3.4 and 3.5:

$$\alpha_x = C(\sigma) \left( \frac{Q_+ - Q_-}{V} \right) \quad (3.4)$$

$$\beta_x = C(\sigma) \frac{Q_{+/-}}{V} \quad (3.5)$$

where  $C(\sigma)$  is the distance between the velocity points in the hydrodynamic grid,  $Q_{+/-}$  is the flow through the upwind or downwind surface of the grid cell, and  $V$  is the volume of the grid cell. The  $\frac{Q_{+/-}}{V}$  term represents the inverse of the travel time of the grid cells with this  $Q_{+/-}$ . The path acceleration is neglected for the implemented numerical integration and therefore the rate of change of the streamline distance is assumed to be constant:  $\frac{ds}{dt} = 1$ . Additionally, given that the velocity field is directly linked to the hydrodynamic flow field, see hydrodynamic model, the flow field satisfies the following volume conservation, described in Equation 3.6:

$$\frac{\partial}{\partial x}(\alpha_x x + \beta_x) = 0 \quad (3.6)$$

#### Dispersion process

The dispersive part, or the random walk step, is solved with an Euler-type numerical scheme in Delft3D-PART. Dispersion in both the horizontal and vertical direction is based on a white noise process, which is described by Equation 3.7:

$$\Delta s = \sqrt{6D_{x,y}\Delta t} \quad (3.7)$$

where  $\Delta s$  is the maximum displacement,  $\Delta t$  is the Lagrangian time step, and  $D$  is the dispersion coefficient. Given that the fish eggs are assumed to be surface bound, the vertical dispersion is neglected and limits the transport to 2DH within the surface layer. Since the dispersion is horizontal, the dispersion in the simulation will be due to turbulence and increases with time according to the turbulence theory. The dispersion coefficient  $D$  is defined as follows, given in Equation 3.8:

$$D_{x,y} = \sqrt{at^b} \quad (3.8)$$

Here  $a$  and  $b$  are constant coefficients and account for all random fluctuations that are not resolved in the hydrodynamics. It is recommended to calibrate these coefficients to the spread of the observed particle. However, given the fact that the dispersal of a passive Lagrangian particle is mostly governed by advection, the values of  $a$  and  $b$  are set to 1 and 0.01, respectively. This follows a similar approach to that of Onsri et al. (2024).



### Numerical settings

The numerical settings of the particle simulation influence the resolution and computation time. These settings include numerical settings of the hydrodynamic output files, the time step of the particle model and the total number of particles used. The numerical settings of the hydrodynamic model, described in Section 3.2.1, influence the numerical settings of the flow provided to the particle module. The flow within the hydrodynamic model of the fine domain is calculated for every 30 seconds. The resulting output is then stored into multiple communication files, which limits the size of these files and will be loaded into Delft3D-PART. Given that the estimated flow velocities are within the order of centimetres per second and to limit computation time, it was chosen to have a communication output time step of 20 minutes. Therefore the communication time step between the hydrodynamic model and particle tracking model is 20 minutes.

The time step used for the particle movement should be less or equal to the communication time step with the hydrodynamic model. Other than this guideline, the time step of the particle tracking simulation is not limited to numerical conditions, such as the Courant number for the hydrodynamic model. The time step for particle tracking should be sufficiently small to ensure the particles follow the hydrodynamic streamlines accurately. At the same time, it must be large enough to keep the computation times reasonable. A time step of 5 minutes acquires this and is therefore used in the particle simulations.

The accuracy of the computed results is related to the number of particles used in the simulation. The general guideline by Delft3D-PART is that accuracy of the dispersal varies with the square-root of the number of particles (Deltares, 2025b). The amount of pelagic eggs released within a general spawning event can range from several thousands up to billions eggs (Gardner et al., 2015, Vons, 2019). However, using such amounts per release would lead to long computation time, which is not desired. It was chosen to release 1000 particles per location, as accuracy remains relatively high while obtaining a reasonable computation time.

Particle dispersal is simulated over a 24-hour period. This duration reflects the maximum time pelagic fish eggs typically remain in the egg stage. After 24 hours, the eggs begin transitioning into hatchling larvae, at which point they can influence their own dispersal. Beyond this stage, the assumption of passive particle behaviour is no longer valid for this study. Furthermore, the survival rate of the eggs are set to be 100%. This is chosen such that emphasis lies on understanding the dispersal resulting from the abiotic drivers. Table 3.3 provides a summary of the numerical settings and parameters for the particle tracking model.

| Parameter           | Value             |
|---------------------|-------------------|
| Time step PART      | 5 minutes         |
| Number of particles | 1000 per location |
| Simulation time     | 24 hours          |
| Survival rate       | 100%              |

**Table 3.3:** Numerical settings used for the particle tracking simulation and their fixed values.

### 3.3. Model scenarios

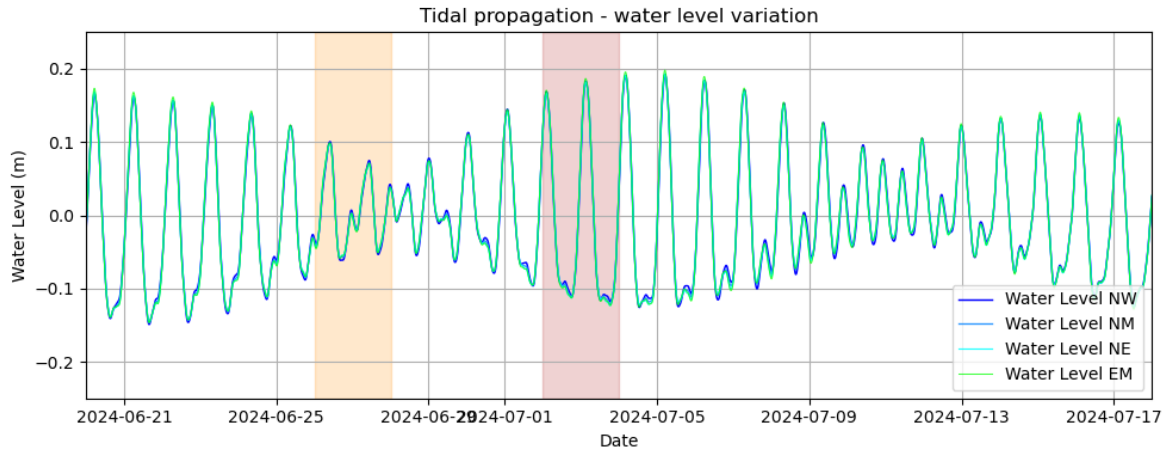
Understanding the individual and combined effects of different drivers requires insight into both their isolated impacts and their interactions. Scenario-based simulations offer a structured approach to obtain this knowledge and evaluate the resulting outcomes. Initially, representative conditions are explored in the scenario-based simulations by varying abiotic drivers and egg release locations. Subsequently, more realistic scenario's are simulated, informed by sampling data from RoffaReefs on both abiotic conditions and egg parameters. The following sections outline the different simulation periods, conditions and the parameter values applied in the scenarios.

### 3.3.1. Abiotic driver conditions

Spawning events are often triggered by optimal abiotic conditions, which vary among species (Putri et al., 2024). Given that this study does not focus on a specific species, the precise timing of spawning events remains uncertain. The sampling data of RoffaReefs ranges from March 2024 up to January 2025, therefore the period considered here is 2024. Due to the scope of this study, simulating every sampling moment and its associated conditions is not feasible. To ensure characteristic conditions are included in the analysis, each abiotic driver is considered separately. These characteristic conditions per abiotic driver lead to the "base" scenarios, where one characteristic condition is applied per scenario to visualize the impact of that specific condition. Some of these conditions are then combined, to further analyse the impact of their interaction on the velocity field at the water surface layer near Bachelor's Beach.

#### Tidal forcing

Tidal forcing has a harmonic characteristic, as described in section 2.2.5, which results in cycles with similar conditions. A common cycle to consider is a spring-neap tidal cycle with a rough duration of 14.5 days (Pietrzak, 2021). A spring-neap tidal cycle encompasses the full range of tidal amplitudes, from the highest during spring tide to the lowest during neap tide. Figure 3.8 shows the water levels over two spring-neap cycles. This period, also known as a lunar month, was observed in the Caribbean Sea based on the tidal constituents by FES (AVISO+, 2024). The tidal forcing is characterized by spring and neap periods, representing the largest and smallest tidal ranges, respectively (Iwasaki et al., 2015). To capture this variation, the periods from 26 to 28 June (neap, yellow) and 2 to 4 July 2024 (spring, red) were selected, as shown in Figure 3.8. Due to a late-discovered oversight, these periods occur one day prior to the peak spring and neap tides. While this may slightly influence the magnitude of modelled velocities, the deviation is expected to be minor given the limited amplitude variation. Importantly, the selected periods still capture the contrast between spring and neap tidal conditions for comparative analysis.



**Figure 3.8:** A spring-neap tidal cycle during the dry season in Bonaire. The water level variations on the northern and eastern boundary of the coarse domain for a spring-neap tidal cycle during dry season of Bonaire. The spring period is highlighted in red and the neap period in orange.

#### Wind forcing

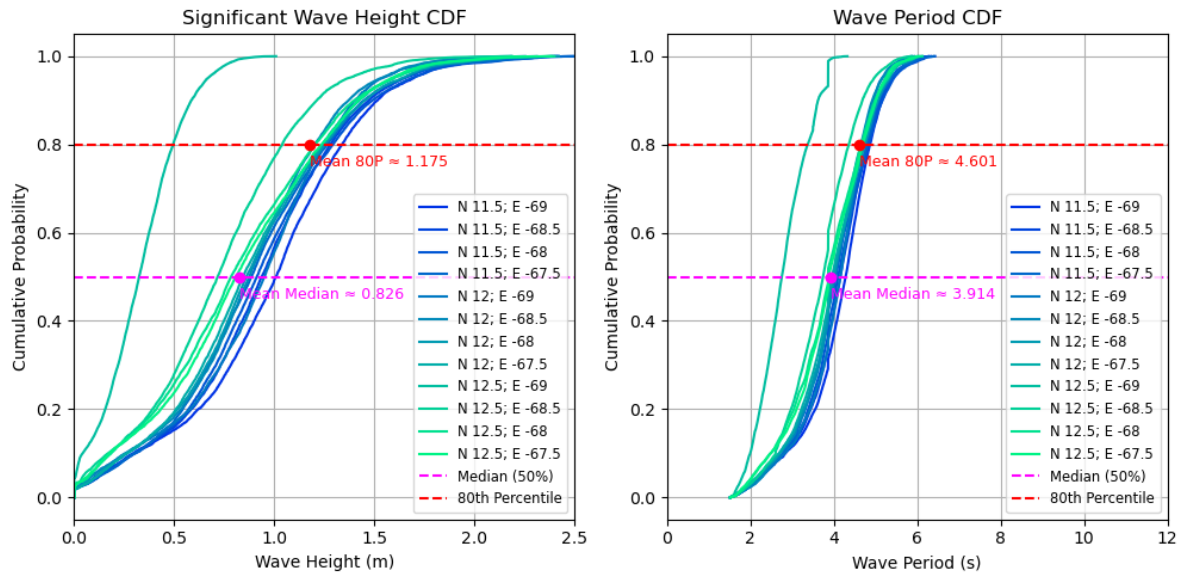
The base scenarios which include wind forcing, will use uniform parameters for magnitude and direction. This will allow the resulting spreading and current patterns to be correlated with the characteristic forcing conditions. In addition, the wind forcing is gradually increased over three hour period, and afterwards kept constant. This approach minimizes the risk of introducing non-physical transients into the model, which can occur when the external forcing is applied too abruptly (Deltares, 2025a). The characteristic wind forcing conditions are based on the four cardinal directions: North, East, South, and West. Since the dominant wind typically comes from the East as a result from the Trade Winds, the other directions are included to introduce variation and explore alternative wind scenarios. Based on Figure 2.3a, the mean velocities for wind coming from the North, East, South and West wind are determined and shown as reds dots. Their corresponding values are provided in Table 3.4.

|                    | North       | East        | South       | West        |
|--------------------|-------------|-------------|-------------|-------------|
| Velocity magnitude | 1.431 [m/s] | 7.703 [m/s] | 1.527 [m/s] | 1.534 [m/s] |
| Velocity direction | 0 [°]       | 90 [°]      | 180 [°]     | 270 [°]     |

**Table 3.4:** Overview of the uniform wind conditions applied in the base wind scenarios, based on the ERA5 data (ECMWF, 2025).

#### Wave forcing

Two types of waves are characterised by ERA5, namely short-crested wind-generated waves and swell waves, shown in Figure 2.6. Their difference and variability in wave period and significant wave height is clearly illustrated. Subsequently, they are the two characteristic conditions considered for the base scenarios of waves, one for each wave type. The significant wave height, mean wave period and direction of each wave type during 2024 are translated to a Cumulative Distribution Function (CDF). The CDF provides a quick visualization of the variability within their conditions. Based on the resulting values, illustrated in Figure 3.9 and in Appendix A, the 80<sup>th</sup> percentile is chosen for each parameter which is shown in red. This percentile occurs frequently enough, but has a higher impact than for example the mean value of the parameters, shown in pink. Using this percentile will therefore better showcase the impact of the wave type. Furthermore, the wave conditions are applied stationary, because of similar reasons to the uniform wind conditions.



**Figure 3.9:** An overview of the CDF curves for the wave conditions within the coarse domain. Each station of the ERA5 data along the north and east boundary of the coarse domain is plotted in a different colour blue. Their coordinates are shown in the legend. The red lines and dots represent the 80<sup>th</sup> percentile, and pink the 50<sup>th</sup> percentile, or in other words, the mean values.

The obtained 80<sup>th</sup> percentile values are gathered in Table 3.5. The Delft3D-WAVE asks for the peak period instead of the mean period. As ERA5 only provides the mean period, the relation between the mean and peak wave period is used to obtain the peak period. The ratio peak to mean period usually ranges between 1.1 and 1.25 (Muraleedharan et al., 2023), and is accurately depicted by 1.15. The resulting peak periods are added in Table 3.5. Secondly, the wave spectral directional width  $s$  of ERA5 cannot directly be given as input to Delft3D-WAVE. ERA5 makes use of the cosine<sup>2s</sup> model (Kuik, 1988), while Delft3D-WAVE use the cosine<sup>m</sup> model. The values of ERA5 cannot be directly translated to the desired  $m$  values, but an approximation is made based on the cosine<sup>2s</sup> relation and the Table provided by Deltares in the WAVE manual.

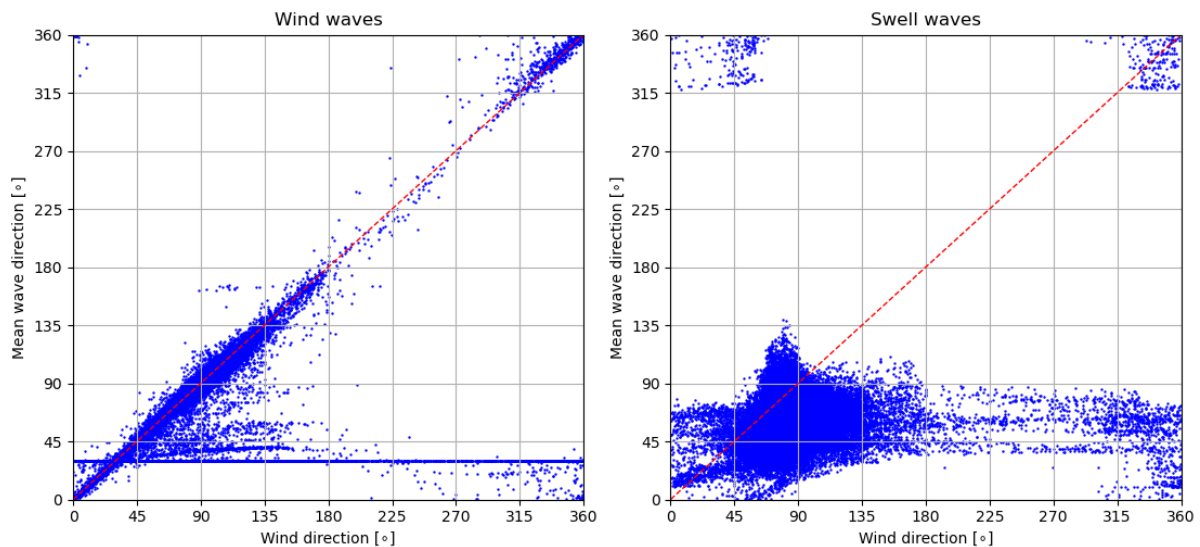
| Wave             | Sign. wave height | Mean period | Peak period | Nautical dir. | Dir. spreading |
|------------------|-------------------|-------------|-------------|---------------|----------------|
| Short wind-waves | 1.175 [m]         | 4.601 [s]   | 5.291 [s]   | 99.27 [°]     | 11.12 [-]      |
| Swell waves      | 0.965 [m]         | 6.908 [s]   | 7.944 [s]   | 72.41 [°]     | 12.77 [-]      |

**Table 3.5:** Overview of the two base wave scenarios based on the obtained by ERA5 (ECMWF, 2025).

#### Realistic scenarios - combination of drivers

The base scenarios provide a fundamental understanding of the effects of individual abiotic drivers. However, in reality, the likelihood of a single, uniform abiotic driver acting in isolation is low. It is more realistic to consider the combined influence of multiple abiotic drivers. Examining these combinations offers a more accurate estimation of potential real-world conditions, while still maintaining a relatively simplified framework that builds directly on the base scenarios. The interaction between multiple abiotic drivers alters the resulting velocity fields, as their combined forcing leads to complex and potentially non-linear effects.

Combinations of each of the abiotic drivers are considered. Tidal forcing, whether during spring or neap tide, is a persistent influence in the nearshore region near Bachelor's Beach. It is particularly relevant to investigate whether the interaction between tidal forcing and other abiotic drivers differs between spring and neap tide conditions. This comparison will provide insight into whether the velocity fields and the resulting particle dispersal patterns vary depending on the timing of egg release within the spring-neap tidal cycle. Furthermore, the impact of easterly trade winds is explored in combination with the other abiotic drivers. As illustrated in Figure 2.3, the trade winds are the most persistent and dominant wind direction and magnitude throughout the year. Examining how the east wind interacts with other abiotic drivers will provide valuable insights into the hydrodynamic conditions that are close to the daily occurrences on Bonaire.



**Figure 3.10:** The relation between the nautical wind and wave direction, where the left figure exhibits the relation for the short-crested wind-generated waves and the right figure the relation for the swell waves. The red dashed diagonal represents the situation where the nautical wave and wind direction were to be the same value.

Moreover, Figure 3.10 illustrates the relationship between nautical wave and wind directions for the two wave types. In the case of swell waves, no clear correlation with wind direction is observed. This aligns with their definition, as swell waves originate from distant storms and have travelled far enough to become decoupled from the local wind conditions. In contrast, short-crested wind-generated waves show a clear directional alignment with the prevailing wind. As such, one of the scenarios will incorporate a uniform easterly wind in combination with short-crested, locally generated wind waves. This scenario will provide insight to whether their interaction will enhance or diminish the observed

flow velocities.

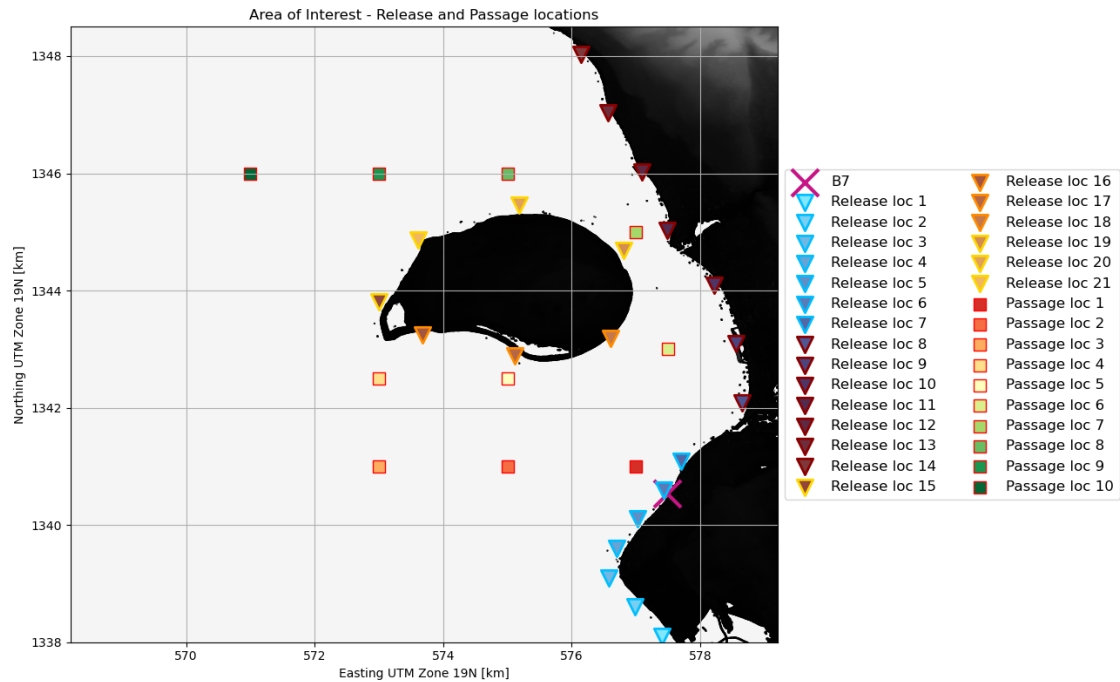
Lastly, to obtain particle tracks that closely align with the fish egg sampling data, five periods featuring the simultaneous influence of all three abiotic drivers are included. Unlike the previous scenarios, the wind and wave forcing in these cases are no longer assumed to be uniform over time. Instead, they are treated as time-varying forces based on observational data obtained from KNMI for wind conditions and ERA5 for wave characteristics (Koninklijk Nederlands Meteorologisch Instituut, 2025, ECMWF, 2025). The selected periods for this analysis are from the 25<sup>th</sup> to the 27<sup>th</sup> of June, 2<sup>nd</sup> to the 4<sup>th</sup> of July, 9<sup>th</sup> to the 11<sup>th</sup> of July, 26<sup>th</sup> to the 28<sup>th</sup> of September and 5<sup>th</sup> to the 7<sup>th</sup> of December 2024. The time-varying wind and wave conditions of these periods are presented in Appendix A.3. These periods coincide with several observed fish egg sampling events. An overview of all the considered scenarios and their corresponding abiotic drivers is provided in Table 3.6.

| Scenario numbers   | Abiotic drivers           | Description of conditions                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------|---------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 0                  | All three abiotic drivers | Time-varying wind and wave forcing, together with tidal forcing. This scenario is used for validating the hydro-dynamic model with WUR data, for period July 12 to 14 2022.                                                                                                                                                                                                                                                  |
| 1, 2               | Tidal forcing             | Neap and spring tide conditions.                                                                                                                                                                                                                                                                                                                                                                                             |
| 3, 4, 5, 6         | Wind forcing              | Four cardinal wind directions; North, East, South and West.                                                                                                                                                                                                                                                                                                                                                                  |
| 7, 8               | Wave forcing              | Short-crested wind-generated and swell waves.                                                                                                                                                                                                                                                                                                                                                                                |
| 9, 10              | Tidal and wind forcing    | Neap and spring tide combined with uniform wind from East direction.                                                                                                                                                                                                                                                                                                                                                         |
| 11, 12             | Tidal and wave forcing    | Neap and spring tide combined with short-crested wind generated waves.                                                                                                                                                                                                                                                                                                                                                       |
| 13                 | Wind and wave forcing     | Uniform wind from East direction combined with short-crested wind generated waves.                                                                                                                                                                                                                                                                                                                                           |
| 14, 15, 16, 17, 18 | All three abiotic drivers | Time-varying wind and wave forcing together with tidal forcing. Number 14 represents the period from 25 <sup>th</sup> to 27 <sup>th</sup> , number 15 the period from 2 <sup>nd</sup> to 4 <sup>th</sup> July, number 16 the period 9 <sup>th</sup> to 11 <sup>th</sup> July, number 17 the period 26 <sup>th</sup> to 28 <sup>th</sup> September and number 18 the period 5 <sup>th</sup> to 7 <sup>th</sup> December 2024. |

**Table 3.6:** The different scenarios to investigate the impact of the abiotic drivers on the velocity field.

### 3.3.2. Release conditions

To infer the spawning locations based on the dispersal of pelagic fish eggs, it is essential to consider three key factors, namely the abiotic drivers, the timing of the egg release, and the spawning location itself. By creating different scenarios for these conditions in the fine domain, it is possible to assess the impact of the separate abiotic drivers on the dispersal within the first 24 hours of spawning. Moreover, it is possible to estimate what likely spawning locations are when comparisons are made with the sampling data. For the latter the realistic scenarios of the abiotic drivers are used. The scenarios for the abiotic drivers have been detailed in the previous section. This section focusses on the scenarios concerning spawning and passage locations and timing of the egg release.



**Figure 3.11:** The considered release locations which are used for the release of the eggs during the dispersal simulations, shown as triangles. Location of Bachelor's Beach is marked by the purple cross (B7), and Release loc 6 is located just below Bachelor's Beach. In addition, the passage locations, considered for the dispersal matrix, are shown as squares.

#### Release locations

The most likely spawning locations for reef fish are located on or near the fringing reef of Bonaire (Ip et al., 2022). On the Southwest coast of Bonaire, this coral reef extends to depths of approximately 20 meters (Slagter, 2023). Based on this, multiple potential release locations were selected along the coasts of both Bonaire and Klein Bonaire. Specifically locations at depths ranging from 10 to 15 meters within the fine model domain are selected. All selected release locations are presented in Figure 3.11. Locations 1 to 7 are grouped as the Coral-Close cluster (CC cluster), locations 8 to 14 as the Coral-Distant cluster (CD cluster), locations 15 and 19 to 21 as Klein Bonaire - North cluster (KB-North cluster) and locations 16 to 18 as Klein Bonaire - South (KB-South cluster). Moreover, ten passage locations are defined and shown as squares in Figure 3.11. These locations are used to analyse the paths of egg dispersal within the first 24 hours after spawning.

#### Release moment

The release moment for the simulated eggs during realistic scenarios is set at 18:00 in the afternoon on the first day of the selected abiotic periods. This moment is chosen based on RoffaReefs advice, as they expect this to be the moment of spawning. Since the simulation duration for egg dispersal covers only the initial 24 hours post release, the dispersal patterns may be sensitive to the specific timing of release within the tidal cycle. To investigate this potential sensitivity, additional simulations with different release moments are performed. The additional release times are set at the start of the same day, at 00:00 (midnight) and at 12:00 (noon). The 12 hour difference between the first two release moments was deliberately chosen due to the diurnal tidal characteristics observed in the Caribbean Sea. These two moments represent distinct phases of the daily tidal cycle. As illustrated in Figure 3.8, the flood tide typically occurs around 00:00, while the ebb tide is dominant around 12:00. For the analysis of abiotic drivers and process parameter sensitivity, the 12:00 release time is used as the default. Although this does not align with the expected spawning moment advised by RoffaReefs, it is unlikely to significantly affect the results, as the aim is to assess relative differences in dispersal patterns rather than replicate expected biological timing.



### 3.3.3. Process parameters

Parameters such as the release radius and diffusion coefficient  $a$  are linked to the biological characteristics of pelagic fish eggs and directly influence the simulated dispersal. However, the sensitivity of dispersal outcomes to these parameters remains uncertain. To address this, a range of values was applied to these process parameters within Delft3D-PART. These ranges were selected based on available literature where possible, or otherwise determined through pragmatic choices.

#### Release radius $R$

The initial spread of the particles at the moment of release is identified by the release radius. It governs how the particles are initially dispersed within the domain, influencing the dispersion process from the first moment. Studies suggest that the release radius can vary depending on the scale of the spawning event. Point or individual spawning events typically range between 10 - 50 meters, while 50 - 200 metres may represent a broader spawning event or account for spatial uncertainty (Onsri et al., 2024, Almany et al., 2017). In this study, a default release radius of 20 m is used to ensure the dispersal begins within a single grid cell distance from the release location. To assess the sensitivity to this parameter, additional scenarios with release radii of 50 m and 200 m are tested.

#### Diffusion coefficient $a$

The diffusion coefficient  $a$  from turbulence theory (Eq. 3.8) determines the rate at which particles spread due to turbulent diffusion. This parameter directly influences particle dispersion and ideally should be calibrated to reflect the biological characteristics of pelagic fish eggs. However, the eggs are approached as passive, Lagrangian particles and therefore the default value is set to  $1 \text{ m}^2/\text{s}$ , similar to Onsri et al. (2024) and Heiberg Espeland et al. (2015) approach. The sensitivity of this parameter is tested by changing the value by 50%, leading to values of 0.5 and  $1.5 \text{ m}^2/\text{s}$ .

| Category           | Parameter                 | Value                                    | Description                                                                                                                         |
|--------------------|---------------------------|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Forcing conditions | Type of forcing           | Single or multiple forcing(s)            | See Table 3.6.                                                                                                                      |
|                    | Simulation period         | 2 different periods during tidal forcing | For spring (2 <sup>nd</sup> and 3 <sup>th</sup> of July) or neap tide (25 <sup>th</sup> and 26 <sup>th</sup> of June).              |
| Release parameters | Release location          | Different points along the coast         | Pragmatic choice of locations to obtain insight into the dispersal in the region as well as inferring realistic spawning locations. |
|                    | Release time              | 3 different moments                      | At 18:00 and during flood or ebb, which respectively occur at 00:00 or 12:00 of the first day.                                      |
| Process parameters | Release radius $R$        | 20, 50, 200                              | Values representing different spatial scales for a spawning event.                                                                  |
|                    | Diffusion coefficient $a$ | 0.5, 1, 1.5                              | Testing the sensitivity of the coefficient through the use of pragmatic chosen values.                                              |

**Table 3.7:** All conditions and parameters which will be investigated in this modelling study.

| Abiotic scenario                | Release time   | Release location | Radius | Diffusion coeffi.        |
|---------------------------------|----------------|------------------|--------|--------------------------|
| July 2 to 4, scenario number 15 | 12 or 18 hours | Location 6       | 20 m   | $1 \text{ m}^2/\text{s}$ |

**Table 3.8:** The default conditions and parameters for the different scenarios.

The varying abiotic scenarios, release conditions and process parameters, detailed in Section 3.3, lay the foundation for the simulations that are run in this study. A summary of all variations in simulations is presented in Table 3.7, and Table 3.8 shows the default values of the scenarios.

# 4

## Results

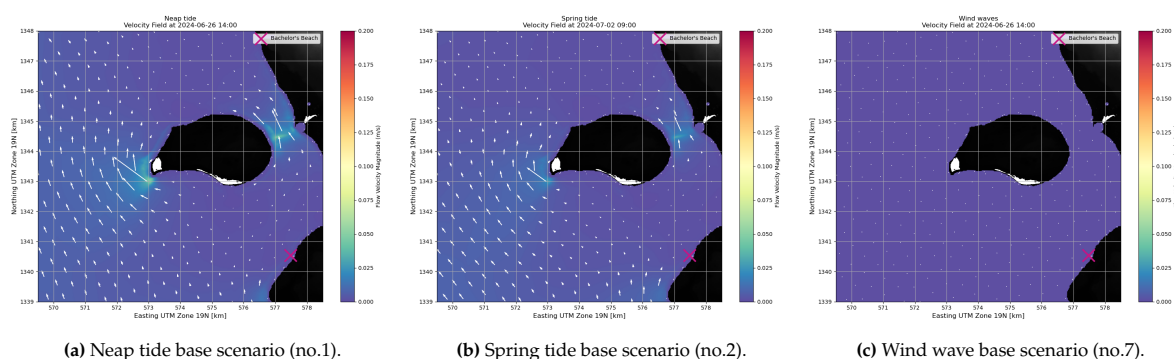
The velocity fields at the surface layer obtained per abiotic driver scenario after running the hydrodynamic model are presented and analysed in Section 4.1. Section 4.2 shows the dispersal of the eggs released from the default location and moment for the different scenarios of abiotic drivers. This provides insight into the impact each driver has on the dispersal within one day. This is followed by Section 4.3 which analyses the dispersal for the different release locations and moments. The retention rates at Bachelor's Beach are quantified and compared to the sampling data of the relevant period. Lastly, the sensitivity of the dispersal to the process parameters is investigated in detail in Section 4.4.

### 4.1. Abiotic driver flows

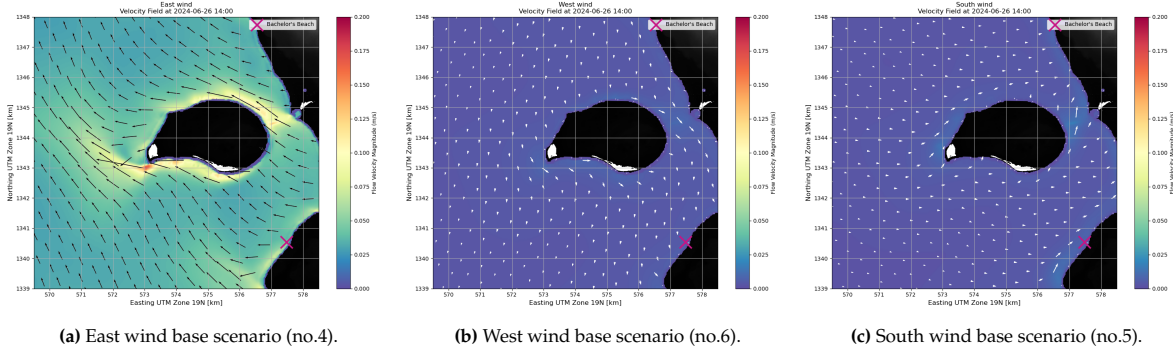
The velocity fields are considered to evaluate the influence of different abiotic drivers. The analysis begins with the base scenarios, followed by the scenarios incorporating interactions between drivers. For each scenario, flow velocities are first examined across the fine domain to understand regional patterns. Then attention is directed to the flow velocities near Bachelor's Beach, contributing to the partial answer of sub-research question two.

#### 4.1.1. Base scenarios

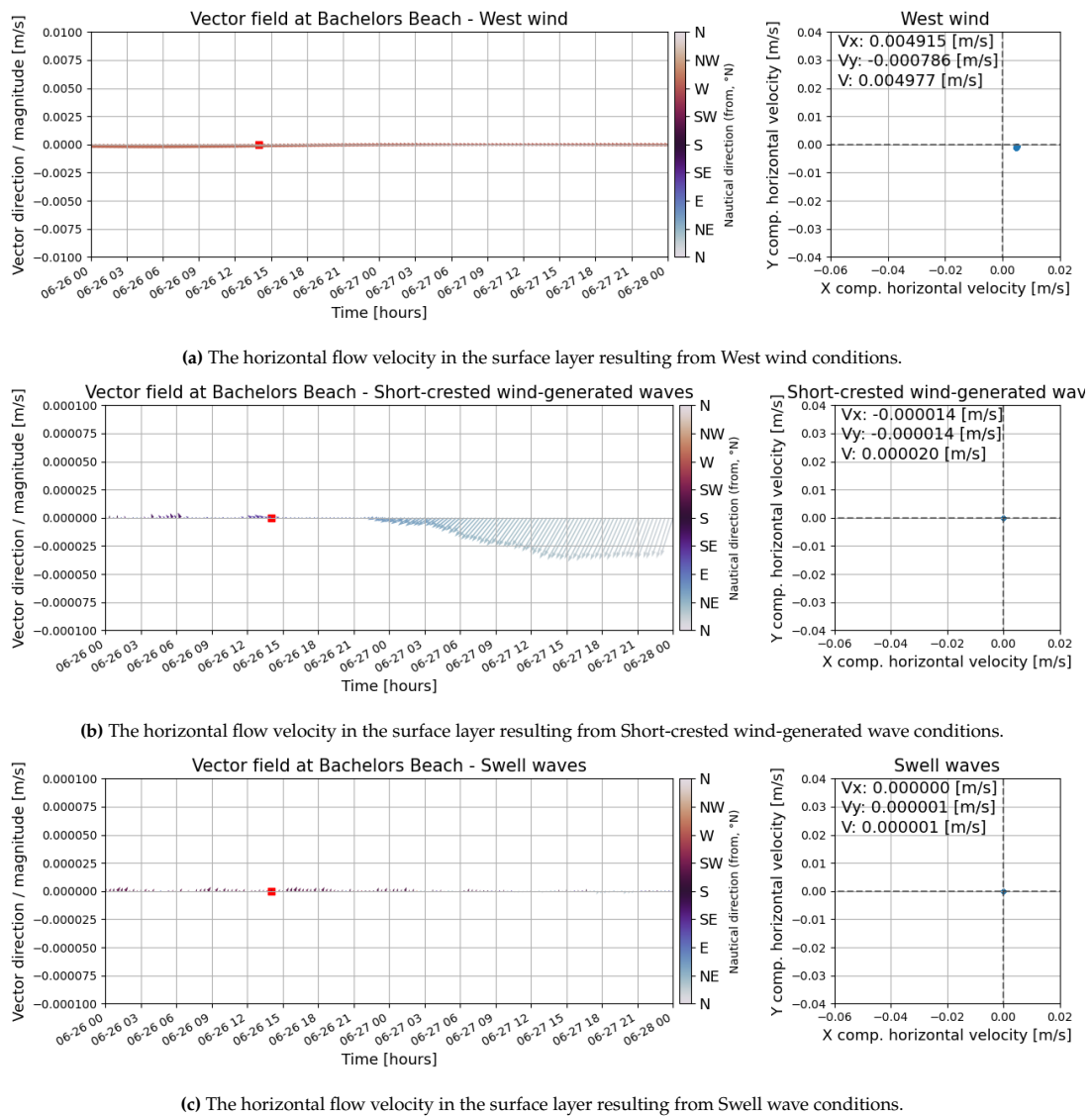
The results for the horizontal flow velocities are retrieved from the hydrodynamic model and shown in Figures 4.1, 4.2, 4.4 and 4.3. Figure 4.1 and 4.2 show one moment in time of the flow velocities in the fine domain, to see the regional patterns which result from singular forcing. Figures 4.4 and 4.3 illustrate the same flow velocities, but obtained from one location in front of Bachelor's Beach. This location is similar to RoffaReefs sampling location. The direction and magnitude of the horizontal velocity over time are visualised on the left side of Figures 4.4 and 4.3, while the right side shows the x- and y-components separately. The results for the scenarios not shown the above mentioned Figures can be found in Appendix C.1.



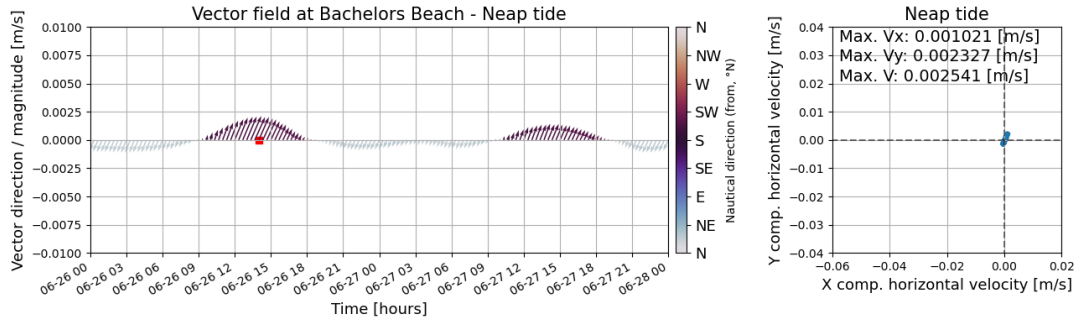
**Figure 4.1:** Horizontal flow velocities for the base scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Vector colours change for better readability. Figures 4.4 and 4.3 depict flow conditions near Bachelor's Beach, marked by a purple cross in this Figure.



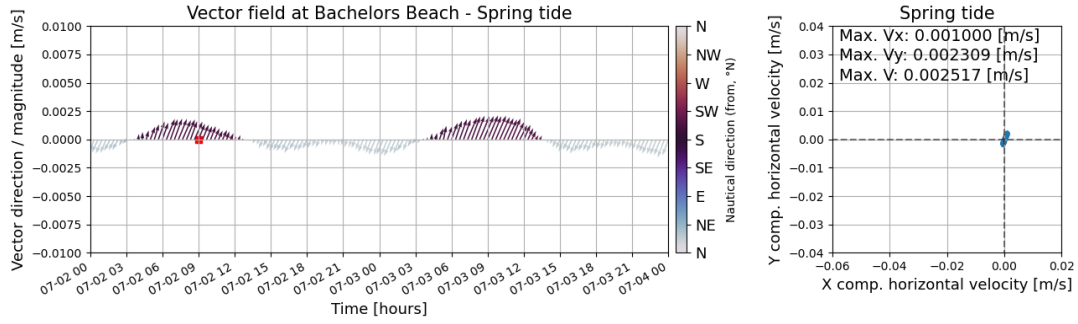
**Figure 4.2:** Horizontal flow velocities for the base scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Vector colours change for better readability. Figures 4.4 and 4.3 depict flow conditions near Bachelor's Beach, marked by a purple cross in this Figure.



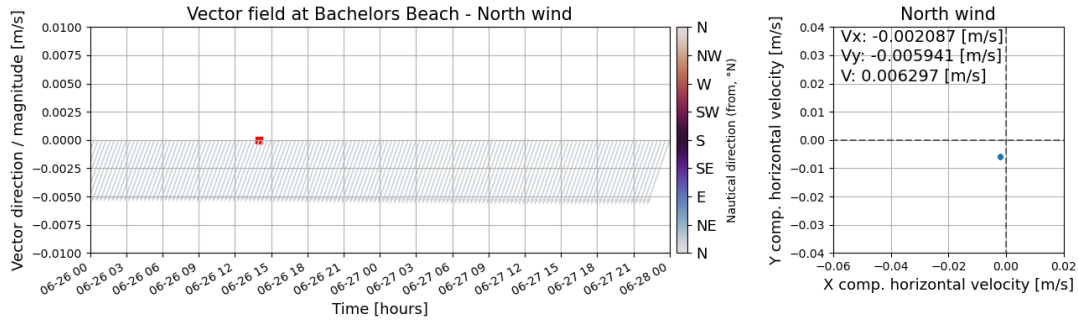
**Figure 4.3:** The horizontal flow velocities for the West wind, wind-generated waves, and swell wave scenarios are shown. Flow vectors over time are plotted on the left, while the corresponding x- and y-components are displayed on the right to clarify flow direction. The red squares indicate the time points at which domain flow velocities are evaluated for each scenario.



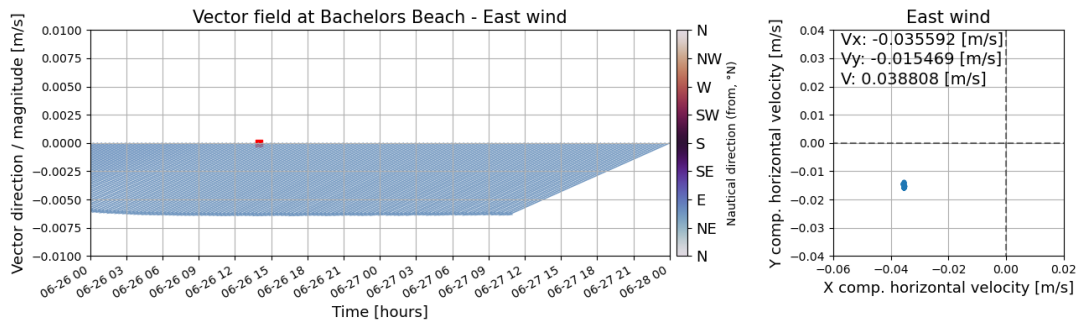
(a) The horizontal flow velocity in the surface layer resulting from Neap tide conditions.



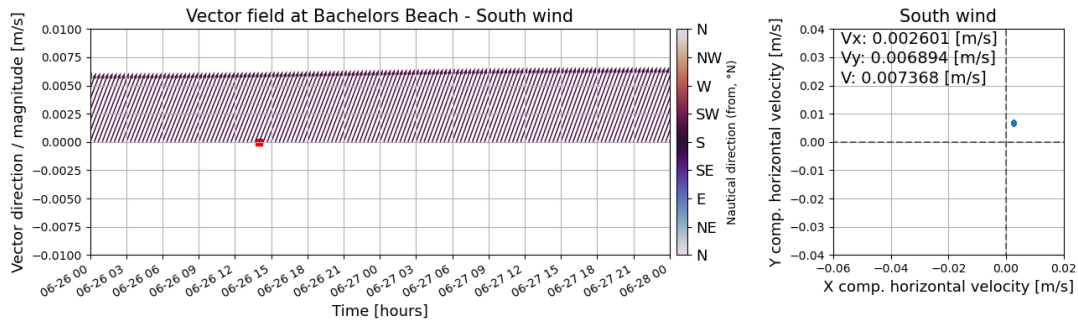
(b) The horizontal flow velocity in the surface layer resulting from Spring tide conditions.



(c) The horizontal flow velocity in the surface layer resulting from North wind conditions.



(d) The horizontal flow velocity in the surface layer resulting from East wind conditions.



(e) The horizontal flow velocity in the surface layer resulting from South wind conditions.

**Figure 4.4:** The horizontal flow velocities for the Spring and Neap tide, and the North, East and South wind scenarios are shown. Flow vectors over time are plotted on the left, while the corresponding x- and y-components are displayed on the right to clarify flow direction. The red squares indicate the time points at which domain flow velocities are evaluated for each scenario.

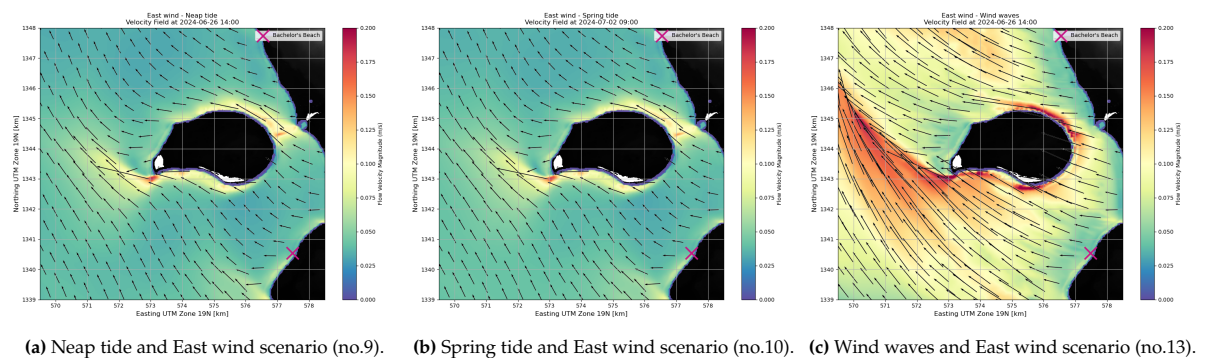
Figure 4.1 shows that flow velocities under the base tidal scenarios are relatively low. Similar patterns and magnitudes are observed during the Low-to-High water transition, despite occurring at different moments in the lunar cycle, also visible in Figures 4.4a and 4.4b). The maximum tidal velocity estimated in Section 2.2.5 aligns with the domain's peak velocity, but does not occur near Bachelor's Beach. There, tidal velocities are on the order of several millimetres per second, which is nearly an order of magnitude lower than the domains maximum. Based on these velocities, a particle would take approximately seven minutes to travel one metre solely due to tidal motion. Therefore, under only tidal forcing (and advection processes), a particle would remain within roughly 250 metres of its release point over time.

Figures 4.2, 4.4 and 4.3 include the cardinal wind directions. Figure 4.2a illustrates that stronger East winds generate higher flow velocities compared to other wind scenarios, as also reflected in the velocity vectors and magnitudes in Figure 4.4. Across all scenarios, uniform winds produce consistent flow patterns in both magnitude and direction within the fine domain. Furthermore, the velocity magnitudes near Bachelor's Beach align with the estimates in Table 2.3. Under North, East, and South winds, flows suggest that eggs would advect alongshore rather than remain nearshore, travelling about one metre in a few minutes. In contrast, West winds induce predominantly shoreward flow near Bachelor's Beach. The flows enable particles to move approximately one metre shoreward in three minutes and supporting local retention.

In contrast, the horizontal flow velocities generated by both base wave scenarios are two orders of magnitude smaller than those observed under wind forcing, as indicated by the y-axes of Figures 4.6c and 4.3c. This discrepancy is likely attributable to the model settings applied for the wave scenarios. In particular, wind-generated waves need continuous wind input to avoid dissipating within the model domain. The results suggest that wave energy dampened before reaching Bachelor's Beach, see Figure C.2a, and therefore do not align with the estimated flow velocities in Section 2.2.6. Consequently, given the low time-averaged flow velocities, advection processes under only wave conditions, without wind input, are expected to have minimal influence on particle dispersal near Bachelor's Beach.

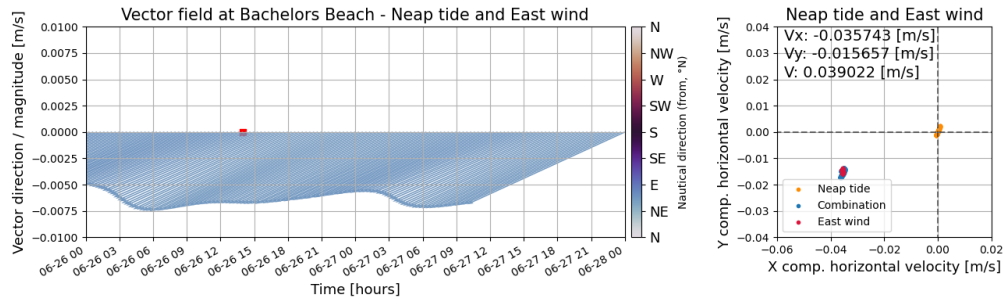
#### 4.1.2. Interaction between abiotic drivers

Residual flows from different drivers often exhibit non-linear interactions. To assess these, horizontal flow velocities for selected combinations (Table 3.6) are analysed and presented in Figures 4.5, 4.6, and Appendix C.1. Regional patterns are examined first, followed by local flow velocities near Bachelor's Beach to evaluate localised impacts. This approach is repeated for the realistic scenarios on 25 June and 2 July (Figures 4.7 and 4.8) to assess the effects of time-varying abiotic drivers. Additional results are provided in Appendix C.1.

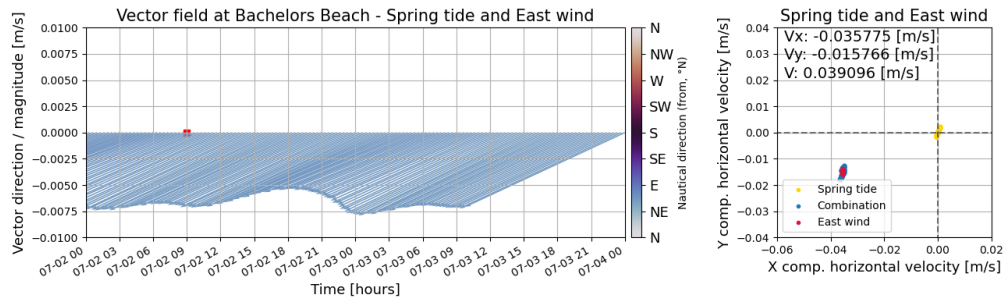


**Figure 4.5:** Horizontal flow velocities for combination scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Figure 4.6 depicts flow conditions near Bachelor's Beach, marked by a purple cross in this Figure.

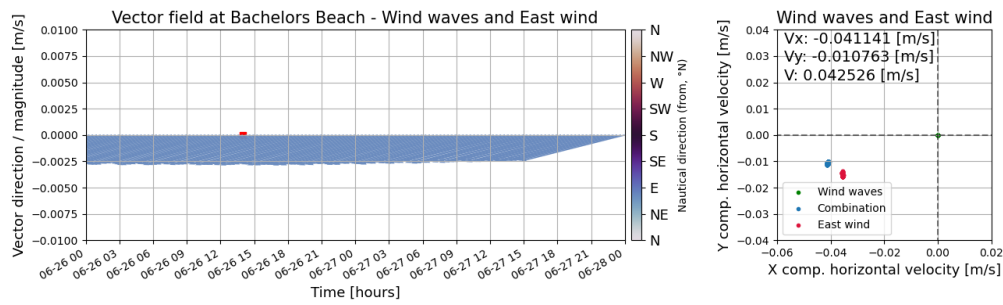




(a) The horizontal flow velocity in the surface layer resulting from the interaction between Neap tide and East wind conditions.

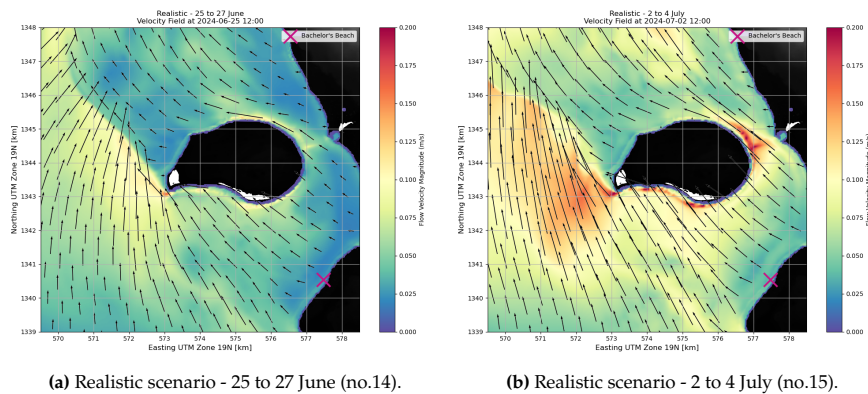


(b) The horizontal flow velocity in the surface layer resulting from the interaction between Spring tide and East wind conditions.



(c) The horizontal flow velocity in the surface layer resulting from the interaction between wind-generated waves and East wind conditions.

**Figure 4.6:** The horizontal flow velocities resulting from the interactions between East wind and Neap tide, Spring tide, and wind-generated waves are shown. Flow vectors over time are plotted on the left, with the corresponding x- and y-components displayed on the right to illustrate flow direction. The red squares indicate the time points at which domain flow velocities are evaluated for each scenario, in Figure 4.5.

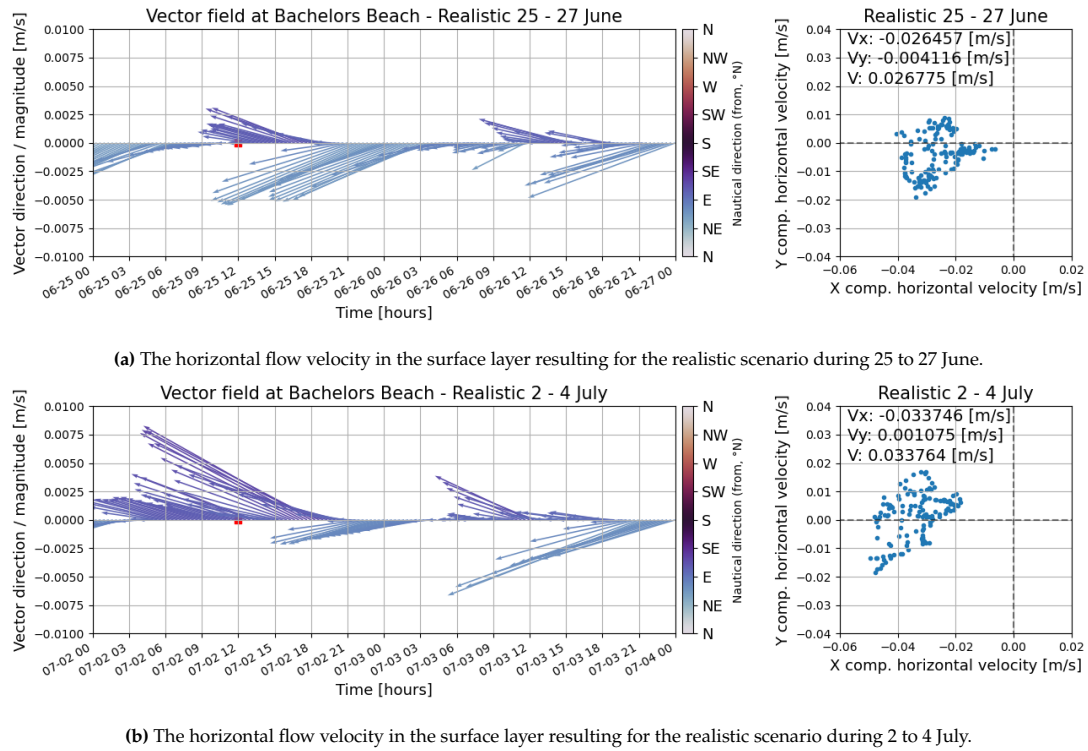


(a) Realistic scenario - 25 to 27 June (no.14).

(b) Realistic scenario - 2 to 4 July (no.15).

**Figure 4.7:** Horizontal flow velocities for realistic scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Figure 4.8 depicts flow conditions near Bachelor's Beach, marked by a purple cross in this Figure.





**Figure 4.8:** The horizontal flow velocities resulting from the realistic scenarios, where on the left the velocity is plotted over time as a vector. For better understanding of the x- and y-component are visualised on the right side. The red squares indicate the time points at which domain flow velocities are evaluated for each scenario, in Figure 4.7

Figures 4.5 and 4.6 show combinations involving East wind conditions, which aligns with the Trade Winds observed in Bonaire. These Figures illustrate the influence of uniform East winds on residual horizontal flow within the fine domain and near Bachelor's Beach. When combined with tidal forcing, the flow pattern in the fine domain closely resembles that of the base East wind scenario. Although tidal features are visible in Figure 4.6, flow direction and magnitude remain largely dominated by East wind conditions.

The interaction between short-crested wind-generated waves and East wind results in greater deviations from their respective base scenarios, with increased flow velocities both within the fine domain and near Bachelor's Beach. The overall flow shifts slightly westward, featuring a pronounced northwest current west of Klein Bonaire. Due to the alignment of wind and wave directions, wave damping is reduced, allowing the waves to reach the nearshore, see Figure C.2. The resulting velocity magnitudes is of similar order as the Stokes drift estimate in Table 2.4, indicating that this combination produces the strongest net advection among those considered.

| Abiotic | driver           | Approximated velocity     | Velocity obtained at Bachelor's Beach                                           |
|---------|------------------|---------------------------|---------------------------------------------------------------------------------|
| Tide    |                  | 0.0325 [m/s] (Figure 2.5) | 0.0025 [m/s] (Figure 4.4) (0.0300 [m/s] in the fine domain, Figure 4.1)         |
| Wind    | East direction   | 0.0351 [m/s] (Table 2.3)  | 0.0388 [m/s] (Figure 4.4)                                                       |
|         | Other directions | 0.0066 [m/s] (Table 2.3)  | 0.0050 - 0.0074 [m/s] (Figure 4.4 and 4.3a)                                     |
| Wave    | Stokes drift     | 0.0482 [m/s] (Table 2.4)  | 0.0425 [m/s] (For combined wind and wind-generated wave conditions, Figure 4.6) |
|         | Surface roller   | 2.5513 [m/s] (Table 2.5)  | Not registered                                                                  |

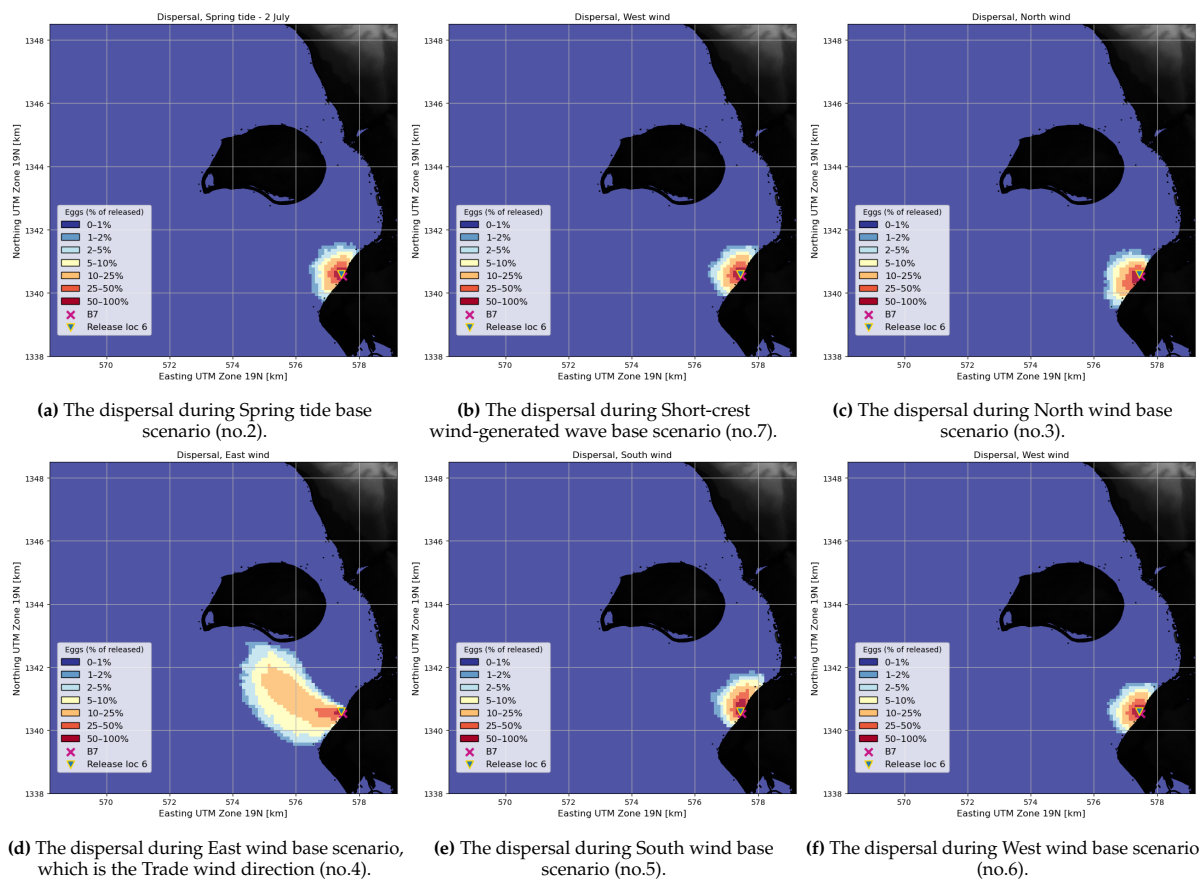
**Table 4.1:** Comparison overview for the approximated velocity magnitudes based on literature (Chapter 2) and the model output results.

The modelled velocity results are compared to literature based velocity estimates in Table 4.1, showing general agreement in order of magnitude. While tidal velocities are captured within the fine domain, they are not evident near Bachelor's Beach. Surface roller velocities are absent in the model output, likely due to their occurrence very close to shore and the possibly limited resolution of the fine domain. The 25 by 25 metre grid cells may still be too large to sufficiently resolve these processes. Overall, these results suggest that the model generally captures the physical processes well and can be estimated with the presented formula's in Chapter 2.

Lastly, the realistic scenarios further illustrate the influence of wind conditions through the resulting residual flow directions. The directional shifts in the vectors of Figure 4.8 correspond to changes in nautical wind direction shown in Figure A.3. As previously discussed, these directional shifts are amplified by the interaction between wind-generated waves and prevailing wind conditions. In all realistic scenarios considered, flow patterns are westward from the area in front of Bachelor's Beach, reducing nearshore retention and promoting offshore transport. This westward movement aligns with the longshore currents observed by Van Leeuwen (2022) in the same region.

## 4.2. Dispersal per abiotic drivers

To further assess the impact of abiotic drivers near Bachelor's Beach, dispersal from release location 6 is analysed. This represents transport driven by local flow conditions and informs sub research question two. Rather than individual particle trajectories, dispersal is evaluated by the percentage of released eggs entering 100 by 100 metre grid cells, providing a clearer overview of dispersal patterns. The dispersal patterns are assessed both qualitatively and quantitatively, using mean distance as a measure of advection and standard deviation as an indicator of horizontal dispersion. As in Section 4.1, analysis begins with the base scenarios, followed by combination and realistic scenarios.



**Figure 4.9:** The dispersal of released eggs shown as percentages of the released eggs that enter 100 by 100 metre grid cells. Each sub Figure represents the dispersal of a different base scenario after 24 hours. The different percentage categories are defined as follows: 0-1% dark blue, 1-2% blue, 2-5% light blue, 5-10% light yellow, 10-25% light orange, 25-50% dark orange and 50-100% red.

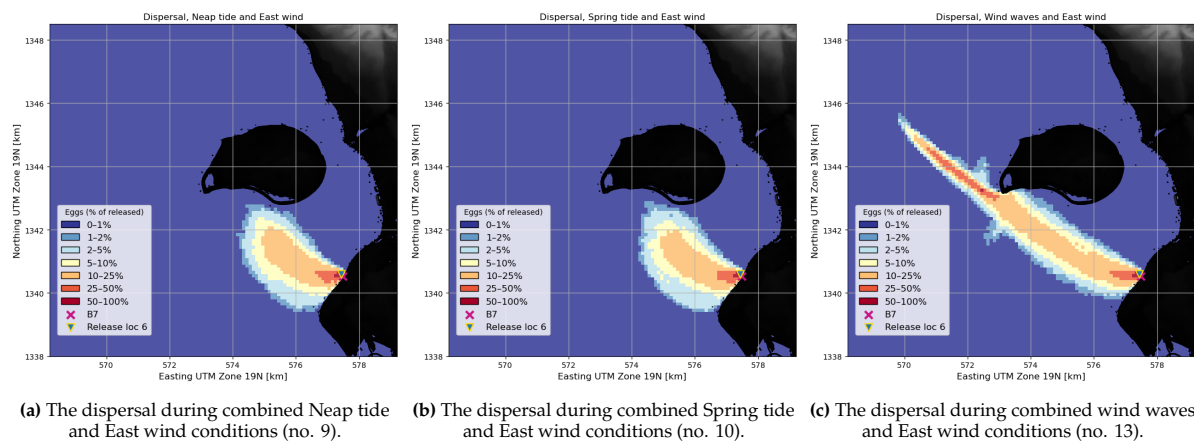
| Abiotic driver | Scenario no.       | Mean distance | Standard deviation | Max. distance | Mean path length | Area of Occupancy       |
|----------------|--------------------|---------------|--------------------|---------------|------------------|-------------------------|
| Tide           | 1 - Neap           | 473.64 [m]    | 293.79 [m]         | 1595.68 [m]   | 9556 [m]         | 2.98 [km <sup>2</sup> ] |
|                | 2 - Spring         | 471.36 [m]    | 285.08 [m]         | 1735.16 [m]   | 9527 [m]         | 3.00 [km <sup>2</sup> ] |
| Wind           | 3 - North          | 590.23 [m]    | 336.57 [m]         | 2064.82 [m]   | 9541 [m]         | 2.98 [km <sup>2</sup> ] |
|                | 4 - East           | 2882.23 [m]   | 437.81 [m]         | 4415.11 [m]   | 10095 [m]        | 9.11 [km <sup>2</sup> ] |
|                | 5 - South          | 585.43 [m]    | 331.46 [m]         | 1635.05 [m]   | 9567 [m]         | 2.73 [km <sup>2</sup> ] |
|                | 6 - West           | 446.65 [m]    | 272.32 [m]         | 1619.41 [m]   | 9508 [m]         | 2.73 [km <sup>2</sup> ] |
| Wave           | 7 - Wind-generated | 455.32 [m]    | 281.84 [m]         | 1724.49 [m]   | 9545 [m]         | 2.73 [km <sup>2</sup> ] |
|                | 8 - Swell          | 473.88 [m]    | 293.03 [m]         | 1754.02 [m]   | 9550 [m]         | 2.95 [km <sup>2</sup> ] |

**Table 4.2:** Quantification of the dispersal of the released eggs for each base scenario. It should be noted that the Area of Occupancy is based on the percentage grid cells, which are 100 by 100 metre.

Figure 4.9d and Table 4.2 show that the East wind scenario exhibits the largest impact on the obtained dispersal, similar to its obtained flow velocities in the fine domain and in front of Bachelor's Beach. The East wind conditions leads to the largest mean travelled distance, with 2882.23 metres. The dispersal pattern is relatively wide spread and obtains an Area of Occupancy of roughly 9 km<sup>2</sup>. This is at least thrice as high compared to the other base scenarios.

The neap and spring tide scenarios show minimal differences in dispersal (Figures 4.9a and C.6a), consistent with the similar horizontal flow velocities observed. Despite varying flow magnitudes near Bachelor's Beach, the tidal and wave scenarios exhibit comparable spatial dispersal patterns, indicating that dispersion dominates over advection. This is further supported by the relatively small differences between mean distances and standard deviations. The West wind scenario, in contrast, shows a somewhat reduced dispersal, with particles remaining closer to their release point, shown in Figure 4.9f. Although its standard deviation is similar to other scenarios, the onshore directed flow suggests that West winds limit offshore transport and promote local retention.

The North and South wind scenarios exhibit greater particle displacement than the West wind, tidal, and wave scenarios. As shown in Figure 4.9, dispersal patterns align with the corresponding flow directions in Figure 4.4, indicating directional consistency. The larger mean distances relative to standard deviation suggest that advection plays a more prominent role in dispersal under North and South wind forcing than in the other scenarios.

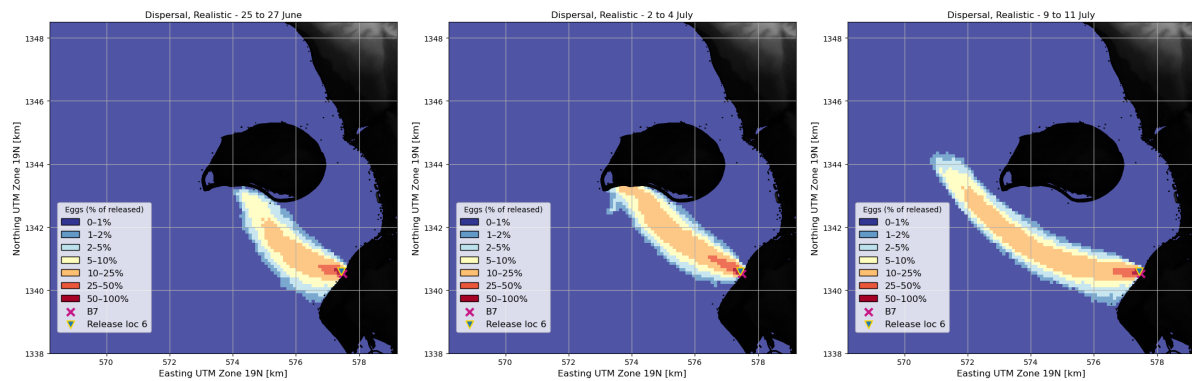


**Figure 4.10:** The dispersal of released eggs shown as percentages of the released eggs that enter 100 by 100 metre grid cells. Each sub Figure represents a different combination scenario.

| Abiotic driver               | Scenario no.                        | Mean distance | Standard deviation | Max. distance | Mean path length | Area of Occupancy        |
|------------------------------|-------------------------------------|---------------|--------------------|---------------|------------------|--------------------------|
| Combin., released at 12:00   | 9 - Neap tide, East wind            | 2886.85 [m]   | 433.51 [m]         | 4607.07 [m]   | 10081 [m]        | 9.19 [km <sup>2</sup> ]  |
|                              | 10 - Spring tide, East wind         | 2902.75 [m]   | 426.53 [m]         | 4712.08 [m]   | 10087 [m]        | 9.35 [km <sup>2</sup> ]  |
|                              | 11 - Neap tide, wind waves          | 468.04 [m]    | 278.61 [m]         | 1584.75 [m]   | 9527 [m]         | 2.84 [km <sup>2</sup> ]  |
|                              | 12 - Spring tide, wind waves        | 472.28 [m]    | 286.36 [m]         | 1579.72 [m]   | 9550 [m]         | 2.87 [km <sup>2</sup> ]  |
|                              | 13 - Wind waves, East wind          | 7505.49 [m]   | 989.26 [m]         | 9687.83 [m]   | 12183 [m]        | 14.67 [km <sup>2</sup> ] |
| Realistic, released at 18:00 | 14 - 25 to 27 June                  | 2856.30 [m]   | 842.388 [m]        | 4705.11 [m]   | 7727.13 [m]      | 7.95 [km <sup>2</sup> ]  |
|                              | 15 - 2 to 4 July, released at 0:00  | 4665.48 [m]   | 303.08 [m]         | 7831.57 [m]   | 11211 [m]        | 9.67 [km <sup>2</sup> ]  |
|                              | 15 - 2 to 4 July, released at 12:00 | 4919.18 [m]   | 541.40 [m]         | 7383.02 [m]   | 11303 [m]        | 10.68 [km <sup>2</sup> ] |
|                              | 15 - 2 to 4 July                    | 4000.60 [m]   | 517.76 [m]         | 5246.53 [m]   | 8135.83 [m]      | 7.94 [km <sup>2</sup> ]  |
|                              | 16 - 9 to 11 July                   | 6020.22 [m]   | 1055.99 [m]        | 7916.76 [m]   | 9242.88 [m]      | 12.49 [km <sup>2</sup> ] |
|                              | 17 - 26 to 28 Sept.                 | 1393.14 [m]   | 551.49 [m]         | 3125.90 [m]   | 7387.60 [m]      | 5.03 [km <sup>2</sup> ]  |
|                              | 18 - 5 to 7 Dec.                    | 3354.77 [m]   | 593.35 [m]         | 5054.93 [m]   | 7931.53 [m]      | 9.22 [km <sup>2</sup> ]  |

**Table 4.3:** Quantification of the dispersal of the released eggs for combination and realistic scenarios. It should be noted that the Area of Occupancy is based on the percentage grid cells, which are 100 by 100 metre.

Scenarios involving East wind conditions show a clear increase in mean dispersal distance (Figure 4.10). When combined with tidal forcing, the dispersal pattern remains similar to the East wind base scenario, but with greater central concentration. Specifically, the southern area of the dispersal falls within the 2–5% dispersal range under tidal forcing, compared to 5–10% in the base scenario, indicating reduced lateral spread. Despite comparable mean distances and standard deviations, tidal interaction appears to focus dispersal rather than enhance transport. In contrast, combining East wind with short-crested waves increases mean dispersal distance by a factor of two to three relative to the tidal combinations. The larger mean distance relative to standard deviation suggests a shift toward advection dominated transport, with reduced influence from dispersion. The mean travelled distances and standard deviations, presented in Table 4.3, indicate that interactions between the tidal conditions and the short-crested wind-generated waves differ only slightly from their respective base scenarios. This observation is consistent with the flow velocity results.



(a) The dispersal during realistic scenario of 25 to 27 June (no. 14). (b) The dispersal during realistic scenario of 2 to 4 July (no. 15). (c) The dispersal during realistic scenario of 9 to 11 July (no. 16).

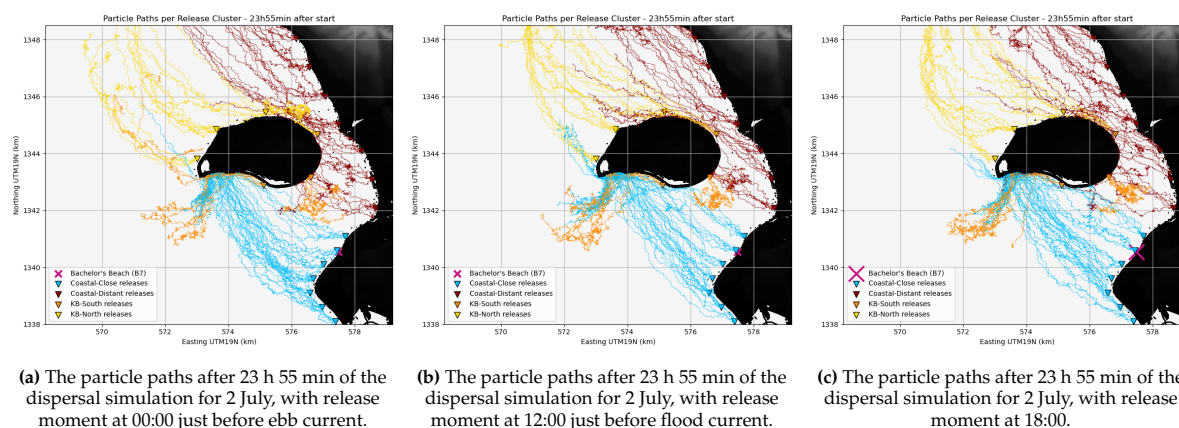
**Figure 4.11:** The dispersal of released eggs shown as percentages of the released eggs that enter 100 by 100 metre grid cells. Each sub Figure represents a different realistic scenario.

Dispersal patterns for three realistic scenarios with egg release at 18:00, reflecting typical spawning times, are shown in Figure 4.11 and quantified in Table 4.3. These results highlight the influence of time-varying abiotic drivers on dispersal. From 25 to 27 June, conditions were relatively mild, while 2 to 4 July exhibited more consistent and stronger wind conditions (Figures A.3 and A.4). In contrast, the 9 to 11 July scenario began with strong winds at 18:00, which declined significantly in subsequent hours (Figure A.5). The magnitude of these drivers, particularly wind, directly influences mean dispersal distance. As wind strength decreases, dispersal becomes increasingly governed by dispersion, as reflected in higher standard deviations relative to the mean.

Overall, the results from the base, combination and realistic scenarios indicate that wind forcing is the primary driver of surface layer flow. Its influence is further amplified by the presence of waves, while the impact of waves alone remains negligible in the absence of wind. The temporal variations in abiotic drivers, which are clearly reflected in the dispersal patterns of the realistic scenarios, further support this conclusion.

### 4.3. Impact of release conditions

To infer potential spawning grounds, dispersal simulations were conducted using varying release locations and moments. The resulting dispersal patterns provide insights into regional transport dynamics, indicating whether eggs are likely to be retained locally or advected offshore depending on their origin. The analysis first compares different release times to qualitatively assess their influence, followed by an examination of dispersal evolution within the first 24 hours. The 2 to 4 July realistic scenario is used to assess release conditions around spring tide, with a focus on the 18:00 release moment, which aligns closely with observed spawning behaviour by RoffaReefs.

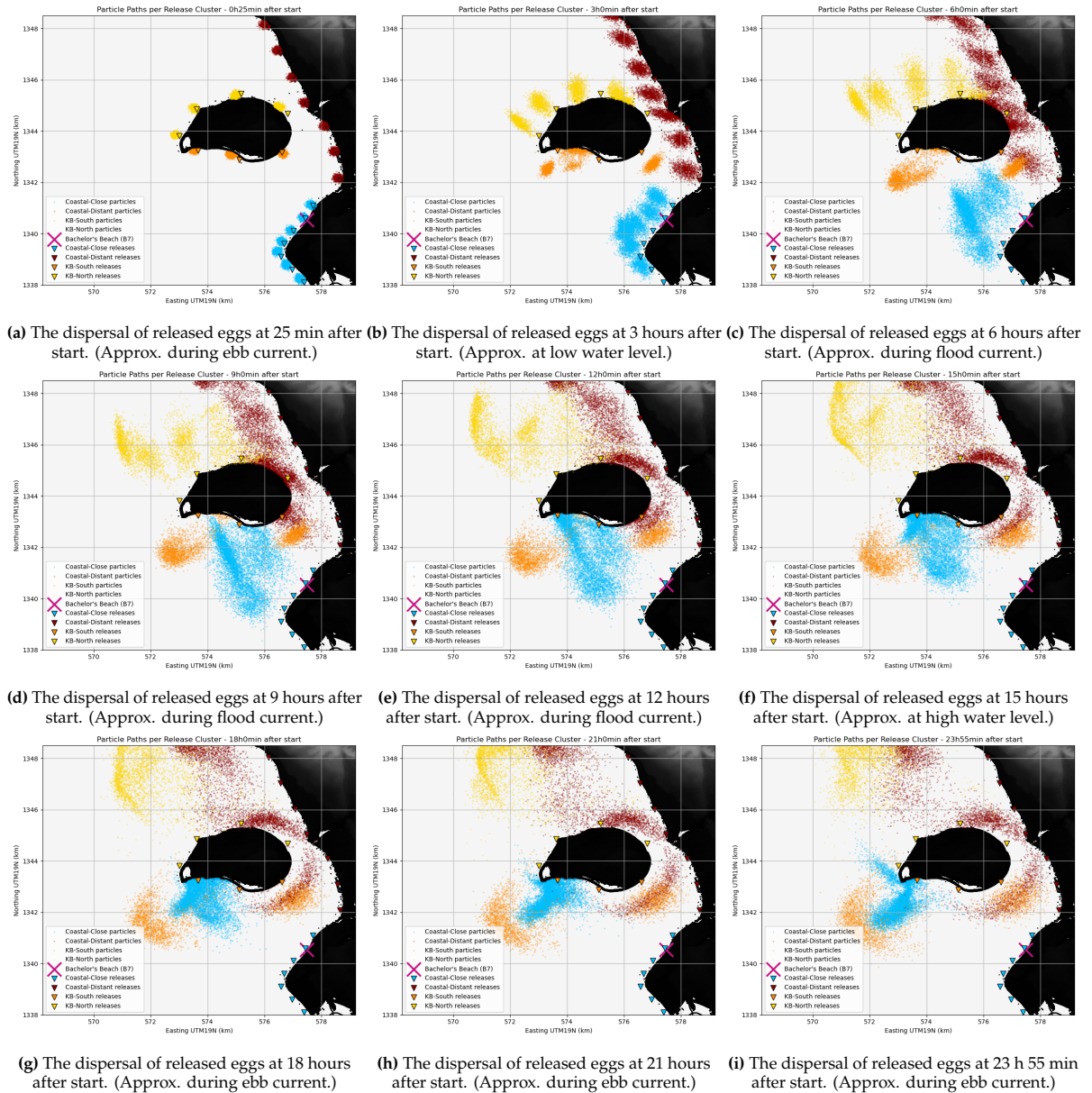


**Figure 4.12:** Five particle paths per considered release location categorised per cluster. Each cluster is given its own colour; CC is shown in blue, CD in dark red, KB - South in orange and KB - North in yellow, to visualize the overall dispersal of each cluster.

Figure 4.12 presents particle paths within 24 hours of release for each release time. For clarity, only five paths per release location are shown. Overall, dispersal patterns are in tune across release moments, with most paths directed north west, in agreement with regional flow velocities. The 0:00 release shows slightly more offshore curved paths (Figure 4.12a), likely due to the ebb current acting during the initial hours post release. In contrast, the 12:00 release exhibits minimal onshore curvature, consistent with reduced tidal influence in the area between Klein Bonaire and Bachelor's Beach (Figure 4.1b). Notably, this release produces the most comprehensive offshore plume from the Coral-Close Cluster (blue). It is likely driven by stronger north west directed winds accelerating dispersal during the first few hours.

The 18:00 release (Figure 4.12c) shows moderate offshore curvature, greater than at 12:00, but less pronounced than at 0:00. Lastly, the irregularity in individual dispersal paths, across all release moments, reflects the influence of the random walk component used to represent horizontal dispersion. A consistent north westward dispersal trend, driven by advection and prevailing easterly trade winds, is evident across all release moments, though release timing introduces some variation in the paths.





**Figure 4.13:** Timestamps of the dispersal simulation during the 2<sup>nd</sup> of July, starting at 18:00 (afternoon) during ebb. Each cluster is given its own colour; CC is shown in blue, CD in dark red, KB - South in orange and KB - North in yellow, to visualize the overall dispersal of each cluster.

The dispersal transition over time for the different clusters are presented in Figure 4.13. The time difference between each snapshot is about 3 hours. The transition over time for each cluster is considered, to further investigate how dispersal behaves in certain areas near Bachelor's Beach and whether they move towards Bachelor's Beach. For this analysis, the time-varying abiotic drivers, shown in Figure A.4, are closely kept in mind to systematically analyse the dispersal patterns.

For the KB-North cluster (yellow), dispersal predominantly follows a north westerly path. The westernmost point, location 15, exhibits a notably elongated plume in this direction during the initial hours post release. This pattern aligns with prevailing easterly wind conditions. After 12 hours, dispersal continues primarily northward, with limited westward spread. As shown in Figure 4.7b, this is likely due to a convergence zone north west of Klein Bonaire, where slightly stronger onshore flows counter offshore movement, restricting further westward advection of particles from the KB-North cluster.



The Coral-Distant (CD, red) and Coral-Close (CC, blue) clusters exhibit similar dispersal patterns during the first 12 hours, generally directed northward to north westward. The degree of elongation varies with wind direction. For both clusters, several release locations interact with Klein Bonaire midway through the dispersal. In the CD cluster, locations 8–11 encounter the island, with locations 10 and 11 showing initial deflection before rejoining the dominant north westward flow. In contrast, particles from locations 8 and 9 remain confined between Bonaire and Klein Bonaire, experiencing limited advection during the first 24 hours. All CC cluster release points eventually interact with Klein Bonaire, after which particles are diverted south westward, preventing further north westward transport. This south westward plume is quite compact following the 18:00 (and 0:00) release and more dispersed after the 12:00 release (see Figures C.9i and C.10i).

In contrast, the Klein Bonaire - South cluster exhibits a distinctly different dispersal behaviour. Unlike the other clusters, these release locations do not initially move towards the north or north west. Locations 16 and 17 disperse toward the south west from the first moment on, closely resembling the end pattern of the CC cluster. Meanwhile, particles from location 18 move south east and appear largely unaffected by the prevailing wind direction. Instead they become trapped between Klein Bonaire and Bonaire during the first 24 hours.

In summary, the dispersal patterns of the different clusters highlight distinct hydrodynamic regions within the fine-scale domain. North of Klein Bonaire, dispersal is strongly influenced by the direction and magnitude of wind conditions enhanced by the waves. Release locations along the coastline of Bonaire initially follow similar patterns, but are subsequently deflected by the presence of Klein Bonaire. Once redirected, these particles tend to maintain their new dispersal pathways, indicating that these areas are less sensitive to variations in the abiotic drivers. A similar pattern is observed for release locations on the southern coast of Klein Bonaire, where dispersal appears to be less affected by changing wind and tidal conditions. Overall, the results suggest that for eggs to reach the sampling location near Bachelor's Beach, they must be released from within the confined area between the southern side of Klein Bonaire and Bonaire.

#### 4.3.1. Passage rates

The dispersal simulations across different release locations aim to identify potential source regions for eggs observed near Bachelor's Beach. In addition to the qualitative analysis of dispersal paths, passage rates are quantified to assess the likelihood of eggs passing specific locations within a defined radius. These rates offer a probabilistic indication of origin, thereby supporting inference of potential spawning grounds. Passage rates near Bachelor's Beach for all realistic scenarios are quantified and compared to RoffaReefs' egg sampling data. The results are presented in Tables 4.4 and 4.5.

| Cluster            | Location | 26 <sup>th</sup> of June,<br>released June<br>25 18:00 |       | 3 <sup>rd</sup> of July,<br>released<br>July 2 0:00 |       | 3 <sup>rd</sup> of July,<br>released<br>July 2 12:00 |       | 3 <sup>rd</sup> of July,<br>released<br>July 2 18:00 |       |
|--------------------|----------|--------------------------------------------------------|-------|-----------------------------------------------------|-------|------------------------------------------------------|-------|------------------------------------------------------|-------|
|                    |          | 5 m                                                    | 150 m | 5 m                                                 | 150 m | 5 m                                                  | 150 m | 5 m                                                  | 150 m |
| Coral-Close (CC)   | 1 - 5    | 0                                                      | 0     | 0                                                   | 0     | 0                                                    | 0     | 0                                                    | 0     |
|                    | 6        | 39                                                     | 1000  | 0                                                   | 0     | 36                                                   | 1000  | 33                                                   | 1000  |
|                    | 7        | 0                                                      | 31    | 0                                                   | 0     | 0                                                    | 1     | 0                                                    | 1     |
| Coral-Distant (CD) | 8 - 14   | 0                                                      | 0     | 0                                                   | 0     | 0                                                    | 0     | 0                                                    | 0     |
| Klein-Bonaire (KB) | 15 - 21  | 0                                                      | 0     | 0                                                   | 0     | 0                                                    | 0     | 0                                                    | 0     |
| Sampled amounts    |          | 16                                                     |       | 3                                                   |       |                                                      |       |                                                      |       |

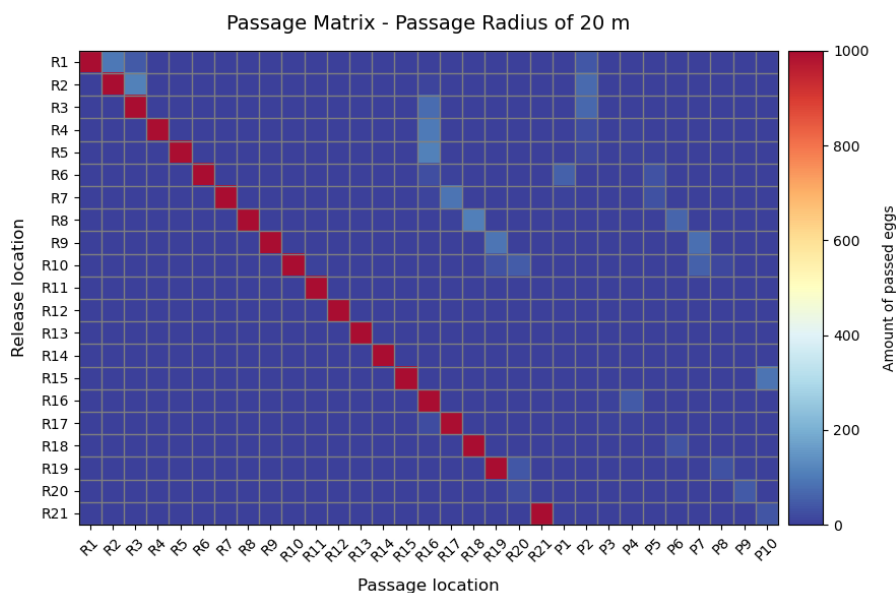
**Table 4.4:** Number of eggs that passed Bachelor's Beach within a radius of 5 or 150 metres. The number of eggs are defined for each release location categorised per cluster.

| Cluster            | Location | 10 <sup>th</sup> of July,<br>released<br>July 9 18:00 |       | 27 <sup>th</sup> of September,<br>released<br>Sept. 26 18:00 |       | 6 <sup>th</sup> of December,<br>released Dec. 5<br>18:00 |       |
|--------------------|----------|-------------------------------------------------------|-------|--------------------------------------------------------------|-------|----------------------------------------------------------|-------|
|                    |          | 5 m                                                   | 150 m | 5 m                                                          | 150 m | 5 m                                                      | 150 m |
| Coral-Close (CC)   | 1 - 4    | 0                                                     | 0     | 0                                                            | 0     | 0                                                        | 0     |
|                    | 5        | 0                                                     | 0     | 1                                                            | 1     | 0                                                        | 0     |
|                    | 6        | 18                                                    | 1000  | 46                                                           | 1000  | 28                                                       | 1000  |
|                    | 7        | 0                                                     | 15    | 0                                                            | 21    | 2                                                        | 121   |
| Coral-Distant (CD) | 8        | 0                                                     | 0     | 0                                                            | 0     | 0                                                        | 1     |
|                    | 9 - 14   | 0                                                     | 0     | 0                                                            | 0     | 0                                                        | 0     |
| Klein-Bonaire (KB) | 15 - 21  | 0                                                     | 0     | 0                                                            | 0     | 0                                                        | 0     |
| Sampled amounts    |          | 6                                                     |       | 153                                                          |       | 10                                                       |       |

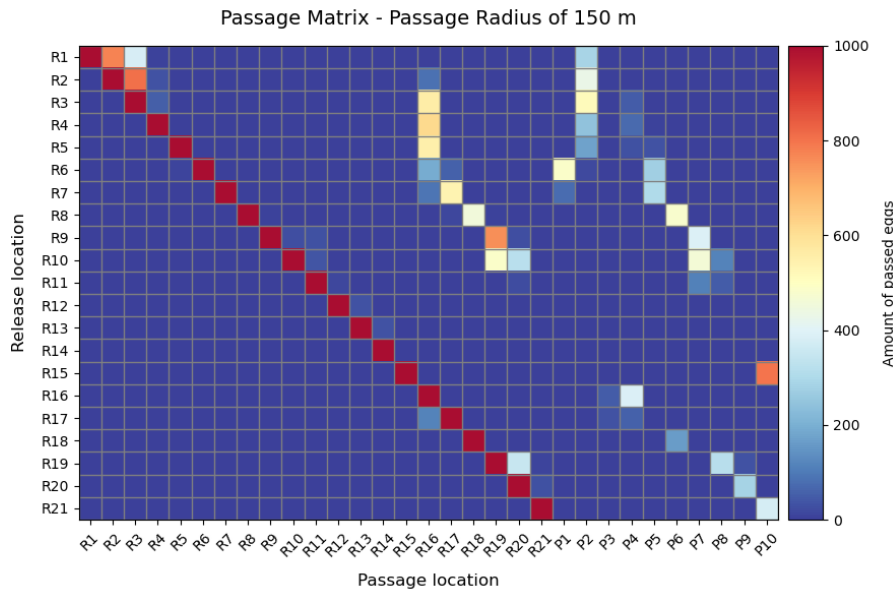
**Table 4.5:** Number of eggs that passed Bachelor's Beach within a radius of 5 or 150 metres. The number of eggs are defined for each release location categorised per cluster.

Both Figure 4.12 and Tables 4.4 and 4.5 show that particles released from most release locations rarely pass the sampling site near Bachelor's Beach. Only release location 6 consistently results in particles reaching the site, primarily within the initial hours post release, before being advected offshore. For the 00:00 release on 2 July, no particles from location 6 reach the sampling site, as dispersal is initially directed away from it (Figure 4.12a). During 26 to 28 September, also a single particle passes within 5 m of the site from release location 5. Similarly, during 5 to 7 December this occurs for location 7. No other locations produce paths within this radius range. This trend remains largely unchanged when expanding the radius to 150 m, though a small number of particles from location 7 and one from location 8 are then observed within the range.

Overall, the simulated passage rates suggest that, under favourable abiotic conditions, sufficient eggs pass within 5 m of the sampling site to plausibly align with egg sampling data. However, this is not the case for the 25 to 27 September period, during which modelled passage rates fall significantly short of the sampled egg numbers. This discrepancy highlights a potential mismatch between model output and observations. Overall, these findings imply that the sampled eggs likely originated within a 150 metre radius of the site. Notably, their presence in front of Bachelor's Beach is somewhat unexpected, given the prevailing north westerly flow, which typically limits egg passage rates near Bachelor's Beach.



**Figure 4.14:** Passage matrix of dispersal simulation of 3 July, with released eggs on 2 July 18:00 and a passage radius of 20 metres.



**Figure 4.15:** Passage matrix of dispersal simulation of 3 July, with released eggs on 2 July 18:00 and a passage radius of 150 metres.

To better illustrate potential passage points along egg dispersal from different release locations, passage matrices are presented in Figures 4.14 and 4.15. The y-axis indicates release locations, while the x-axis represents locations checked for egg passage. With a passage radius of 20 m, matching the default release radius, Figure 4.14 confirms that most all eggs pass their release points. Except those from R20, which are rapidly advected westward (Figure 4.11), reducing local passage rates. Passage radius of 150 metres, shown in Figure 4.15, more clearly illustrates differences between the passage rates of the considered locations.

Of particular interest are cases where eggs pass other locations, which help to identify key passage zones. Release locations R1 to R3, aligned along a north west line, show mutual passage and collectively contribute to high passage rates at offshore location P2. Similarly, R16 (KB-South cluster), situated along the southern curve of Klein Bonaire, receives frequent passage from Coral-Close cluster locations and R17. As seen in Figure 4.11, their dispersal is initially in north west direction, eventually reaching this southern curve. R19 and passage location P7, positioned in the narrow channel between Bonaire and Klein Bonaire, also receive substantial passage from R9 and R10. These passage rates reflect the strong north westward flow through this corridor. Overall, the passage matrices suggest that eggs observed near R16 likely originate either from the southern coastline of Klein Bonaire or from Bonaire's southern coastline of the considered domain. For the remaining release locations, egg dispersal is predominantly directed offshore toward the north west, reducing the likelihood of passage along the coastlines.

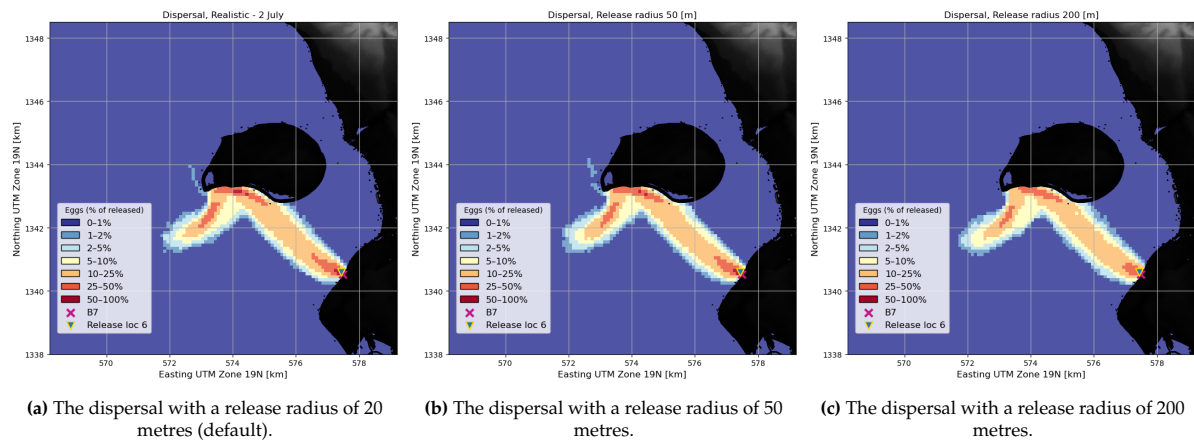
#### 4.4. Effect of parameters

Additional simulations were conducted to evaluate the influence of the release radius  $R$  and diffusion coefficient  $a$  on the dispersal patterns. To quantify the impact of these parameter variations, a sensitivity index ( $SI$ ) was calculated. The  $SI$  is defined as one minus the absolute relative difference between the variation scenario and the default scenario. A  $SI$  value close to one indicates low sensitivity, meaning the parameter change has little effect on the model output. Conversely, a negative  $SI$  signifies that the scenario deviates substantially from the default, with the relative difference exceeding 100%. The most relevant variables for sensitivity evaluation are the mean dispersal distance and its standard deviation, as these reflect the dominant advection and dispersion processes governing the dispersal.

#### 4.4.1. Effect of Release radius

Figure 4.16 shows the percentage of released eggs that enter 100 by 100 metre grid cells for different release radii. A qualitative assessment indicates that a release radius of 20 metres produces the widest band of high egg concentrations, with percentages ranging from 10–25%. As the release radius increases, this high percentage band narrows, and a larger area is instead characterised by lower percentages (5–10%). The quantified results are presented in Table 4.6. For the sensitivity index ( $SI$ ) calculation, the scenario with a 20 metre release radius serves as the reference. The  $SI$  values for a 50 metre radius suggest that dispersal patterns remain relatively consistent with the reference scenario.

In contrast, when the release radius increases to 200 metres, the standard deviation nearly triples. The resulting  $SI$  is therefore negative for this variable, while other metrics still show reasonable agreement. The substantial increase in standard deviation can be attributed to the larger initial spread of particles when released over a broader area. This initial spatial separation exposes the eggs to varying advection pathways, potentially subjecting them to different current regimes. Additionally, horizontal dispersion over time further amplifies the spread, leading to the observed divergence in dispersal patterns.



**Figure 4.16:** The dispersal during realistic scenario of 2<sup>nd</sup> of July for different release radii  $R$ .

| Release radius<br>$R$ value | Mean distance | Standard deviation | Max. distance | Mean path length | Area of Occupancy        |
|-----------------------------|---------------|--------------------|---------------|------------------|--------------------------|
| 20 [m] (default)            | 4919.18 [m]   | 541.40 [m]         | 7383.02 [m]   | 11303 [m]        | 10.68 [km <sup>2</sup> ] |
| $SI$                        | 1             | 1                  | 1             | 1                | 1                        |
| 50 [m]                      | 4932.58 [m]   | 534.17 [m]         | 7058.42 [m]   | 11300 [m]        | 11.18 [km <sup>2</sup> ] |
| $SI$                        | 0.997         | 0.987              | 0.956         | 1.000            | 0.953                    |
| 200 [m]                     | 4455.65 [m]   | 1511.14 [m]        | 6714.21 [m]   | 10561 [m]        | 10.91 [km <sup>2</sup> ] |
| $SI$                        | 0.906         | <b>-0.792</b>      | 0.909         | 0.934            | 0.978                    |

**Table 4.6:** Quantification of the dispersal of the released eggs for combination and realistic scenarios. It should be noted that the Area of Occupancy is based on the percentage grid cells, which are 100 by 100 metre.

These findings highlight the importance of correctly characterising the spawning scale. If spawning occurs as a point or localised event, variations in the release radius between 10 to 50 metres have limited influence on dispersal. However, in cases of broader, aggregation-based spawning, the dispersal pattern becomes highly sensitive to the assumed release radius.

#### 4.4.2. Effect of diffusion coefficient

A similar assessment was conducted to evaluate the influence of varying diffusion coefficients  $a$  on the dispersal patterns. The default diffusion coefficient of 1.0 m<sup>2</sup>/s is shown in the centre of Figure 4.17, with a lower coefficient of 0.5 m<sup>2</sup>/s on the left and a higher coefficient of 1.5 m<sup>2</sup>/s on the right. Visually,

the dispersal patterns broaden from left to right, indicating that higher diffusion coefficients lead to a wider spatial spread.

As the diffusion coefficient increases, the proportion of eggs within the highest concentration categories (50–100% and 25–50%) decreases, while the two successive lower concentration categories expand. This trend is confirmed by the quantified dispersal metrics in Table 4.7. The Table shows that both the standard deviation and the area of occupancy increase with a higher diffusion coefficient.

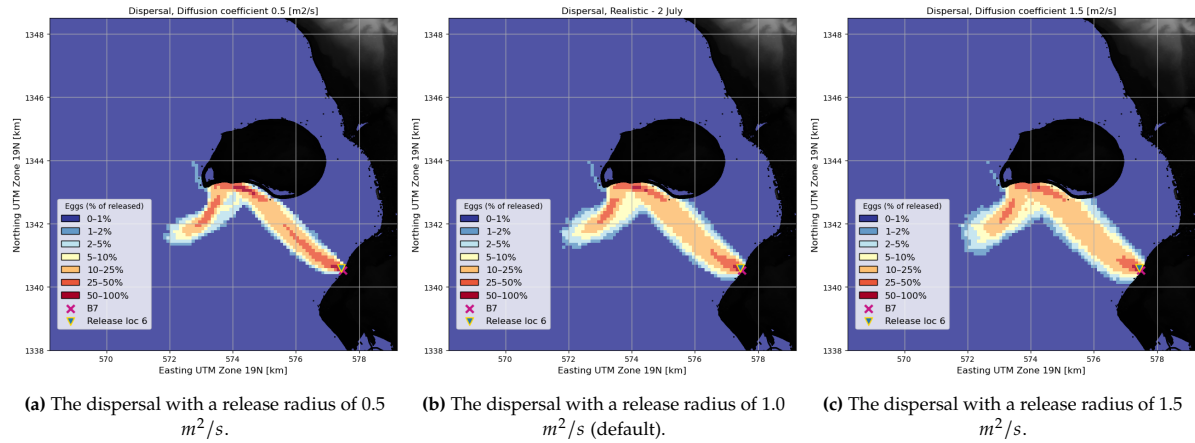


Figure 4.17: The dispersal during realistic scenario of 2<sup>nd</sup> of July for different diffusion coefficients  $a$ .

| Diffusion coefficient $a$ value | Mean distance   | Standard deviation | Max. distance   | Mean path length | Area of Occupancy |
|---------------------------------|-----------------|--------------------|-----------------|------------------|-------------------|
| 0.5 [ $m^2/s$ ]                 | 4958.84 [ $m$ ] | 460.90 [ $m$ ]     | 6571.70 [ $m$ ] | 9171 [ $m$ ]     | 8.28 [ $km^2$ ]   |
| <i>SI</i>                       | 0.992           | 0.851              | 0.890           | 0.811            | 0.775             |
| 1.0 [ $m^2/s$ ] (default)       | 4919.18 [ $m$ ] | 541.40 [ $m$ ]     | 7383.02 [ $m$ ] | 11303 [ $m$ ]    | 10.68 [ $km^2$ ]  |
| <i>SI</i>                       | 1               | 1                  | 1               | 1                | 1                 |
| 1.5 [ $m^2/s$ ]                 | 4884.75 [ $m$ ] | 578.91 [ $m$ ]     | 7194.28 [ $m$ ] | 13137 [ $m$ ]    | 12.77 [ $km^2$ ]  |
| <i>SI</i>                       | 0.993           | 0.931              | 0.974           | 0.838            | 0.804             |

Table 4.7: Quantification of the dispersal of the released eggs for combination and realistic scenarios. It should be noted that the Area of Occupancy is based on the percentage grid cells, which are 100 by 100 metre.

In contrast, the mean dispersal distance decreases. This can be explained by the nature of diffusion-driven dispersion, which increases over time proportional to  $\sqrt{a}$  for a value higher than one. The mean distance decreases slightly with increasing diffusion, because the dispersal becomes less directionally focused and more laterally spread. This reduces the mean distance reached in the dominant advection direction. This broader dispersal results in greater variability and less predictability in the dispersal pathway.

Overall, these findings suggest that although the diffusion coefficient does influence the dispersal to some extent, its sensitivity between values ranging from 0.5 to 1.5  $m^2/s$  is limited. The main differences are observed in the relation between the mean distance and the standard deviation. When pelagic fish eggs have a low diffusion coefficient, the dispersal remains more centralised, increasing the eggs within one defined dispersal pattern. Conversely, higher diffusion coefficients lead to a more dispersed pattern, reducing the defined dispersal pattern and making the final pattern less predictable.

## Discussion

Before addressing the research questions and the main conclusions, it is essential to critically evaluate the key assumptions and implications of the study. It first addresses the assumptions regarding the pelagic behaviour of the eggs and their potential influence on the results. Subsequently, the potential impact of the model limitations on the outcomes are discussed, followed by a reflection on the broader implications of the findings.

### 5.1. Influence of the pelagic trait

Pelagic fish eggs are typically (slightly) positively buoyant, with densities lower than its ambient water (Sundby and Kristiansen, 2015). Consequently, they ascend until reaching neutral buoyancy, usually near the water surface. Fish populations can adapt the buoyancy of their eggs to local salinity conditions, resulting in population specific vertical distributions. In this study, eggs are approached as passive, Lagrangian particles released into and remaining near the surface layer, explained in Section 2.1. This common assumption in larval dispersal modelling, particularly when focussing on abiotic drivers, has important implications for both the temporal and spatial aspects of dispersal.

Typically, eggs are spawned at depth, and their ascent to the surface layer is not instantaneous. The rate of ascent depends on the egg's buoyancy, which is influenced by both its intrinsic density and the ambient waters density. According to Stokes' Law, as described in the one-dimensional model by Sundby (Sundby, 1983), eggs with lower densities, compared to the ambient water, rise faster. For example, assuming an ambient water density of approximately  $1023 \text{ kg/m}^3$ , aligning with the density near Bachelor's Beach (Van Duyl et al., 2024), an egg with a density of  $1000 \text{ kg/m}^3$  would ascend from 15 m depth to the surface in approximately 11 minutes. An egg with a density of  $1020 \text{ kg/m}^3$  would take about 80 minutes for the same conditions. During this ascent, eggs experience different abiotic drivers compared to the surface layer. As detailed in Section 2.2, wind and wave forcing predominantly affect the upper water layer, while deeper layers are more influenced by background currents and other advective processes. This vertical separation could slightly alter the initial dispersal pattern during the ascent. However, given the relatively low depth-averaged flow velocities (see Figure 3.7d), the horizontal displacement during this period is expected to be limited. A conservative estimate suggests that even for eggs with lower buoyancy, the displacement would likely remain within approximately 500 metres of the release location.

When considering the model's spatial resolution and the scale of the dispersal patterns observed (Figure 4.12), this initial displacement is unlikely to significantly alter the broader dispersal pattern. Therefore, the assumption of immediate surface layer entrainment is considered acceptable for the objectives of this study, particularly regarding the evaluation of surface layer abiotic drivers. Nevertheless, while the assumption is valid for assessing large scale dispersal trends, it introduces some uncertainty in pinpointing exact spawning locations. To further refine spawning ground identification, future studies should consider and incorporate the eggs buoyancy into the modelling framework.



## 5.2. Model limitations

### Nesting approach

In this study, a hydrodynamic model was developed using Delft3D-FLOW and Delft3D-WAVE to simulate nearshore conditions around Bonaire. A modelling approach was conducted, due to the limited availability of local hydrodynamic measurements. Regional data were used and translated to local conditions through grid nesting. Although the overall flow patterns appear to be accurately translated, supported by the qualitative agreement in Figure 3.6, the relatively low  $R^2$  values between the intermediate and fine domains (Table 3.2) suggest potential issues. These values, calculated along the boundaries, where the fine domain receives input from the intermediate domain, imply a possible nesting error or that resolution refinement is already influencing local conditions.

Ideally, correct nesting should yield matching boundary conditions between the domains. The observed mismatch may therefore indicate a mismatch through coupling, potentially affecting the reliability of the nested results. However, the effect is difficult to isolate, as finer grids inherently capture more localised processes that are unresolved in coarser domains. To assess the source of the low  $R^2$  values, a sensitivity analysis involving different fine domain grid resolutions is recommended. If the  $R^2$  values remain low across resolutions but qualitative agreement persists, the discrepancy likely arises from resolution differences rather than a nesting flaw. Conversely, if coarser fine domain resolutions increase the  $R^2$  values, decreasing the discrepancies between the conditions, a nesting issue is more probable. In that case, further investigation of the imposed boundary conditions would be warranted to identify and resolve the source of the mismatch. Given the good qualitative agreement between the domains and the computational time of the fine domain, this sensitivity analysis was not conducted. However, it is strongly recommended for future work.

### Applied forcing and data

The selection of abiotic drivers in this study was guided by Table 2.6, considering estimated flow velocities, expected relevance, and the feasibility of simulating each driver. Although regional circulation is associated with the highest flow magnitudes, it was excluded due to limited means for accurate local representation. Figure 2.2 indicates that regional currents likely drive a prevailing north westward flow, consistent with realistic patterns in Section 4.1. Including regional circulation could therefore amplify this trend. However, the precise influence on nearshore dynamics along Bonaire's south west coast remains uncertain in the absence of site specific observations or high resolution models beyond those provided by Richardson (2005).

Furthermore, the conditions used to represent each abiotic driver in this study were derived from global and regional datasets, primarily reflecting open water dynamics in the Caribbean Sea, from north west to east of Bonaire. Through the nesting procedure (Figure 3.1), these broader conditions were translated to nearshore hydrodynamics along Bonaire's south west coast. However, the input datasets do not resolve more localised wave or wind conditions, which could originate from the south or south west of Bonaire. As a result, localised conditions from these directions are limited, potentially omitting important drivers of nearshore transport. This omission is particularly relevant given the demonstrated sensitivity of egg dispersal to wind direction and the enhanced transport associated with wave-induced currents (Figure 4.10). The lack of southern forcing may thus lead to an underestimation of dispersal variability under less frequent, but potentially impactful conditions. To improve model accuracy and reliability of future simulations, it is recommended to incorporate locally measured hydrodynamic data throughout one year, particularly on Bonaire's south west coast.

### Sensitivity to process parameters

RoffaReefs' sampling data does not differentiate between species of reef fish eggs, necessitating a generalised approach to spawning conditions and egg characteristics in this study. This generalisation influences the selection of dispersion and process parameter values. Specifically, the horizontal dispersion settings are intended to approximate unresolved small-scale variability, potentially linked to species specific traits. However, this approach risks oversimplifying the physical traits of reef fish eggs, potentially diverging from real world dynamics. Moreover, studies that address egg dispersal apply varying formulations for horizontal diffusion (Ertfemeijer et al., 2009, Chanson and Tan, 2011,

Onsri et al., 2024), making it challenging to align their findings with the parametrisation used here. Although sensitivity analysis indicates that variations in diffusion coefficients have a limited impact on dispersal patterns, it remains possible that the true diffusion magnitude differs from the assumed range. Further research is recommended to determine appropriate horizontal dispersion settings for accurately modelling the dispersal of pelagic reef fish eggs.

In addition, it is assumed that the eggs originate from localised spawning events, with release radii ranging between 10 to 50 metres. Within this scale, differences in dispersal patterns are relatively minor. If spawning occurs as part of broader aggregation events, common among many reef fish species, the effective release radius would become significantly larger. This wider initial spread increases variability in dispersal patterns due to greater exposure to advective processes, expanding the potential spawning area. Inferring likely spawning ground of the fish eggs would therefore require a more comprehensive investigation. This should include a broader range of possible release locations and potentially account for species specific behavioural traits.

#### Impact of specific events

The abiotic drivers analysed in this study were evaluated under scenarios representing average conditions, typical of the region around Bonaire and the wider Caribbean. This provides a solid foundation for understanding dispersal dynamics under typical, day-to-day conditions. It also offers a structured basis for refining model realism by systematically adding or adjusting individual drivers. However, this focus on average conditions limits the model's capacity to represent more extreme or irregular events that can significantly influence dispersal. Bonaire occasionally experiences heavy rainfall during the wet season, as well as indirect impacts from hurricanes and tropical storms passing through the Caribbean (Frade et al., 2019, Deen, 2024). Such events can significantly alter local wind fields, wave conditions, and surface currents. In addition, wind reversal events have been observed along Bonaire's southwest coast (Godsey, 2024). These can shift wave direction and intensity, temporarily redirecting swell energy toward typically sheltered areas. Although infrequent, such events can persist for several hours to days and significantly impact local hydrodynamics. Because these episodic phenomena were not included in the current model setup, the results primarily reflect dispersal under average conditions. Future studies should incorporate storm events, seasonal anomalies, and wind reversals to improve model robustness and better capture the full range of environmental variability influencing dispersal.

### 5.3. Broader implications

To evaluate the influence of abiotic drivers on pelagic egg dispersal, relevant literature was reviewed. The diversity of drivers considered across studies indicates that their relevance is often site specific and shaped by each study's objectives. This underscores the need to assess local environmental conditions rather than assuming universally dominant processes. In this study, a systematic approach was used to identify key abiotic drivers near Bachelor's Beach (see Section 2.2 and Table 2.1). This method combines literature based insights with local flow magnitude assessments and simplified velocity approximations for each driver. This allows for the targeted inclusion of only the most influential drivers, helping to balance model reliability with computational efficiency—particularly valuable when data availability or computational resources are limited.

While the methodology was tailored to the conditions near Bachelor's Beach, it is applicable to other coastal settings. However, dominant processes will likely differ due to variations in geography, wind regimes, and tidal dynamics. Successful application elsewhere requires access to reliable literature and, ideally, sufficient local hydrodynamic data for both model setup and validation. In this study, full validation of the hydrodynamic model was limited by a lack of detailed flow measurements near Bachelor's Beach. Nonetheless, the simulated flow patterns align reasonably with theoretical expectations (see Table 4.1). While the overall model framework appears robust, uncertainties remain regarding the absolute accuracy of the dispersal patterns. Although the modelled and observed flow magnitudes differ in order, their directional alignment suggests that discrepancies likely affect the rate at which patterns develop, rather than the patterns themselves. To improve model calibration and site specific reliability, future studies should incorporate more extensive in situ measurements.

# Conclusions and Recommendations

## 6.1. Conclusions

This study analyses the abiotic flow drivers near Bachelor's Beach, to understand their impact on the dispersal of released eggs in the region. The objective is ultimately to be able to infer where the sampled eggs in front of Bachelor's Beach came from based on the obtained dispersal patterns for the same period. The main research question of the thesis is as follows: "How can spawning grounds near Bachelor's Beach be inferred using nearshore fish egg sampling data and varying abiotic drivers?". First the sub research questions are answered, which will pose as a guideline for answering the main research question.

### 1. *"Can fish eggs be considered as Lagrangian particles when tracking their dispersal?"*

The reef fish eggs considered in this study are slightly positively buoyant, causing them to ascend toward the surface where they remain in the upper water layer. During the first 24 hours after being spawned, these eggs lack active swimming or orientation capabilities. Therefore, their movement is fully governed by external hydrodynamic forces. Approaching the eggs as passive Lagrangian particles thus becomes a valid and widely accepted method for dispersal studies. This assumption captures the primary drivers of horizontal transport and aligns with common modelling practices. While vertical ascent may influence initial dispersal within the first few hours, this effect is expected to be minimal over the broader timescales considered. Overall, this simplification is appropriate for understanding the abiotic influences on dispersal patterns in this study.

### 2. *"What are the dominant abiotic drivers influencing the dispersal of fish eggs near Bachelor's Beach?"*

A review of literature and flow velocity analyses identified regional circulation, wind-driven currents, and wave-induced flows as the primary abiotic factors potentially influencing fish egg dispersal near Bachelor's Beach. Due to the study's scope limitations, detailed resolution of regional circulation was not undertaken. However, tidal forcing was incorporated, due to its consistent presence in the area and easy implementation. The results from the developed hydrodynamic model to simulate their individual and combined forcing indicate that wind-driven currents are the dominant force shaping surface flow patterns near Bachelor's Beach. Both the magnitude and direction of the surface velocity field are strongly governed by wind conditions, whether steady or time-varying, impacting the mean distance and spread of the resulting dispersal pattern. Wave effects, particularly from short-crested wind-generated waves, enhance flow velocities but are only substantial when wind is present. Conversely, tidal forcing alone induces minimal flow variation near Bachelor's Beach. The region's low tidal amplitude shows the strongest flows on the west and east sides of Klein Bonaire, with negligible differences observed between spring and neap tide conditions. In summary, wind is considered the primary abiotic driver of dispersal near Bachelor's Beach, with waves providing a secondary, wind-dependent effect. Tidal forcing plays a limited role near Bachelor's Beach.

### 3. *"Does the Delft3D Tracer model offer insights for inferring spawning grounds under varying abiotic drivers near Bonaire?"*

The hydrodynamic model and the RoffaReefs sampling data near Bachelor's Beach form the basis for inferring potential spawning grounds within the fine model domain. Delft3D's structured grid version includes a particle tracking module that uses the hydrodynamic model output to simulate dispersal patterns. Ideally, backward in time simulations would be used to trace egg origins. However, Delft3D-PART only supports forward in time dispersal. To address this, multiple release locations and times were simulated to assess the likelihood of particles passing near Bachelor's Beach under varying abiotic drivers. Based on the passage rates insights on possible spawning grounds are obtained. Among the tested release locations, only location 6 (CC cluster) produced eggs that reliably passed the sampling area. Considering the north westward dispersal trends in the region, these results suggest that the eggs sampled near Bachelor's Beach likely originated from spawning grounds of close proximity. Sensitivity analyses indicate that assumptions about the release radius of spawning significantly affect the variability in dispersal patterns. This suggests that refining the understanding of spawning event scales is essential and should be addressed in future research.

*"How can spawning grounds near Bachelor's Beach be inferred using nearshore fish egg sampling data and varying abiotic drivers?"*

Spawning grounds near Bachelor's Beach can be inferred by integrating nearshore fish egg sampling data with hydrodynamic, dispersal modelling that incorporates the dominant abiotic drivers of the region. In this study, fish eggs were treated as passive Lagrangian particles, a valid assumption for the first 24 hours post spawning, when eggs lack active swimming capabilities. The hydrodynamic model developed in this study identified wind-driven currents as the primary mechanism driving surface dispersal near Bachelor's Beach. Wave-induced flows were found to enhance dispersal, but their effect was dependent on the presence of wind. Tidal forcing had a limited influence in the nearshore area of Bachelor's Beach. Among the multiple hypothetical spawning locations tested, only the Coral-Close cluster released eggs that reached Bachelor's Beach under the combined influence of time-varying wind, wave, and tidal conditions. These results suggest that the eggs sampled near Bachelor's Beach, likely originated from spawning grounds of close proximity. Sensitivity analyses further highlighted the importance of considering the spatial extent of spawning events, as the assumed release radius significantly influenced dispersal variability.

In summary, by combining nearshore egg sampling, hydrodynamic modelling, and scenario-based particle tracking, likely spawning grounds can be inferred despite model limitations. However, refining knowledge on process parameters influenced by the biotic drivers and incorporating additional time-varying abiotic scenarios, such as wind reversals and episodic events, would further strengthen the reliability of these inferences.

## 6.2. Recommendations

This study represents one of the first efforts to investigate abiotic drivers influencing pelagic egg dispersal along the south west coast of Bonaire. Consequently, there is considerable potential to further advance the understanding of local coastal processes near Bachelor's Beach and the associated reef fish egg dispersal dynamics. A key recommendation to RoffaReefs is to consider relocating their breeding system to the southern curve of Klein Bonaire, where model results (Section 4.3) suggest frequent passage of dispersal trajectories. If sampled eggs at this location correspond with model predictions, it would enhance confidence in the model's validity. Alternatively, improved alignment could also be achieved by simulating more realistic scenarios that reflect egg sampling conditions. Such realistic simulations would not only refine model confidence, but also offer additional insights into likely spawning locations. Moreover, RoffaReefs could use the presented formulas in the literature review, along with wind direction data, to estimate flow magnitudes and predict likely egg dispersal paths from known spawning sites. Given the agreement between literature-based estimates and model results, this practical approach can help identify potential locations for the breeding system, without requiring full hydrodynamic modeling.

Another key recommendation is to conduct local hydrodynamic measurements along the south west coast of Bonaire. As conditions likely behave differently than on the more exposed northern and

eastern shores. The sheltered nature of this region introduces uncertainty regarding the extent to which regional processes affect local dynamics. Long term data collection in this area would provide critical insights into these localised processes and their variability in relation to broader Caribbean conditions. While a full year of observations would yield the most comprehensive understanding, even a shorter monitoring period, of several months, would significantly enhance model calibration, validation, and overall system knowledge. In parallel, testing different grid resolutions within the fine domain would help determine whether the current refinement accurately captures local dynamics. If discrepancies persist across grid scales, this may indicate limitations in the nesting procedure, highlighting an area for further model improvement which can be validated with the local measurements.

The sensitivity of dispersal outcomes to release conditions and process parameters related to species specific traits is discussed in Section 5.2. Incorporating additional biotic drivers, such as release radius, positive egg buoyancy, and diffusion coefficients, into the dispersal simulations would enhance the accuracy of spawning ground inferences. Currently, the Tracer model employs a simplified species representation to simulate dispersal. However, the Oil model type within Delft3D-PART enables the inclusion of these more detailed biological parameters. Alternatively, the extensively validated Connectivity Modelling System offers a broader range of biotic drivers and can be integrated with the hydrodynamic model developed in this study. Utilizing such approaches would improve the realism and predictive power of dispersal simulations.

# References

- Almany, G., Planes, S., Thorrold, S., Berumen, M., Bode, M., Saenz-Agudelo, P., Bonin, M., Frisch, A., Harrison, H., Messmer, V., Nanninga, G., Priest, M., Srinivasan, M., Sinclair-Taylor, T., Williamson, D., & Jones, G. (2017). Larval fish dispersal in coral-reef seascape. *Nat Ecol Evol*, 1(0148). <https://doi.org/10.1038/s41559-017-0148>
- Anwar, H., & Weller, J. (1981). An experimental study of the structure of a freshwater-saltwater interfacial mixing. *La Houille Blanche*, 67(6), 405–412. <https://doi.org/10.1051/lhb/1981041>
- AVISO+. (2024). *Fes2014 (finite element solution) - global tide* [Accessed: 2025-01-31]. <https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html>
- Berenshtein, I., Faillettaz, R., Irisson, J., Kiflawi, M., Siebeck, U., Leis, J., & Paris, C. (2022). Evidence for a consistent use of external cues by marine fish larvae for orientation. *Communications Biology*, 5(1307). <https://doi.org/10.1038/s42003-022-04137-7>
- Bertoncelj, V., Mienis, F., Stocchi, P., & van Sebille, E. (2024). Flow patterns, hotspots and connectivity of land-derived substances at the sea surface of curaçao in the southern caribbean. *EGUsphere*, 2024, 1–29. <https://doi.org/10.5194/egusphere-2024-3112>
- BonaireTax. (2023). *Hurricanes in bonaire* [Accessed: 2025-03-12]. <https://bonairetax.com/hurricanes-in-bonaire/>
- Bosboom, J., & Stive, M. J. (2023). *Coastal dynamics* (Vol. 1). TU Delft Open. <https://doi.org/10.5074/T.2021.001>
- Cai, c., Hong, B., Zhu, L., Xu, H., & Wang, L. (2025). Impact of stokes drift and washing-off on the pathways and accumulation of microplastics originating from a subtropical estuary. *Ocean Modelling*, 194, 102492. <https://doi.org/10.1016/j.ocemod.2024.102492>
- Chanson, H., & Tan, K. (2011). Dispersion of fish eggs under undular and breaking tidal bores. *FDMP*, 7(4), 403–418. [https://staff.civil.uq.edu.au/h.chanson/reprints/fdmp\\_2011.pdf](https://staff.civil.uq.edu.au/h.chanson/reprints/fdmp_2011.pdf)
- Chaput, R., Sochala, P., Miron, P., Kourafalou, V., & Iskandarani, M. (2022). Quantitative uncertainty estimation in biophysical models of fish larval connectivity in the florida keys. *ICES, Journal of Marine Science*, 79(3), 609–632. <https://doi.org/10.1093/icesjms/fsac021>
- Chérubin, L., & Richardson, P. (2007). Caribbean current variability and the influence of the amazon and orinoco freshwater plumes. *Deep-sea Research*, 54(9), 1451–1473. <https://doi.org/10.1016/j.dsr.2007.04.021>
- Cole, S., & Quessenberry, M. (2025). *Ocean layering: Density, salinity, temperature, and circulation* [Accessed: 2025-04-07]. <https://earthref.org/SCC/lessons/2009/oceanlayers/>
- Colin, P., & de Mitcheson, Y. (2011). *Reef fish spawning aggregations: Biology, research and management* (Vol. 1). Springer Dordrecht. <https://doi.org/10.1007/978-94-007-1980-4>
- Courtene-Jones, W., Maddalene, T., James, M., Smith, N., Youngblood, K., Jambeck, J., Earthrowl, S., Delvalle-Borrero, D., Penn, E., & Thompson, R. (2021). Source, sea and sink—a holistic approach to understanding plastic pollution in the southern caribbean. *Science of The Total Environment*, 797, 149098. <https://doi.org/10.1016/j.scitotenv.2021.149098>
- Daudén-Bengoa, G., Sheinbaum, J., RodríguezOuterelo, J., & Herzka, S. (2024). Coupling of potential habitat models with particle tracking experiments to examine larval fish dispersal and connectivity in deep water regions. *PLOS ONE*, 19, 1–23. <https://doi.org/10.1371/journal.pone.0308357>
- De Falco, C., Desbiolles, F., Bracco, A., & Pasquero, C. (2022). Island mass effect: A review of oceanic physical processes. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.894860>
- de Oliveira Júnior, L., Relvas, P., & Garel, E. (2024). Upwelling processes variability and water circulation along the northern margin of the gulf of cadiz. *Continental Shelf Research*. <https://doi.org/10.1016/j.csr.2024.105310>
- Deen, T. (2024). *Hurricane beryl expected to pass north of bonaire* [Accessed: 2025-06-16]. <https://infobonaire.com/hurricane-beryl-expected-to-pass-north-of-bonaire/>

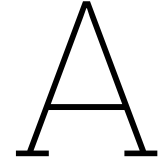


- Deltares. (2025a). Delft3d-flow - simulations of multi-dimensional hydrodynamic flows and transport phenomena, including sediments user manual. *Deltares systems*. [https://content.oss.deltares.nl/delft3d4/Delft3D-FLOW\\_User\\_Manual.pdf](https://content.oss.deltares.nl/delft3d4/Delft3D-FLOW_User_Manual.pdf)
- Deltares. (2025b). Delft3d-part - simulations of mid-field water quality and oil spills, using particle tracking user manual. *Deltares*. [https://content.oss.deltares.nl/delft3d4/Delft3D-PART\\_User\\_Manual.pdf](https://content.oss.deltares.nl/delft3d4/Delft3D-PART_User_Manual.pdf)
- Deltares. (2025c). Delft3d-wave - simulation of short-crested waves with swan user manual. *Deltares*. [https://content.oss.deltares.nl/delft3d4/Delft3D-WAVE\\_User\\_Manual.pdf](https://content.oss.deltares.nl/delft3d4/Delft3D-WAVE_User_Manual.pdf)
- DiBattista, J., West, K., Ceccarelli, D., Hoggett, A., Vail, L., Garcia, R., & Richards, Z. (2025). An examination of seasonal variation in taxonomic richness and community composition using edna on a tropical coral reef. *Coral Reefs*, 44, 163–178. <https://doi.org/10.1007/s00338-024-02594-6>
- Drivdal, M., Broström, G., & Christensen, K. (2014). Wave-induced mixing and transport of buoyant particles: Application to the statfjord a oil spill. *Ocean Science*, 10(6), 977–991. <https://doi.org/10.5194/os-10-977-2014>
- ECMWF. (2025). *Era5 hourly data on single levels from 1940 to present* [Accessed: 2025-02-11]. <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>
- Eddy, T., Lam, V., Reygondeau, G., Cisneros-Montemayor, A., Greer, K., Palomares, M., Bruno, J., Ota, Y., & Cheung, W. (2021). Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*, 4, 1278–1285. <https://doi.org/10.1016/j.oneear.2021.08.016>
- El-Regal, M., Manaa, A., Basaham, A., & Ghandour, I. (2024). Density and diversity of larval fish in some coastal bays in sharm el-sheikh, northern red sea, egypt. *Egyptian Journal of Aquatic Research*.
- EMODnet. (2023). *Emodnet map viewer* [Accessed: 2025-01-16]. <https://emodnet.ec.europa.eu/geoviewer/#>
- Erftemeijer, P., van Beek, J., Bolle, L., Dickey-Collas, M., & Los, H. (2009). Variability in transport of fish eggs and larvae. i. modelling the effects of coastal reclamation. *Marine Ecology Progress Series*, 390, 167–181. <https://doi.org/10.3354/meps08173>
- Frade, P., Bongaerts, P., Baldwin, C., Trembanis, A., Bak, R., & Vermeij, M. (2019). Bonaire and curaçao. In Y. Loya, K. Puglise, & T. Bridge (Eds.), *Mesophotic coral ecosystems* (pp. 149–162, Vol. 12). Springer International Publishing. [https://doi.org/10.1007/978-3-319-92735-0\\_9](https://doi.org/10.1007/978-3-319-92735-0_9)
- Fujimura, A., Reniers, A., Paris, C., Shanks, A., MacMahan, J., & Morgan, S. (2013). Slope-dependent biophysical modeling of surf zone larval transport. *Coastal Dynamics* 2013.
- Fujimura, A., Reniers, A., Paris, C., Shanks, A., MacMahan, J., & Morgan, S. (2018). Mechanisms of cross-shore transport and spatial variability of phytoplankton on a rip-channeled beach. *Frontiers in Marine Science*, 5. <https://doi.org/10.3389/fmars.2018.00183>
- Garcés-Ordóñez, O., Espinosa, L., Costa Muniz, M., Pereira, L., & Meigikos dos Anjos, R. (2021). Abundance, distribution, and characteristics of microplastics in coastal surface waters of the colombian caribbean and pacific. *Environmental Science and Pollution Research*, 28, 43431–43442. <https://doi.org/10.1007/s11356-021-13723-x>
- Gardner, P., Frazer, T., Jacoby, C., & Yanong, R. (2015). Reproductive biology of invasive lionfish (pterois spp.) *Frontiers in Marine Science*, 2. <https://doi.org/10.3389/fmars.2015.00007>
- Godsey, M. (2024). *Caribbean wind and reef blog, part 3: "wind reversal" damage on bonaire and curaçao*. [Accessed: 2025-06-16]. <https://blog.tempest.earth/caribbean-wind-reef-blog-part-3-recent-wind-reversal-damage-on-bonaire-and-curacao/>
- Gordon, A., & Cenedese, C. (2025). Ocean current. *Encyclopedia Britannica*. <https://www.britannica.com/science/ocean-current>
- Graham, J., Watson, J., García, L., Bradley, K., Bradley, R., Brown, M., Ciotti, B., Goodwin, D., Nash, R., Roche, W., Wogerbauer, C., & Hyder, K. (2023). Pelagic connectivity of european sea bass between spawning and nursery grounds. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.1046585>
- Graham, N., & Nash, K. (2013). The importance of structural complexity in coral reef ecosystems. *Coral Reefs*, 32, 315–326. <https://doi.org/10.1007/s00338-012-0984-y>
- Grimaldi, C., Lowe, R., Benthuisen, J., Cuttler, M., Green, R., Radford, B., Ryan, N., & Gilmour, J. (2022). Hydrodynamic drivers of fine-scale connectivity within a coral reef atoll. *Limnology and Oceanography*, 67, 2204–2217. <https://doi.org/10.1002/lno.12198>

- Heiberg Espeland, S., Albretsen, J., Olsen, E., & Bodvin, T. (2015). Modelling drift of pelagic offspring: The importance of egg surveys in providing a realistic model initialization. *ICES Journal of Marine Science*, 72(9), 2578–2589. <https://doi.org/10.1093/icesjms/fsv134>
- Hernández, C., Paris, C., Vaz, A., Jones, B., Kellner, J., Richardson, D., Sponaugle, S., Cowen, R., & Llopiz, J. (2023). Diverse patterns of larval coral reef fish vertical distribution and consequences for dispersal and connectivity. *Coral Reefs*, 42, 453–465. <https://doi.org/10.1007/s00338-023-02355-x>
- Hixon, M., & Randall, J. (2019). Coral reef fishes. *Encyclopedia of Ocean Sciences*, 3, 142–150. <https://doi.org/10.1016/B978-0-12-409548-9.11059-0>
- Holthuijsen, L. (2007). *Waves in oceanic and coastal waters*. Cambridge University Press. <https://doi.org/10.2277/0521860288>
- Holthuijsen, L., Booij, N., & Ris, R. (1993). A spectral wave model for the coastal zone. *Proceedings of 2nd International Symposium on Ocean Wave Measurement and Analysis, New Orleans*.
- Ip, Y., Chang, J., Tun, K., Meier, R., & Huang, D. (2022). Multispecies environmental dna metabarcoding sheds light on annual coral spawning events. *Molecular Ecology*, 32, 6474–6488. <https://doi.org/10.1111/mec.16621>
- Iwasaki, S., Isobe, A., & Miyao, Y. (2015). Fortnightly atmospheric tides forced by spring and neap tides in coastal waters. *Scientific reports*, 5(10167). <https://doi.org/10.1038/srep10167>
- James, M., Armsworth, P., Mason, L., & Bode, L. (2002). The structure of reef fish metapopulations: Modelling larval dispersal and retention patterns. *Royal Society*, 269(1505). <https://doi.org/10.1098/rspb.2002.2128>
- Johns, W., Townsend, T., Fratantoni, D., & Douglas Wilson, W. (2002). On the atlantic inflow to the caribbean sea. *Deep Sea Research Part I: Oceanographic Research Papers*, 49(2), 211–243. [https://doi.org/10.1016/S0967-0637\(01\)00041-3](https://doi.org/10.1016/S0967-0637(01)00041-3)
- Koninklijk Nederlands Meteorologisch Instituut. (2025). *Uurgegevens van het caribisch gebied* [Accessed: 2025-01-31]. [https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens\\_Caribisch\\_gebied](https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens_Caribisch_gebied)
- Kuik, A. (1988). A method for the routine analysis of pitch-and-roll buoy wave data. *Journal of Physical oceanography*, 18(7), 1020–1034. [https://doi.org/10.1175/1520-0485\(1988\)018<1020:AMFTRA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1988)018<1020:AMFTRA>2.0.CO;2)
- Lanzafame, R., van Woudenberg, T., & Verhagen, S. (2024). *Modelling, uncertainty and data for engineers (mude) textbook*. Delft University of Technology. <https://mude.citg.tudelft.nl/book>
- Leis, J. (2021). Perspectives on larval behaviour in biophysical modelling of larval dispersal in marine, demersal fishes. *Oceans*, 2(1), 1–25. <https://doi.org/10.3390/oceans2010001>
- Leis, J., Wright, K., & Johnson, R. (2007). Behaviour that influences dispersal and connectivity in the small, young larvae of a reef fish. *Marine Biology*, 153(1), 103–117.
- Lenain, L., Pizzo, N., & Melville, W. (2019). Laboratory studies of lagrangian transport by breaking surface waves. *Journal Fluid Mechanics*, 876. <https://doi.org/10.1017/jfm.2019.544>
- Lesser, G., Roelvink, D., Van Kester, J., & Stelling, G. (2004). Development and validation of a three-dimensional morphological model. *Coastal Engineering*, 51(8), 883–915. <https://doi.org/10.1016/j.coastaleng.2004.07.014>
- Lin, Y., Sheng, J., & Greatbatch, R. (2011). A numerical study of the circulation and monthly-to-seasonal variability in the caribbean sea: The role of caribbean eddies. *Ocean Dynamics*, 62, 193–211. <https://doi.org/10.1007/s10236-011-0498-0>
- Lyard, F., Allain, D., Cancet, M., Carrère, L., & Picot, N. (2021). Fes2014 global ocean tide atlas: Design and performance. *Ocean Science*, 17(3), 615–649. <https://doi.org/10.5194/os-17-615-2021>
- Majoris, J., Foretich, M., Hu, Y., Nickles, K., Persia, C., Chaput, R., Schlatter, E., Webb, J., Paris, C., & Buston, P. (2021). An integrative investigation of sensory organ development and orientation behavior throughout the larval phase of a coral reef fish. *Scientific Reports*, 11(12377). <https://doi.org/10.1038/s41598-021-91640-2>
- McDonald, M. (2024). *Hycom overview* [Accessed: 2024-12-30]. <https://www.hycom.org/hycom/overview>
- Monismith, S. (2007). Hydrodynamics of coral reef. *Annual Review of Fluid Mechanics*, 39, 37–55. <https://doi.org/10.1146/annurev.fluid.38.050304.092125>
- Muraleedharan, G., Lucas, C., & Guedes Soares, C. (2023). Spectral wave energy period and peak period statistics concomitant with maximum significant wave heights. *Coastal Engineering*, 183, 104260. <https://doi.org/10.1016/j.coastaleng.2022.104260>

- Murphy, M. (2024). *Redesign of a floating fish breeding system* [Master's thesis, Delft University of Technology].
- Nguyen, B., Liu, Y., Stallings, C., Breitbart, M., Murawski, S., Weisberg, R., Kerr, M., Bonnelycke, E., & Peebles, E. (2023). Retention and export of planktonic fish eggs in the northeastern gulf of Mexico. *Fisheries Oceanography*, 33. <https://doi.org/10.1111/fog.12655>
- NOAA, N. O. A. A. (2019). *Coral reef ecosystems* [Accessed: 2024-11-21]. <https://www.noaa.gov/education/resource-collections/marine-life/coral-reef-ecosystems>
- Onsri, N., Sivaipram, I., Boonsanit, P., Sagulsawasdiapan, K., & Saramul, S. (2024). Larval dispersal modelling of the blue swimming crab *Portunus pelagicus* (Linnaeus, 1758) from the crab banks along the coast of Trang province, southern Thailand. *Water*, 16(2), 349. <https://doi.org/10.3390/w16020349>
- Paris, C., & Cowen, R. (2004). Direct evidence of a biophysical retention mechanism for coral reef fish larvae. *Limnology and Oceanography*, 49(6), 1964–1979. <https://doi.org/10.4319/lo.2004.49.6.1964>
- Paris, C., Helgers, J., Van Sebille, E., & Srinivasan, A. (2013). Connectivity modeling system: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. *Environmental Modelling and Software*, 42, 47–54. <https://doi.org/10.1016/j.envsoft.2012.12.006>
- Petterson, O. (1930). The tidal force: A study in geophysics. *Geografiska Annaler*, 12(4), 261–322. <https://doi.org/10.1080/20014422.1930.11880529>
- Pietrzak, J. (2021). *An introduction to coastal and basin-scale physical oceanography for civil and offshore engineers*. Environmental Fluid Mechanics Section, Department of Hydraulic Engineering, TU Delft.
- Pineda, J., Hare, J., & Sponaugle, S. (2007). Larval transport and dispersal in the coastal ocean and consequences for population connectivity. *Oceanography Society*, 20(3), 22–39. <http://www.jstor.org/stable/24860094>
- Putri, R., Jaya, I., Pujiyati, S., Agus, S., & Palo, M. (2024). Spawning grounds literature review: Spawning success factors. *AACL Bioflux*, 17(3).
- Richardson, P. (2005). Caribbean current and eddies as observed by surface drifters. *Deep-Sea Research*, 52(3-4), 429–463. <https://doi.org/10.1016/j.dsr2.2004.11.001>
- Roelvink, J. A., & Reniers, A. (2011). *A guide to modeling coastal morphology*. World Scientific Publishing.
- RoffaReefs. (2024). *Bonaire pilot* [Accessed: 2024-11-21]. <https://www.roffareefs.com/bonaire-pilot/>
- Ross, R., Nimmo-Smith, W., Torres, R., & Howell, K. (2020). Comparing deep-sea larval dispersal models: A cautionary tale for ecology and conservation. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00431>
- Rühs, S., Van den Bremer, T., Clementi, E., Denes, M., Moulin, A., & Van Sebille, E. (2024). Non-negligible impact of Stokes drift and wave-driven Eulerian currents on simulated surface particle dispersal in the Mediterranean Sea. *EGU sphere*. <https://doi.org/10.5194/egusphere-2024-1002>
- Shimada, S., Takeyama, Y., Kogaki, T., Ohsawa, T., Kawaguchi, K., & Nakamura, S. (2018). Investigation of the fetch effect using onshore and offshore vertical lidars. *The National Institute of Advanced Industrial Science and Technology*, 10(1408).
- Siegel, D., Kinlan, B., Gaylord, B., & Gaines, S. (2003). Lagrangian descriptions of marine larval dispersion. *Marine Ecology-progress Series*, 260, 83–96. <https://doi.org/10.3354/meps260083>
- Slagter, K. (2023). *Mapping the bathymetry of Bonaire through the use of satellite data* [Master's thesis, Wageningen University and Research].
- Slijkerman, D., Van der Geest, M., & Mûcher, S. (2019). *Nexus interventions for small tropical islands: Case study Bonaire* (Report). Wageningen University and Research.
- STINAPA. (2018). *Part 1. Bonaire national marine park: Background information* [Accessed: 2025-04-07]. <https://stinapabonaire.org/wp-content/uploads/2018/10/BNMP-managementplan-part1.pdf>
- STINAPA. (2025). *Home page stinapa* [Accessed: 2025-01-12]. <https://stinapa.bonairenaturefee.org/>
- Sundby, S. (1983). A one-dimensional model for the vertical distribution of pelagic fish eggs in the mixed layer. *Deep Sea Research*, 30(6), 645–661.
- Sundby, S., & Kristiansen, T. (2015). The principles of buoyancy in marine fish eggs and their vertical distributions across the world oceans. *PLoS ONE*, 10(10). <https://doi.org/10.1371/journal.pone.0138821>
- Svendsen, I. (1984). Wave heights and set-up in a surf zone. *Coastal Engineering*, 8, 347–365.
- Toschi, F., & Bodenschatz, E. (2008). Lagrangian properties of particles in turbulence. *Annual Review of Fluid Mechanics*, 41, 375–404. <https://doi.org/10.1146/annurev.fluid.010908.165210>

- Tracey, S., Hartmann, K., & Hobday, A. (2012). The effect of dispersal and temperature on the early life history of a temperate marine fish. *Fisheries Oceanography*, 21(5), 336–347. <https://doi.org/10.1111/j.1365-2419.2012.00628.x>
- Van Duyl, F. (1985). Atlas of the living reefs of curacao and bonaire (netherlands antilles). *Studies of Flora and Fauna of Surinam and the Netherlands Antilles*, 117, 1–37 plus maps.
- Van Duyl, F., Post, V., Van Breukelen, B., Bense, V., Visser, P., Meesters, E., Koeniger, P., & Vermeij, M. (2024). Composition and distribution of the near-shore waters bordering the coral reefs of aruba, bonaire, and curacao in the southern caribbean. *Marine Pollution Bulletin*, 209, 117297. <https://doi.org/10.1016/j.marpolbul.2024.117297>
- Van Leeuwe, J. (2023). *Mixing over shallow coral reefs in relation to the reef rugosity* [Master's thesis, Wageningen University].
- Van Leeuwen, A. F. M. (2022). *Assessing the relationship between coastal currents and water quality indicators on bonaire: Adcp & ctd approach* (Report). Wageningen University and Research.
- Van Wiechen, P. (2020). *Wave dissipation on a complex coral reef* [Master's thesis, Delft University of Technology].
- van Utenhove, E. (2018). *Modelling the transport and fate of buoyant macroplastics in coastal waters* [Master's thesis, Delft University of Technology].
- Vons, F. (2019). *Pumping coral-spawn slicks for large scale reef rehabilitation* [Master's thesis, Delft University of Technology].
- Wallace, J. M., & Hobbs, P. V. (2006). *Atmospheric science: An introductory survey* (2nd). Academic Press.
- Webb, P. (2023). *Introduction to oceanography*. Roger Williams University.
- WUR, Wageningen University & Research. (2024). *Impact of climate change on marine ecosystems* [Accessed: 2024-11-19]. <https://www.wur.nl/en/research-results/research-institutes/marine-research/research-themes/climate-and-coast/impact-of-climate-change-on-marine-ecosystems.htm>
- Xu, X., Chassignet, E., Miron, P., & Zavala-Romero, O. (2024). Seasonality of marine litter hotspots in the wider caribbean region. *MDPI*, 12(2). <https://doi.org/10.3390/jmse12020319>



# Condition analysis

## A.1. Dispersion relationship - waves

The dispersion relationship is an implicit expression in terms of wave number  $k$ , which requires an iteration procedure to calculate the wave number for a given frequency  $\omega$  and depth  $d$  (Holthuijsen, 2007). Fenton (1988) provides an explicit expression that approximates the solution for all situations between the limits of deep and shallow water. The error for  $k$  is less than 5 percent. The approximation can be made based on the following Equations (A.1, A.2, A.3):

$$\alpha = \frac{\omega^2 d}{g} \quad (\text{A.1})$$

$$\beta = \alpha(\tanh \alpha)^{-1/2} \quad (\text{A.2})$$

$$kd \approx \frac{\alpha + \beta(\cosh \beta)^{-2}}{\tanh \beta + \beta(\cosh \beta)^{-2}} \quad (\text{A.3})$$

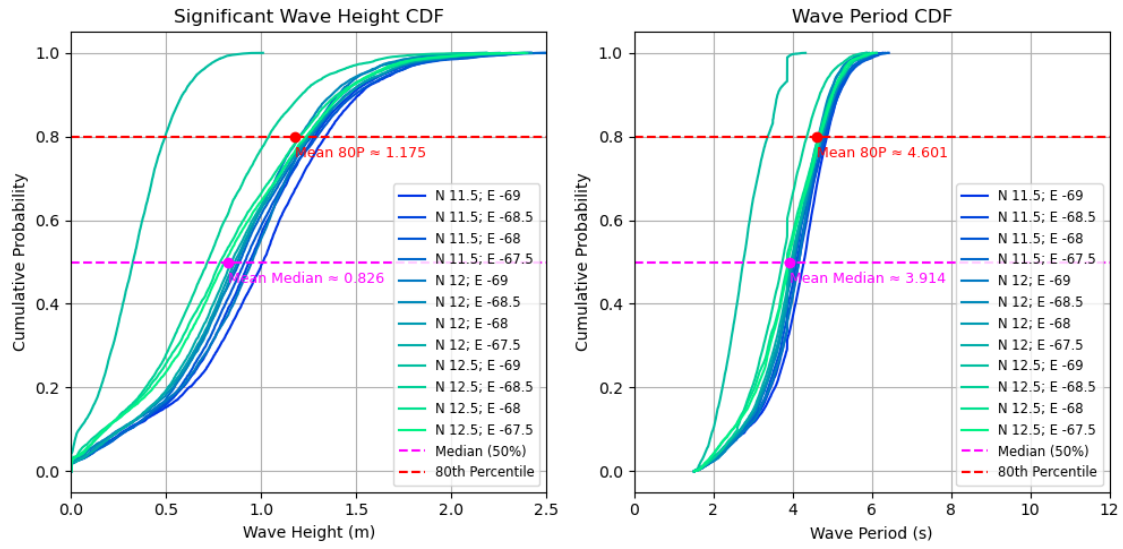
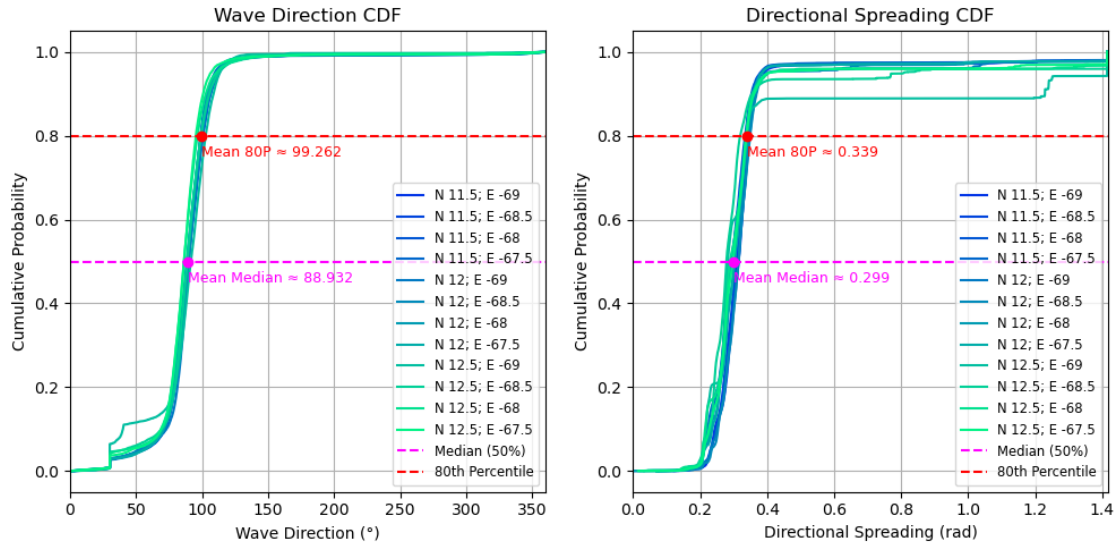
where:

- $\omega$  is the radian frequency [ $\text{rad}^{-1}$ ]
- $d$  is the water depth [ $m$ ]
- $g$  is the gravitational acceleration, which equals  $9.81 \text{ [m/s}^2\text{]}$

## A.2. Wave conditions in the Caribbean Sea

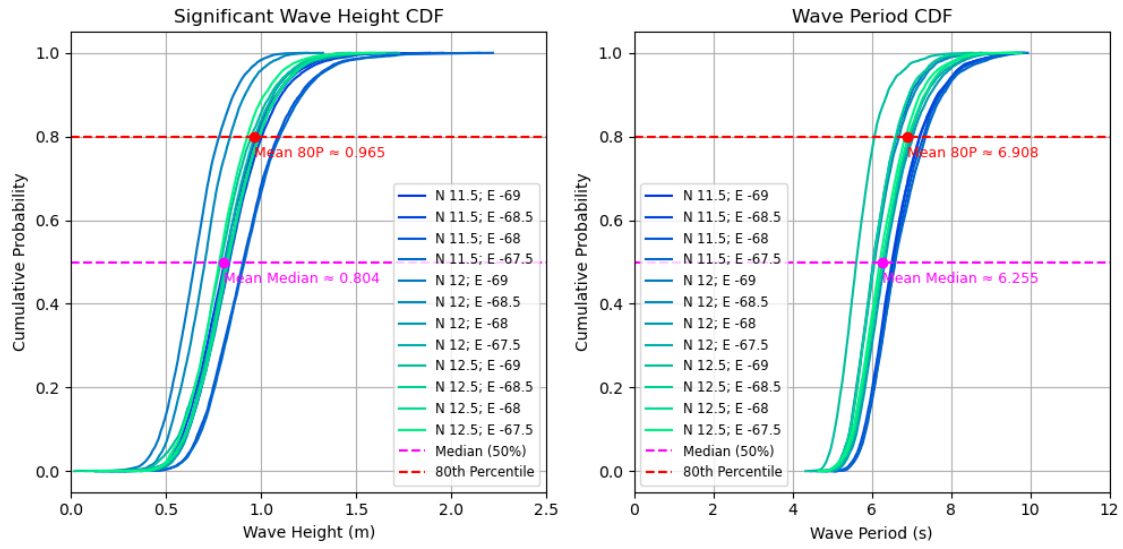
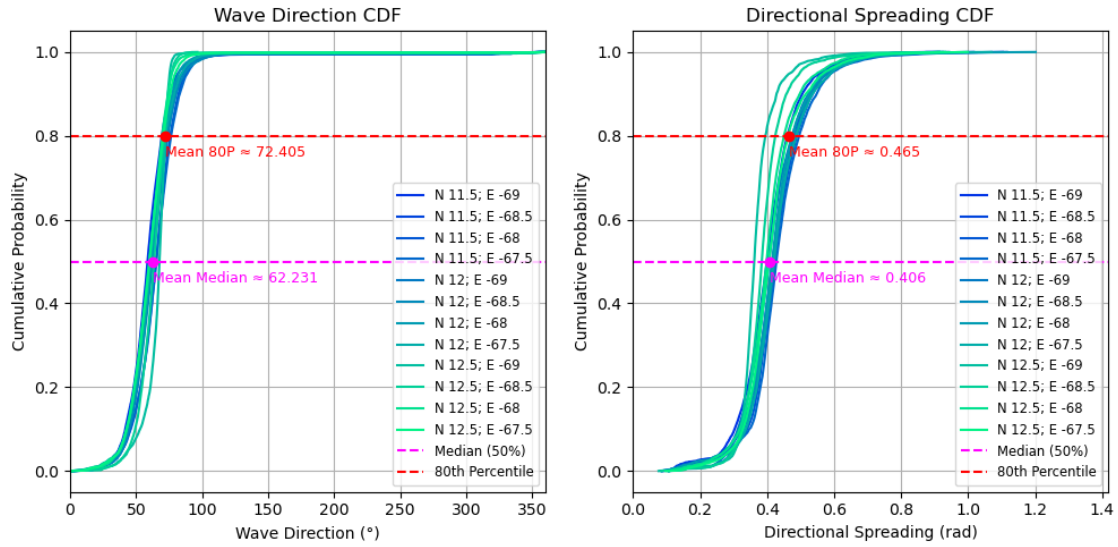
For the analysis of the wave conditions within the Caribbean Sea, the Cumulative Distribution Function of each wave characteristic is plotted. This includes the mean wave period, significant wave height, nautical direction and directional spreading of the wave, presented by EMCWF's ERA5 (ECMWF, 2025). For this analysis, both short-crested wind-generated and swell waves are considered. The coordinates of the coarse modelling domain (see Table 3.1) provide the boundaries of the region considered here. Each measurement location of ERA5 within that domain is presented in the Figures below. The red lines and dots represent the 80<sup>th</sup> percentile, and the pink lines and dots the 50<sup>th</sup> percentile, or in other words, the mean values.

## A.2.1. Short-crested wind-generated waves

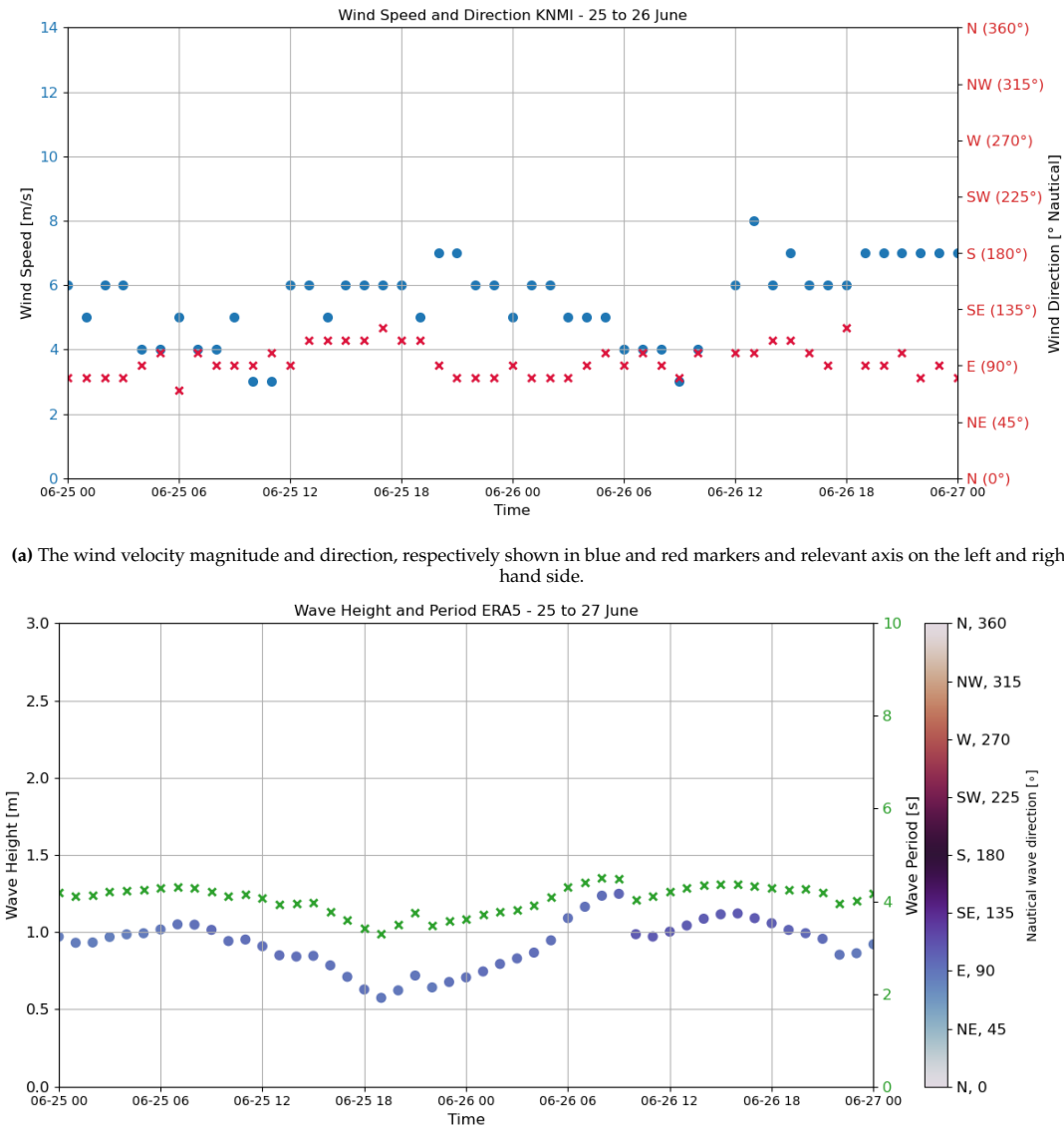
(a) Mean wave period ( $T_m$ ) and significant wave height ( $H_s$ ) for wind-generated short-crested waves within the Caribbean Sea.(b) Mean wave period ( $T_m$ ) and significant wave height ( $H_s$ ) for swell waves within the Caribbean Sea.**Figure A.1:** Wave conditions of the short-crested wind-generated waves observed within the Caribbean Sea based on the ERA5 reanalysis of ECMWF during 2024 (ECMWF, 2025). Each measurement location is presented in a different shade of blue-green.



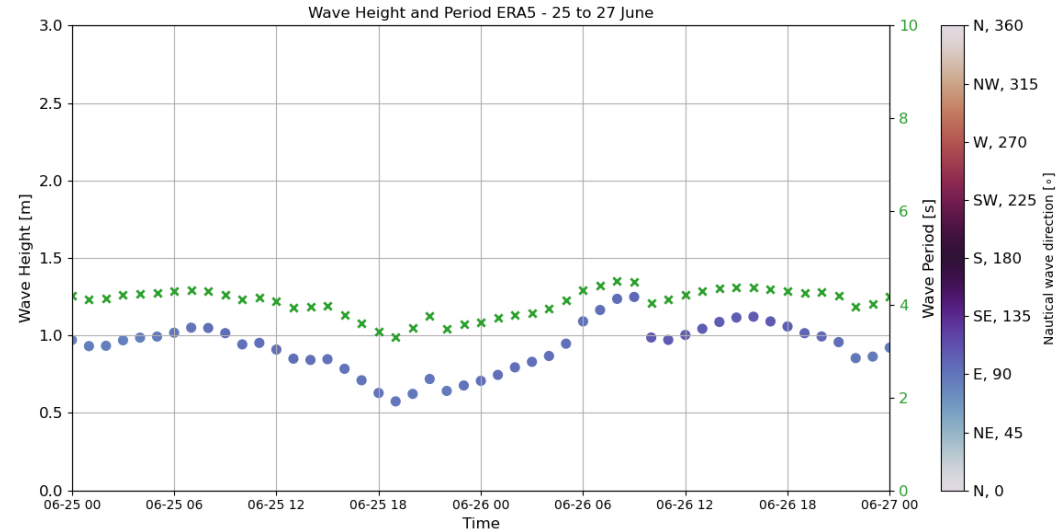
## A.2.2. Swell waves

(a) Mean wave period ( $T_m$ ) and significant wave height ( $H_s$ ) for wind-generated short-crested waves within the Caribbean Sea.(b) Mean wave period ( $T_m$ ) and significant wave height ( $H_s$ ) for swell waves within the Caribbean Sea.**Figure A.2:** Wave conditions of the swell waves observed within the Caribbean Sea based on the ERA5 reanalysis of ECMWF during 2024 (ECMWF, 2025). Each measurement location is presented in a different shade of blue-green.

A.3. Time-varying wind and wave conditions

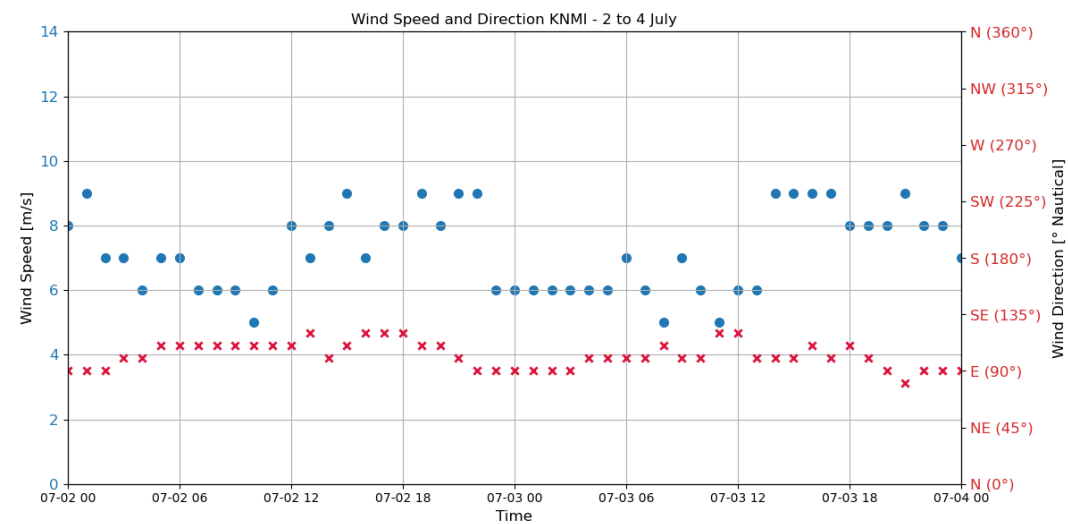


(a) The wind velocity magnitude and direction, respectively shown in blue and red markers and relevant axis on the left and right hand side.

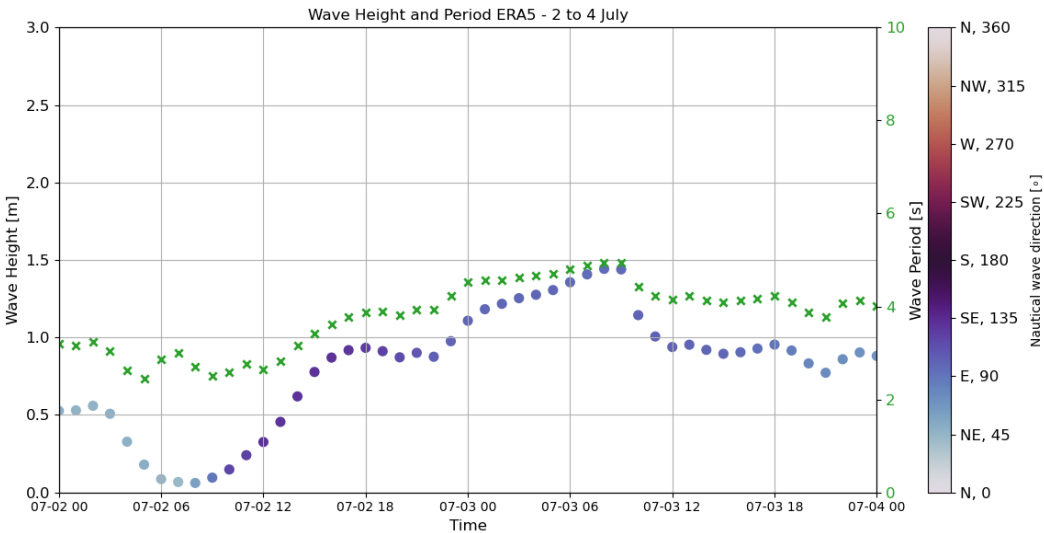


(b) The wave height and period are respectively shown in blueish and green markers. The colour of the wave height is determined by the nautical direction of the wave.

**Figure A.3:** The time-varying wind and wave conditions for the realistic scenario of June 25<sup>th</sup> to 27<sup>th</sup>.

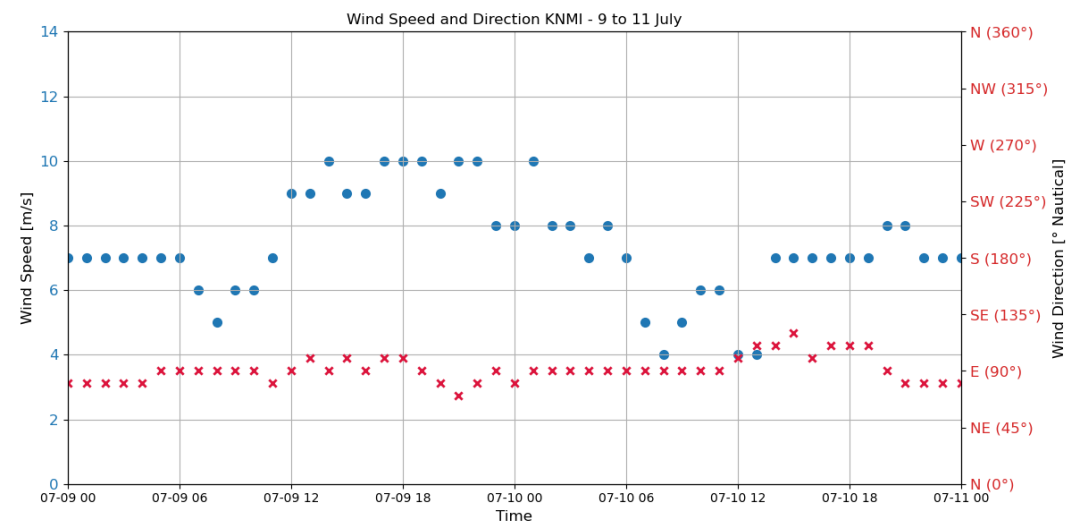


(a) The wind velocity magnitude and direction, respectively shown in blue and red markers and relevant axis on the left and right hand side.

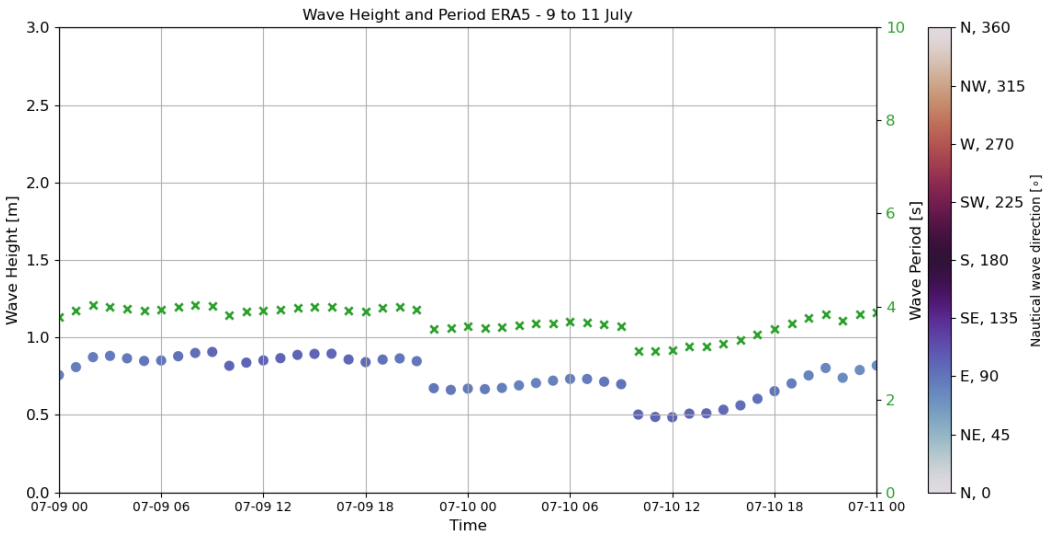


(b) The wave height and period are respectively shown in blueish and green markers. The colour of the wave height is determined by the nautical direction of the wave.

**Figure A.4:** The time-varying wind and wave conditions for the realistic scenario of July 2<sup>nd</sup> to 4<sup>th</sup>.

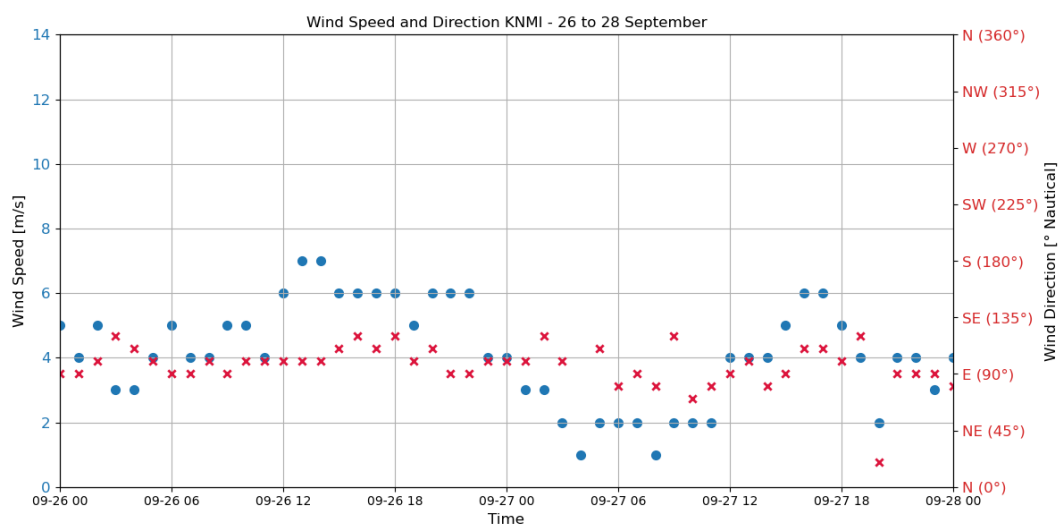


(a) The wind velocity magnitude and direction, respectively shown in blue and red markers and relevant axis on the left and right hand side.

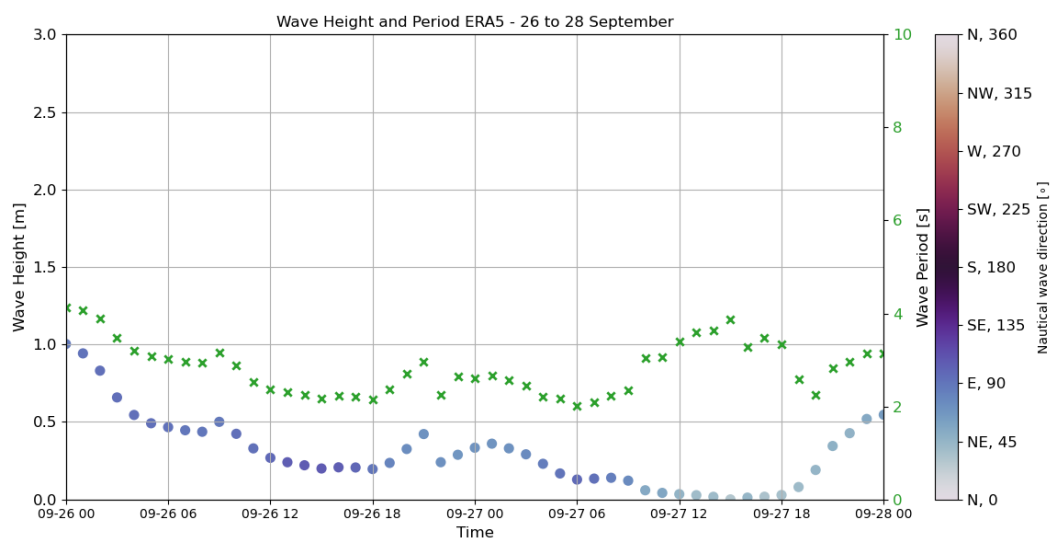


(b) The wave height and period are respectively shown in blueish and green markers. The colour of the wave height is determined by the nautical direction of the wave.

**Figure A.5:** The time-varying wind and wave conditions for the realistic scenario of July 9<sup>th</sup> to 11<sup>th</sup>.

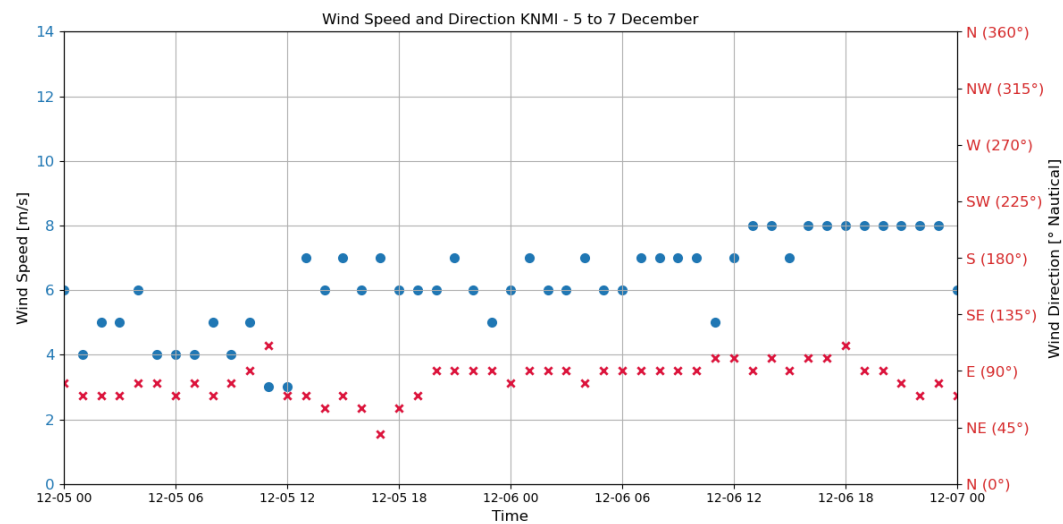


(a) The wind velocity magnitude and direction, respectively shown in blue and red markers and relevant axis on the left and right hand side.

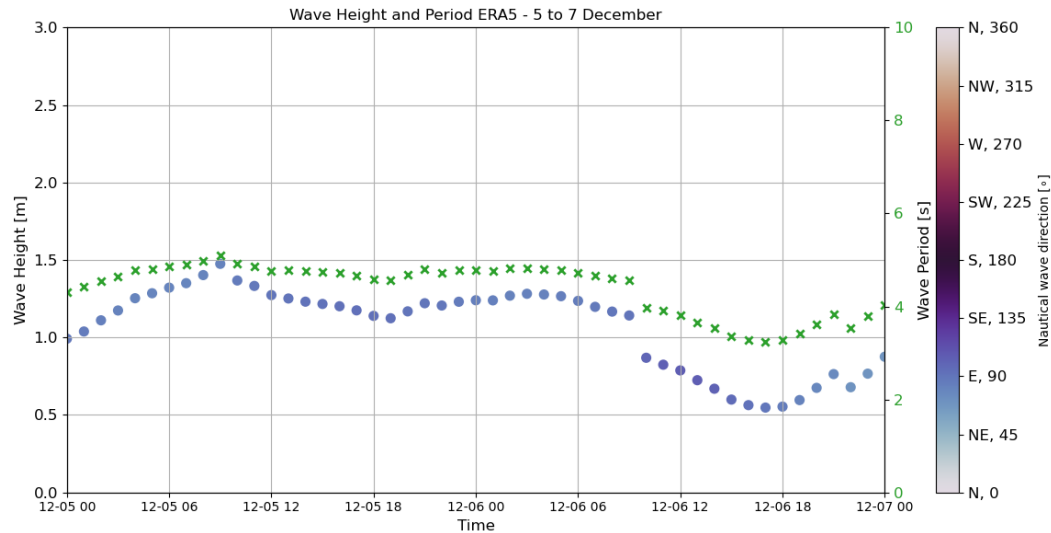


(b) The wave height and period are respectively shown in blueish and green markers. The colour of the wave height is determined by the nautical direction of the wave.

**Figure A.6:** The time-varying wind and wave conditions for the realistic scenario of September 26<sup>th</sup> to 28<sup>th</sup>.



(a) The wind velocity magnitude and direction, respectively shown in blue and red markers and relevant axis on the left and right hand side.



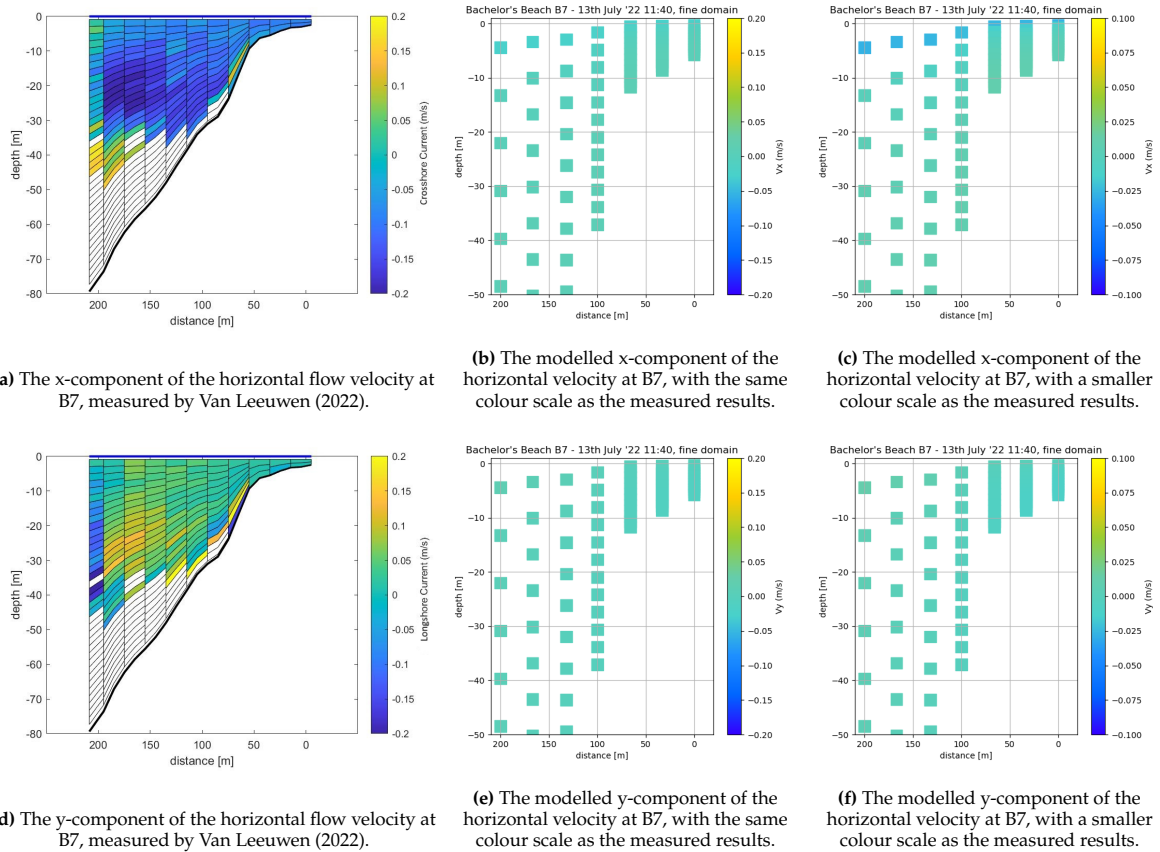
(b) The wave height and period are respectively shown in blueish and green markers. The colour of the wave height is determined by the nautical direction of the wave.

**Figure A.7:** The time-varying wind and wave conditions for the realistic scenario of December 5<sup>th</sup> to 7<sup>th</sup>.

# B

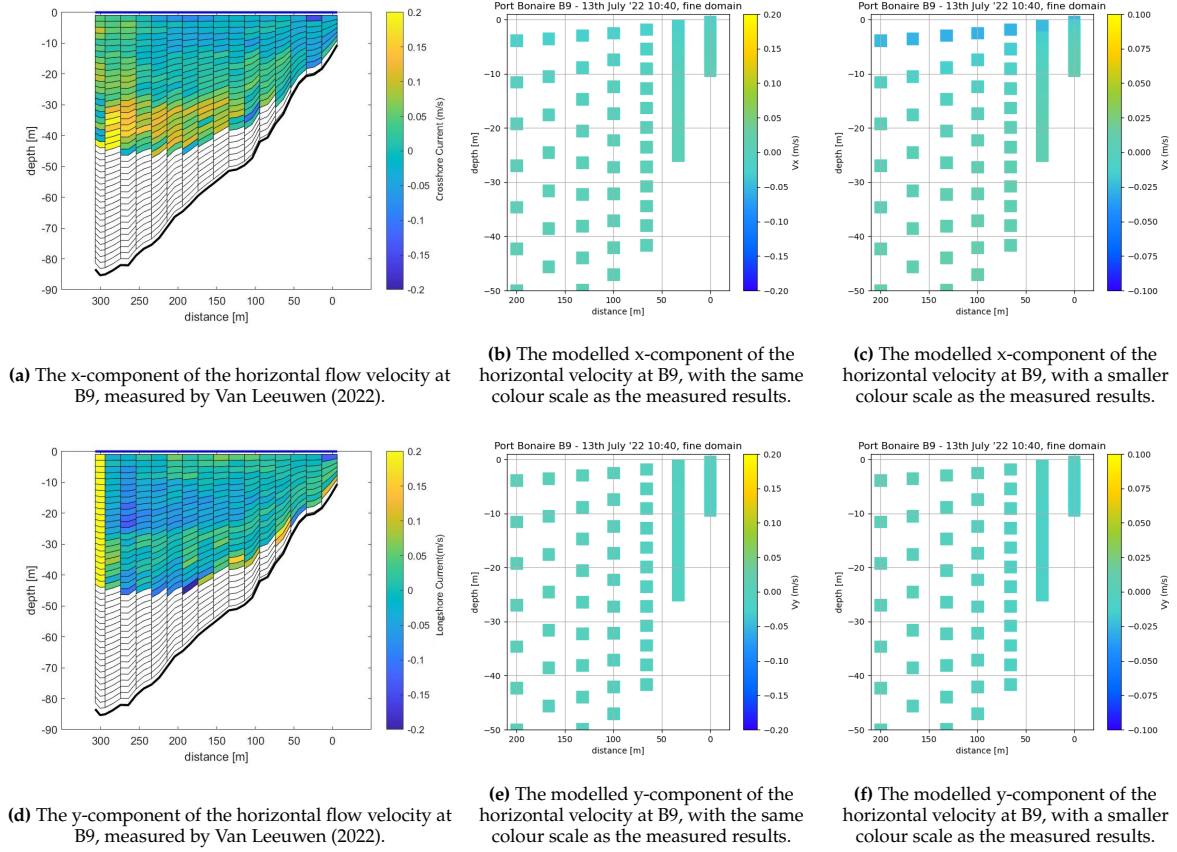
## Validation figures

### B.1. Comparison WUR measurements



**Figure B.1:** The measured (a, d) and modelled (b, c, e, and f) results for the horizontal velocity at Bachelor's Beach, Bonaire, on July 13, 2022, at 11:40 h. The two figures on the right hand side exhibit a smaller colorbar, to better visualize the modelled flow directions.



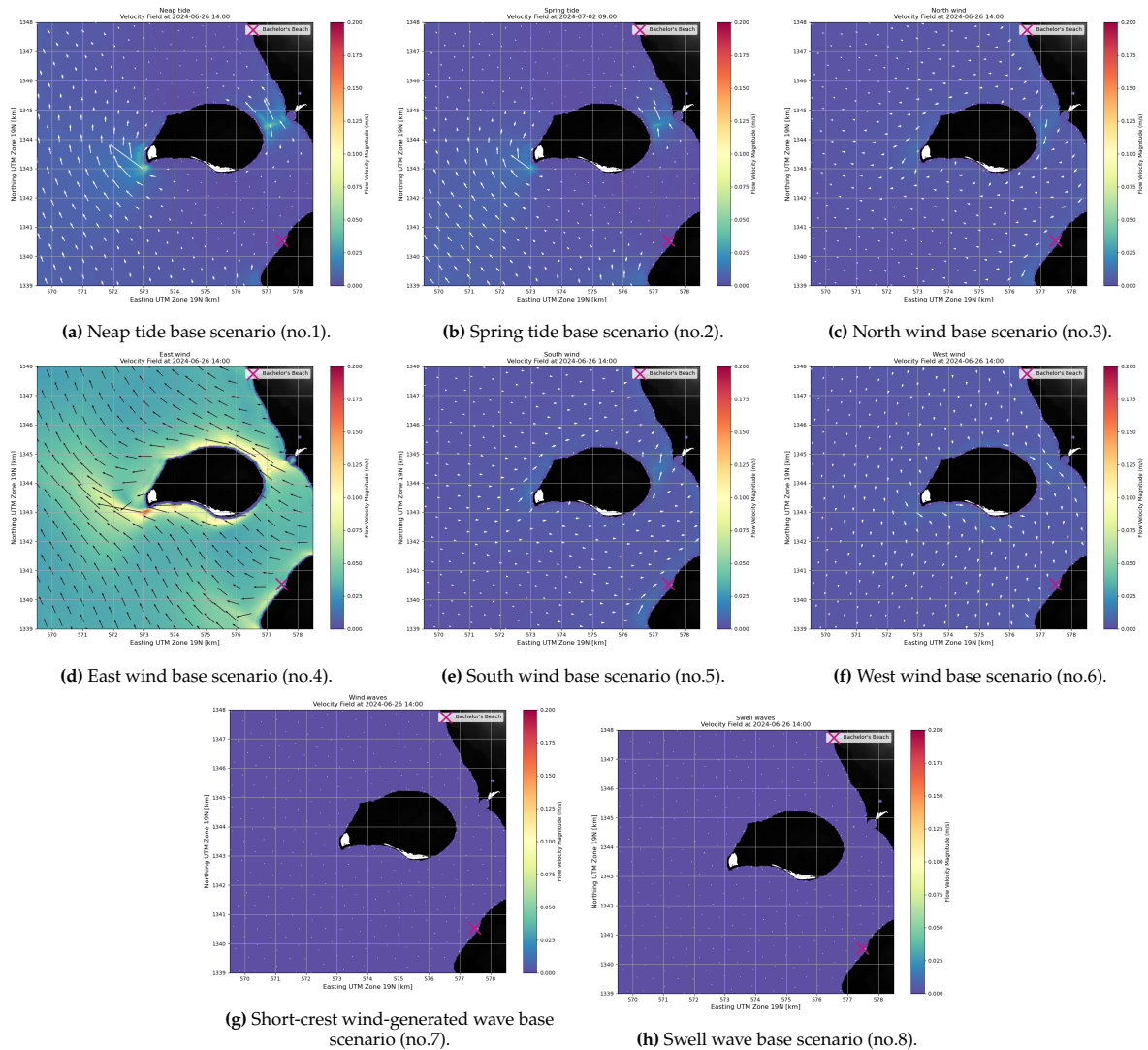


**Figure B.2:** The measured (a, d) and modelled (b, c, e, and f) results for the horizontal velocity at Port Bonaire, Bonaire, on July 13, 2022, at 10:40 h. The two figures on the right hand side exhibit a smaller colorbar, to better visualize the modelled flow directions.

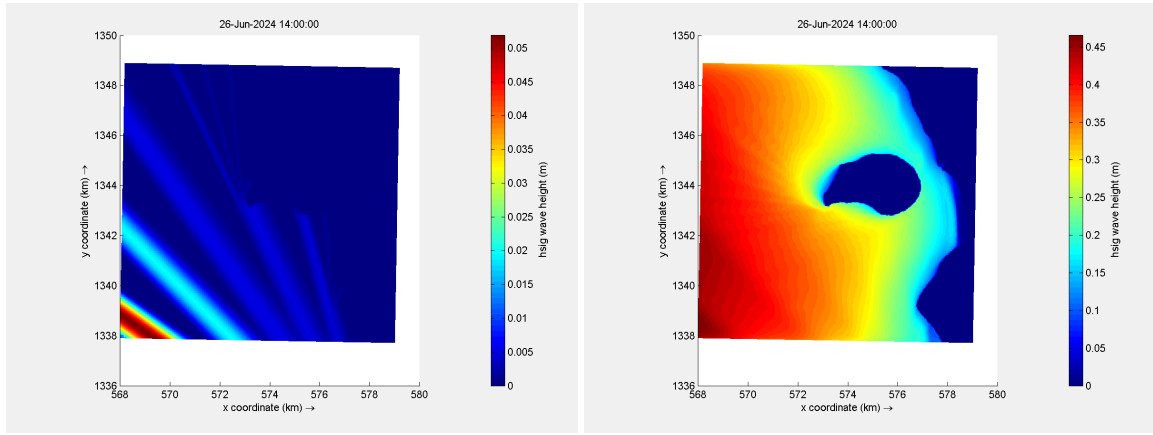
C

# Additional results

## C.1. Horizontal velocities - abiotic driver scenarios



**Figure C.1:** Horizontal flow velocities for the base scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Vector colours change for better readability.



(a) Short-crested wind-generated wave scenario (no.7), with scale going from 0 to 0.05 metres significant wave height. (b) Wind waves and East wind scenario (no.13), with scale going from 0 to 0.45 metres significant wave height.

Figure C.2: Significant wave heights obtained for the scenarios including short-crested wind-generated waves.

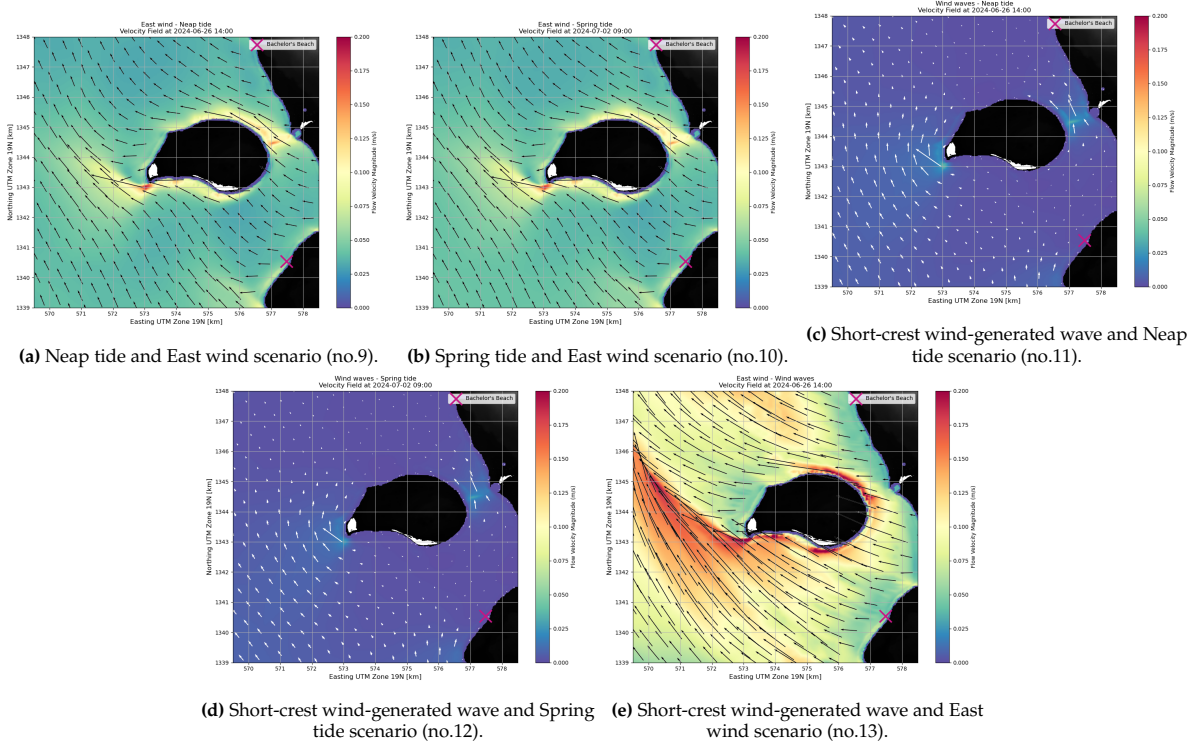
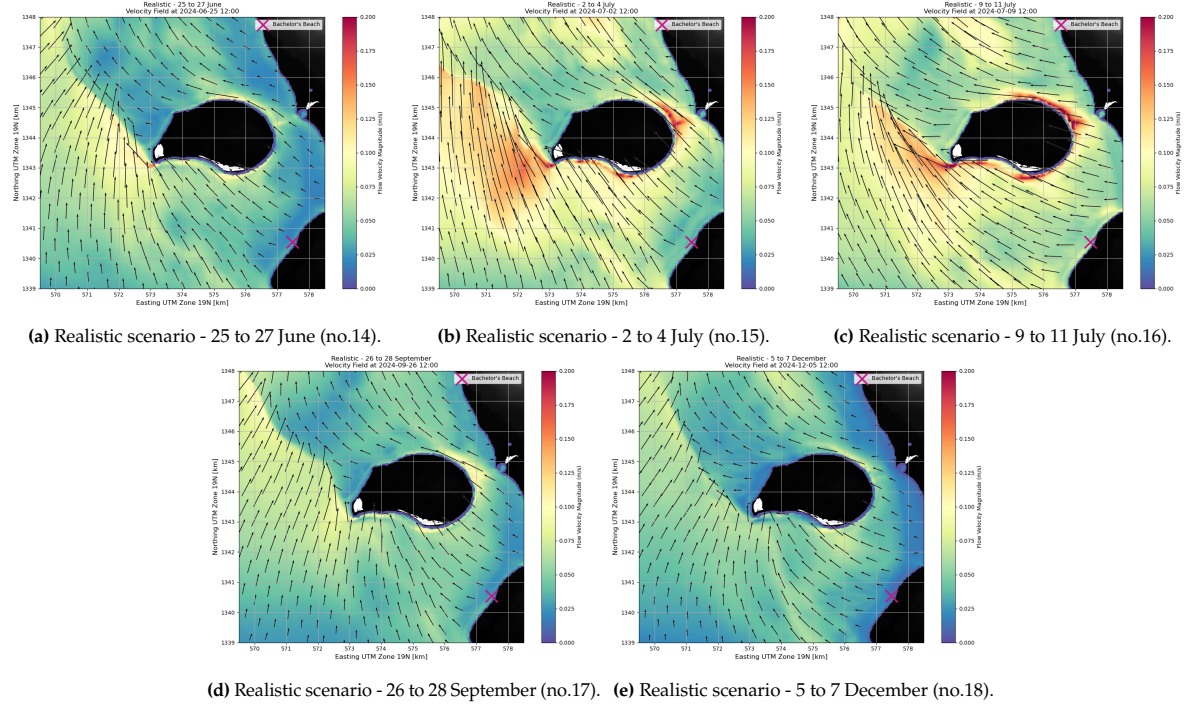
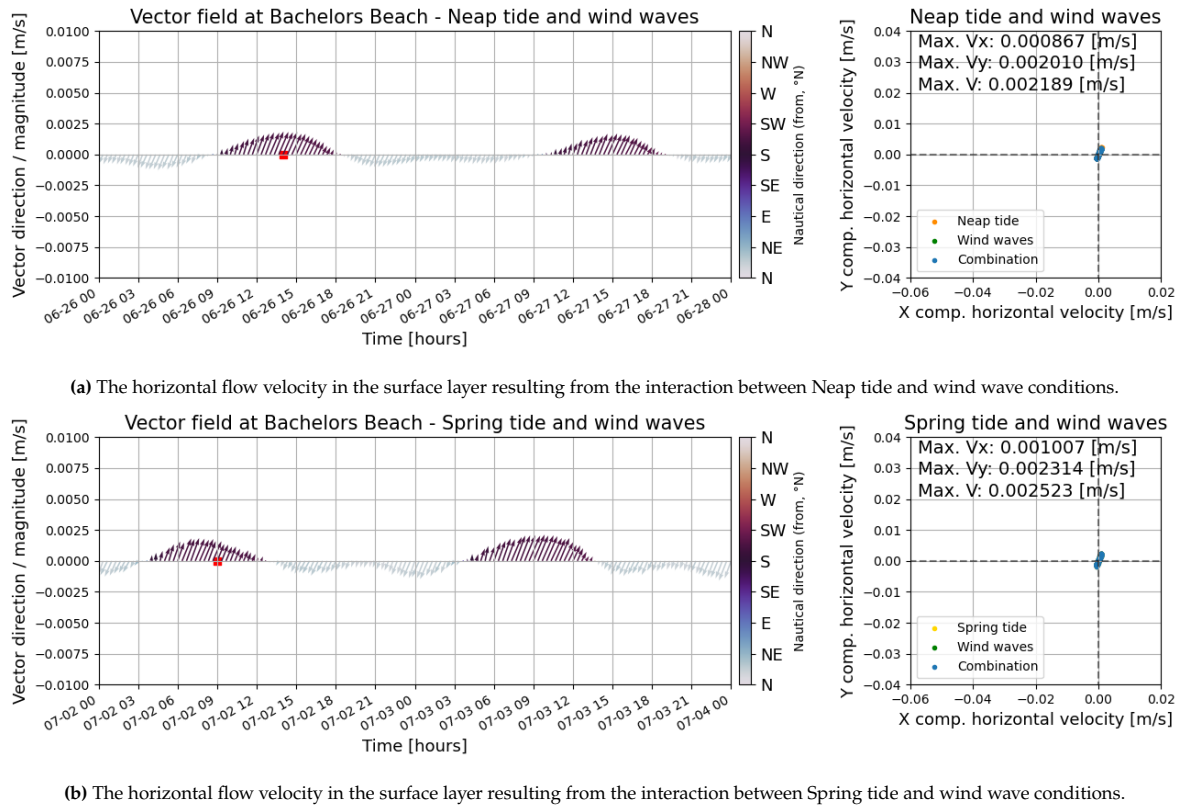


Figure C.3: Horizontal flow velocities for the combination scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario. Vector colours change for better readability.



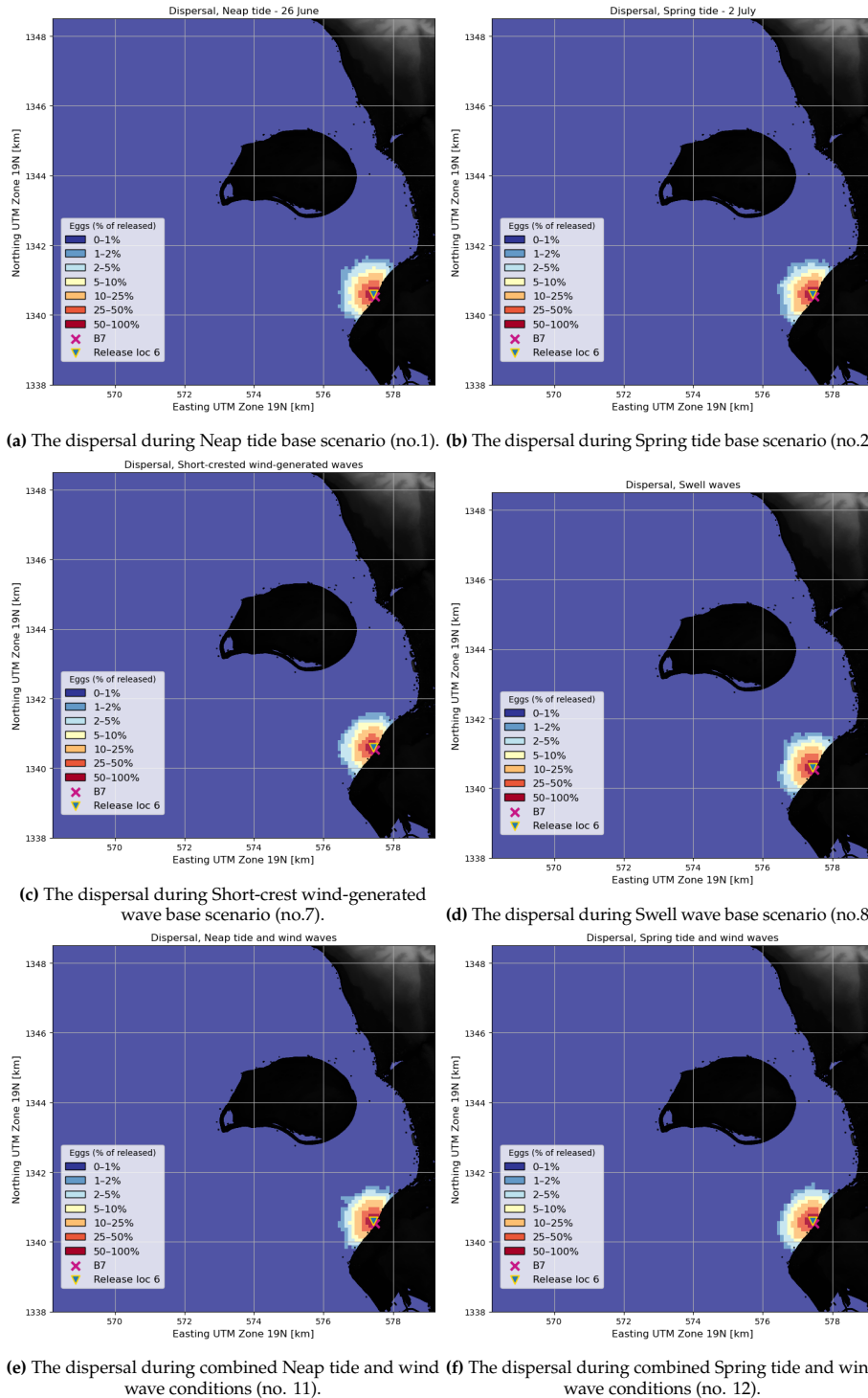
**Figure C.4:** Horizontal flow velocities for the realistic scenarios are shown, with colours indicating magnitude and vectors representing direction from their origin points. Vector lengths are scaled relative to their magnitude, with scales varying by scenario.



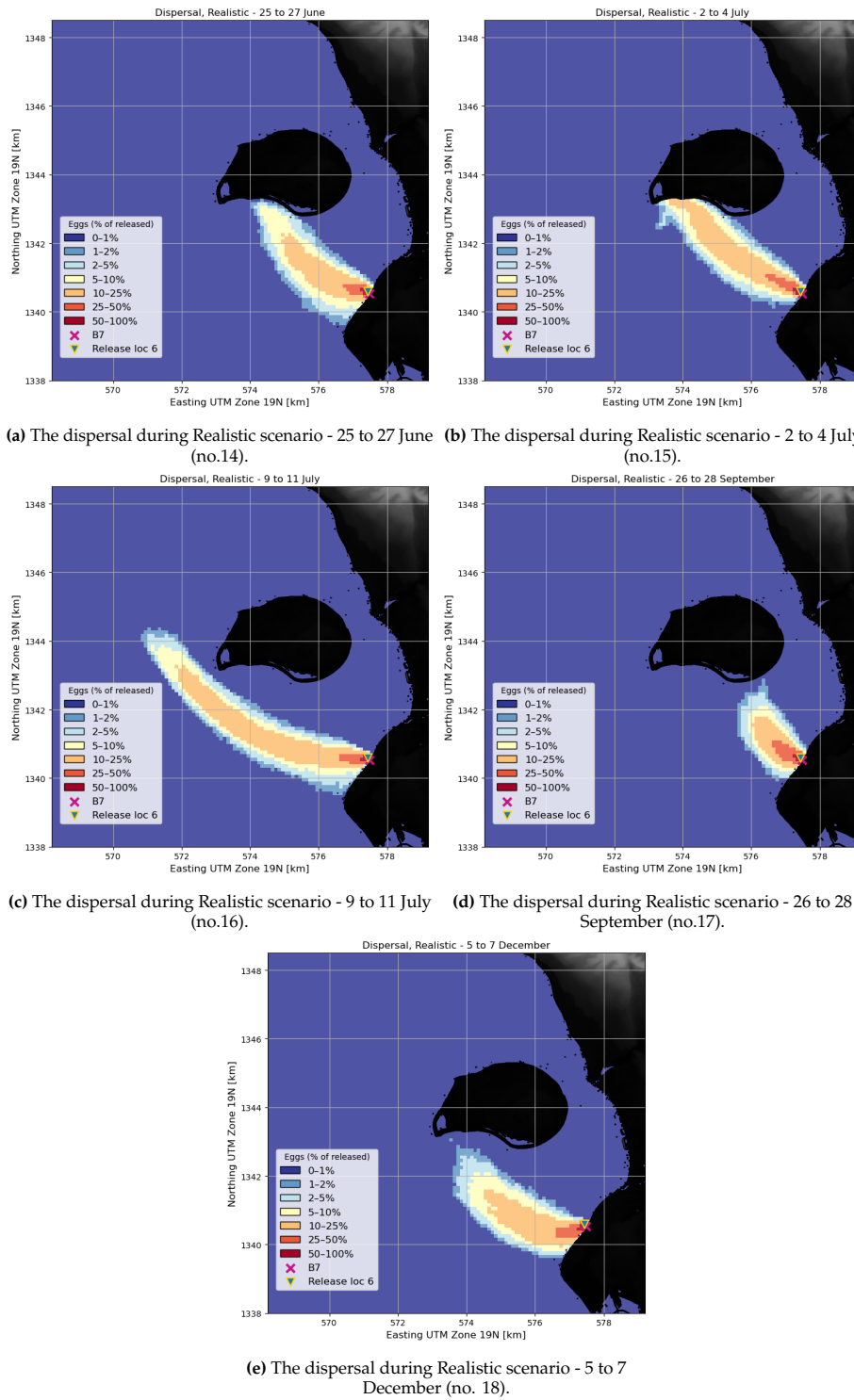
**Figure C.5:** The horizontal flow velocities resulting from the interactions between Neap and Spring tide with wind-generated waves are shown. Flow vectors over time are plotted on the left, with the corresponding x- and y-components displayed on the right to illustrate flow direction.

## C.2. Dispersal - abiotic driver scenarios

The interaction between wave and tidal forcing, seen in Figure C.1, under the studied conditions appears to be minimal. The resulting flow velocities do not differ substantially from those in the respective base tidal scenarios. Due to the relatively low flow velocities induced by the wave scenarios, the tidal forcing remains dominant in their interaction.



**Figure C.6:** The dispersal of released eggs shown as percentages of the released eggs that enter 100 by 100 metre grid cells. Each sub Figure represents a different base or combination scenario.



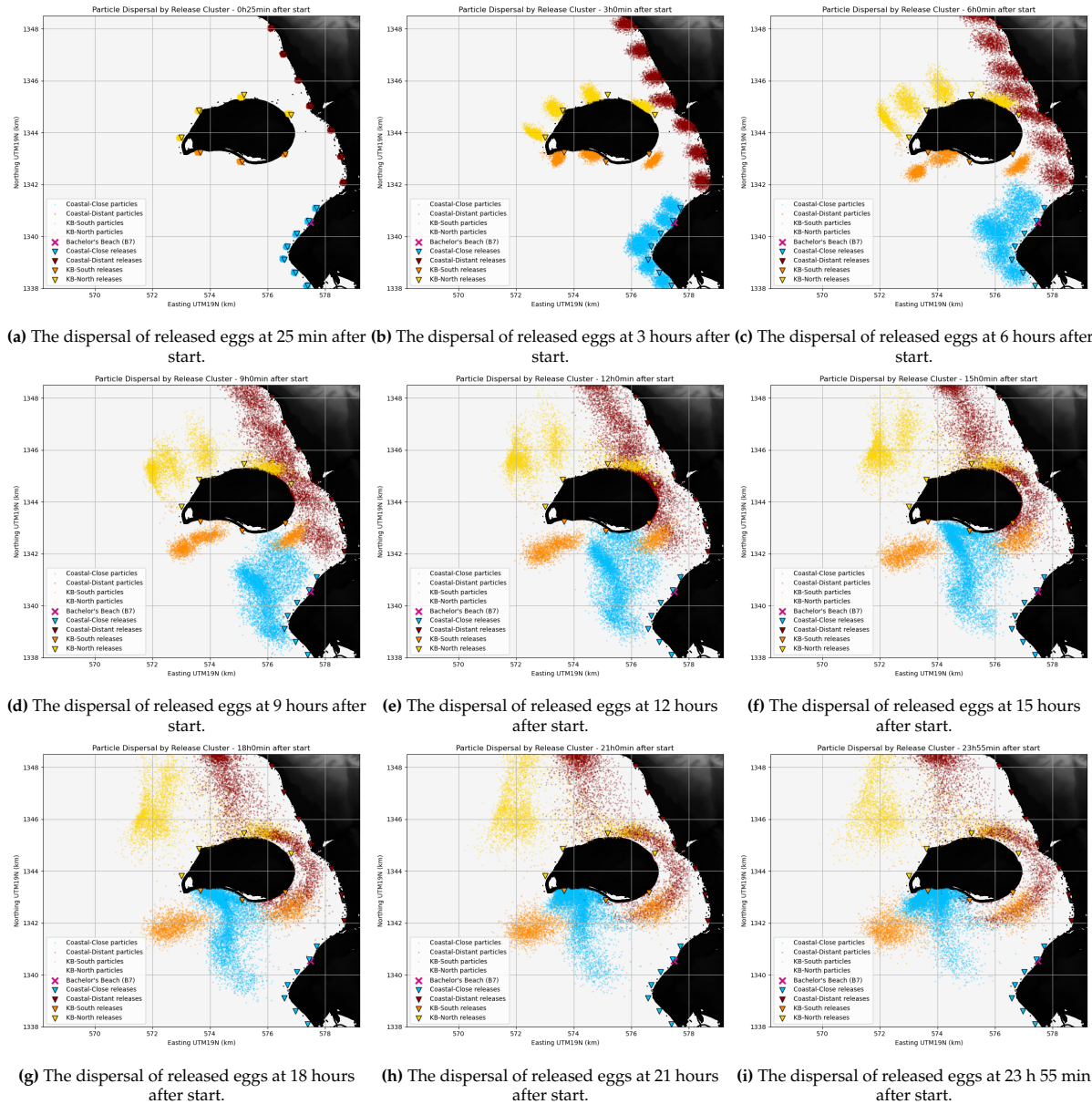
**Figure C.7:** The dispersal of released eggs shown as percentages of the released eggs that enter 100 by 100 metre grid cells. Each sub Figure represents a different realistic scenario.

## C.3. Release conditions

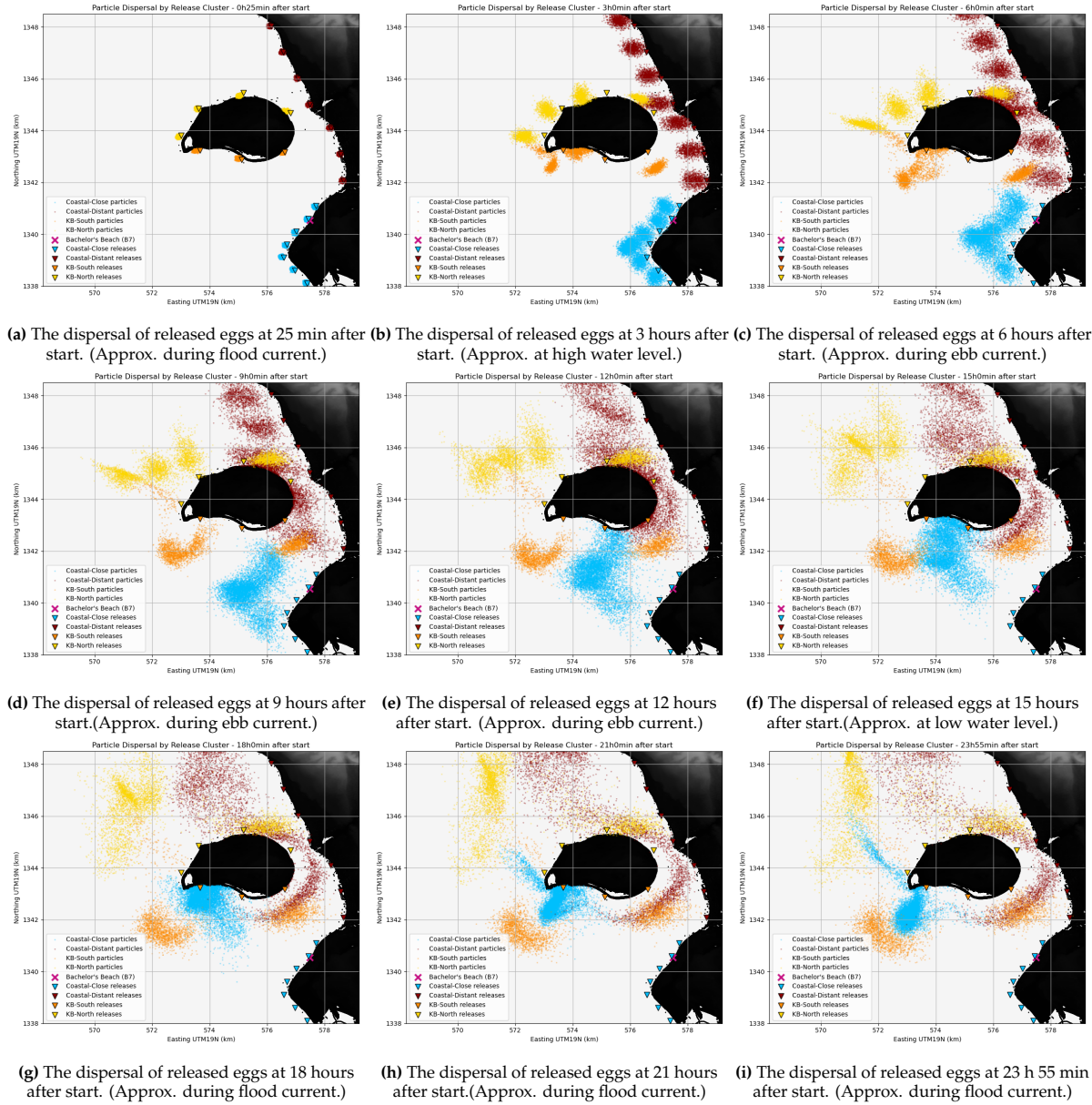
| Abiotic driver | Scenario no.       | Mean path length | Standard deviation | Max. path length |
|----------------|--------------------|------------------|--------------------|------------------|
| Tide           | 1 - Neap           | 9556 [m]         | 292.91 [m]         | 10193 [m]        |
|                | 2 - Spring         | 9527 [m]         | 286.85 [m]         | 10318 [m]        |
| Wind           | 3 - North          | 9541 [m]         | 301.67 [m]         | 10425 [m]        |
|                | 4 - East           | 10095[m]         | 243.89 [m]         | 11053 [m]        |
|                | 5 - South          | 9567 [m]         | 281.00 [m]         | 10402 [m]        |
|                | 6 - West           | 9508 [m]         | 297.76 [m]         | 10380 [m]        |
| Wave           | 7 - Wind-generated | 9545 [m]         | 291.38 [m]         | 10392 [m]        |
|                | 8 - Swell          | 9550 [m]         | 298.44 [m]         | 10280 [m]        |

**Table C.1:** Quantification of the dispersal path lengths of the released eggs for each base scenario.

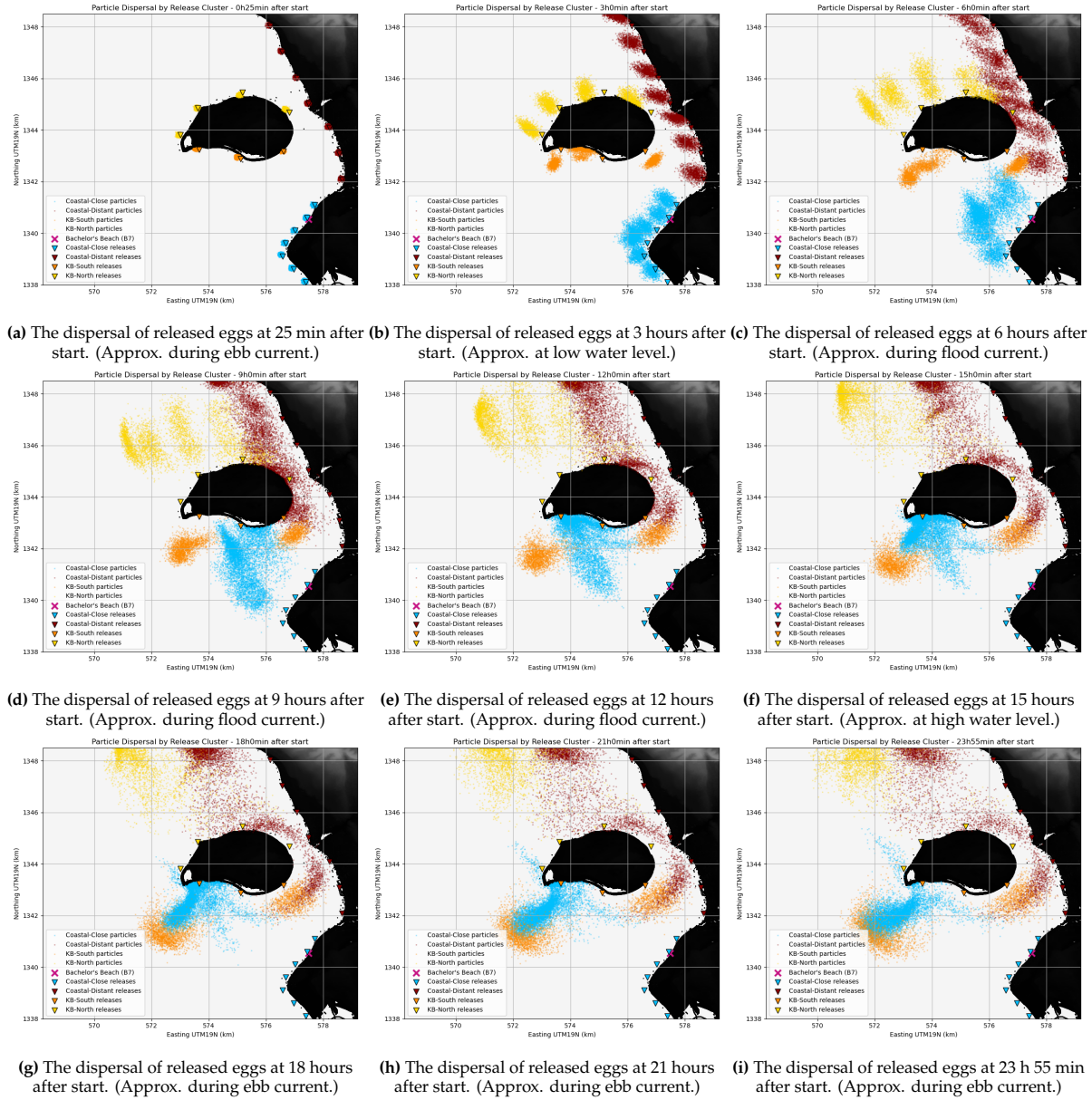




**Figure C.8:** Timestamps of the dispersal simulation during the 25<sup>th</sup> of June, starting at 12:00 (afternoon). Each cluster is given its own colour; Coral-Close is shown in blue, Coral-Distant in dark red and Klein-Bonaire in orange, to visualize the overall dispersal of each cluster.



**Figure C.9:** Timestamps of the dispersal simulation during the 2<sup>nd</sup> of July, starting at 00:00 (midnight) during flood. Each cluster is given its own colour; CC is shown in blue, CD in dark red, KB - South in orange and KB - North in yellow, to visualize the overall dispersal of each cluster.



**Figure C.10:** Timestamps of the dispersal simulation during the 2<sup>nd</sup> of July, starting at 12:00 (afternoon) during ebb. Each cluster is given its own colour; CC is shown in blue, CD in dark red, KB - South in orange and KB - North in yellow, to visualize the overall dispersal of each cluster.