Modelling the effect of twin storms on dune erosion

Applying XBeach to model the dune erosion for single and twin storms constructed using simulated weather data

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Cover Image: Foamy sea washing sandy beach by Amber Janssens on Pexels

Preface

This thesis marks the end of the Master of Science in Civil Engineering (Hydraulic Engineering) at Delft University of Technology. A time which proved to be a wonderful experience both on the social and academical aspect. Thankfully, I had the opportunity to execute my research at HKV lijn in water, where I gained valuable insights into the practical application of academic knowledge. In this preface I would like to express my gratitude to a lot of people that helped and supported me during the past few months.

First of all, I would like to thank the four members of my graduation committee that mentored me during this period. Starting with the chair of my committee, Sierd de Vries; thank you for the enthusiasm, for inviting me to events with other persons in the field and of course for guiding the process. Thank you, Ad Reniers, for the critical and intriguing questions. Your experience and valuable insights helped me to take this study to a higher level. The person I had most contact with, definitely was Jochem Caspers. Thank you for explaining me everything about storms and for the great suggestions you had to improve the model. Last but not least, thank you Carolien Wegman for your endless positivity and for the trust you showed in me.

Although sometimes I think I can, I clearly couldn't have done all of this without the help of my friends and family. Thanks to all the people that made studying in Delft such a beautiful experience. The group projects, practicals and coffee breaks were great fun, but what truly made it unforgettable where all the leisure activities besides studying. Finally, I want to thank my family for believing in me and for always being there for me.

While this thesis has come to an end, a new chapter in life begins. One in which I want to learn even more about the oceans, rivers and storms. So that one day, we're able to harness the power of the ocean to serve our purposes rather than battling against it.

Thomas Nieuwhuis
Delft, November 2023

Abstract

In February 2022, storms Dudley, Eunice and Franklin passed the Netherlands in a time period of five days. When two storms quickly succeed one another, it can be called a twin storm. Storm conditions at sea lead to increased water levels and larger waves. When these waves approach the shore, they can attack the dunes and lead to dune erosion. Therefore, after a storm the dunes are smaller than before the storm. Dune accretion is a much slower process than dune erosion; it can take weeks to months of time for a dune to grow the volume of sand it lost during a storm. If the interval time between two storms is smaller than the time it takes for a dune to gain the same volume of sand it loses during the storm, the second storm can lead to additional impact. So when storms quickly succeed one another, like the storms in February 2022, there is not enough time for the dune to significantly grow in between the storms. Due to additive impact, a twin storm might lead to more damage than a single storm with the same return period. The question raised in this research is:

How does the amount of dune erosion caused by a twin storm compare to the amount of dune erosion due to a single storm that has the same probability of occurrence for storms along the Dutch coast?

To answer this question, the research is divided into two parts. The first part consists of creating representative storm schematisations for single storms and for twin storms using simulated weather data from the European Centre for Medium Range Weather Forecasts (ECMWF). To start with, the storms from the dataset are divided into several clusters. For each cluster the normalised time evolution of wind speed and surge height are derived from all storms within that cluster. This is done using the percentile averaging method. The obtained normalised time evolutions are scaled with the extreme values (wind speed or surge height) that are expected according to a certain return period. The time evolutions of wind speed and surge height are combined with the time evolution of the averaged wind direction and the tidal level. Next, the wave parameters are estimated using wind speed and wind direction. All in all, a storm can be constructed by combining the time evolutions of all parameters.
In part two, the storm schematisations are used to calculate the dune erosion for each defined storm cluster. The dune erosion is modelled using XBeach, which is a model that is developed to simulate the evolution of the dune profile during extreme storms. The dune erosion will be modelled for two locations along the Dutch coast: Hoek van Holland and Nieuwvliet-Groede.

In this research, storms are selected using the peak-over-threshold method. If the wind speed exceeds 20.8 m/s it's considered a storm. In case there are two storms with a time interval between the wind peaks of at least 24 hours and at most 120 hours, it is considered a twin storm.
When applying this definition, it turns out that at Hoek van Holland 25-30% of all storms can be considered a twin storm. At Nieuwvliet-Groede, 15-20% of all storms are twin storms.
For Hoek van Holland almost none of the constructed twin storms (approximately 10%) give more dune erosion than the constructed single storms. At location Nieuwvliet-Groede approximately 30% of the twin storms cause a larger dune erosion volume than the single storms. In most cases where twin storms result in more erosion than a single storm, this effect can be attributed to deviations in the storm schematisations.

For further research it's recommended to investigate how the prediction of the time evolution of the water level can be improved. This is relevant because the dune erosion volume is strongly correlated with the water level. Improving the prediction of the water level can be achieved by discerning key factors such as the governing surge height, tidal phase and tidal height expected during extreme storm events.
Furthermore, it is advised to do more research into the time scales and modelling of dune growth. If the dune growth can be modelled, longer interval periods between twin storms can be investigated. When a larger interval period is chosen, more extreme twin storms might be found. Also, storm groups with interval periods of multiple weeks can be investigated with better predictions of dune growth.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
BOI	Beoordelings- en Ontwerpinstrumentarium
CDF	Cumulative Distribution Function
ECMWF	European Centre for Medium-Range Weather Forecasts
GPD	Generalised Pareto Distribution
JARKUS	JAaRlijkse KUStmetingen
KNMI	Koninklijk Nederlands Meteorologisch Instituut
NAP	Normaal Amsterdams Peil
PDF	Probability Density Function
POT	Peak-Over-Threshold
WAQUA	WAter beweging en water QUAlity modellering
WBI	Wettelijk Beoordelingsinstrumentarium
WTI	Wettelijk Toetsinstrumentarium

Symbols

Symbol	Definition	Unit
g	Gravitational acceleration	[m/s^2]
$H_{1/3}$	Significant wave height	[m]
H_s	Significant wave height	[m]
t	Time	[hours]
$T_{m-1,0}$	Spectral wave period	[s]
T_p	Wave peak period	[s]
U_{10}	Wind speed at a height of 10 meters	[m/s]
u	Wind speed	[m/s]
u_x	Wind speed in x-direction	[m/s]
u_y	Wind speed in y-direction	[m/s]
X	Fetch length	[m]
ϕ	Phase difference	[h]

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Introduction

1.1. Outline

The Dutch coastline has a total length of 353 kilometers of which 254 kilometers consists of dunes. The dunes play an important role in flood protection as for a large part of the coast, they are the primary defense against the sea. The dunes are constantly changing under the influence of wind, waves and currents. During a storm, the wind, waves and currents are stronger than usual, which leads to erosion of the dune. Sand is moved from the dune to the beach. Thus, storms lead to smaller dunes and therefore a reduced protection against storm surges and large waves. After a storm, calm weather conditions return. During calm weather conditions, the dunes gradually grow over time. Moderate waves and wind transport sand from the beach to the dunes. It can take multiple years or decades before the sand volume that was lost during a storm, is transported back to the dune system (Houser et al., 2015; Morton, Paine, and Gibeaut, 1994).

Storms are caused by the interaction between low pressure and high pressure systems in the atmosphere. Air tends to move from a high pressure to a low pressure area. In a low pressure area, the air rises and clouds are formed. These low pressure systems, also known as depressions, have the potential to generate storms. The atmospheric conditions that lead to storms often stay intact for multiple days and therefore large storms occasionally occur in clusters (KNMI, 1999). This means that multiple storms can happen in only a few days' time. When two storms happen in short succession, this is called a twin storm.

1.2. Problem statement

In 1954, two storms reached the Netherlands within a time span of two days. The KNMI started an investigation into the frequency of storms and the probability of having multiple storms in a short time span. It was found that, the chances of having a second storm two or three days later, is higher than when assuming a random distribution of storms over the year (Rijkoort and Hemelrijk, 1957). This is confirmed by van den Brink (2017) who showed that extreme event clustering can happen for storms with an inter-arrival time of 5 days or less. Geerse (2006) endorses the phenomenon of twin storms and found that up to 20% of storms might be considered a twin storm.

In literature, sequential storms are often referred to as storm groups. Storm groups are defined as a multiple of storms within a certain time span. When the time between two storms is short, dune accretion in the period between the two storms will be minimal. Thus, the second storm can have an additive impact (Birkemeier, Nicholls, and Lee, 1999). Furthermore, research shows that storm groups give more erosion than single storms with a similar return period (Ferreira, 2005).

Summarising, it has been identified that twin storms occur on the North Sea and research at multiple beaches has shown that twin storms can cause more damage to the dunes than (similar) single storms do. However, it is not known how often twin storms occur at the Dutch coast and how dune erosion due to twin storms relates to dune erosion induced by single storms.

1.3. Background

The intention of this section is to give background information on several topics that are discussed in this report. The topics can be divided into three categories: storm characteristics, storm groups and dune erosion. The following paragraphs focus on each of the categories.

1.3.1. Storm characteristics

Storm is defined as an atmospheric disturbance that leads to strong winds, possibly combined with precipitation and thunder. When storm occurs above sea, the wind generates waves. Besides waves, the wind can also lead to storm surge. Storm surge is a rise of the water level due to strong winds associated with a storm. When the wind blows to the shore, the water levels along the coast are higher than during normal conditions. The wind, waves and storm surge are important parameters that characterise a storm. In figure 1.1 a visual overview is given of these storm parameters.

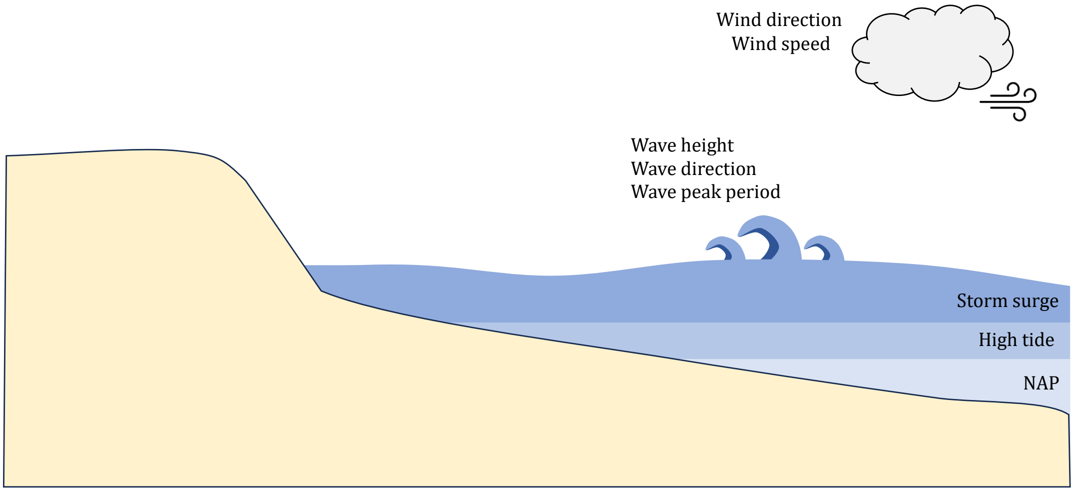


Figure 1.1: Graphical overview of storm parameters

1.3.2. Storm groups

When multiple storms happen in a short period, this is often called a storm group or storm cluster. In this section, some more background on storm groups is given. First, the definition of storm groups is studied. Thereafter, the meteorological cause of storm groups is identified.

Definition

There is not one clear definition for a storm group as characteristics are site specific. Though, there are three distinct features that all definitions have in common (Eichentopf, Karunarathna, and Alsina, 2019). These are elaborated upon below.

- Storm selection parameter
  A distinction should be made between storms and normal weather conditions. Often, this is done with the peak-over-threshold method (Goda, 1988). For the peak-over-threshold method, first a parameter should be chosen that is used for the storm selection. There are several parameters like wind speed, wave height and surge level that can be good indicators for storm conditions. Once a parameter is chosen, the extreme values for this parameter are selected from a time series. The extreme values indicate the peak of a storm.
- Parameter threshold value
  When the parameter that will be used for the peak-over-threshold method is decided, a threshold value should be chosen. If there is a value above the threshold during the time series, that point is considered (part of) a storm. An additional criterion that can be used states that the storm should have a minimum duration above the threshold.

- Interval period
  For storms to be considered a group, they should be spaced within a certain time period. A maximum allowable interval period should be defined in which the storms occur. This interval period often is chosen based on the time scale of dune growth.

  If the interval time between two storms is smaller than the time it takes for a dune to gain the same volume of sand it loses during the storm, the second storm can lead to additional impact. Therefore, the interval should be chosen smaller than the time it takes for a dune to gain the same volume of sand it loses during the storm.

  Besides a maximum period between the storms, also a minimum period can be established to distinct one large storm from two smaller storms.

Figure 1.2 gives an example of such a storm definition. It shows the time evolution of the wind speed during the storm. Also the interval period and the threshold are indicated.

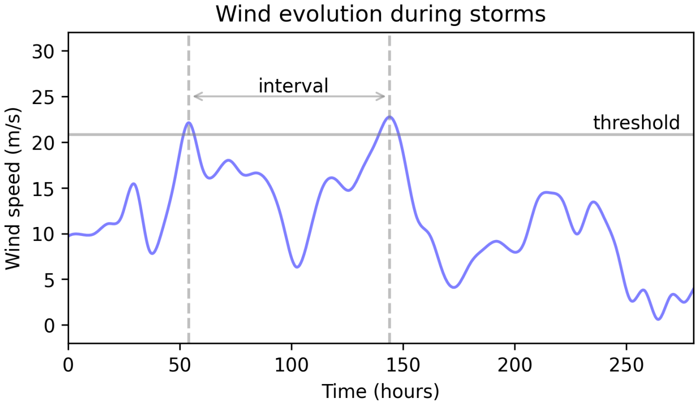


Figure 1.2: Illustrative example of a twin storm

Meteorological cause
Although a detailed description of the meteorological cause of storm clustering falls outside the scope of this work, a short introduction on the topic is given. According to research, there are three main reasons why storm clustering occurs (Priestley et al., 2020).

- By chance
  Even if storms happen in a random manner, there's always a chance of two storms occurring quickly after one another.
- Modulation of atmospheric patterns
  Several large-scale atmospheric patterns have an influence on the weather in Europe. For example, the North Atlantic Oscillation (NOA) is known to have an influence on the occurrence and magnitude of storms over Europe (Mailier et al., 2006).
- Dependence of successive cyclones
  So called cyclone families can occur when a secondary cyclone is formed either upstream (due to secondary cyclogenesis) or downstream (associated with Rossby wave breaking) of a primary cyclone (Pinto et al., 2014).

1.3.3. Dune erosion

Dune erosion is the process where sand gets eroded from the dune and is deposited on the beach. Waves, wind and currents can lead to erosion of the dunes. In the following paragraphs, more explanation on dune erosion is given. First, different storm impact regimes are elaborated followed by the nearshore processes influencing dune erosion. Lastly, the beach profile before and after the storm is considered.

Storm impact regime

The amount of dune erosion during a storm is largely dependent upon the magnitude of a certain storm. To better predict the consequences of a storm, Sallenger (2000) divided storms into four regimes with different impact. These comprise the swash regime, collision regime, overwash regime and inundation regime. The swash regime means that the water level remains below the dune foot. When the water level gets higher than the dune foot but remains below the dune crest, it is called the collision regime. When the water starts washing over the dune it reached the overwash regime. When the area behind the dune gets flooded it is defined the inundation regime. A visual overview is given in figure 1.3. In this research the focus is on the collision regime.

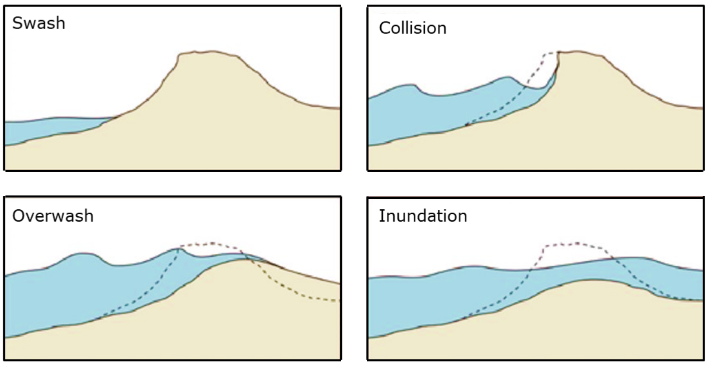


Figure 1.3: Storm impact regimes as defined by Sallenger (Sallenger, 2000) [*figure from (Hallin et al., 2019)]*

Nearshore processes

Dune erosion is influenced by several processes that correlate to the waves and wind. In the collision regime there are four nearshore processes that drive dune erosion (van Rijn, 2009). In this paragraph, all of these components are explained shortly.

- Wave impact
  Dune erosion is proportional to the force in the uprushing waves. During this uprush, the waves exert high shear stresses on the beach. The waves get decelerated over a small distance and thereafter collide with the dune face (Fisher, Overton, and Chisholm, 1986). This exerts a force on the dune face that causes the volume change.
  The wave impact is largely dependent upon the profile of the beach. The forces exerted by the waves are smaller for a wide and shallow beach than for a beach with a steep slope. During a storm, the beach gets wider and therefore dune erosion decreases over the course of the storm.
- Turbulence
  Close to the dunes a lot of turbulence is generated by breaking waves, rollers and reflected waves. The increased turbulence brings sediment into suspension. Experiments showed that the highest sediment concentrations are observed in the region close to the dune (van Thiel de Vries et al., 2008). The suspended sediment can be moved further offshore by currents.
- Long waves
  The short waves start breaking when they come close to the shore. The long waves, on the other hand, do not break but keep increasing when they approach the dunes (van Thiel de Vries et al., 2008). As the long waves can propagate all the way to the dune toe, a lot of wave energy is present at the dune toe due to these long waves. The long waves are able to remove sand from the dunes.
- Avalanching
  If the lower part of the dune is eroded, the higher part may slide down as it is not stable anymore. When the upper part slides down, the dunes become smaller. Also, now the currents and waves are able to pick up the sand.
  Palmsten (2011) found that the moisture content plays a large role in avalanching of the dune. Due to the water the weight and thereby the load increases. Also, the angle of repose decreases for wet slopes. Lastly, vegetation can be of importance for the strength of the dune. Vegetation is able to hold together the soil and thereby strengthens the dune.

Beach profile
During a storm, the water level rises above the dune foot. As the waves and currents can reach the dune, sand will be removed from the dune. Close to the dune there is a large undertow that ensures transport of sediment offshore. Further offshore, the sediment transport capacity decreases again and the sand is deposited on the beach. Therefore the beach get larger during the storm. The larger beach is better at dissipating energy and the wave energy that reaches the dune decreases. After the storm, the dune features a sharp incline, while the beach has expanded in width. An overview of the pre- and post-storm beach profile can be seen in figure 1.4.

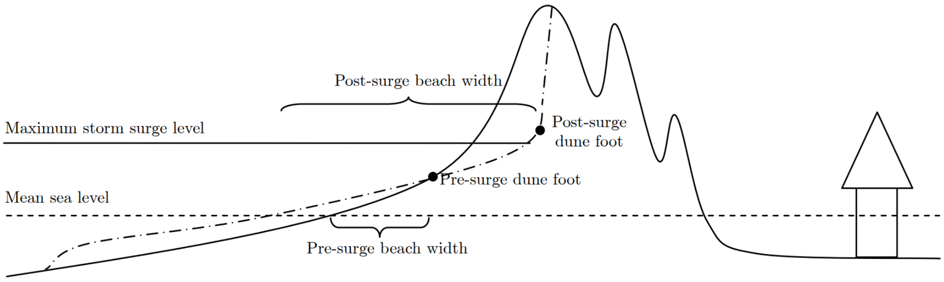


Figure 1.4: Pre- and post-surge beach profile (van Thiel de Vries, 2009)

1.4. Scope

1.4.1. Twin storm definition

To select twin storms from the data, it should first be decided what is considered a twin storm. In this paragraph, a definition is set up that is used in the remainder of this report. First a parameter is chosen that is used to select storms. For this parameter, a threshold value is set above which storms are selected. Lastly, the interval time between two storms is defined.

Storm parameter
In the majority of studies concerning dune erosion caused by storm groups, wave height serves as the parameter for the selection of storms from the dataset. In this research, the wind speed is used to select storms from the data. In essence this is similar to a certain wave height as the wave height is largely correlated with the wind speed. There are two reasons to choose wind speed over wave height. First, besides wave height the surge level is important for dune erosion too. The surge level is correlated with wind speed, wind direction and sea level pressure and not directly to the wave height (Timmerman, 1977). Second, the storm definition most commonly used in the Netherlands is that by the KNMI in which a storm is defined based on a certain wind speed.

Storm threshold
As the threshold for selection of storms, the definition from the KNMI is used. This states that a period is considered a storm if the mean hourly wind speed is above 20.8 m/s. This is closely related to the Beaufort wind scale in which a period is considered storm if the 10 minute average is above 20.8 m/s (KNMI, 2023b).

Interval period
The interval period between the peaks is the time that passes between the first and second peak. There are two important objectives with this choice. First, the minimum interval should be chosen such that the second peak belongs to a second storm and not to one very long storm. On the other hand, the maximum interval should be chosen such that dune growth between the two storms is minimal as only in that case the second storm can give additional impact.

The minimum interval duration is chosen as 1 day (24 hours). This is done because both storm duration and storm surge duration at Hoek van Holland are approximately 48 hours (Tijssen and Diermanse, 2010). it is assumed that this duration is similar for all locations along the Dutch coast. Also, it is assumed that the peak is halfway the storm so if the second peak falls at least 24 hours later, it can be considered a different storm.

For the maximum interval duration, a period of five days is taken based on two considerations. The first consideration takes into account the time scales of storm clustering. Following a research into recurrence intervals for closing of the Maeslant barrier, it was found that extreme storms tend to cluster for time intervals of 5 days (van den Brink and de Goederen, 2017). Secondly, the interval duration should be chosen such that dune growth in between the storms is minimal. A duration of five days is much smaller than the time scale of dune growth which can take up to multiple months (Houser et al., 2015; Morton, Paine, and Gibeaut, 1994). Therefore, a duration of five days appears to be a good choice.

1.4.2. Location

In this report, two locations at the Dutch coast are considered. These are referred to as Hoek van Holland and Nieuwvliet-Groede. In figure 1.5 it is shown where both locations can be found. Hoek van Holland is located North-East from Nieuwvliet-Groede.

(a) The Netherlands

(b) Hoek van Holland

(c) Nieuwvliet-Groede

Figure 1.5: Locations

1.4.3. Climate change

Although climate change can have effects on both the frequency of occurrence of storms and the extreme conditions during storms (KNMI, 2023a), it is not considered within this research. The data used within this research is based on simulations forced with weather conditions from 1981 until 2020. Therefore, extrapolation is needed to find extreme values for the future climate. This falls outside the scope of this work. A short notion on the effect of climate change can be found in section 6.1.

1.5. Relevance

For coastal safety, the Dutch government and waterboards are interested in very extreme storms that rarely occur. As measurements go back only about a hundred years, it is hard to predict the extreme storms that only occur, on average, once in a 1000 or 10000 years. To do this, often extrapolation of measurements is used. As extrapolation comes with large uncertainties, decision-making is hard. Nowadays, there are new ways of predicting extreme storms. The European Centre for Medium-Range Weather forecasts (ECMWF) has a dataset that consists of 8000 years of simulated weather based on current climate. Using this large dataset, more extreme storms can be predicted that can be expected to be found on longer timescales.

1.6. Research question

The goal of this research is to investigate whether twin storms can cause more erosion than single storms. The research question to be answered is formulated:

How does the amount of dune erosion caused by a twin storm compare to the amount of dune erosion due to a single storm that has the same probability of occurrence for storms along the Dutch coast?

To come up with an answer to this question, the research will be subdivided into two parts. First the occurrence of twin storms and their characteristics will be defined. To accomplish this, the following subquestions are answered:

1. What is the frequency of occurrence of single- and twin storms?
2. How can single- and twin storms be categorised according to their characteristics?
3. How can the storm-evolution of single- and twin storms be schematised?

The second part of this research considers the effect of single- and twin storms on dune erosion. A comparison will be made between dune erosion induced by single- and twin storms in order to look into potential additional effects of twin storms. The subquestion belonging to this part of the research are given below.

4. How can the dune erosion volumes of single- and twin storms be estimated?

1.7. Structure

This report is structured into five distinct parts: introduction, methodology, results, discussion and conclusion. The methodology will start with the data collection and thereafter four sections follow that are ordered according to the structure of the research objectives. First, the selection of storms will be explained, followed by defining the storm characteristics. Thereafter the schematising of storms is explained and lastly the modelling of dune erosion is elaborated. The results will be structured following the research questions, so: storm selection, storm characteristics, storm schematisation and dune erosion. The discussion in chapter 4 gives more background and explanation of the results. Finally chapters 5 and 6 consist of the conclusion and recommendations.

2

Methodology

In this chapter, the methodology of this research is described. First the data sources that are used in this research are described. The methodological approach, that is described after, is divided into four parts. The first part consists of selecting the single- and twin storms from the dataset. Thereafter, storm characteristics are defined and the storms are divided into clusters. The third part describes how the storms are schematised and lastly, the modelling of dune erosion is elaborated.

2.1. Data collection

This section will describe the different datasets used within this research. First, an overview will be given of locations used. Thereafter, the datasets used for respectively wind data, water level data, wave data and bottom profiles will be described.

2.1.1. Data locations

In figure 2.1 the locations are shown where data is retrieved from. The locations Europlatform and Jarkus 11244 belong to Hoek van Holland. The locations Vlakte van de Raan, Scheur West and Jarkus 778 belong to Nieuwvliet-Groede. In the remainder of this report, these locations will be referred to frequently.

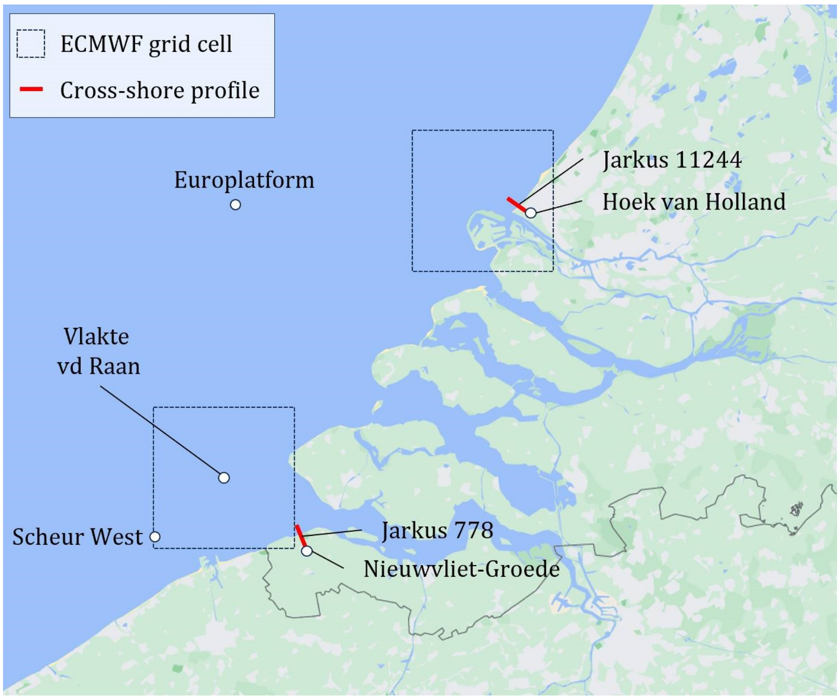


Figure 2.1: Overview of data-locations

2.1.2. ECMWF

The European Centre for Medium-Range Weather Forecasts (ECMWF) makes long term (7 months) weather predictions. This is done to incorporate the effect of large scale climate variations that can have periods of several months. Current weather models only have predictive skills for periods up to two weeks. For longer periods, uncertainty increases and outcomes vary largely. It is impossible to predict the weather conditions for the coming months but by using ensemble forecasting it is possible to say something about the possible range of weather conditions for the coming months. Ensemble forecasting is the principle of doing multiple simulations and changing the initial conditions slightly. By varying the initial conditions, a range of different outcomes is generated. Although this doesn't give a perfect prediction for the long term weather, it does show the variation of possible outcomes. A visual representation is given in figure 2.2.

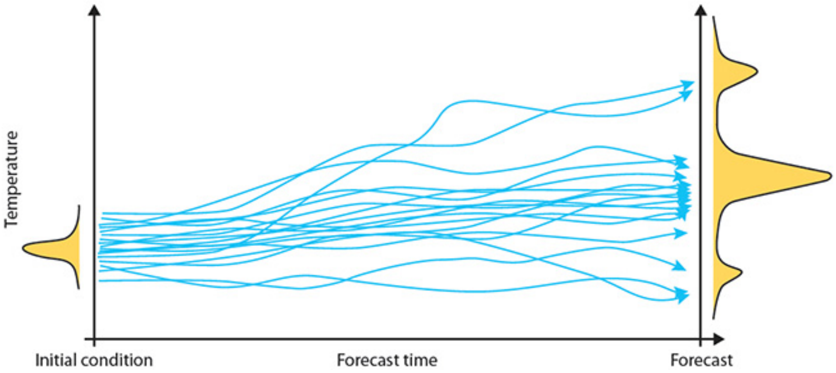


Figure 2.2: Ensemble prediction system as used by the ECMWF (Grönquist et al., 2019)

From November 2011 and on, each month an ensemble of predictions is made for the upcoming seven months. For the period 1981 - 2011, hindcasts are made to calibrate the system. The fifty forecasts within the ensemble are dependent during the first month but thereafter they are independent from each other. Therefore, when the first month is removed from all the predictions, we can obtain a large amount of independent predictions with a duration of six months. These can be combined into one large dataset with a duration of about 8000 years. The data consists of wind speed, wind direction and air pressure with spacial resolution 30x30 km and values every 6 hours. Research has shown that discontinuities in the dataset are limited and the dataset can be well used to predict extreme weather conditions (van den Brink, 2020).

Wind speed from wind stress

The wind data from the ECMWF dataset consists of wind speed, wind direction and wind stress. The wind speeds obtained from the storms are smaller than expected according to the WBI-statistics. To prevent underestimation of the wind speeds, the wind can be calculated from the wind stress. The wind stress can be converted to wind speeds using a Charnock relation with a value of 0.020 (Geerse et al., 2022).

Spline interpolation wind speeds

The wind speed and wind direction time series of the ECMWF has an interval time of six hours. The corresponding water level data is available every 10 minutes. To match the time interval of both datasets, the wind speed is extended to 10-minute values by using (cubic) spline interpolation (Geerse et al., 2022). This spline interpolation is done before the peak-over-threshold analysis as the spline interpolation might lead to new maxima in the wind time series.

2.1.3. WAQUA

The ECMWF model provides meteorological data. The meteorological data is used to compute the water level in the North Sea. This is done using the WAQUA Dutch Continental Shelf Model (Lynch and Davies, 1995). Input for the WAQUA model consists of the sea level pressure and the 10m-wind. The 10m-wind is computed from the wind stress. The tide is defined at the boundaries of the grid and penetrates into the domain (van den Brink, 2020).

2.1.4. WTI-2011

Both the ECMWF and WAQUA model do not compute wave parameters. Therefore, the wave parameters are determined using relations that correlate the wind speed and wind direction to wave parameters. The relations used are described in the Wettelijk Toetsinstrumentarium (WTI) 2011 (Stijnen and Kallen, 2010). The relations are derived for the locations Europlatform and Scheur West. As Vlakte van de Raan and Scheur West are located at a similar depth and at equal distance from the coast, the expected wave heights at these locations are assumed similar (Coosen et al., 2006).

2.1.5. JARKUS

To calculate the dune erosion, measurements of the cross shore bottom profile are required. This research will focus on the Dutch coast and therefore representative bottom profiles of the Dutch coast are used. The bottom profiles used are extracted from the JARKUS dataset by Rijkswaterstaat. The JARKUS dataset consists of yearly measurements of the Dutch coast approximately every 250 meters. The Jarkus profiles extracted from the dataset are the 2021 profiles of Jarkus raai 778 and Jarkus raai 11244.

2.2. Storm selection

In this section it is described how storms are selected from the dataset. First, the peak-over-threshold method is explained. Thereafter, it is explained how twin storms are selected and finally it is explained how the data is stored.

2.2.1. Peak-over-threshold method

To select storms from the dataset, the peak-over-threshold method is used. The Generalised Pareto Distribution (GPD) is fitted to the exceedances above the threshold. The distribution has a shape (k) and scale (α) parameter. When the threshold is chosen large enough, the observations can be considered Poisson distributed. With the threshold value written as ξ, The cumulative distribution function of the GPD can be written as:

$$F(x) = 1 - [1 - \frac{k}{\alpha}(x - \xi)]^{(1/k)} \tag{2.1}$$

In case the shape factor is taken as 0, the distribution is equal to the exponential distribution:

$$F(x) = 1 - \text{exp}[-\frac{(x - \xi)}{\alpha}] \tag{2.2}$$

Within this method the exceedances are considered independent. Therefore, a minimum time interval between consecutive peaks should be used to make sure each value belongs to one storm (Palutikof et al., 1999).

Storm criterion

After selection of all extreme peaks, it is checked whether the hourly mean speed around the peak is at least 20.8 m/s to satisfy the KNMI storm criterion. In case the criterion is not satisfied, the storm is not taken into account.

2.2.2. Selecting twin storms

The twin storms can be selected by comparing the duration between consecutive peak values. If the wind peaks of two storms have at least 24 hours and at most 120 hours in between, the storms are labeled a twin storm.

The ECMWF-dataset also contains cases where after the twin storm another peak can be found at least 24 hours later and at most 120 hours later. These storms with more than two peaks above the threshold are not considered in this research. Those storms are excluded as their time evolution is different than that of twin storms.

2.2.3. Time window of storms

For all storms, a certain duration before and after the peaks is stored. For single storms, a period of 36 hours before and 36 hours after the wind peak is stored. For the twin storms, the data is stored from 36 hours before the first wind peak up to 36 hours after the second wind peak.

2.3. Storm characteristics

In this section, storm characteristics are introduced that are used for the analysis of storms. In the last section, clustering of storms is explained.

2.3.1. Introducing characteristics

In this subsection, the characteristics will be introduced that are used in the further analysis of the storms. These characteristics are used for selecting storms and schematisation purposes. First, the definition of the water level and surge is elaborated. Subsequently, the characteristics will be introduced first for single storms and thereafter the characteristics of twin storms will be elaborated.

Storm surge

During a storm, water levels are higher due to surge. In this report, the name surge refers to the height that remains when subtracting the tidal level from the water level. Figure 2.3 shows the water level, which can be divided into surge level and tidal level.

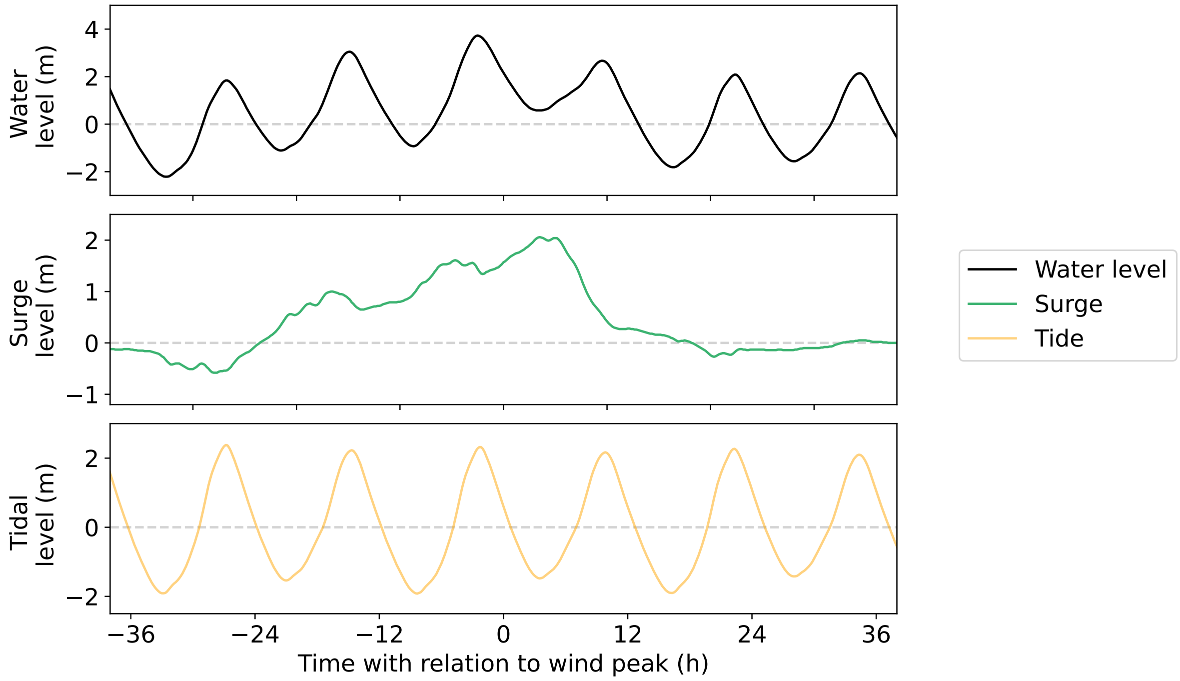


Figure 2.3: Illustrative example showing how water level is composed of surge- and tidal level

Single storms

The characteristics introduced here are all related to the wind, tide and surge during a storm. Below, a list is given of all parameters and explanations. Figure 2.4 gives a visual overview of the characteristics.

u : Maximum wind speed [m/s] during storm
r : Wind direction [degrees] at time of maximum wind speed

s : Maximum surge height [m] in a window 24 hours before and 24 hours after the maximum wind speed of storm (the window in which the surge is found is shown in grey)

ϕ_s : Phase [h] between the peak of the wind and peak of the surge of the storm
ϕ_t : Phase [h] between the peak of the surge and the nearest high tide peak. The tide peak is selected by choosing the maximum value in the period 6.167 hours before and 6.167 hours after the surge peak (the search window is indicated in grey)

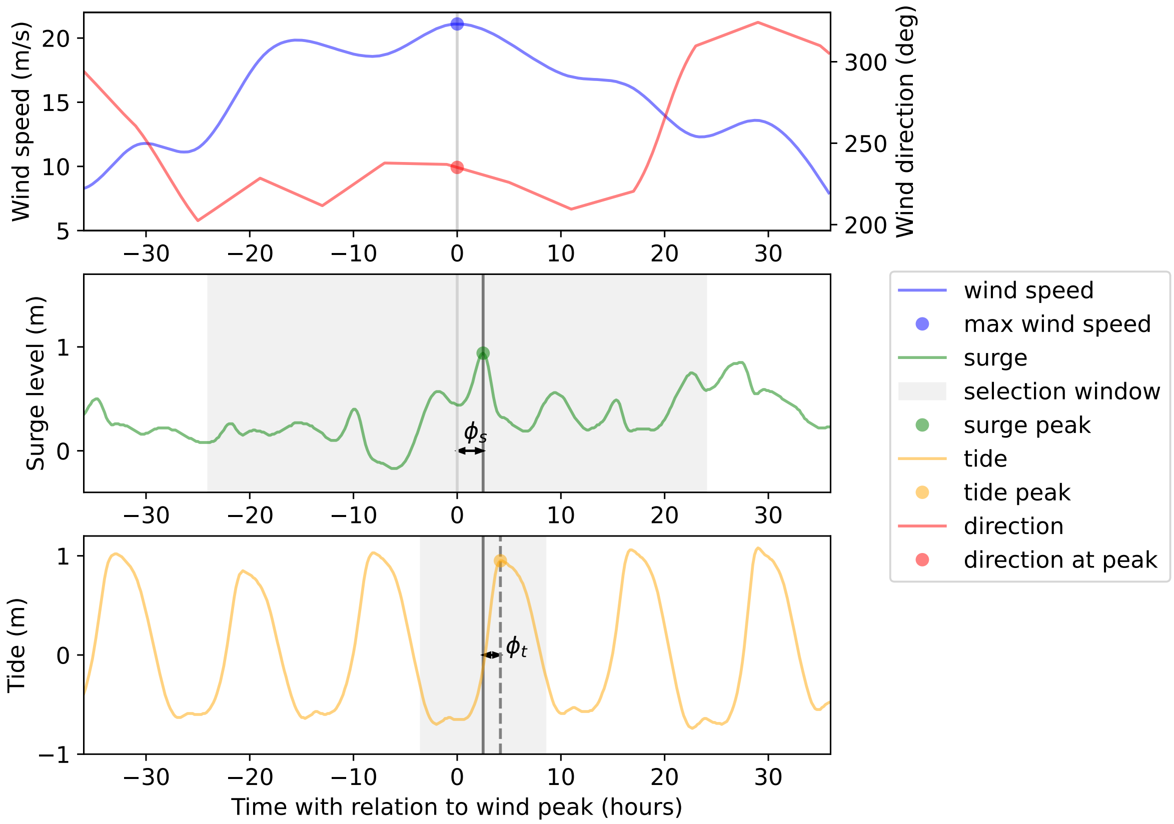


Figure 2.4: Graphical overview of storm characteristics for a single storm

Twin storms

The twin storm characteristics are selected in the same way as for single storms. Instead there are now two peaks rather than one, all parameters get two values; one for the first storm and one for the second storm. Furthermore, two time-characteristics are added: the time interval between the wind peaks and the time interval between the surge peaks. The list of all characteristics of twin storms is given below. A visual representation of the added time-characteristics is given in figure 2.5.

(Storm 1 refers to the first storm in time, storm 2 is the second storm.)

u_1 : Maximum wind speed [m/s] of storm 1
u_2 : Maximum wind speed [m/s] of storm 2
r_1 : Wind direction [degrees] at time of maximum wind speed of storm 1
r_2 : Wind direction [degrees] at time of maximum wind speed of storm 2
$t_{int,w}$: Time [h] between the maximum wind speeds of both storms

s_1 : Maximum surge height [m] in a window 24 hours before and 24 hours after the maximum wind speed of storm 1 (this window is indicated in grey)
s_2 : Maximum surge height [m] in a window 24 hours before and 24 hours after the maximum wind speed of storm 2 (this window is indicated in grey)
$t_{int,s}$: Time [h] between maximum surge heights of both storms

ϕ_{s1}	:	Phase [h] between the peak of the wind of storm 1 and peak of the surge of storm 1
ϕ_{s2}	:	Phase [h] between the peak of the wind of storm 2 and peak of the surge of storm 2
ϕ_{t1}	:	Phase [h] between the peak of the surge of storm 1 and nearest high tide peak. The tidal peak is selected by choosing the maximum value in the period 6.167 hours before and 6.167 hours after the surge peak
ϕ_{t2}	:	Phase [h] between the peak of the surge of storm 2 and nearest high tide peak. The tidal peak is selected by choosing the maximum value in the period 6.167 hours before and 6.167 hours after the surge peak

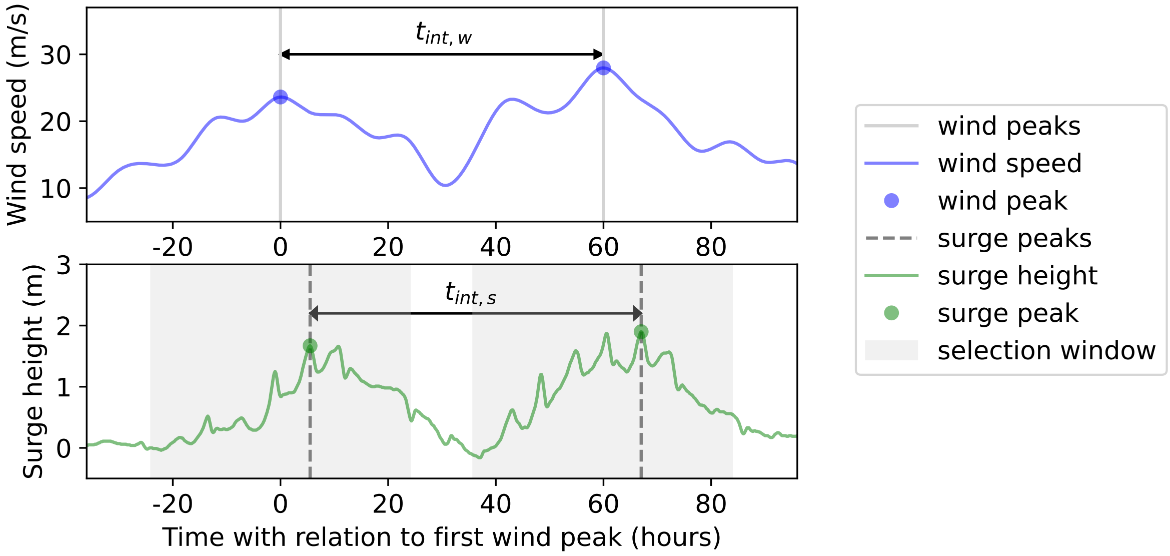


Figure 2.5: Visual overview of the interval duration between wind speed peaks and between surge height peaks

Modified surge peak selection

The maximum surge height is defined as the maximum height of the surge during a storm. As the storm duration is approximately 48 hours, it is assumed that the maximum surge can be found in a window of 24 hours before and 24 hours after the wind peak. In case the interval time between the wind peaks of two storms is smaller than 48 hours, this can lead to the selection of the same surge peak which is considered physically not possible. In that case, an extra condition is added when selecting the peaks.

This is illustrated with figure 2.6. The first plot shows the wind speed of the storm and the corresponding peaks. The selection window for maximum surge of storm 2 is given in grey; it can be seen that the selected surge peak does not represent the second storm. Therefore, the selection window is cropped at the location of the wind speed through as is shown in the lower figure. This way the second surge peak cannot occur before the second storm arrived.

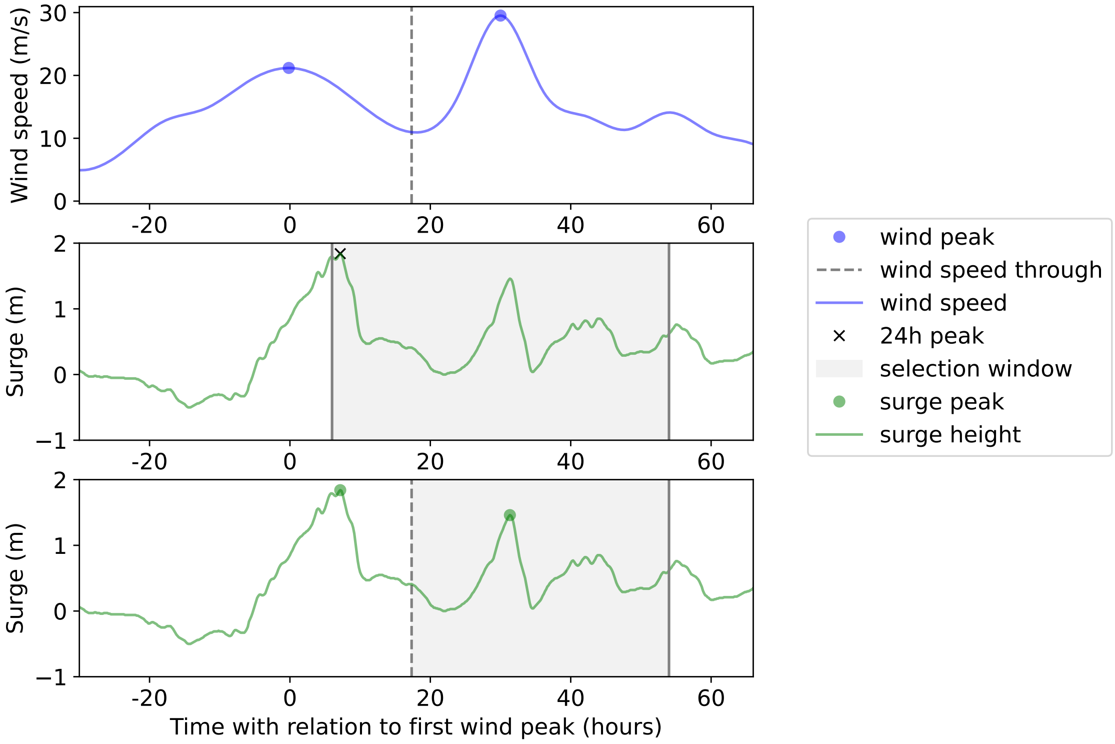


Figure 2.6: Selection of surge peaks for storms where interval duration between wind peaks is less than 48 hours

2.3.2. Define storm clusters

The storms are divided into clusters according to five characteristics: location, wind direction, return period, wind evolution pattern and surge evolution pattern. The characteristics wind evolution pattern and surge evolution pattern are only for the twin storms. For the wind direction, wind evolution pattern and surge evolution pattern, a description can be found below. This subsection is closed off with the constructed storm clusters.

Wind direction

The wind direction is measured in degrees from North. The wind direction of a storm defined at the moment of the peak wind speed. For single storms this is quite evident. For twin storms, this means that the storm with the maximum wind speed defines the direction of the twin storm. As wind from different directions have different storm characteristics, a distinction can be made. In this research, the storms are divided over 12 directional bins (30 degree angles). The bins are named after their middle value, so ’210 degrees’ means the bin that contains storms from 195 - 225 degrees. Early analysis has shown that the largest number of storms are in the 210-, 240-, 270- and 300 degree bins. Therefore only these directions are considered in the remainder of this report.

Wind speed evolution

From the data, there seems to be no clear correlation between the maximum wind speed of the first storm and the maximum wind speed of the second storm. This means that the wind speed of the first wind peak is not dependent on the wind speed of the second wind peak and the other way around. The order of the storms might have an effect on the amount of dune erosion and therefore, should be accounted for in the storm clustering.

In this research, storms are divided into three categories: a large storm followed by a smaller storm (high-low), a small storm followed by a larger storm (low-high) and two storms with both a moderate high wind speeds (mid-mid). A storm is considered high-low if the height of the second wind peak is 90% or less than the height of the first wind peak. Low-high storms are all storms where the height of the first wind peak is 90% of the second wind peak or below. Mid-mid storms are all storms that remain. Figure 2.7 shows an example for all three categories.

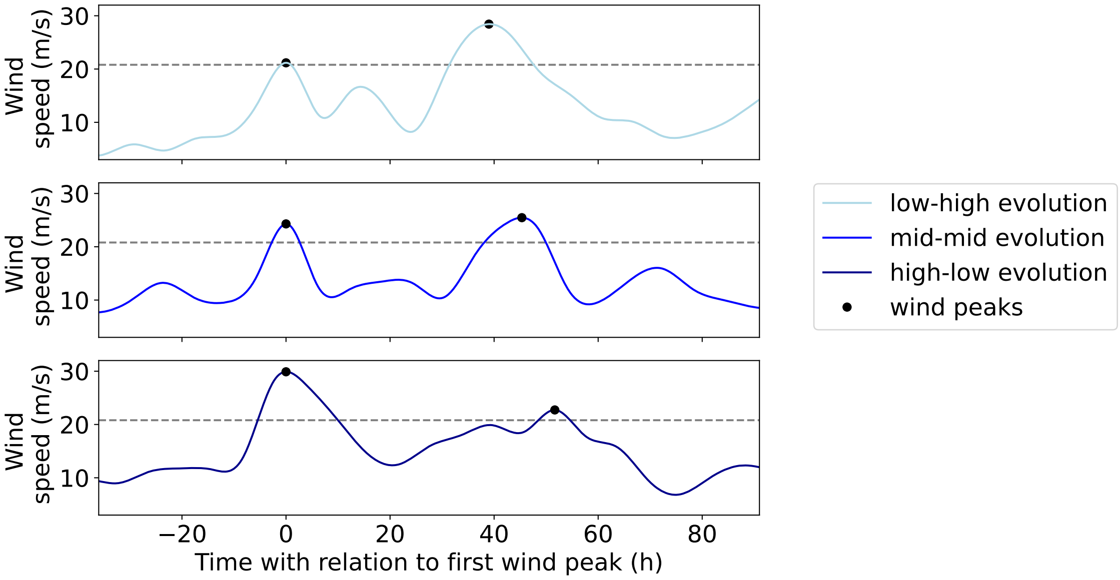


Figure 2.7: Time evolution of wind speed for different types of wind speed evolution

Surge height evolution

The surge level during a storm is largely related to the wind speed and wind direction. As the surge height is also dependent on wind direction, the highest wind speed during a twin storm does not necessarily gives the highest surge peak during the twin storm. Therefore, the surge height evolution should also be taken into account in the storm clustering procedure.

Similar as for the wind speed evolution, the surge height evolution will be divided into three categories: the high-low, mid-mid and low-high evolutions. High-low means that the first surge peak is higher than the second, mid-mid means almost equal in height and low-high means that the second surge peak is higher. A high-low surge pattern means that the height of the second surge peak is 80% or less of the height of the first surge peak. The low-high case indicates exactly the opposite. The mid-mid case is for all storms that fall in between. Figure 2.8 gives an overview of the three different categories.

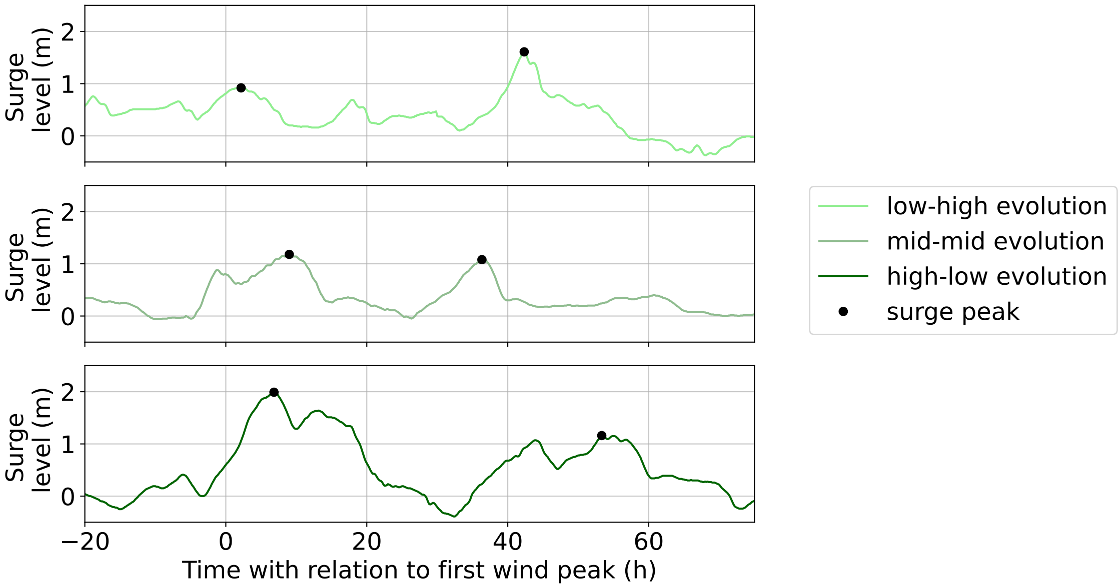


Figure 2.8: Time evolution of surge height for different types of surge height evolution

Clustering storms

Storms can occur in many different forms and with different characteristics. Therefore, storms are clustered into several categories that represent the most important differences between parameters. In this section, the clusters will be described for both single and extreme storms.

For single storms, a distinction will be made over three categories: location, direction and return period. The location indicates from which location the storms are selected, in this case either Nieuwvliet-Groede or Hoek van Holland. The direction indicates the wind direction at the moment of the maximum wind speed within the storm. The return period indicates the difference in the intensity of the storms being modeled. By choosing one option from all three categories, 24 different storm clusters can be obtained.

Table 2.1: Storm clusters for single storms

Location	Direction	Return period
Nieuwvliet-Groede Hoek van Holland	210 deg 240 deg 270 deg 300 deg	1000 years 3000 years 10,000 years

The approach for twin storms is similar to that of single storms but some extra categories are added. First, the location is the location from which the storm data is selected. The direction is defined as the direction at the moment of the highest wind peak. The wind speed evolution indicates the order of the storm's wind peaks: high-low means that the first storm from the two has the highest maximum wind speed, the low-high works exactly the way around. The mid-mid evolution is meant to describe storms where the maximum wind speed for both storms is similar. Furthermore, the surge evolution is meant to distinct the different surge evolution that can occur. Lastly, the return period is included so that the intensity of storms is varied.

Table 2.2: Storm clusters for twin storms

Location	Direction highest peak	Wind speed evolution	Surge height evolution	Return period
Nieuwvliet-Groede Hoek van Holland	210 deg 240 deg 270 deg 300 deg	High - Low Low - High Mid - Mid	High - Low Low - High Mid - Mid	1000 years 3000 years 10,000 years

2.4. Storm schematisation

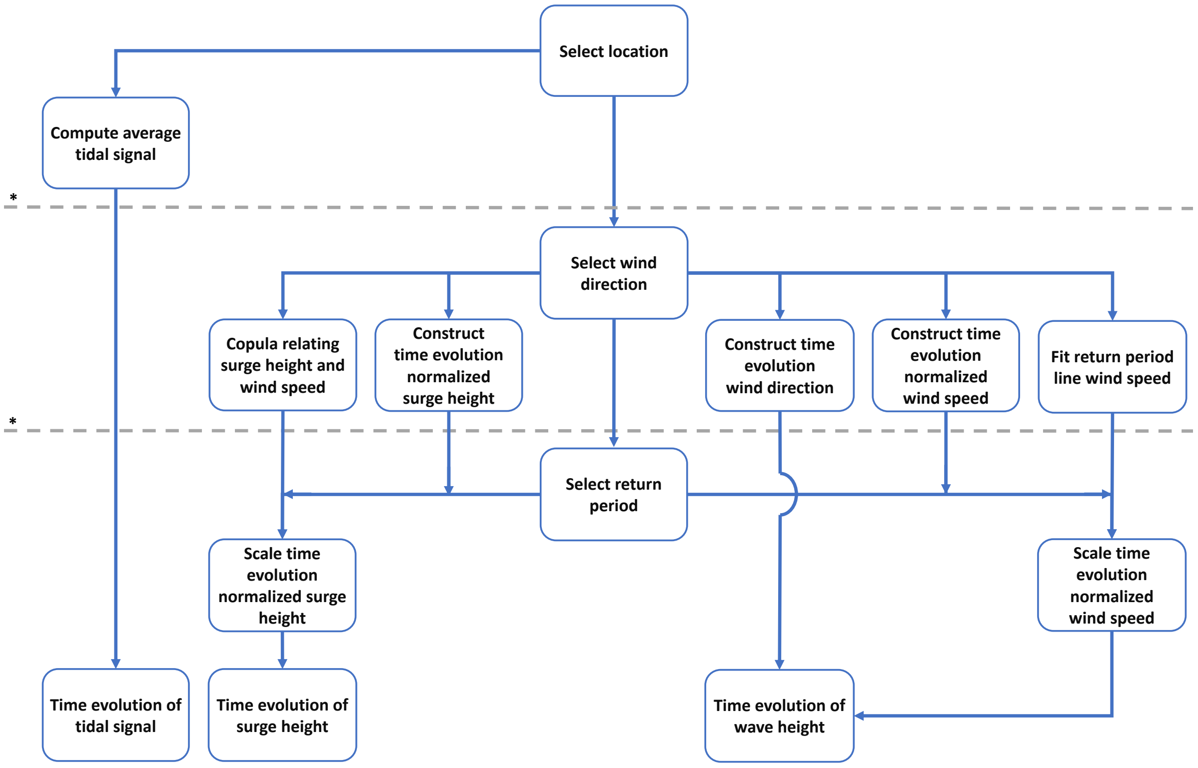
This section will describe how for each storm cluster a storm schematisation is made. To construct a storm schematisation, six steps are taken:

1. Normalisation: all storms within the cluster are normalised in height. The twin storms are not only normalised in height but also normalised in time.
2. Averaging: from the normalised evolutions, one representative evolution will be derived.
3. Height scaling: the representative evolution will be scaled in height.
4. Time scaling (for twin storms): the representative evolution will be scaled in time.
5. Time distribution: the evolutions of wind, surge and tide are shifted in time.
6. Computing wave parameters: from the wind direction and wind speed, the wave parameters are derived.

In subsection 2.4.1, the procedure that is followed to make storm schematisations is described in more detail. Explanation of the distinct steps can be found in subsections 2.4.2 up and until 2.4.7.

2.4.1. Procedure

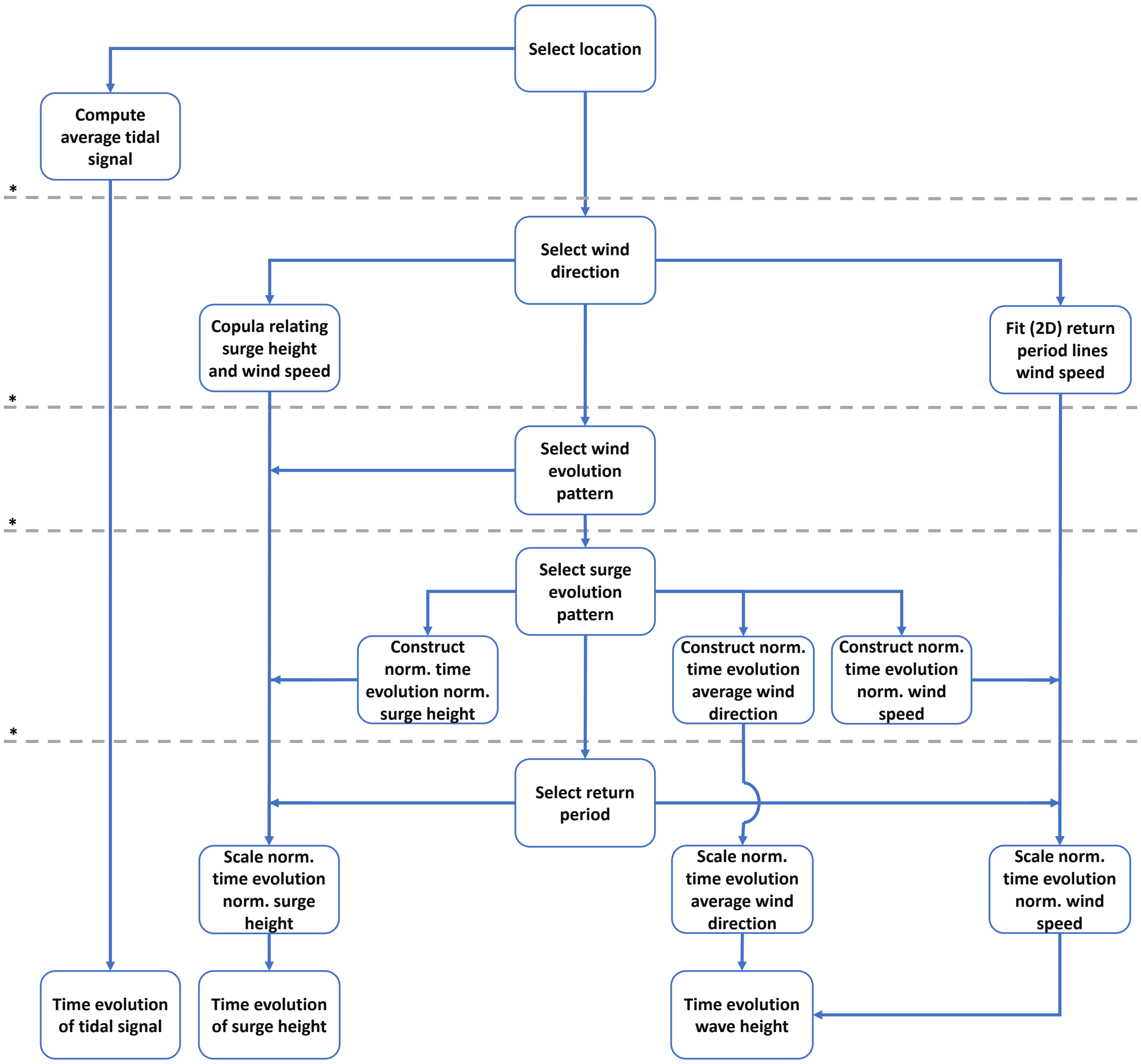
In figure 2.9 a flowchart is shown that describes the schematisation procedure for single storms. First, one location is chosen and the average tidal signal is computed. Thereafter, storms from one direction are chosen and a representative normalised time evolution is calculated. Then, a return period is chosen that is used to scale the representative normalised time evolution.



* The grey lines indicate where the selection of storms is further reduced.

Figure 2.9: Flowchart of storm schematisation procedure for single storms

Figure 2.10 shows how the schematisation procedure for twin storms is structured. As the storm clusters for twin storms are more specific, there are more levels in the procedure. However, the steps are comparable to the steps in the procedure for single storms.



* The grey lines indicate where the selection of storms is further reduced.

Figure 2.10: Flowchart of storm schematisation procedure for twin storms

2.4.2. Normalisation

This section explains how for each storm within a cluster normalised evolutions of the wind speed, wind direction and surge heights are obtained. The aim of normalising is to scale the time evolutions of the wind speed and surge height in such a way that they can be compared but that their form doesn't change. This section will describe how this procedure works for both single- and twin storms. This will be done consecutively for the wind speed, wind direction and surge height.

Wind speed

For all single storms, the peak is centered in the selection window. Centering the storms means that the time dimension now is the same for all storms, therefore the only remaining dimension to normalise is the height of the storms. By dividing the wind speed evolution by the peak wind speed value, the peak obtains a height of 1 and the height for all other points is within the interval [0,1]. Figure 2.11 shows both the actual wind evolution and the normalised evolution. It is important to notice that the form of the evolution stays intact during normalisation.

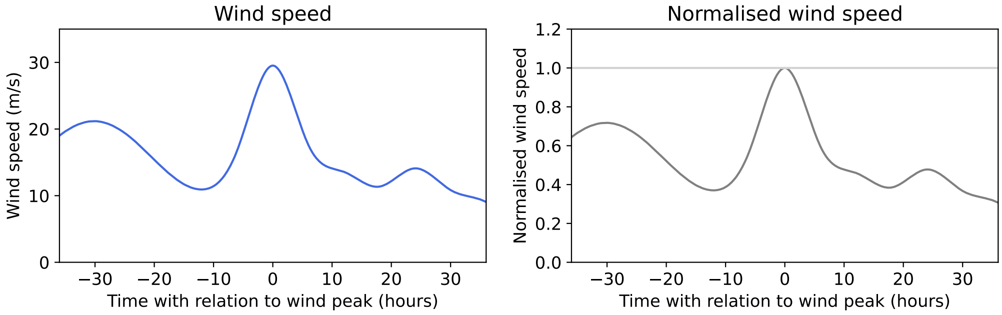


Figure 2.11: Left: time evolution of the wind speed for a single storm
Right: time evolution of the normalised wind speed for a single storm

As twin storms are not only variable in height but also in time, the storms are normalised in both time and in height of the storm. An example for the wind speed is given in figure 2.12. First, the peak of the storm with the highest wind speed is shifted in time to the zero axis. Thereafter, the evolution is normalised in height by dividing by the wind speed of the peak with the highest wind speed. To normalise the time axis, the time is divided by the interval duration (between the wind peaks) such that the peaks are now on -1 and 0 or 0 and 1 on the normalised time axis.

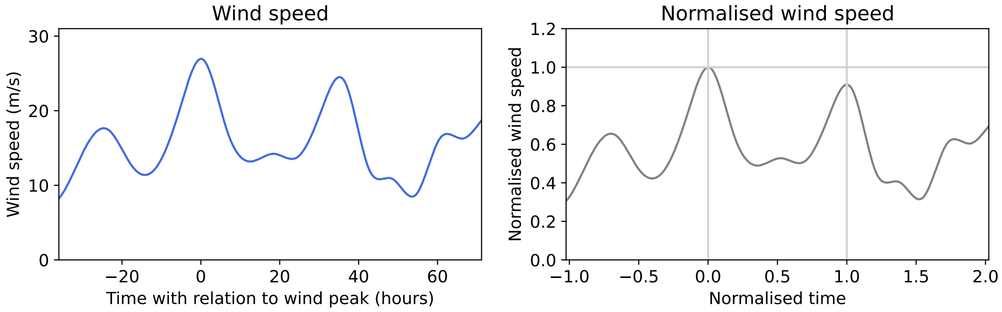


Figure 2.12: Left: time evolution of the wind speed for a twin storm
Right: normalised time evolution of normalised wind speed for a twin storm

Wind direction

The objective of normalising is to obtain evolutions that have the same range of values. For normalised evolutions of the wind speed that means that all values are in the range [0,1]. The wind direction evolution already has a specified interval, all values are on the interval: [0,360]. Therefore, the wind direction is not normalised in height.

Twin storms are not only normalised in height but also in time. The wind speed evolution was normalised in time so that the wind speed peaks are on 0 and 1 on the time axis. As the wind direction and wind speed should have matching time intervals, the wind direction of twin storms is also normalised in time.

Surge level

Before the surge level evolution is normalised, it is shifted in time such that the surge peak is centered at 0. The surge evolution is divided by the maximum surge height that occurs during the storm to normalise the evolution in height. Figure 2.13 shows the normalised evolution for a single storm.

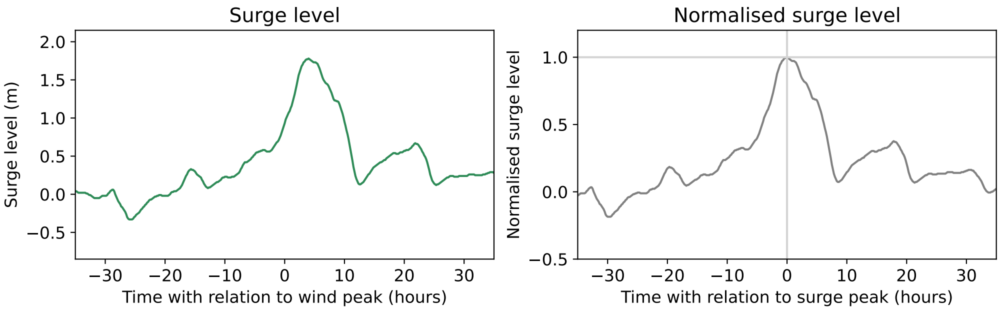


Figure 2.13: Left: time evolution of the surge height for a single storm
Right: time evolution of the normalised surge height for a single storm

For twin storms, the peak with the maximum surge height is shifted in time to zero before normalisation is done. Thereafter, the evolution is normalised in height. This is done by dividing the surge heights by the height of the highest surge peak. The evolution thereafter is also normalised in time. This time, this is not done by dividing by the interval between the wind peaks but by dividing the evolution by the interval duration between the surge peaks. Therefore, the surge peaks will be on -1 and 0 or 0 and 1 on the time axis. This is shown in figure 2.14.

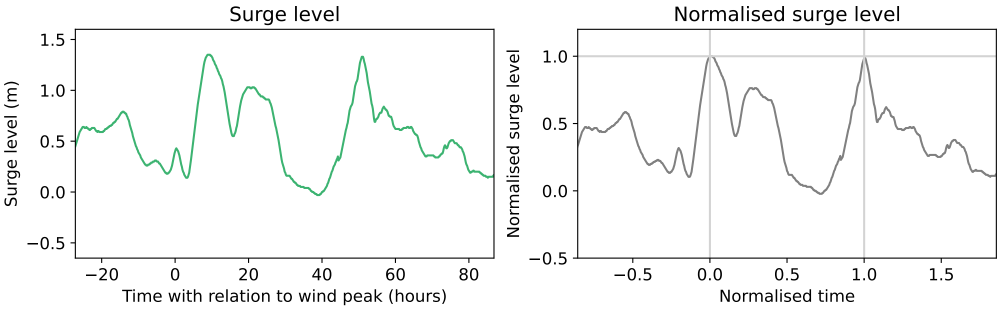


Figure 2.14: Left: time evolution of the surge height for a twin storm
Right: normalised time evolution of normalised surge height for a twin storm

2.4.3. Averaging

After normalising the wind direction, wind speed and surge level, averaging techniques can be used to create one representative evolution. There are three methods that can be used to average storms (Geerse et al., 2022): horizontal averaging, vertical averaging and the percentile method. An overview of the three methods used to create a representative surge evolution is shown in figure 2.15. The three methods are explained in the intermezzo below.

Intermezzo: averaging methods

- Horizontal averaging
  After a storm is normalised, the duration at each normalised height (0.1, 0.2, etc.) can be calculated by integrating the area above that normalised height. By doing this for all normalised heights, each storm provides an estimate of the duration for each normalised height. By taking the average for all storms for each normalised height, the duration of each normalised height for an 'average storm' is known. By assuming a symmetrical evolution, a line can be plotted that adheres to the calculated duration at each height. The horizontal averaging method represents the exceedance hours around the peak well. However, the horizontal method can lead to distortion of storms. The horizontal method is not able to represent complex evolutions as it only knows the total duration but not how that is distributed in time.
- Vertical averaging
  Vertical averaging is the most straightforward method for averaging storms. Before vertical averaging can be executed, first all peaks are centered at the zero point in time. Thereafter, the vertical average evolution can be found by taking the mean value for all storms at each moment in time. The vertical averaging method is better at representing the time evolution but is known to underestimate the exceedance hours around the peak and to overestimate the duration in the tail of the storm.
- Percentile method
  The percentile method is quite similar to the vertical averaging method. At each moment in time, a certain value is chosen based on the normalised value of all storms. In contrast to vertical averaging, not the mean but a certain percentile is chosen at each moment in time. For example, the 50th percentile represents taking the median of all values at each instance in time. The percentile method is good at representing the time evolution of a storm and has more flexibility than the vertical averaging method.

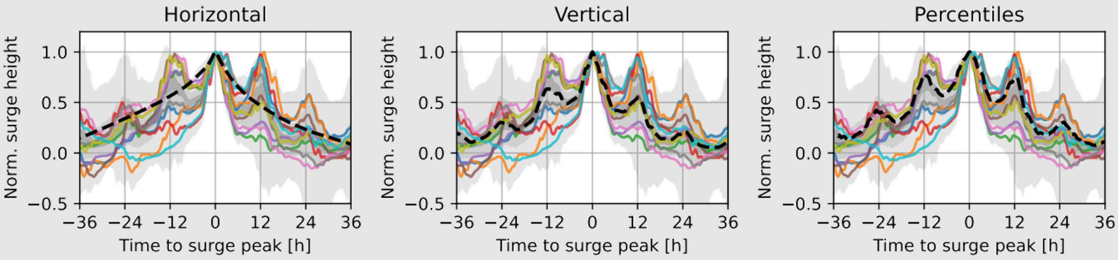


Figure 2.15: Overview of different averaging methods (Geerse et al., 2022)

Horizontal averaging cannot be used for twin storms as that method is not able to cope with complex time evolutions. Using this method would lead to one large peak instead of two peaks. As for consistency the same approach is used for both single and twins storms, there are two options left: vertical averaging and percentiles. The percentile method is better at representing the evolution in time and is more flexible than vertical averaging and will therefore be used to determine the wind speed and surge height evolution. For the wind direction evolution and the tide evolution, vertical averaging will be used.

Wind speed

For all storms within a cluster, the normalised evolution is computed. In figure 2.16 and 2.16 those normalised evolutions are shown in grey. To construct one representative evolution, for each moment in time the percentile value is chosen. In blue the representative evolution is shown. The 60th percentile is chosen to construct the wind speed evolution. The duration of the representative storm is dependent on the chosen percentile. In appendix C.1 the choice of percentile and the implications are explained.

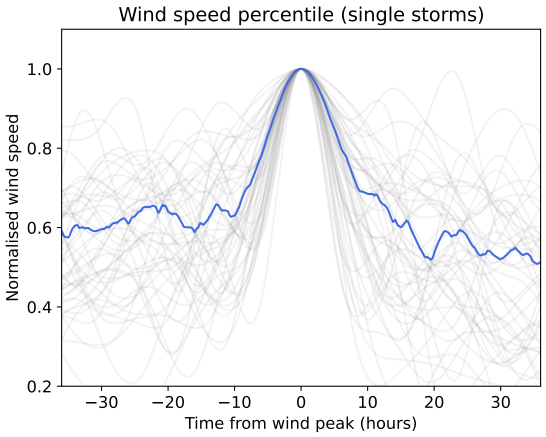


Figure 2.16: Normalised time evolutions of the wind speed for the storms of one cluster [Hoek van Holland, 240 degrees] are shown in grey. In blue the fitted percentile line is shown.

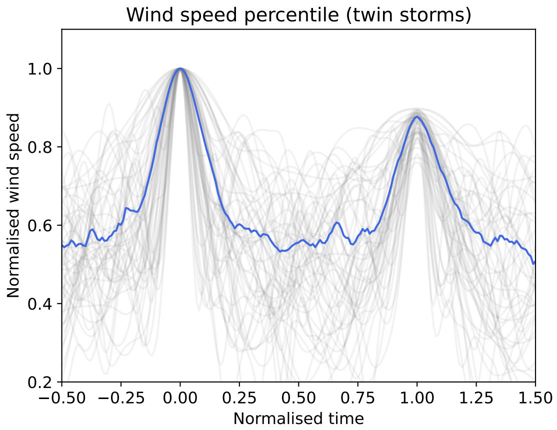


Figure 2.17: Normalised evolutions of the wind speed for the storms of one cluster [Hoek van Holland, 240 degrees, high-low wind, mid-mid surge] are shown in grey. The fitted percentile line is shown in blue.

Wind direction

There are two ways to average the wind direction: the true vector average and the unit vector average approach. For the true vector average, the magnitude of the wind speed is taken into account when averaging. This means that larger wind speeds have more influence on the average than small wind speeds have. For the unit vector approach, only the wind direction is of interest and all storms, regardless of their magnitude, equally influence the wind direction. In this research, the unit vector approach is used to find the vertically averaged wind direction. Thus, all selected storms have an equal influence on the wind direction evolution.

For each instance in time, the x-vector and y-vector are calculated using equation 2.3. In the formula, N indicates the number of storms, θ_i is the direction for one storm and V_x and V_y are the unit vectors that can be calculated for each moment during the storm. The minus sign is introduced as the wind direction, by meteorological convention is where the wind wind is blowing from although vectors indicate where the wind is blowing to. The average direction ($\overline{\theta}$) can be computed with equation 2.4.

$$\begin{aligned} V_x &= -\frac{1}{N}\Sigma sin(\theta_i) \\ V_y &= -\frac{1}{N}\Sigma cos(\theta_i) \end{aligned} \tag{2.3}$$

$$\overline{\theta} = \begin{cases} arctan(V_x/V_y) + 180 & \text{for} \quad arctan(V_x/V_y) < 180 \\ arctan(V_x/V_y) - 180 & \text{for} \quad arctan(V_x/V_y) > 180 \end{cases} \tag{2.4}$$

In figure 2.18 and 2.19 an overview is given of the vertical averaging of the wind direction for single and twin storms respectively. Due to the selection of storms from a certain direction, it can be seen that for time zero, the directions are at most 30 degrees apart. Before and after the wind peak, there is a larger spread of the evolution. Almost all storms show a similar pattern; the wind direction tends to change from a Southerly to a more Westerly direction over the course of the storm.

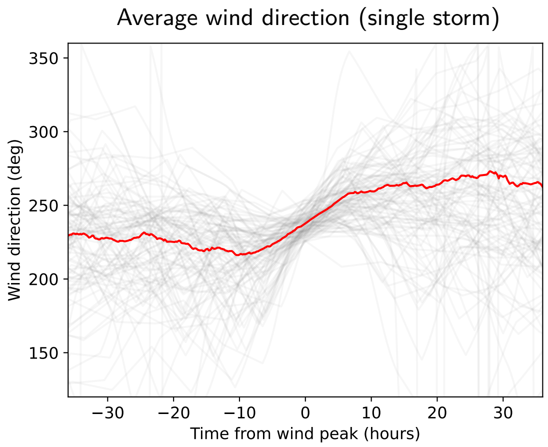


Figure 2.18: Time evolutions of the wind direction for the storms of one cluster [Hoek van Holland, 240 degrees] are shown in grey. The red line gives the mean wind direction.

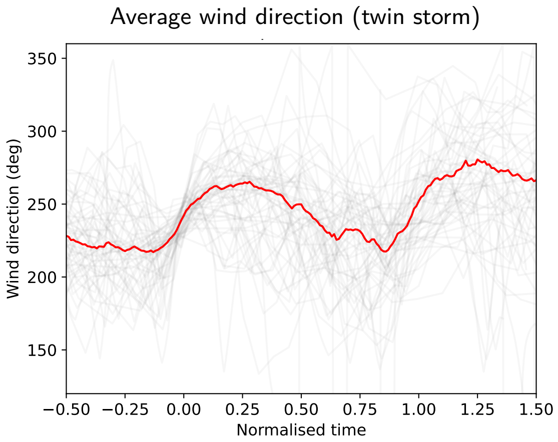


Figure 2.19: Time evolutions of the wind direction for the storms of one cluster [Hoek van Holland, 240 degrees, high-low wind, mid-mid surge] are shown in grey. The red line gives the mean wind direction.

Surge height

To obtain a representative surge evolution, for each moment the 60th percentile value is determined from the normalised surge height evolution of all storms within the cluster. One example for single storms and twin storms is shown in figures 2.20 and 2.21. In appendix C.1 more detail is given on the choice of percentile and its' implications.

From figure 2.20 it can be seen that the surge height evolution shows secondary peaks. The secondary peaks exhibit a pattern that coincides with the tidal cycle. For the twin storm evolution, the secondary peaks are much less clear. This is due to the fact that the twin storm evolution is normalised in time. The twin storm evolutions are all normalised by dividing by the interval between the surge peaks. As for all storms, this interval duration is different, the tidal peaks are averaged out for the twin storms.

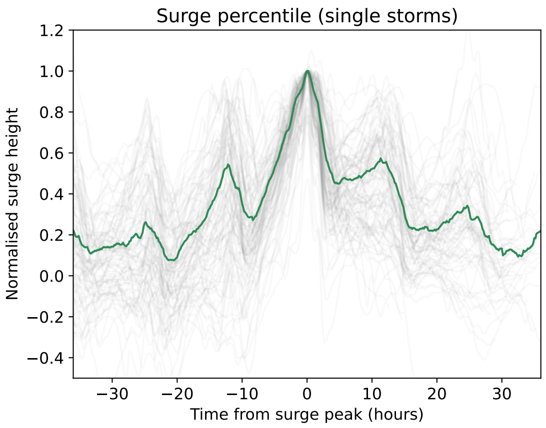


Figure 2.20: Normalised time evolutions of the surge height for the storms of one cluster [Hoek van Holland, 240 degrees] are shown in grey. In green the fitted percentile line is shown.

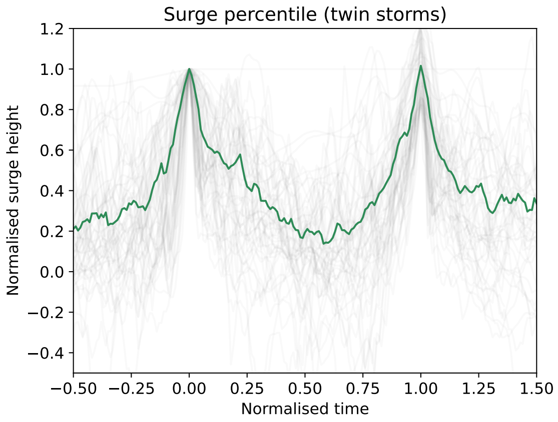


Figure 2.21: Normalised evolutions of the surge height for the storms of one cluster [Hoek van Holland, 240 degrees, high-low wind, mid-mid surge] are shown in grey. The fitted percentile line is shown in green.

Tidal level

The tidal level is required to calculate the water level that is expected during the storm. The tidal water level is determined by averaging the tidal levels during the selected storms. The procedure is the same for both single and twin storms. First all storms are shifted in time such that the tidal peak is located at 0. Thereafter, vertical averaging can be used to estimate the tidal level. Figures 2.22 and 2.23 show the results for the tidal levels at Nieuwvliet-Groede en Hoek van Holland. The tidal water level observed during the selected storms is shown in grey. The line in orange indicates the estimated tidal signal that is obtained.

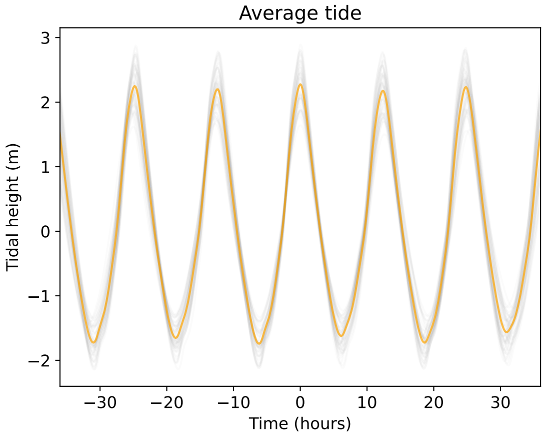


Figure 2.22: Time evolutions of the tidal height for storms at Nieuwvliet-Groede. The orange line indicates the mean tidal height.

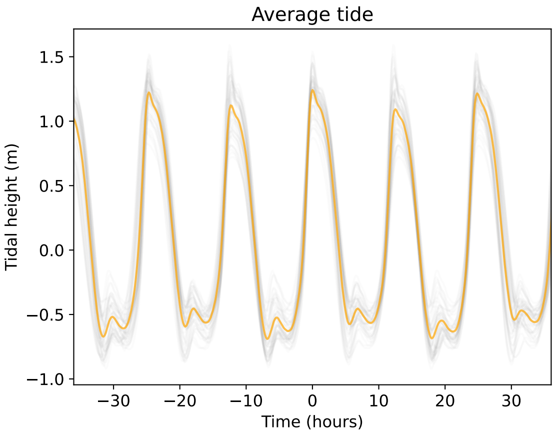


Figure 2.23: Time evolutions of the tidal height for storms at Hoek van Holland. The orange line indicates the mean tidal height.

2.4.4. Height scaling

Height scaling refers to the procedure of scaling the normalised evolution back to physical parameter values. There are two normalised evolutions that are scaled: the wind speed evolution and the surge height evolution. In the next two paragraphs, the scaling procedure will be explained for the wind speed and surge height for both single- and twin storms.

Scaling wind speed evolution

For single storms, the normalised wind speed evolution is multiplied with the wind speed that is expected to occur given a certain return period. To estimate the wind speed that belongs to a certain return period, a Generalised Pareto Distribution (GPD) is used. The GPD should be fitted such that it is a good representation of the extreme values. As the peak wind speed is at least 20.8 m/s, the location parameter of the generalised pareto distribution will be set to 20.8. The scale and shape parameters are fitted using Maximum Likelihood Estimation (MLE). Figure 2.24 shows the probability density function (PDF) and the return periods for the fitted GPD. The wind speed that belongs to a certain return period can be derived from the GPD in figure 2.24.

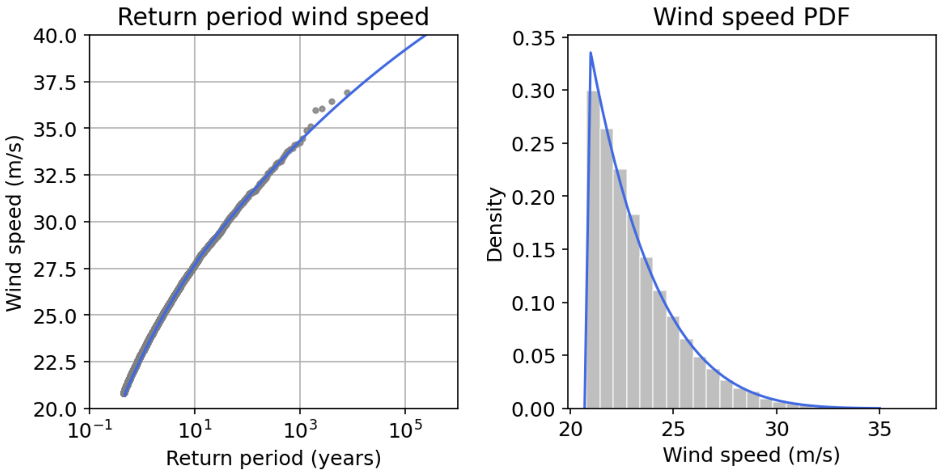


Figure 2.24: Left: return period of the wind speeds for one cluster of single storms and the fitted GPD. Right: histogram of the observed wind speeds and the PDF of the GPD for one cluster of single storms [Hoek van Holland, 240 degrees].

Contrary to single storms, twin storms are defined by two extreme values. The combined probability of these extreme values should be taken into account when constructing a storm evolution. Early analysis showed that the height of the two peaks does not show a clear correlation. Therefore the peaks can be considered independent.

First, twin storms from one direction are selected. All storm peaks of those storms (so both the first peak and second peak) are combined and a GPD is fitted. In the left figure of 2.25 it is shown how this GPD estimates all first storm peaks. The right figure shows the lines on which the storms are expected that occur on average once in a 1000, 3000 and 10000 years. This means that any combination of peak 1 and peak 2 that is on the 1000 year line can represent a '1000-year storm'.

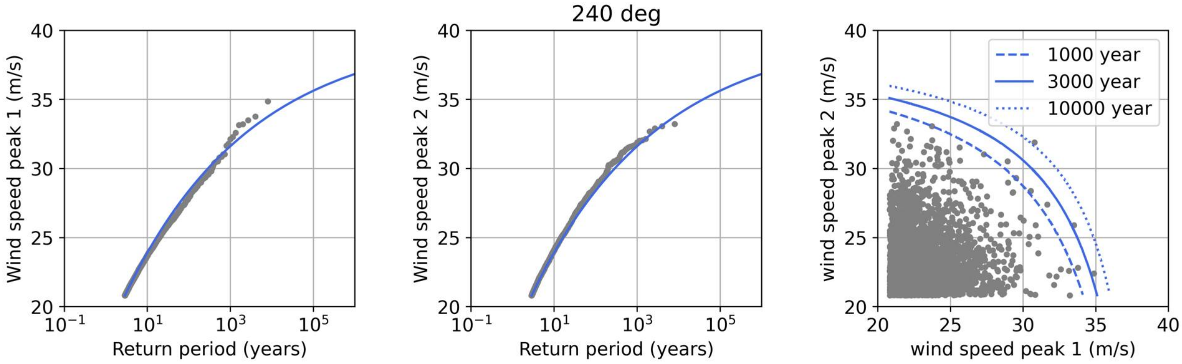


Figure 2.25: Subfigure 1&2: return period of the wind speed and the fitted GPD for the two wind peaks for twin storms. Subfigure 3: Return period lines for the combination of twin storm wind peaks [Hoek van Holland, 240 deg].

Now combining the representative wind speed evolution and the constructed return period line, the evolution can be scaled. From the wind speed evolution as shown in figure 2.26 it can be derived what the height of the first peak is, compared to the second peak. Knowing this relation, a point on the return period line can be selected. From this point, the height of both the peaks can be read.

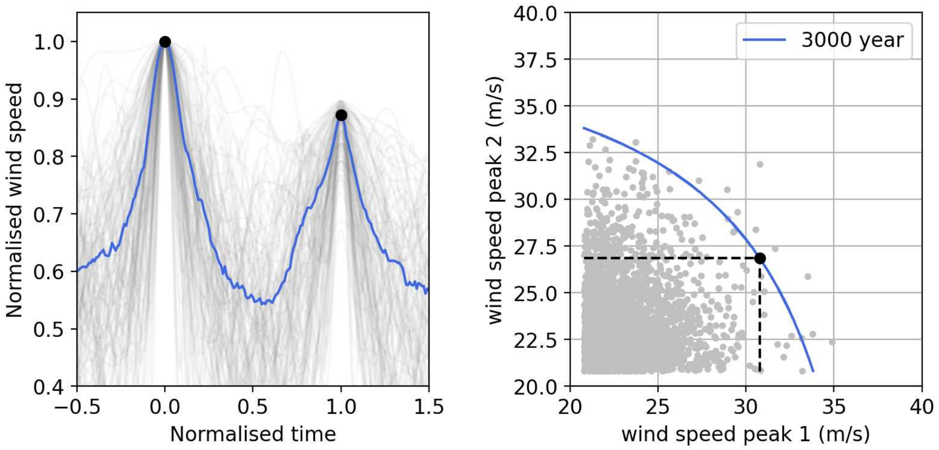


Figure 2.26: Left: normalized evolution of the wind speed for one cluster of twin storms. Right: selection of the combination of wind speeds that corresponds to a certain return period. [Hoek van Holland, 240 deg, high-low wind, mid-mid surge, 3000 years]

Relating surge height to wind speed

The surge height that is expected to occur during an extreme storm is assumed to be correlated to the wind speed. The correlation between the wind speed and surge height can be modelled using a copula. An introduction on copulas is given in appendix C.5. For a detailed description of copulas, one is referred to (Nelsen, 2007).

Before a copula can be fitted, the marginal distributions of the parameters are required. A marginal distribution is derived for the height of the wind peaks and for the surge height. The marginal distribution used for the wind speed is the GPD. For the surge heights, the pareto distribution is applicable to model the most extreme surges that occur, but it cannot describe the lower surges that occur. Therefore, it is combined with another distribution that can describe the lower surge values. A certain threshold will be chosen above which the pareto distribution holds and for values lower than the threshold, a student-t distribution will be applied.

Figure 2.27 shows the PDF and return periods of surge heights that are estimated using the student-t, pareto and combined distribution. It clearly shows that the student-t distribution is not able to represent the most extreme values well. The pareto distribution on the other hand shows a representative fit for the most extreme values but not for the low values. The combined distribution shows that it is able to predict both the extreme and lower values of the surge.

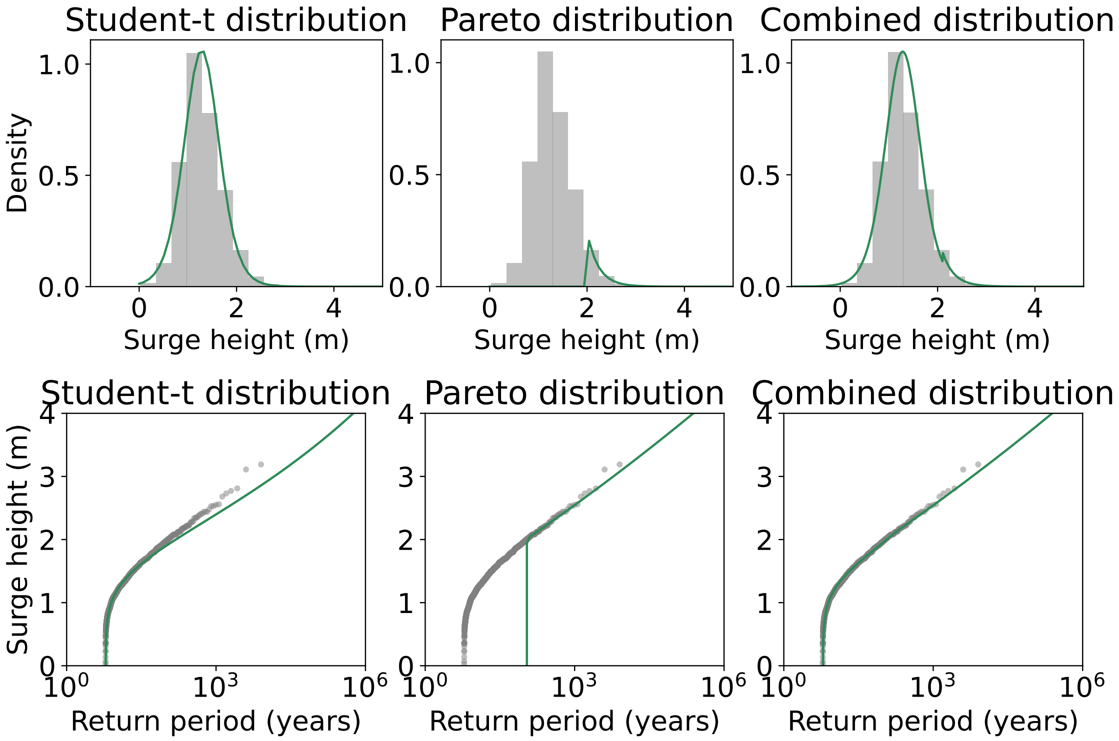


Figure 2.27: Above: histogram of observed surge heights and the PDF of the fitted distributions for storms from one direction. Below: The return period for the surge height and the fitted distribution for storms from one direction [Hoek van Holland, 270 degrees].

In this research, a Gumbel copula will be used to model the relation between the wind and surge. More details about the choice of copula can be found in appendix C.5. The expected surge can be related to the wind speed using the copula structure. Figure 2.28 shows on the left the copula that is fitted in the unit space. The dots indicate the observations, the black lines indicate the 10th, 50th and 90th percentile. The right side of figure 2.28 shows the same plot but converted back to physical space.

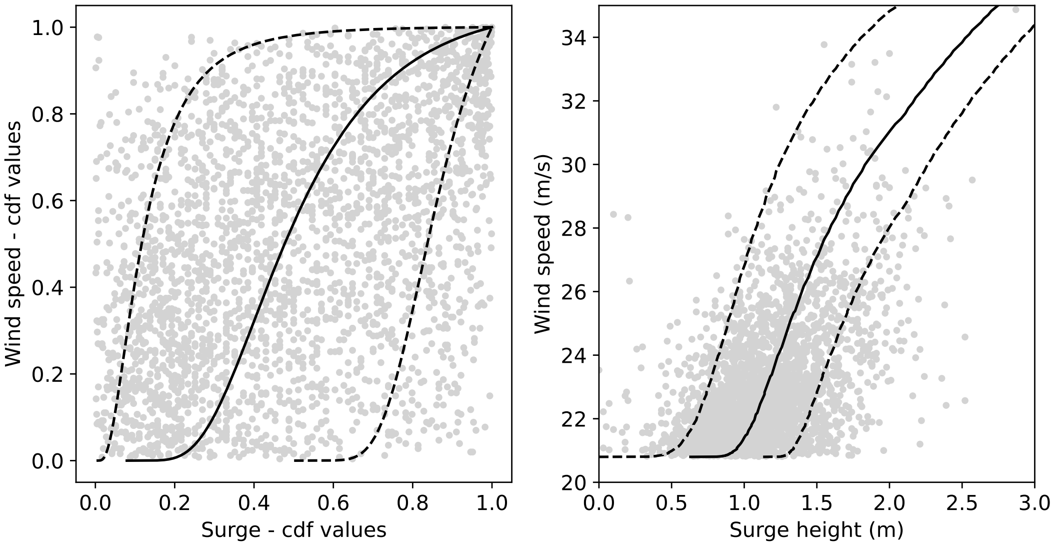


Figure 2.28: The dots indicate combinations of wind speed and surge height observed for storms from one direction [Hoek van Holland, 270 degrees]. The black lines indicate the 10th, 50th and 90th percentiles as computed from the fitted Gumbel copula. The left figure shows the unit space, the right figure the physical space.

Scaling surge height evolution

The surge height for single storms can be determined by using a copula that relates wind speed to surge height for a certain direction. Based on the wind direction at the moment of the peak wind speed, the corresponding copula can be chosen. Thereafter, the surge height can be estimated by selecting the value that corresponds to the wind speed on the 50th percentile line. It is chosen to use the 50th percentile line as that gives the value for the surge height with the highest probability.

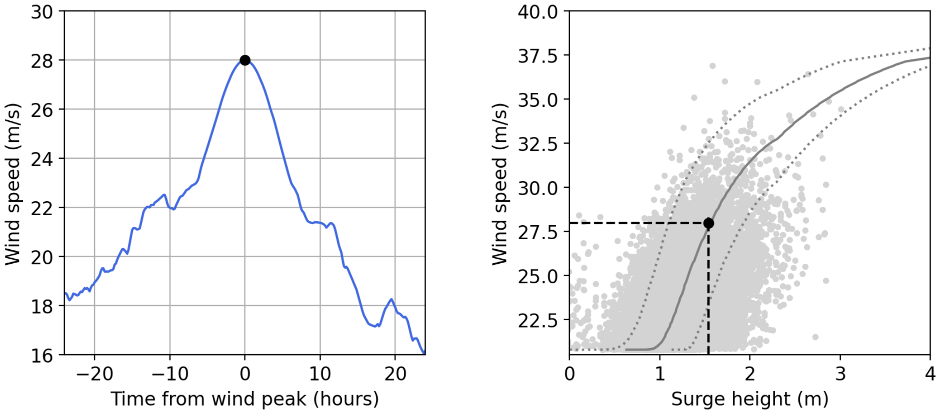


Figure 2.29: Left: time evolution of the wind speed schematisation for one storm cluster. Right: selection of the surge height that corresponds to the maximum wind speed.

For twin storms, there are two surge peaks within the normalised surge evolution. It is argued that to model dune erosion, the maximum surge peak is of highest importance. Therefore, the maximum surge height will be determined based on the highest normalised surge peak. That is, when the surge evolution is 'high-low', the surge height will be estimated based on the wind speed and wind direction of the first storm peak. When the surge evolution is 'low-high', he surge height is computed using the wind speed and wind direction of the second storm peak. As this direction is not necessarily 210, 240, 270 or 300, linear interpolation between the copulas will be used. For example, if the wind direction is 220, the surge height will be estimated from the '210-copula' and the '240-copula'. In figure 2.30 it is shown how the wind speed and wind direction are determined for a low-high surge storm.

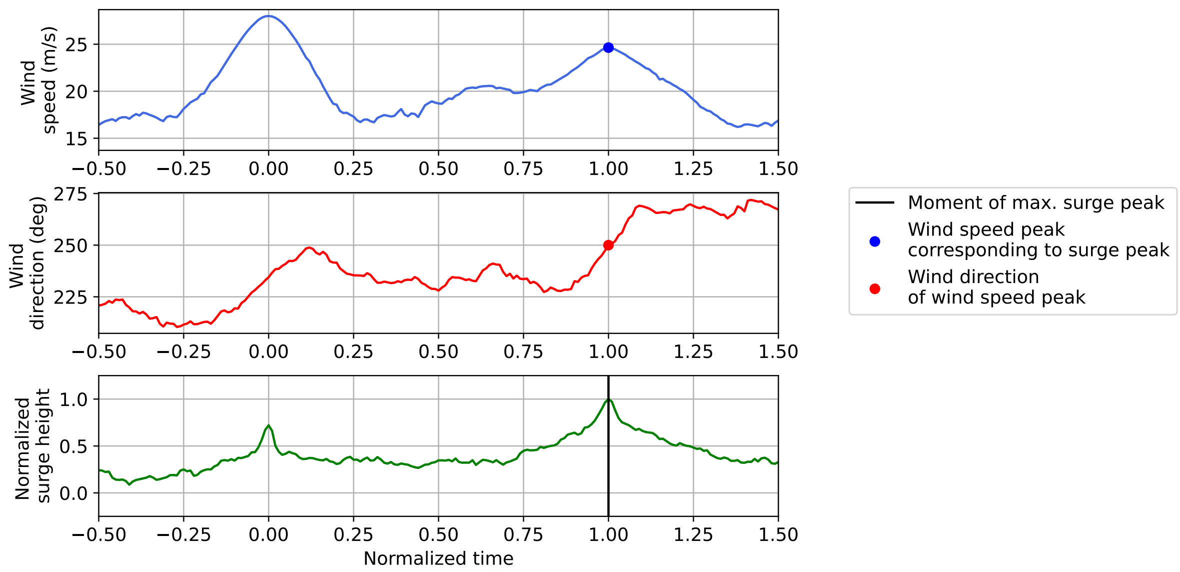


Figure 2.30: Wind direction and wind speed at the moment of the highest surge peak

2.4.5. Time scaling (for twin storms)

The wind speed and surge height evolutions are scaled in time by dividing by the interval duration between the peaks. To scale the pattern back to physical time steps, the time index of the normalised pattern should be multiplied with a certain time duration. In this paragraph, the time duration used for scaling the wind speed and surge height evolutions is explained.

Wind peaks interval duration

For each storm in the cluster, the time index is divided by the interval duration between the wind peaks. To scale up a single storm, the time index should be multiplied with the same interval duration again. Now consider a cluster with multiple storms. Scaling up the representative normalised evolution with the median time interval of the wind peaks of all storms gives a good approximation. This is explained in more detail in appendix C.6.

Surge peaks interval duration

To get a good approximation of the duration of the storm the surge height evolution should be scaled with the median time interval of the surge peaks of all storms within the cluster. However, analysis shows that there also is a physical aspect to the time interval of the surge peaks. The interval duration between the surge peaks is observed to correlate with the tidal cycle to a large extent. In figure 2.31 it can be seen that for Nieuwvliet-Groede the surge interval durations coincide with the tidal cycle, storms at Hoek van Holland have surge interval durations that coincide with half the tidal cycle.

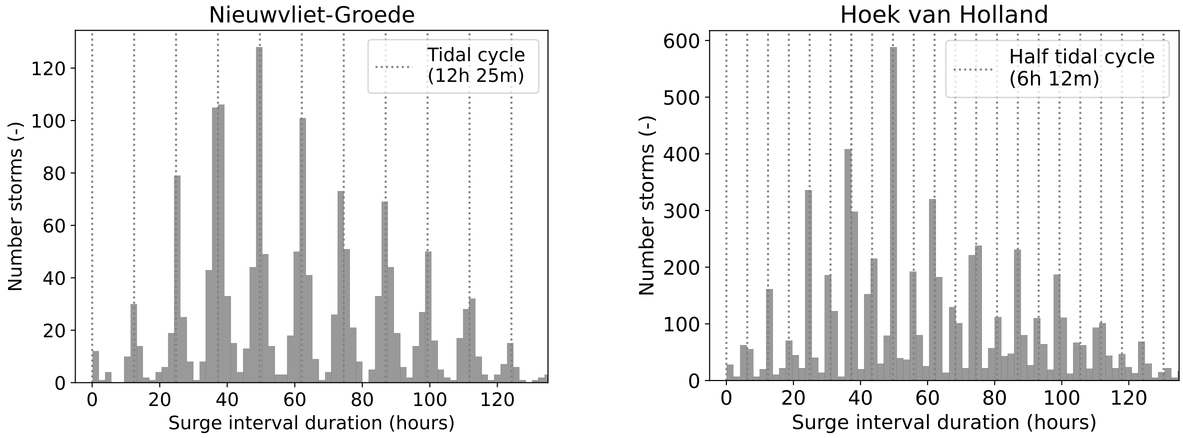


Figure 2.31: Histogram of the interval duration between the surge peaks for all twin storms at both locations

The time index of the surge height evolution is therefore not multiplied with the median interval duration of the surge peaks. Instead, the median surge interval duration of the surge peaks is calculated and then rounded to the closest tidal cycle for Nieuwvliet-Groede and Hoek van Holland. Although the surge interval duration for Hoek van Holland seems to be correlated to half the tidal cycle, it is chosen to round the interval duration to the closest full tidal cycle. There are two reasons to do so: first, it can be seen that the largest number of storms (65%) correlates with the full tidal cycle. Furthermore, storms that have an interval duration that is a multiple of the tidal cycle have much larger water level peaks than storms that have an interval duration that's half a tidal cycle away from the full tidal cycle.

2.4.6. Distribution in time

Within the normalisation procedure, the wind, surge and tide are all shifted to have their peak at time = 0. However, the wind peak, surge peak, and tidal peak rarely occur at the same time. In this subsection it is explained how the profiles are shifted in time with relation to one another.

Phase wind & surge

The phase between wind and surge can be of large importance when calculating hydraulic loads as dune erosion is largely dependent on both wave height and surge height. The largest wave heights are often found around the wind peak. If there is a phase between the wind and surge that means that the highest waves do not coincide with the highest surge levels.

Figure 2.32 shows the phase for wind peak and surge peak for single storms from one direction at both locations. It can be seen that there is a large spread in observed phase. To choose a representative value, it is chosen to shift the surge evolution with respect to the wind speed evolution with the median phase of all storms within the considered cluster. For twin storms, the surge is shifted based on the median phase between the first wind peak and the first surge peak. An overview of the phases for all directions and locations can be found in appendix C.7.

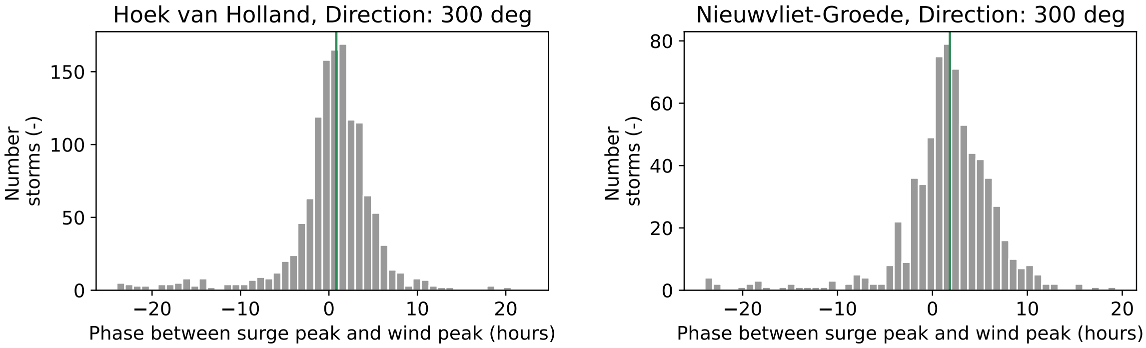


Figure 2.32: Histogram of phase between wind peak and surge peak for storms with a direction of 300 degrees, shown for both locations (vertical green line indicates the median value)

Phase surge & tide

The phase between surge and tide indicates the time shift of the tidal evolution with respect to the surge evolution. The phase between surge and tide is not uniformly distributed; some phases are more likely to happen than others (Chbab, 2015). It is important to consider this time distribution as the water level is a combination of both the surge level and the tidal level. Due to the phase difference, the surge and tidal maxima rarely occur at the same time. Although this phase difference leads to a lower maximum water level, it can lead to a longer duration of relatively high water levels. In figure 2.33 it is shown how the tidal phase is divided over the storms for storms from direction 300 degrees at both locations.

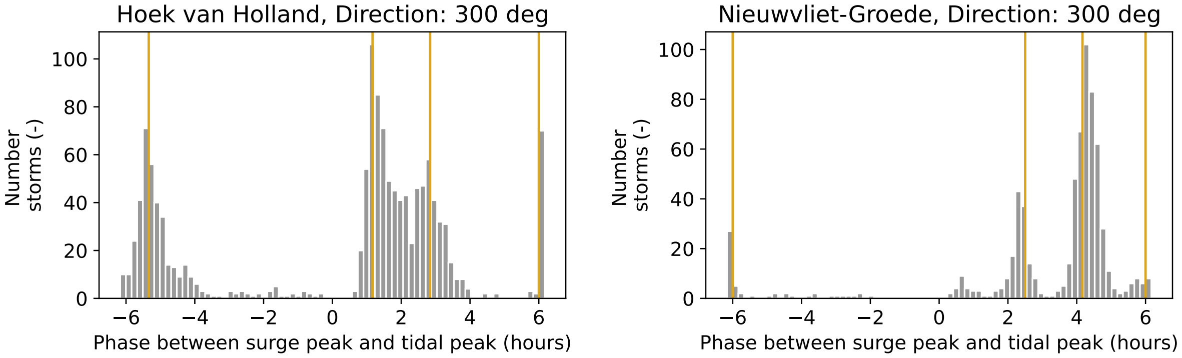


Figure 2.33: Distribution of tidal phase for storms from a direction of 300 degrees, shown for both locations (orange lines indicate the four most frequently occurring tidal phases)

From figure 2.33, it can clearly be seen that there seem to be a few distinct phases for both locations. The orange lines indicate the phases that are identified for both directions. An overview of the distribution of phases for all directions is given in appendix C.8. An overview of the identified phases is given in table 2.3.

Table 2.3: Tidal phases that are most frequently occurring for both locations

Nieuwvliet-Groede	-6.0 h	2.5 h	4.167 h	6.0 h
Hoek van Holland	-5.333 h	1.167 h	2.833 h	6.0 h

The tidal evolution is shifted with respect to the surge evolution. To shift the tidal profile, the following procedure is used: from all storms in the cluster, the mode of the tidal phases is computed. Thereafter, the modal phase is rounded to the closest of the predefined phases.

2.4.7. Computing wave parameters

The wave parameters cannot be obtained from the ECMWF/WAQUA dataset. Therefore, the wave parameters are estimated using the wind direction and wind speed. To do so, relations are used described within the WTI-2011 report (Stijnen and Kallen, 2010). The WTI-2011 provides tables that link the wind speed and wind direction to wave characteristics at a certain location. The location Scheur West will be used to derive waves for Nieuwvliet-Groede and Europlatform will be used for Hoek van Holland. Table 2.4 shows, as an example, the correlations derived for one wind direction at the Europlatform location. In the following paragraphs the different wave parameters are considered in further detail.

Table 2.4: Wave characteristics related to wind speed and wind direction at the Europlatform for a wind direction of 240 degrees

Wind direction [degrees]	**Wind speed [m/s]**	**Wave period $T_{m-1,0}$ [s]**	**Wave height [m]**	**Wave peak period T_p [s]**
240	13.7	6.16	2.62	6.90
240	17.7	6.99	3.38	7.81
240	22.1	7.69	4.58	8.68
240	26.7	8.40	5.55	9.59
240	31.4	9.11	6.42	10.50
240	36.2	9.79	7.22	11.40

Wave height

Figure 2.34 shows measurements and estimations for the wave height that belongs to winds from direction 240 at Nieuwvliet-Groede and Hoek van Holland. The red markers indicate the values estimated by the WTI-2011 (see table 2.4) and the grey markers indicate real-life observations. The wave height is estimated by fitting a linear line through the points from the WTI-table.

To validate the assumption, other empirical formulations that relate wind speed to wave height are compared. In (Ris et al., 2001) various empirical formulations are considered that relate the wind speed to the wave height. In the report it is investigated which formulations can be used for situations with short fetches and high wind speeds. According to (Ris et al., 2001), the empirical growth curve that is best in predicting wave heights for extreme wind speeds is that of (Wilson, 1955). Wilson (1955) states that the wind speed can be related to the wave height by:

$$\frac{H_s g}{U_{10}^2} = \begin{cases} 0.26\, tanh(0.01(\frac{gX}{U_{10}^2})^{0.5}) & for \quad \frac{gX}{U_{10}^2} > 0.1 \\ 2.6 \cdot 10^{-3}(\frac{gX}{U_{10}^2})^{0.5} & for \quad \frac{gX}{U_{10}^2} \to 0 \end{cases} \tag{2.5}$$

In this equation, H_s is the significant wave height, g is the gravitational acceleration, U10 is the wind speed at a height of 10 meters, and X is the fetch in meters. In figure 2.34 the estimation by Wilson is given in blue. The best fit to the data was estimated by varying the fetch length.

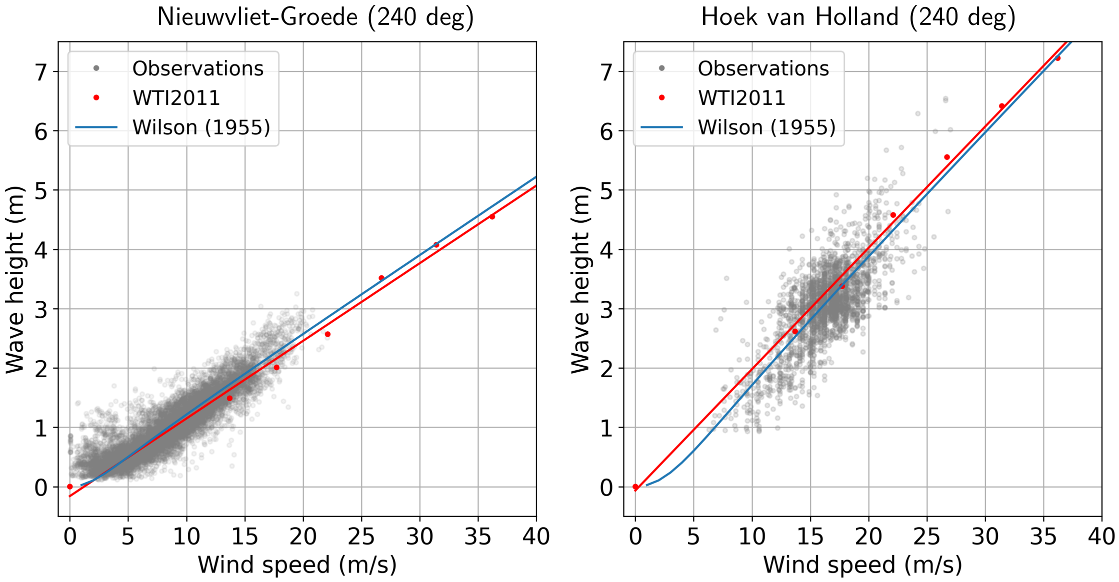


Figure 2.34: Observations of wave height and wind speed for a wind direction of 240 degrees. The estimation of the WTI and the empirical relation by Wilson are also shown.

In reality, wind speed and wind direction do not have distinct values; they vary over time. Therefore, interpolation should be used to cover all wind directions and wind speeds. To give an example; the wave height for a wave from direction 255 is estimated by linearly interpolating between the wave height for 240 degrees and the wave height given a direction of 270 degrees.

Wave period

Figure 2.35 shows the relation between wave height and the corresponding wave peak period. The markers indicate the estimated values by the WTI2011, the grey dots the observations. For simplicity it is assumed that the wave period is linearly related to the wave height.

To verify this assumption, it is compared to an empirical formulation according to (den Heijer, Diermanse, and Gelder, 2005). Den Heijer et al. (2005) states that the peak period can be related to wave height with:

$$T_p = cH_s^d \tag{2.6}$$

In this formula T_p is the peak period, H_s is the wave height and c and d are parameters. When assuming a constant wave steepness, d has to be equal to 0.5. The empirical relation between wave height and wave period is shown in figure 2.35 with the blue line. As can be seen from the figure, the linear approximation holds fairly well. For extreme values at Nieuwvliet-Groede, the linear approximation overestimates the peak period. Also, for low values of the wave height, the wave period is overestimated by the linear approximation.

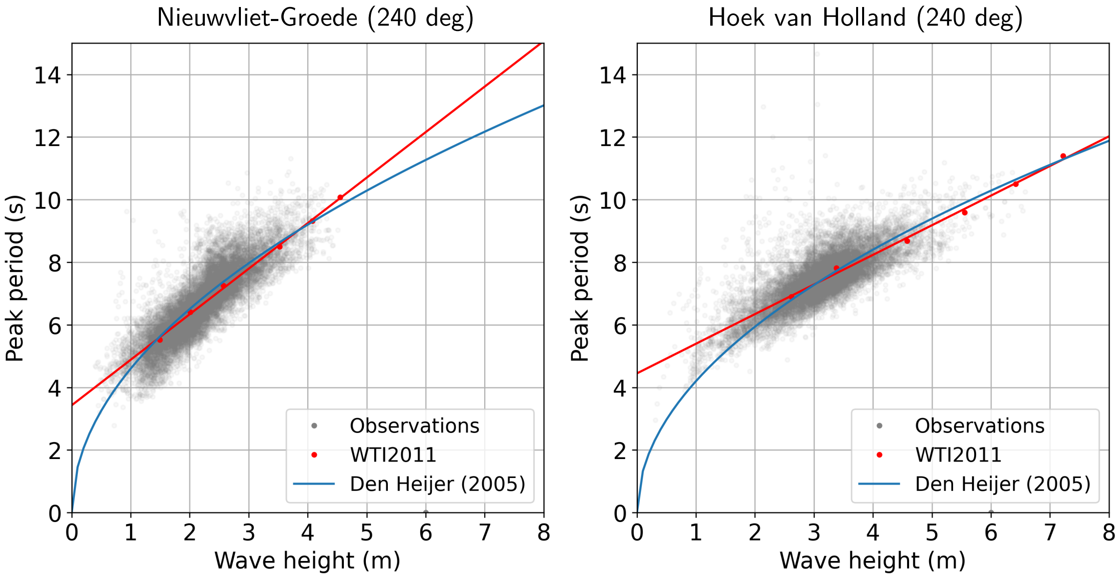


Figure 2.35: Observations of wave height and wave peak period for a wind direction of 240 degrees. The estimation of the WTI and the empirical relation by den Heijer are also shown.

Wave direction

It is assumed that under extreme storm conditions, the wave direction can be considered more or less equal to the wind direction. Although during mild conditions the wave direction can deviate largely from the wind direction, the wind and wave direction seem to align relatively well for extreme conditions (Bowers, Morton, and Mould, 2000; Hildebrandt, Schmidt, and Marx, 2019). As the extreme part of the storm is of most importance, the assumption is assumed justifiable. In appendix C.9 it is shown how the wave direction and wind direction are related during an observed storm. It can be seen that the approximation that wind direction and wave direction holds quite well.

2.5. Model dune erosion

This chapter will focus on the methodology behind the modelling of dune erosion. First it will be explained how the wave input is resampled. Thereafter, the selection of bottom profiles will be explained. The last section will focus on the calculation of dune erosion.

2.5.1. Wave resampling

The estimated wave parameters are defined at ten minute intervals. To decrease computational time and to create a realistic time evolution of the waves, the waves are resampled to an hourly interval. To do so, the significant wave height within this hour should be estimated. The significant wave height can is defined as the mean height of the highest 1/3 of the waves (Bosboom and Stive, 2022). Thus, the hourly significant wave height can be calculated with:

$$H_{1/3} = \frac{1}{N/3} \sum_{i=1}^{N/3} H_i \tag{2.7}$$

2.5.2. Bottom profiles

The hydraulic conditions are known at two locations: Nieuwvliet-Groede and Hoek van Holland. For both locations one representative bottom profile will be chosen. The cross-shore profile for a location at the coast that is representative for Nieuwvliet-Groede can be seen in figure 2.36. Figure 2.37 shows the cross-shore profile at Hoek van Holland. The cross shore distance is measured from the point where the NAP line reaches the bottom.

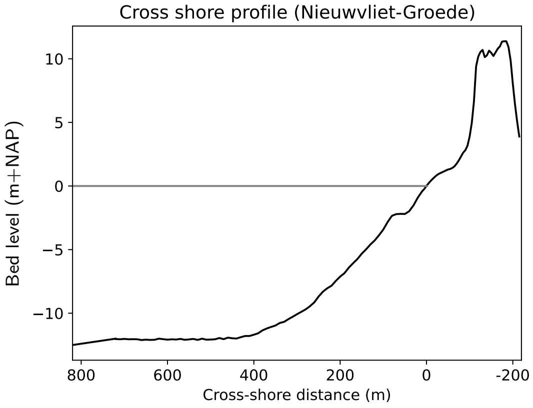


Figure 2.36: Bottom profile Nieuwvliet-Groede (Orientated 128° from North)

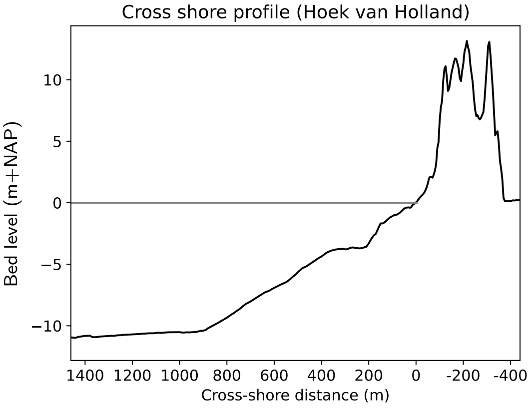


Figure 2.37: Bottom profile Hoek van Holland (Orientated 163° from North)

Extending bottom profiles

The theory that is used in XBeach to model the infragravity wave boundary condition is only valid for deep water conditions. It is known that XBeach overestimates the infragravity wave energy if the boundary is set in shallow water (Deltares, de Bakker, et al., 2021). The required water depth is given by the following two conditions:

$$H_{m0}/d < 0.3$$
$$n(T_p, d) = c_g/c < 0.9$$

In case these are not met, the profile should be extended to a deeper water depth. Within the Dutch dune safety assessments (BOI), this is done by adding an artificial steep part to the required water depth. In this research, the profile is extended such that the requirements are met for the most extreme storm.

Computational grid
The resolution of the bottom profile should be chosen such that it accurately represents reality, and at the same time keep computational times reasonable. The resolution at the dune face should be highest, as this is the area of interest. Furthermore, a certain number of points per wavelength is needed to accurately describe the waves. Above a height of 0 m NAP, the grid size is set to 1 m. At deep water, there should be 40 points per wavelength to model the waves accurately. The minimum wavelength during all storms is chosen to determine the resolution. In the region between deep water and the area above 0 m NAP, the grid size is varied smoothly. This is done prescribed by the BOI literature (Deltares, de Goede, et al., 2021).

2.5.3. XBeach version and settings

The XBeach version used in this research is the XBeach BOI version (23.1.1). This XBeach version is used for the Dutch safety assessments of dunes (Deltares, 2023). The input settings used can be found in appendix D.2.

Wave directional spread
In the BOI assessment of dunes, the wave direction for all waves is assumed perpendicular to the coastline. No change in wave direction during the storm is accounted for in the BOI procedure. In this research, the wave direction corresponding to the storm schematisation will be implemented in the XBeach-input. For 1D simulations, there are two ways to deal with wave direction:

1. Retain directional spreading: refraction only has a small influence on the wave heights, but does allow for non-perpendicular waves and longshore currents.
2. Use one directional bin: this leads to perpendicular waves and no wave refraction is taken into account.

In this report, the second option will be used. By using one directional bin, the waves approach the coastline under an angle of 90 degrees. This option is chosen as it strokes best with the settings in the BOI.

2.5.4. Quantifying dune erosion

To compare the impact of different storms, a method should be chosen to quantify the dune erosion. In this research, storms will be compared by computing the dune erosion volume. The dune erosion volume is the amount of sand that is removed from the dune above a certain reference height. In this research, the reference level is defined at the level of the dune toe. It is assumed that +3m NAP is a good estimation of the vertical dune toe position (Ruessink and Jeuken, 2002; van Ijzendoorn et al., 2021). The dune erosion volume can be calculated by summing the amount of sediment lost above the NAP +3 m line. In figure 2.38 a visual overview is given.

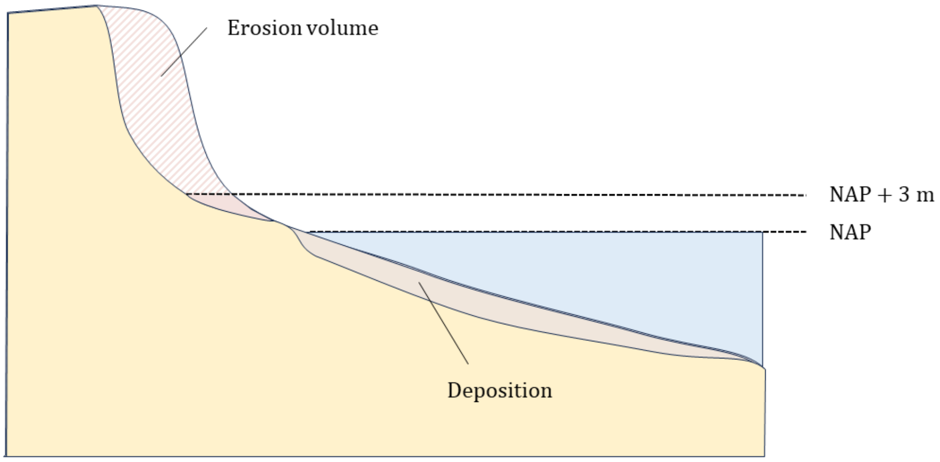


Figure 2.38: Definition of dune erosion volume

3

Results

3.1. Twin storm frequency

In this section, it is described how often twin storms are expected to happen. It is important to note that the number of twin storms is largely dependent upon the chosen definition for twin storms. In this report, the following definition was used:

- The wind speed should exceed 20.8 m/s to be considered a storm.
- The wind speed peaks should be spaced at least 24 hours and at most 120 hours apart.

Other definitions might lead to a frequency that differs from the one calculated in this research. The number of twin storms that is found for a different wind speed threshold and/or interval threshold is further described in appendix A.

In this section, it is described how the number of twin storms varies per wind direction. Also, it is shown how the extreme values for wind speed and surge height for single- and twin storms differ.

3.1.1. Twin storms per direction

In table 3.1 it is shown what the number of single- and twin storms is per wind direction for the locations Nieuwvliet-Groede and Hoek van Holland. As the wind direction varies during the storm, the direction of a storm is defined as the wind direction at the moment of the peak wind speed. The storms are divided over 12 directional bins (30 degrees each). The bins are named after their middle value, so the 240 degree bin contains storms with a wind direction at the peak of 225 - 255 degrees.

First of all, the number of single- and twin storms is higher for Hoek van Holland than for Nieuwvliet-Groede. Apparently, higher wind speeds occur more frequently at Hoek van Holland. When considering all storms, it can be seen that the majority of storms comes from Westerly directions, both at the location of Nieuwvliet-Groede and Hoek van Holland. The wind direction of the peak wind speed is for almost all cases a direction of 180 - 330 degrees from North. Within this research, four directional bins are considered: 210 degrees, 240 degrees, 270 degrees and 300 degrees.

In the table not only the number of single- and twin storms is given, also the proportion of twin storms in relation to single storms. This is calculated by multiplying the number of twin storms by two (one twin storm consists of two storms) and dividing by the number of single storms. It turns out that at Hoek van Holland there are relatively more twin storms than at location Nieuwvliet-Groede. At Hoek van Holland the percentage of twin storms is about 30 % and at Nieuwvliet-Groede only 20%.

Table 3.1: Number of storms per directional bin

	Hoek van Holland			**Nieuwvliet-Groede**		
Direction	Single storms	Twin storms	Proportion	Single storms	Twin storms	Proportion
0	352	32	18.3 %	187	9	9.6 %
30	188	13	13.8 %	55	1	3.6 %
60	185	4	4.3 %	44	1	4.5 %
90	118	3	5.1 %	30	1	6.7 %
120	18	-	-	1	-	-
150	73	8	21.9 %	11	-	-
180	1938	198	20.4 %	440	27	12.3 %
210	9915	1364	27.5 %	2723	222	16.3 %
240	17974	2784	31.0 %	7230	793	21.9 %
270	8181	1306	31.9 %	3231	370	22.9 %
300	3525	485	27.5 %	1693	143	16.9 %
330	1344	148	22.0 %	656	30	9.1 %

** The grey color indicates the directional bins that are considered in this research.*

3.1.2. Wind speed return periods

The conditions during a storm are largely dependent upon the observed wind speed. Therefore, it is important to consider the wind speed that is expected during a single storm and during a twin storm. The left side of figure 3.1 shows the maximum wind speed for single storms and twin storms that is expected to occur at Hoek van Holland for a certain return period. It can be seen that the wind speed expected to occur during a single storm is higher than for a twin storm considering the same return period.

When looking at the left figure, the horizontal distance between the lines indicates the probability of having a twin storm given that there is a storm with a certain wind speed. For example: when considering a wind speed of 25 m/s, the return period for a single storm is 1.5 years, for a twin storm the return period is approximately 6 years. That means that given a storm with a wind speed of 25 m/s the probability is 25% (1.5/6) that the storm is a twin storm. To consider whether twin storms occur more frequently in the extreme domain, for each wind speed the probability can be calculated. The right figure shows the probabilities. It can be seen that the horizontal distance between the lines decreases and thus the probability increases. For wind speeds higher than 25 m/s, the horizontal distance stays quite constant and therefore the probability does so too. For the most extreme wind speeds, some scatter can be observed. This is due to the fact that there are less data points in the extreme domain.

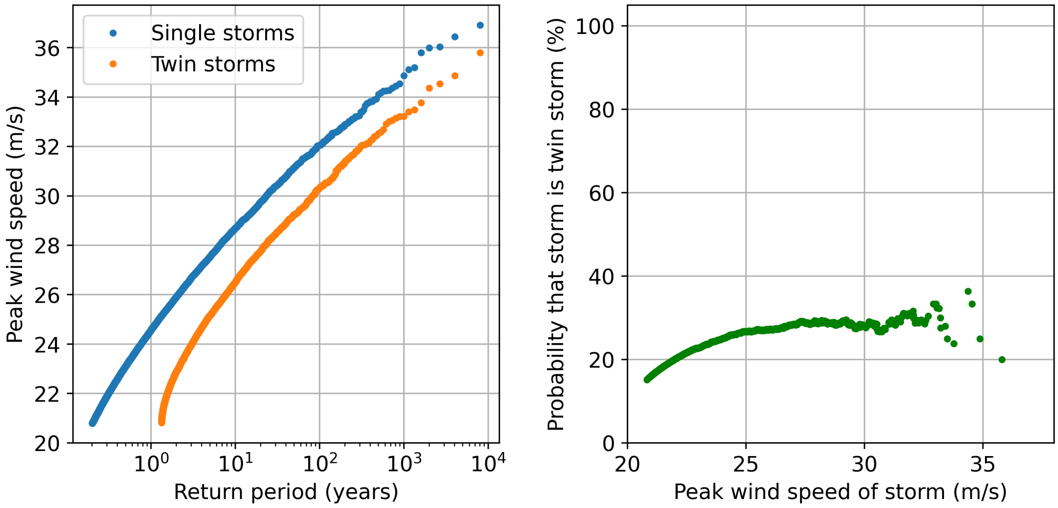


Figure 3.1: Left: return period of peak wind speeds for storms at Hoek van Holland.
Right: probability that a storm is part of a twin storm given certain peak wind speed.

Figure 3.2 shows the same figure but now for Nieuwvliet-Groede instead of Hoek van Holland. In the left figure it can be seen that the most extreme wind speeds observed at Nieuwvliet-Groede are somewhat lower than the most extreme wind speeds at Hoek van Holland. Remarkably, the 4 highest wind speeds observed at Nieuwvliet-Groede are all observed during a twin storm. It is hard to tell whether this is the effect of little data in the extreme domain or because of the fact that the most extreme storms have a higher probability of being a twin storm.

In the right figure it is shown how the probability of observing a twin storm is, given that a storm with a certain wind speed occurs. It can be seen that the probability of observing a twin storm increases for wind speeds from 20.8 - 26 m/s. For wind speeds larger than 26 m/s, there is no clear increase or decrease of probability for increasing the wind speed. As the probability is calculated empirically, a problem arises when considering the four most extreme storms. As those storms all are twin storms, the empirical probability of observing a twin storm is equal to 100%. However, the actual probability of observing a twin storm given an extreme wind speed obviously is not equal to 100%.

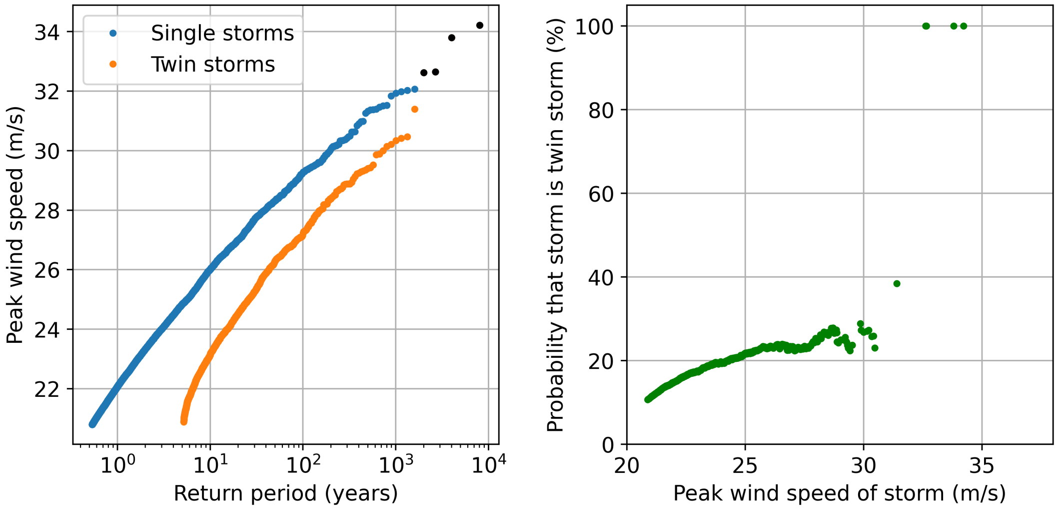


Figure 3.2: Left: return period of peak wind speeds for storms at Nieuwvliet-Groede.
Right: probability that a storm is part of a twin storm given certain peak wind speed.

3.1.3. Surge height return periods

Another important parameter when considering dune erosion during storms is the surge height. In this subsection, the return period for surge heights given single- and twin storms is given. The left side of figure 3.3 shows the surge height for single storms and twin storms, given a certain return period. It can be seen that, when considering the same return period, the single storms have larger surge heights than the twin storms. Also it can be seen that for the most extreme return periods, there is only a small difference for the surge height of single and twin storms.

The right figure shows the probability that a storm is a twin storm given that a storm has a certain surge height. This is closely related to the horizontal distance between the two lines in the left plot. For surge heights between 0 and 1.7 m, it can be seen that the probability of observing a twin storm increases for increasing the surge height. For surge heights larger than 1.7 m, it can be seen that there is no clear increase or decrease of the probability. Scatter is observed for the most extreme surge heights. This is due to the fact that the probability is calculated empirically and there are little datapoints for those most extreme values. The probability that a storm with a surge height higher than 1.7 m is a twin storm seems to be about 25%, this is similar to the percentage that was found when considering the wind speed.

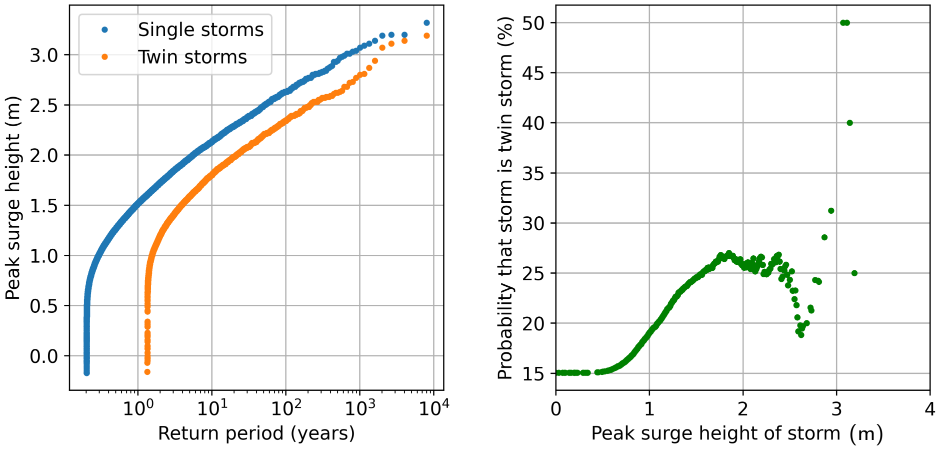


Figure 3.3: Left: return period of peak surge heights for storms at Hoek van Holland. Right: probability that a storm is part of a twin storm given certain peak surge height.

In figure 3.4 the same figure is shown but now for surge heights at Nieuwvliet-Groede. It can be seen that the extreme surge heights are higher at Nieuwvliet-Groede than at Hoek van Holland. Apart from the different values, very comparable results are found; the probability of observing a twin storm increases for surge heights of 0 - 2m. For surge heights larger than 2 meters, the probability shows no clear increase or decrease. From the right figure it can be seen that the probability of a twin storm at Nieuwvliet-Groede given a surge height higher than 2 meters is about 20%. This is somewhat lower than the 25% that was found when comparing the wind speeds of single- and twin storms at Nieuwvliet-Groede.

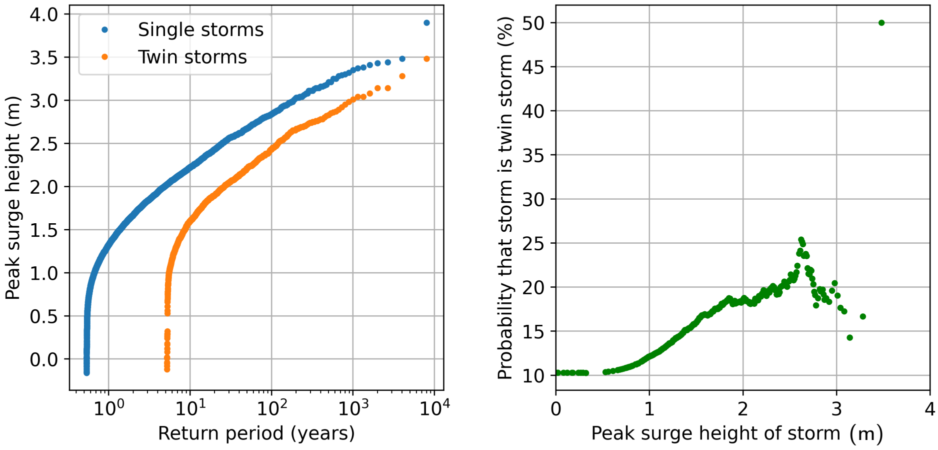


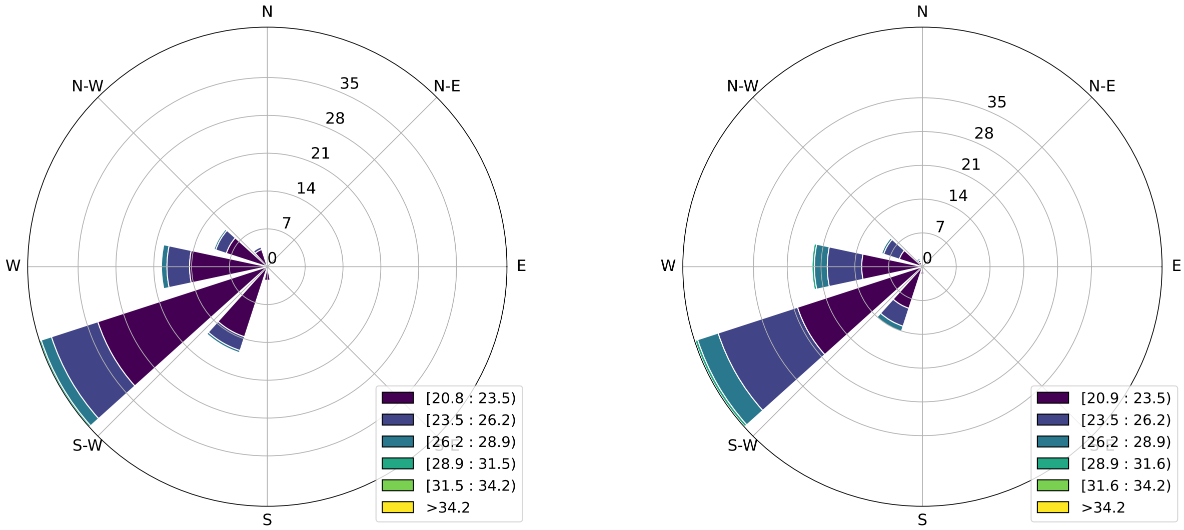
Figure 3.4: Left: return period of peak surge heights for storms at Nieuwvliet-Groede. Right: probability that a storm is part of a twin storm given certain peak surge height.

3.2. Storm characteristics

In this report, storms were split into several storm clusters. For single storms, this led to a total of 24 schematisations and for twin storms 216 storm schematisations were made. The categorisation is based on respectively three and five features for the single- and twin storms. The features for twin storms are the same as for single storms plus two additional features. The three features used for both are location, wind direction, return period. For twin storms the two additional features are wind speed evolution and surge height evolution. In this section, results for the wind direction, wind speed evolution and surge height evolution are shown.

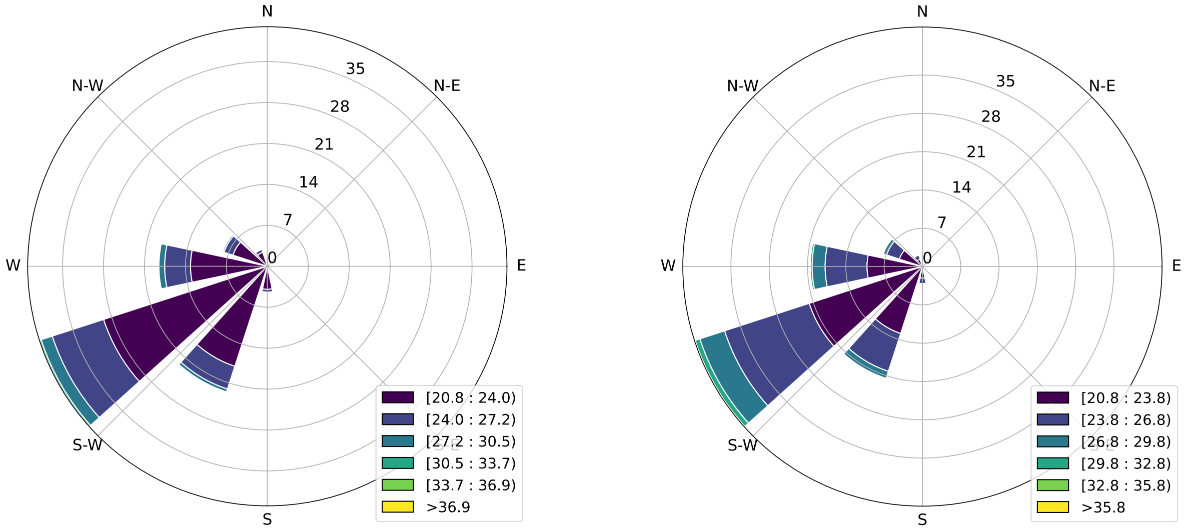
3.2.1. Wind direction

In figure 3.5 the windroses for single storms and twin storms for both locations are shown. The windrose indicates the wind direction at the moment of the peak wind speed of the storm. For twin storms, the wind direction is defined as the direction at the moment of the maximum wind speed of both storms. It can be seen that almost all storms are from Westerly directions, mainly South-West. From the figure it can be seen that the distribution of storms over the directional bins is the same for both single- and twin storms.



(a) Nieuwvliet-Groede - Single storms

(b) Nieuwvliet-Groede - Twin storms

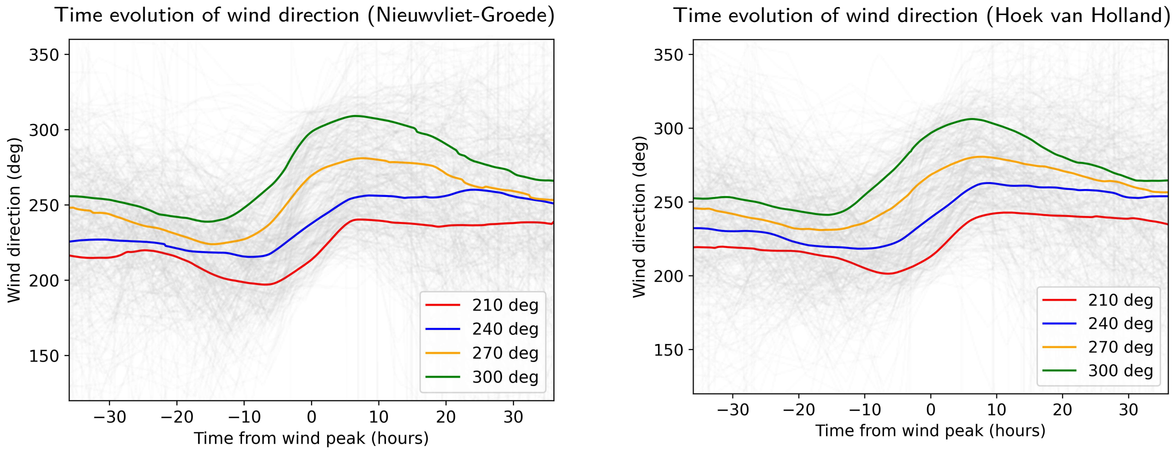


(c) Hoek van Holland - Single storms

(d) Hoek van Holland - Twin storms

Figure 3.5: Windroses for peak wind directions of all single and twin storms at both locations

The wind direction is not constant during the storm. The wind direction changes during the evolution of the storm. Figure 3.6 shows the evolution of the wind direction for single storms from four different directions. It can clearly be seen that all storms from different directions show a similar evolution in time; the wind direction changes from South-West to West or from West to North-West over the course of the storm.



Nieuwvliet-Groede - Single storms

(a) Hoek van Holland - Single storms

Figure 3.6: Time evolution of wind direction for all single storms shown in grey. The colored lines indicate the time evolution of the mean wind direction for storms from one direction.

3.2.2. Wind evolution

A twin storm consists of two wind peaks. Both peaks can have different wind speeds and directions. Analysis has shown that the correlation between the wind speeds for both wind peaks is rather low so that the wind speed peaks of both storms can be considered independent. It was decided to divide the wind evolution into three categories: high-low, mid-mid and low-high. In figures 3.7 and 3.8 the maximum wind speed for storm 1 is given on the x-axis and the maximum wind speed of storm 2 is given on the y-axis. The grey dashed lines indicate the separator line.

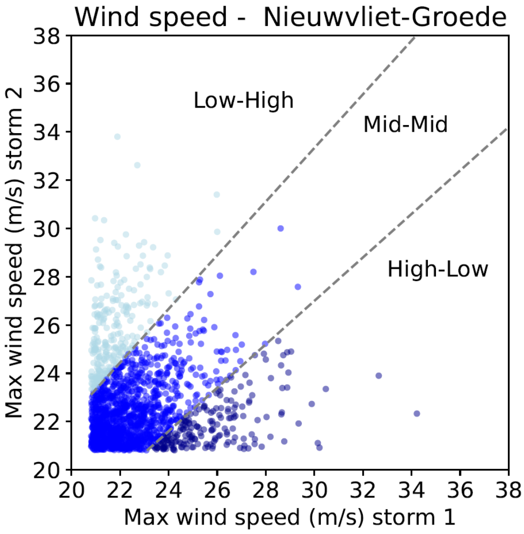


Figure 3.7: Peak wind speeds for all twin storms at Nieuwvliet-Groede

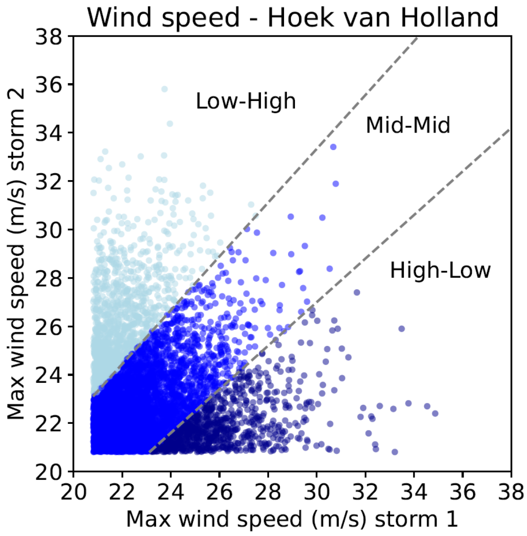


Figure 3.8: Peak wind speeds for all twin storms at Hoek van Holland

3.2.3. Surge evolution

Each twin storm also has two surge peaks. In a similar manner, these are divided into categories. In figure 3.9 three plots are shown: one for the high-low wind storms, one for the low-high wind storms and one for the mid-mid wind storms. On the x-axis, the height of surge peak one is given and on the y-axis the height of surge peak two. For the high-low wind storms it can be seen that most storms have a high-low or mid-mid surge evolution. A combination of high-low wind with low-high surge is quite rare. The low-high wind storms show exactly the opposite. For mid-mid wind storms all surge evolutions are well represented. A table with storms per cluster can be found in appendix B.

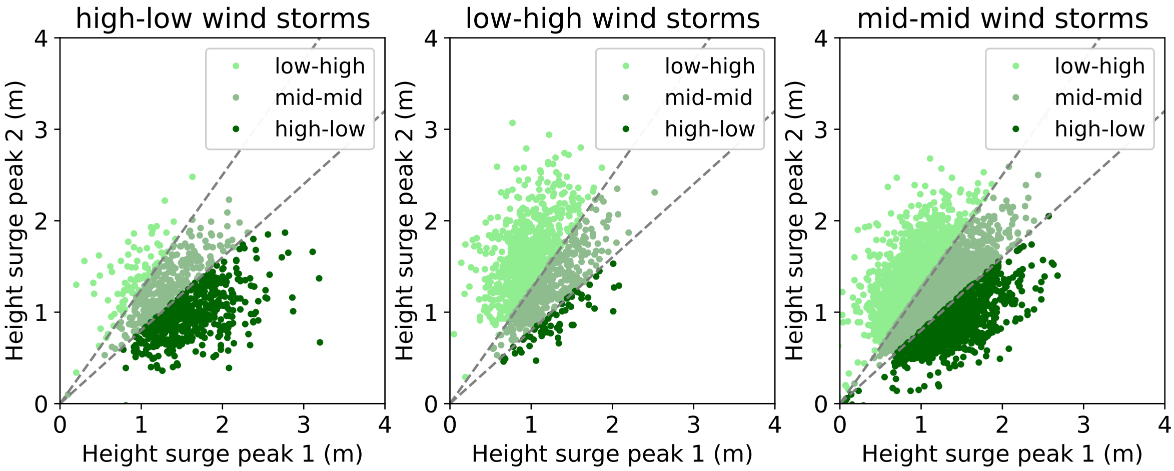


Figure 3.9: Each subfigure shows the peak surge heights of all twin storms at Hoek van Holland, conditional on the type of wind speed evolution. The different shades of green indicate the different types of surge height evolution.

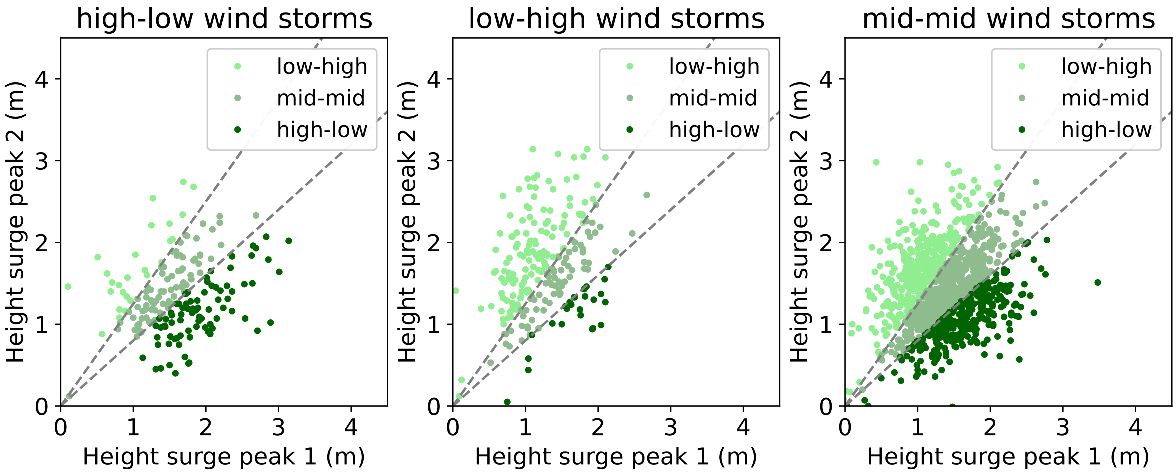


Figure 3.10: Each subfigure shows the peak surge heights of all twin storms at Nieuwvliet-Groede, conditional on the type of wind speed evolution. The different shades of green indicate the different types of surge height evolution.

3.3. Schematisation result

In total 240 storm schematisations were produced. Evidently, it is impossible to show all schematisations here. Therefore, one exemplary single storm and twin storm are elaborated. Thereafter, it is shown how the schematisation compares to an observed reference storm. Finally, a comparison is made with the Dutch safety assessment for sandy coasts (BOI).

3.3.1. Single storms

The single storm that is shown in this section is [Hoek van Holland, 240 deg, 1000 years] which means that the location of the storm is Hoek van Holland, the wind direction at the peak is 240 degrees and the storm has a return period of 1000 years. In figure 3.11 the wind speed and wind direction of the storm are shown. It can be seen that the wind speed quite gradually increases and decreases around the peak. The wind direction tends to go from a south-westerly direction to a more westerly direction during the wind speed peak.

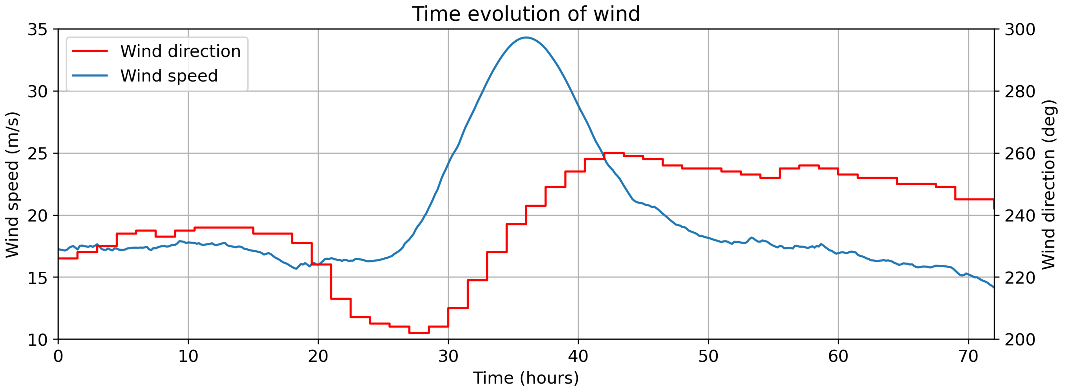


Figure 3.11: Time evolution of wind speed and wind direction for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years]

The surge height and water level that correspond to the storm are shown in figure 3.12. It can be seen that the surge peak occurs some time after the wind peak of the storm. Also, it can be seen that the maxima of the tide and the surge do not occur at the same time.

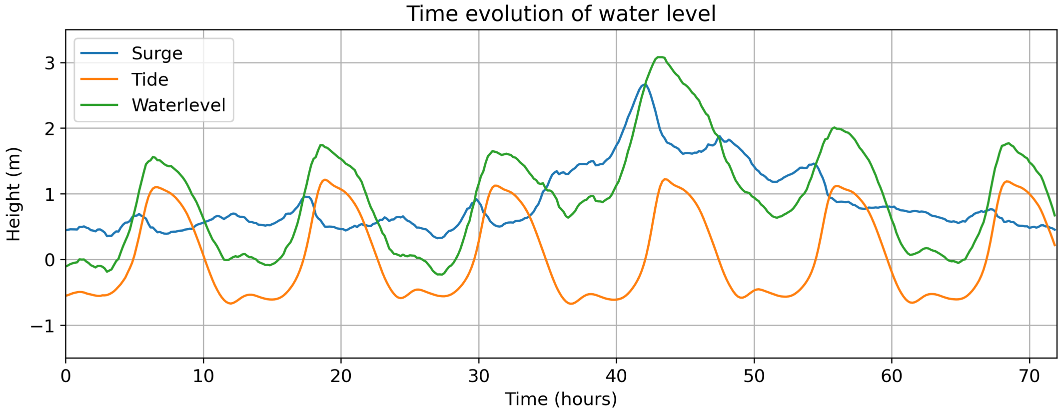


Figure 3.12: Time evolution of surge height, water level and tidal level for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years]

Figure 3.13 shows the wave height and wave period during the storm. As the wave height and wave period are largely related to the wind speed, a similar evolution can be observed. Besides the wave height and wave period, also the wave direction is of influence. As the wave direction is taken equal to the wind direction, it is not shown again here.

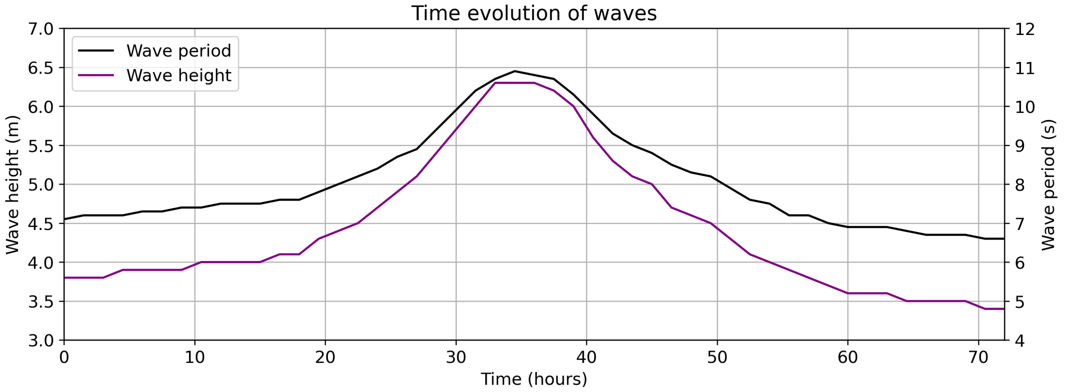


Figure 3.13: Time evolution of wave height and wave peak period for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years]

3.3.2. Twin storms

The twin storm that is shown in this section is [Hoek van Holland, 240 deg, high-low wind, mid-mid surge, 1000 year]. This means that the storm occurs at the location Hoek van Holland, the wind direction of the highest wind peak is 240 degrees, the first wind peak is higher than the second wind peak, the surge heights of peak 1 and two are (almost) equal and the return period of the storm is 1000 years.

Figure 3.14 shows the time evolution of the wind speed and wind direction. It can clearly be seen that the wind speed of the first peak is higher than that of the second peak. Furthermore it can be seen that for both wind peaks, the wind direction tends to deflect to the North after the peak of the wind speed.

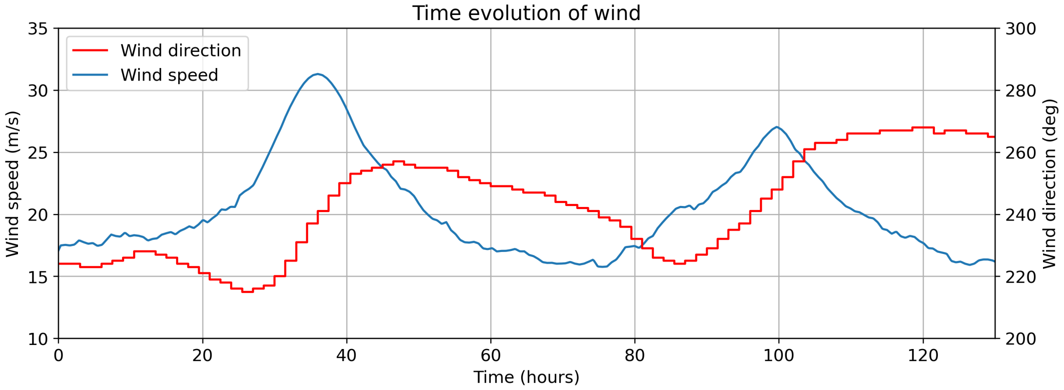


Figure 3.14: Time evolution of wind speed and wind direction for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years, high-low wind, mid-mid surge]

The water levels during the storm are shown in figure 3.15. The surge height of the first peak is almost equal to that of the second peak. Furthermore it can be seen that the surge peak occurs just before the tidal peak.

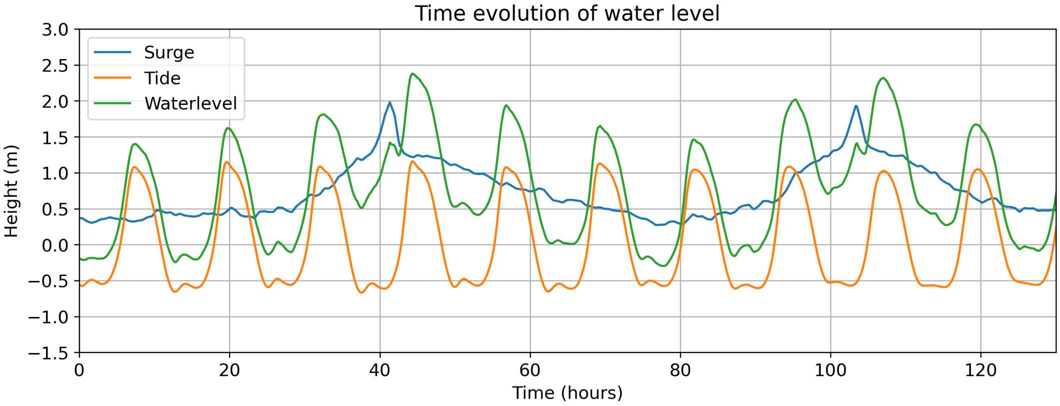


Figure 3.15: Time evolution of water level, surge height and tidal level for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years, high-low wind, mid-mid surge]

In figure 3.16 it is shown how the waves evolve over time. As the waves in this report are related to the wind, the wave evolution resembles the time evolution of the wind. The maximum peak period occurs at the same instance as the maximum wave height.

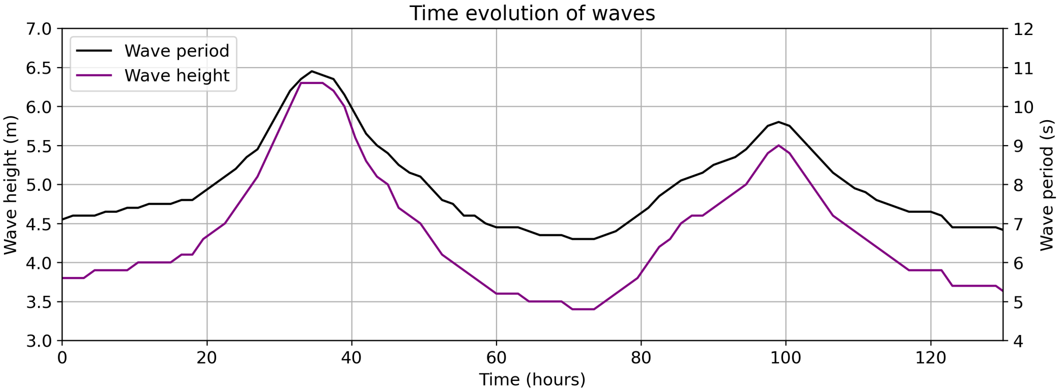


Figure 3.16: Time evolution of wave height and wave peak period for storm schematisation of one cluster [Hoek van Holland, 240 deg, 1000 years, high-low wind, mid-mid surge]

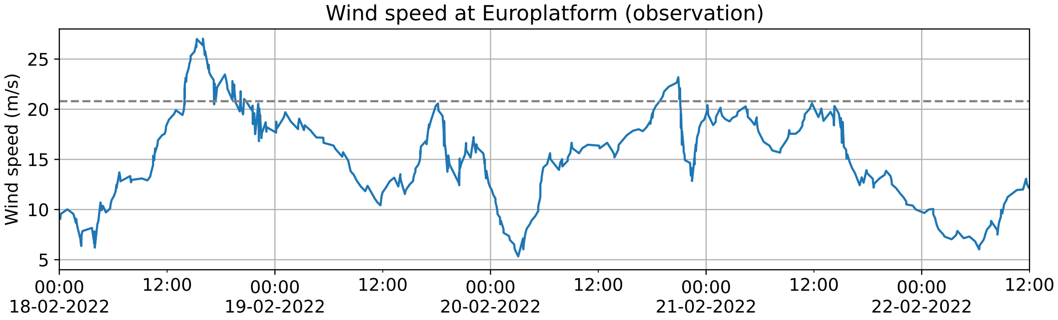
3.3.3. Reference storm

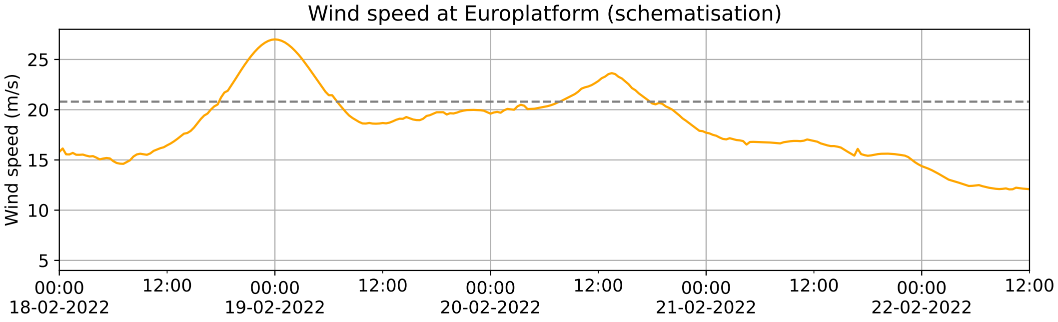
To judge the storm schematisations made, a comparison is made with an observed storm. The observed storm used as reference storm are the storms of february 2022. In the period 17-21 february 2022, the storms Dudley, Eunice and Franklin passed the Netherlands (Zijderveld et al., 2022). As the focus in this research is on twin storms, here only the storms Eunice and Franklin are considered. First it is explained how the storm is categorised according to the clusters proposed in this research. Thereafter, the schematisation is compared to the observed storm.

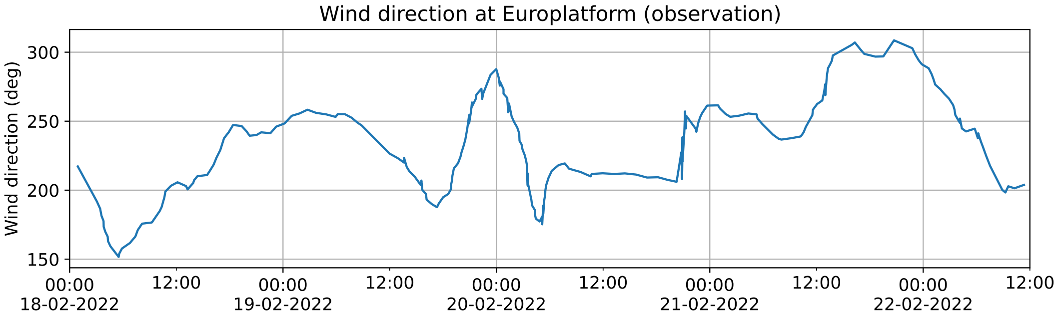
From Eunice and Franklin, Eunice had the highest wind speed peak. The direction at the moment of the first peak is 216 degrees so the storm is considered a ’210 degree’-storm. Furthermore, the wind evolution was high-low and the surge evolution can be described as low-high. According to the estimations within this research, the return period of this storm is 364 years. Thus, a storm schematisation is made for this cluster. Instead of a return period of 1000, 3000, 10000 years as used in this research for this case a storm schematisation is made for a 364-year storm.

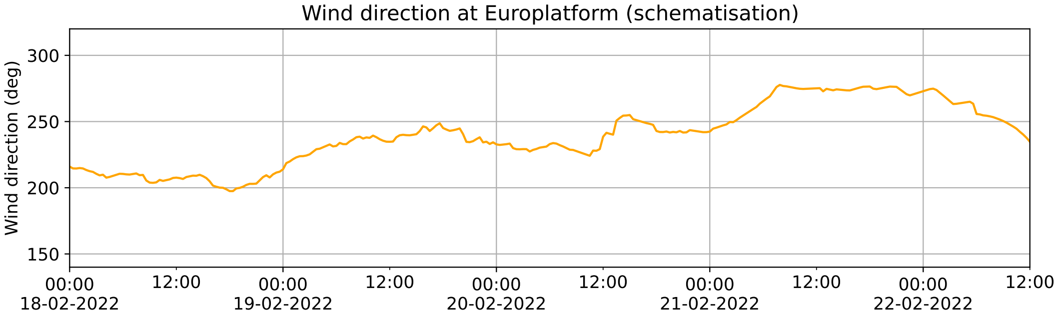
In figure 3.16 it is shown how the storm evolves in time. For both the observed- and schematised storm, the wind speed, wind direction and surge height are shown. The schematised storm is aligned such that the wind peaks are closest to the real wind peaks. However, the interval duration of the observed- and schematised storm is not the same so aligning the peaks at exactly the same moment in time is not possible.

The first thing to notice is that the schematised storm evolves more gradually than the observed storm. This is due to the fact that it is an average of multiple storms. It also explains why the lower wind speed peak around the 20th of February in the observed storm is not reproduced by the schematised storm. Although the values of the parameters do not agree exactly, the overall form seems to be quite comparable.


Wind speed at Europlatform (observation)


Wind speed at Europlatform (schematisation)


Wind direction at Europlatform (observation)


Wind direction at Europlatform (schematisation)

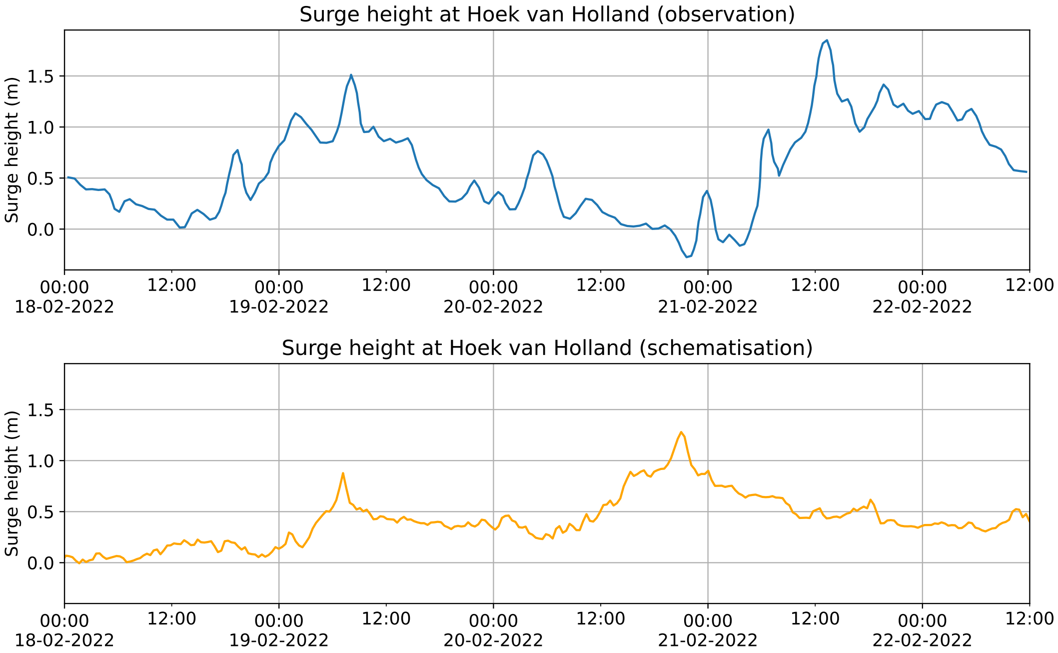
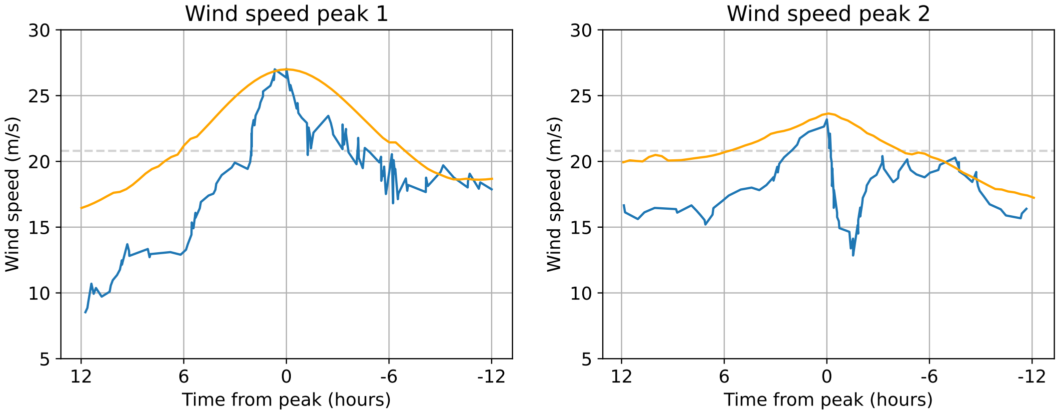


Figure 3.16: Time evolutions of different storm parameters for reference storm and the corresponding storm schematisation of storm

To give a more detailed view on the most extreme parts of the storm, the peaks can be compared to show the differences. In figure 3.16 the peaks of the wind speed, wind direction and surge height are shifted to the same time instance and plotted.

For the wind speed it can be seen that the heights are approximately equal and are thus well represented by the schematisation. Though the duration of the wind peaks are somewhat overestimated when comparing the schematised storm to the observed storm. When it comes to wind direction, the values do not agree exactly but the evolution in time is the same. For the first storm, the direction increases from South-West to North-West and for peak two, a distinct jump in direction can be seen. Considering the surge; the form of the profile seems similar but the surge peaks are clearly underestimated by the schematisation.



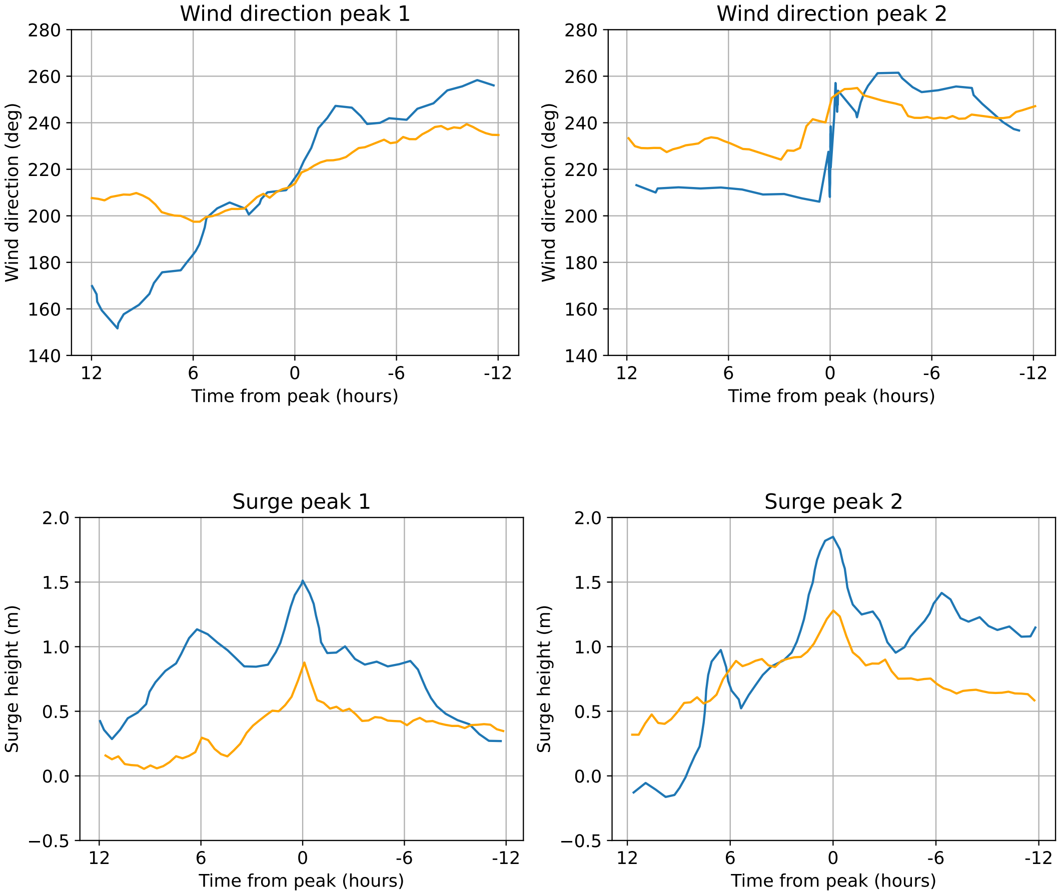


Figure 3.16: Comparison of the peaks of wind speed, wind direction and surge height for the reference storm and schematisation

3.3.4. Dutch dune safety

To assess the resilience of the Dutch coastal dunes against extreme storms, XBeach models are used. To do so, a time evolution of the storm parameters is dictated. In figure 3.17 it is shown how the formulation for the BOI is compared to the storm schematisation used in this report. Note that the BOI is shifted in time so that the wind peaks are at the same time instance. A few important differences can be seen:

- Both the maximum wave height and water level are lower for the constructed schematisation than for the BOI model.
- The duration extreme wave heights and wave periods are longer for BOI than those estimated with the constructed model.
- In the BOI, there is no phase between maximum surge level and maximum wave height.

More elaboration on the differences between the schematisation in this report and the time evolutions as dictated by the BOI can be found in section 4.6.

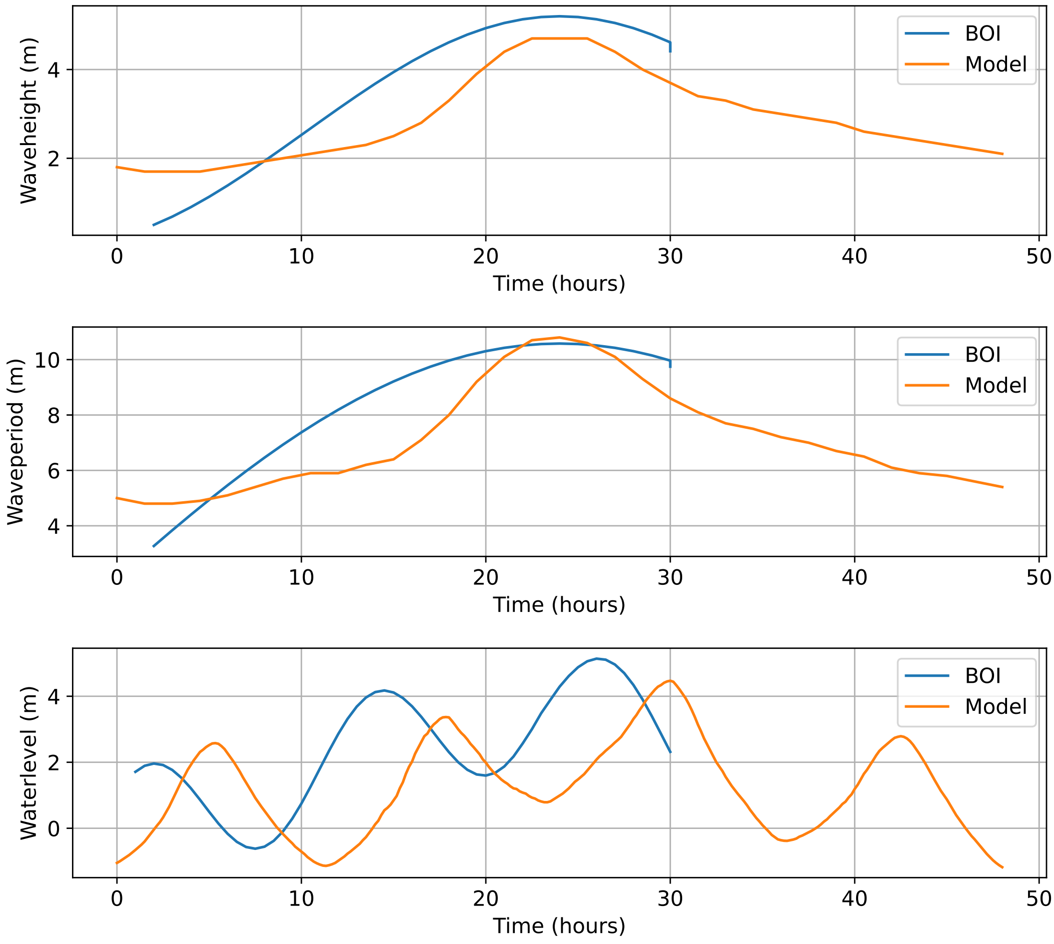


Figure 3.17: BOI compared to storm schematisation for one storm cluster [Nieuwvliet-Groede, 300 deg, 3000 years]

3.4. Dune erosion

To compute the dune erosion that is expected for both single and twin storms, the dune erosion was modelled using the XBeach model. In this section the results are described. First, it is explained how the evolution of the dune profile evolves over time. In the second paragraph, the relation between storm parameters and dune erosion is explained. Thereafter, the dune erosion volumes for each storm cluster are shown and the influence of return period is elaborated. Finally, the dune erosion volumes are compared to the Dutch safety assessment (BOI).

3.4.1. Evolution in time

In figure 3.18 the cross shore profile is shown both before and after the storm. For the twin storms, also the profile after the first storm is included. It can be seen that the single storm gives most dune erosion. Furthermore, it can be seen that for the twin storms the cross shore profile evolution is dependent on the characteristics of the first and second storm.

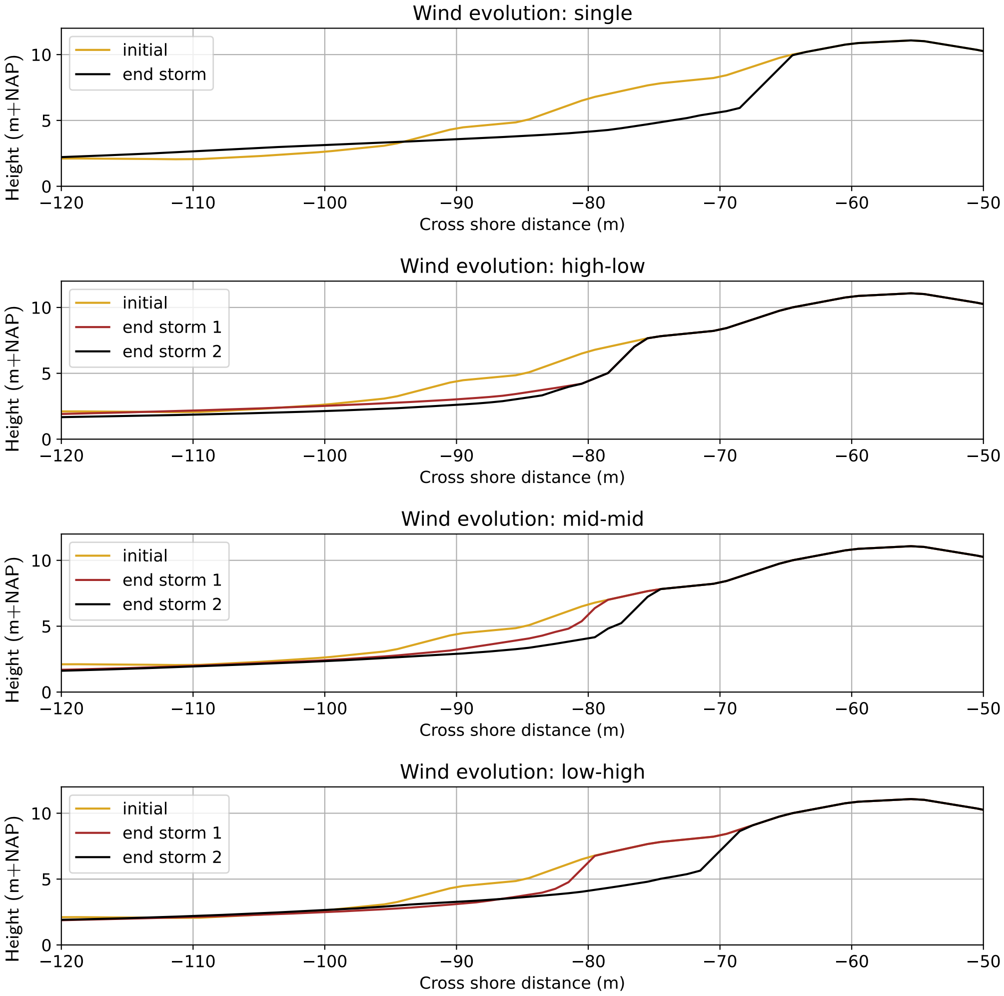


Figure 3.18: Dune profile before and after a storm for different storm clusters. The upper figure shows the dune erosion of a schematisation for a single storm [Hoek van Holland, 300 degrees]. The lower figures show the dune erosion for three different twin storm clusters [Hoek van Holland, 300 deg, mid-mid surge, 10000 years]. The type of wind speed evolution is varied in the three plots.

3.4.2. Dune erosion volume related to storm parameters

In this subsection, the amount of dune erosion is compared to the storm parameters. The parameters that are considered are the maximum wave height during the storm and the maximum surge height.

Figure 3.19 shows the dune erosion volumes related to the maximum surge height within a storm. A large correlation can be found: for Nieuwvliet-Groede the correlation is 0.91 and 0.9 for single and twin storms. The correlations for Hoek van Holland are 0.93 and 0.91. Also, it can be seen that twin storms are more damaging than single storms given they have the same maximum surge height.

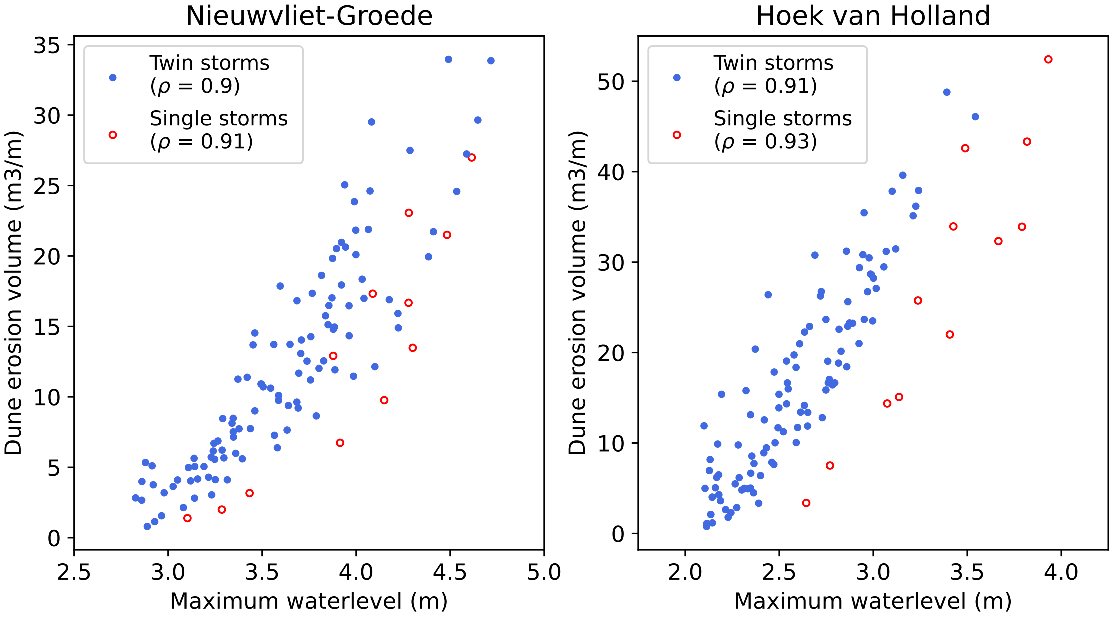


Figure 3.19: Dune erosion volume compared to maximum water level for all storm schematisations

It can be seen that if a twin storm has a higher maximum water level, it gives more erosion than a single storm. However, single storms generally have higher maximum water levels than twin storms. Thus, from this figure no conclusions can be drawn on the relation between dune erosion for single and twin storms.

In figure 3.20 the modelled dune erosion volume is plotted against the maximum wave height during the storm profile. A distinction is made between single- and twin storms. The Pearson's correlations for wave height and dune erosion volume for single storms and twin storms at location Nieuwvliet-Groede are given in the plot.

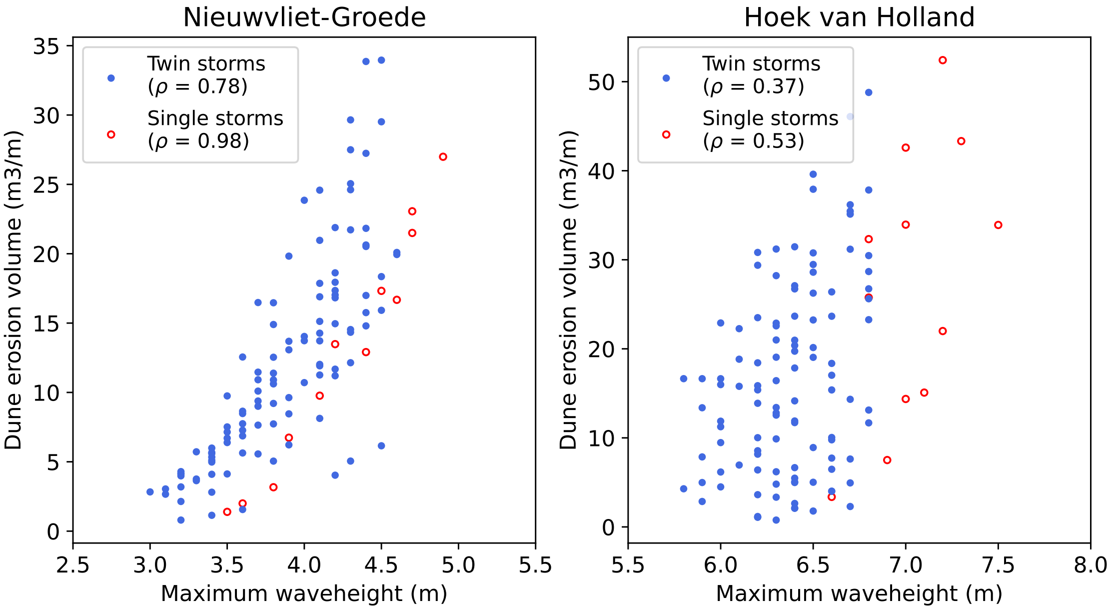


Figure 3.20: Dune erosion volume compared to maximum wave height for all storm schematisations

For Nieuwvliet-Groede, the dune erosion is largely correlated to both the water level and wave height. At Hoek van Holland, the wave height is of minor importance. In figure 3.21 it is shown how for all the storm schematisations, the maximum wave height correlates with the maximum water level. For Nieuwvliet-Groede, the storm schematisations with a high water level also give large wave heights. At Hoek van Holland, a large water level does not necessarily coincide with a large wave height.

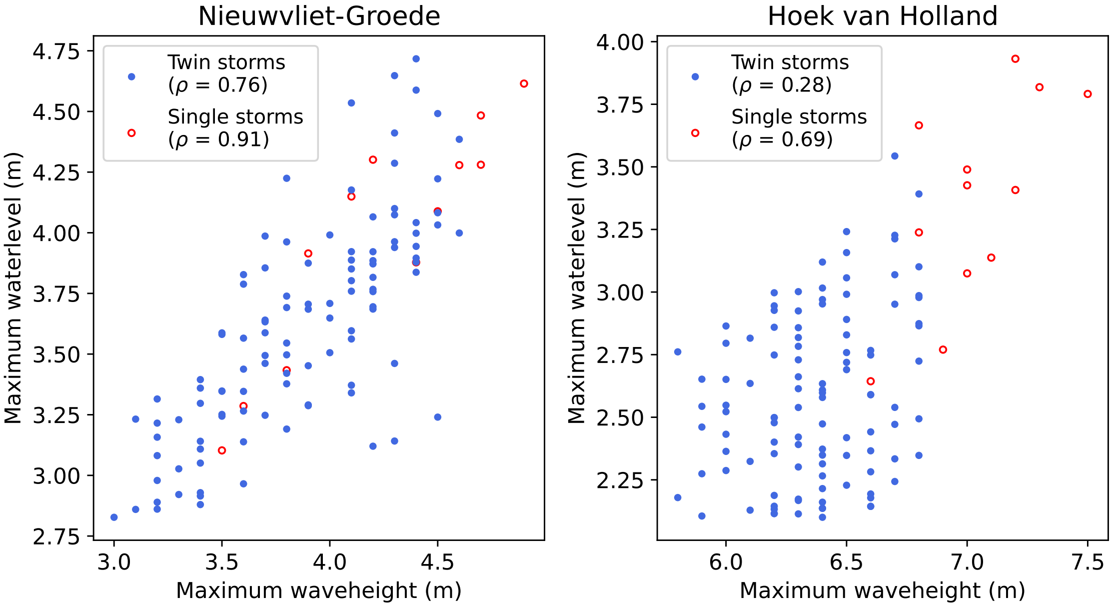


Figure 3.21: Wave height compared to waterlevel for all storm schematisations

3.4.3. Dune erosion volumes

In figure 3.22 the dune erosion volumes are shown for storms at Nieuwvliet-Groede with a return period of 3000 years. The blue bars indicate the amount of dune erosion and the green bars show the percentage of storms that is represented by a certain cluster. The blue dashed lines indicate the amount of dune erosion for a single storm from the same direction with an equal return period. It can clearly be seen that the direction of the storm has a large influence on the amount of dune erosion. Storms from direction 210 degrees give the least dune erosion, storms from direction 270 and 300 degrees the most. Furthermore, it can be seen that for direction 210 degrees, almost all twin storms give more dune erosion than single storms. For the other directions it can be seen that the clusters with the highest percentage of twin storms almost always give less dune erosion than a single storm.

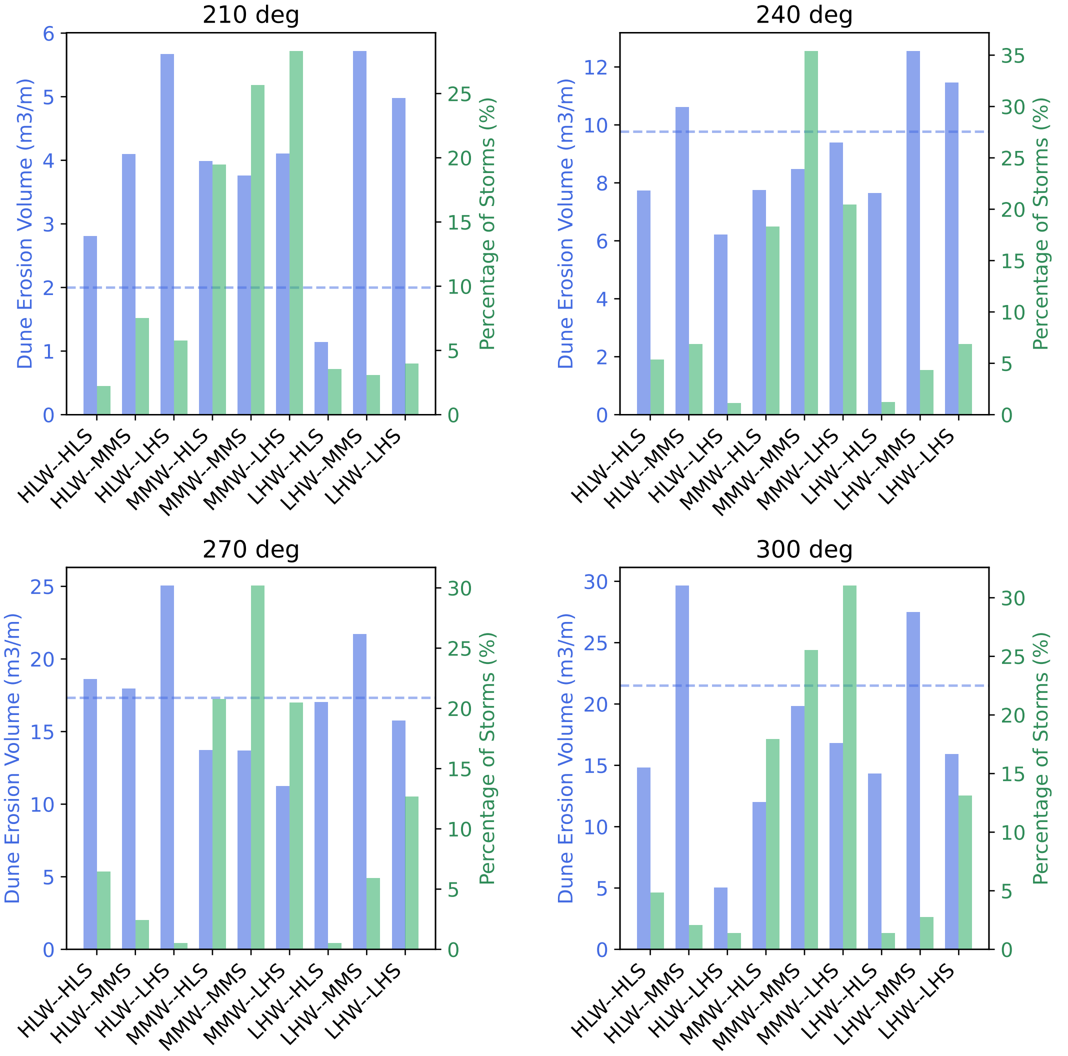


Figure 3.22: Dune erosion volume per cluster for storms at Nieuwvliet-Groede with a return period of 3000 years. The dashed line indicates the dune erosion volume of the single storm corresponding to the same wind direction. (HLW = High Low Wind, MMW = Mid Mid Wind, LHW = Low High Wind, HLS = High Low Surge, MMS = Mid Mid Surge, LHS = Low High Surge)

In figure 3.23 it is shown how much dune erosion occurs due to storms at Hoek van Holland. The blue bars indicate the amount of dune erosion, the green bar the percentage of storms within a certain cluster. The dashed blue line shows how much dune erosion a single storm from the same direction and with the same return period gives. Just as at the location of Nieuwvliet-Groede, it can be seen that the most damaging storms are those from direction 270 degrees and 300 degrees. Where for Nieuwvliet-Groede some twin storm clusters gave more dune erosion than single storms, at Hoek van Holland almost in all cases the single storm gives more dune erosion.

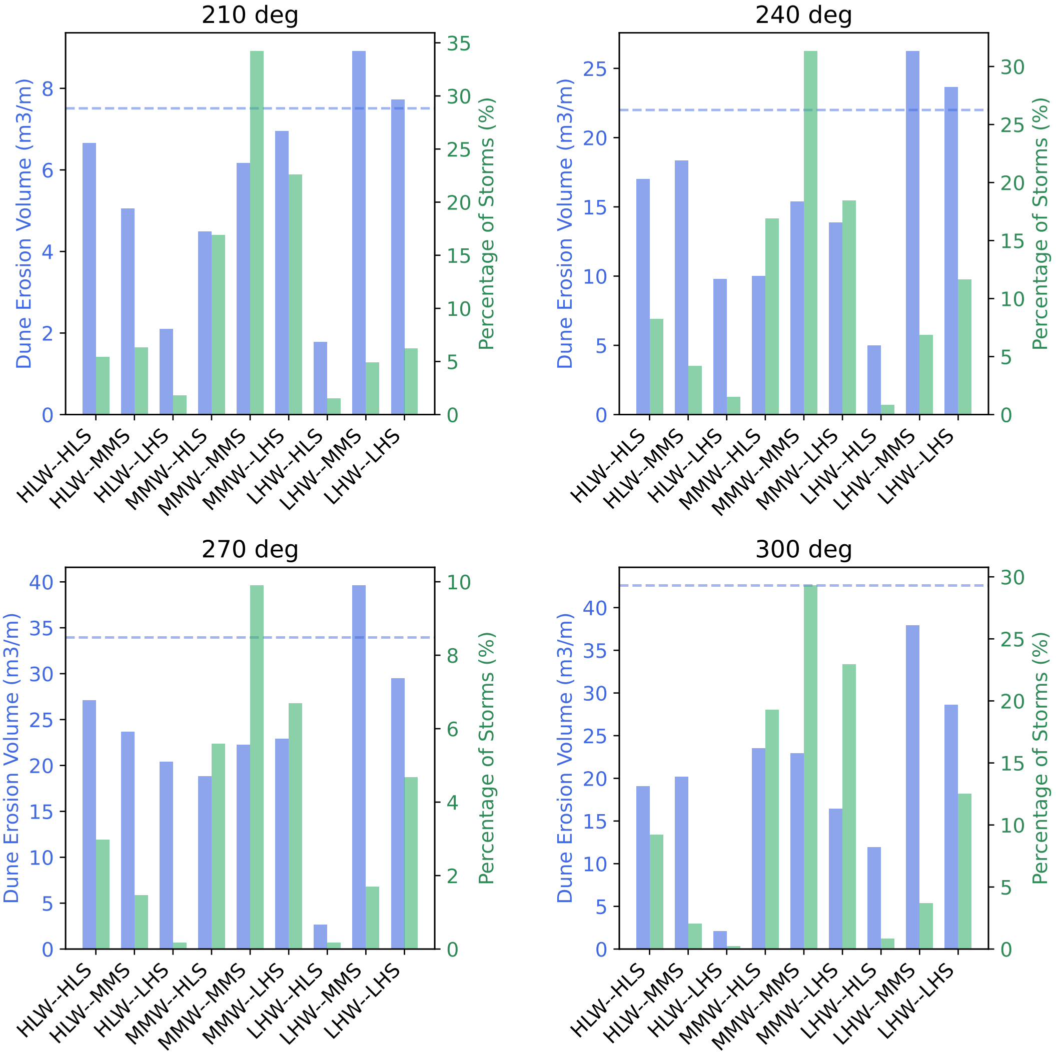


Figure 3.23: Dune erosion volume per cluster for storms at Hoek van Holland with a return period of 3000 years. The dashed line indicates the dune erosion volume of the single storm corresponding to the same wind direction. (HLW = High Low Wind, MMW = Mid Mid Wind, LHW = Low High Wind, HLS = High Low Surge, MMS = Mid Mid Surge, LHS = Low High Surge)

3.4.4. Dune erosion per return period

In figure 3.24 it is shown what the influence is of the return period on the dune erosion induced by storms. In blue, it is shown how much dune erosion each storm cluster gives, normalised with respect to the dune erosion of a single storm. In green it is shown what percentage of storms is within a certain cluster. The blue dashed line shows the amount of dune erosion of a single storm. As the twin storm dune erosion is shown relative to the amount of dune erosion of a single storm, the dune erosion for a single storm is set to 1.

From the figure, the following can be observed:

- Twin storms from direction 210 degrees almost always give more dune erosion than a single storm from that direction. Furthermore, the twin storms from direction 210 degrees can give 2 to 3 times more dune erosion than a single storm from 210 degrees. For the other directions, the amount of dune erosion by a twin storm often is only 0.8 to 1.5 times the dune erosion of a single storm from the same direction.
- Most storms have a wind direction of 240 degrees as can be seen by the fact that the green bars for direction 240 degrees are much higher.

- The amount of dune erosion a twin storm gives, normalised with respect to dune erosion by a single storm from the same wind direction, is similar for different return periods. In other words, twin storms with longer return periods do not result in a higher percentage of dune erosion compared to the corresponding single storm.

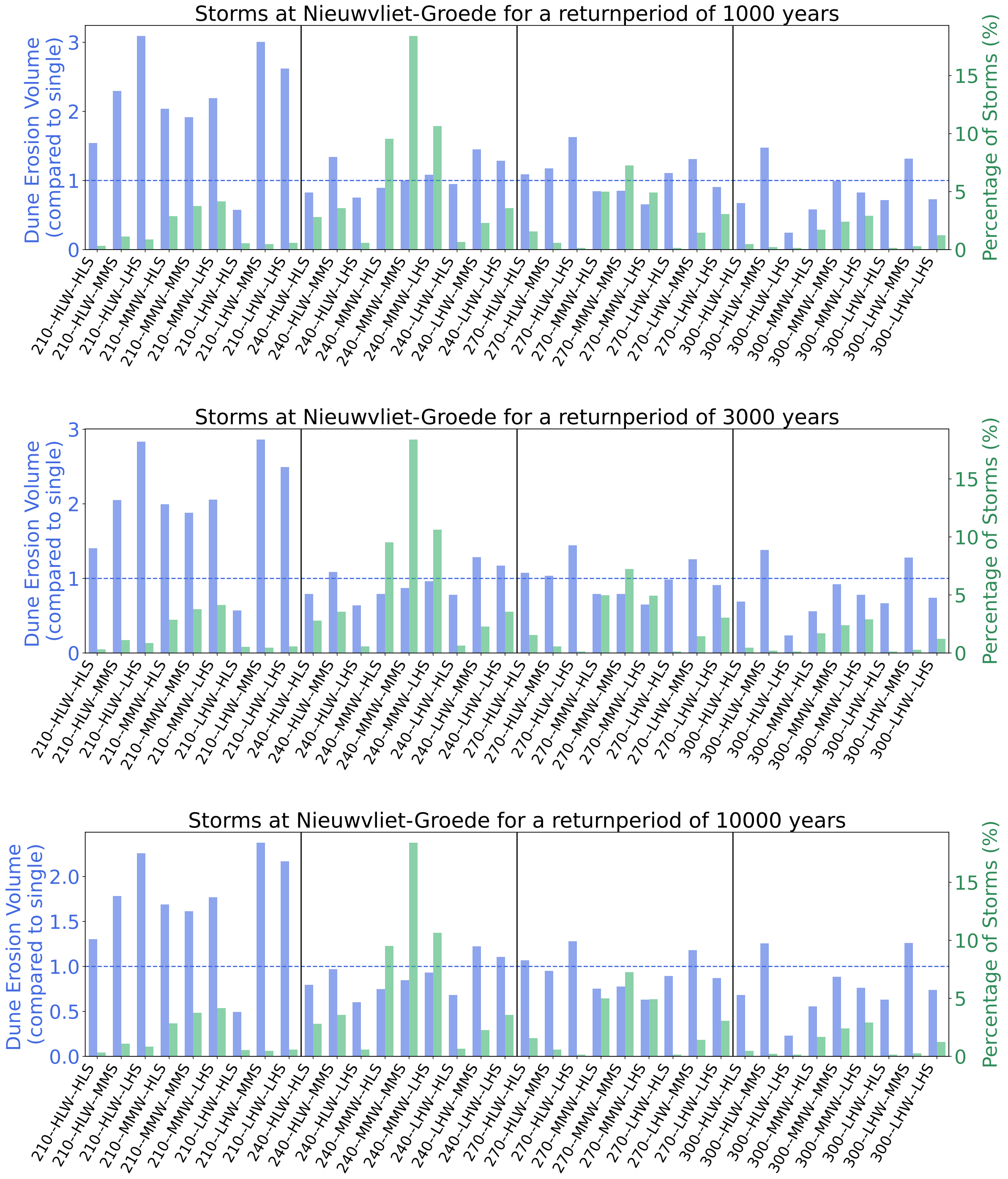


Figure 3.24: Dune erosion volumes per cluster for storms at Nieuwvliet-Groede with different return periods. The dashed line indicates the dune erosion volume of the single storm corresponding to the same wind direction. (HLW = High Low Wind, MMW = Mid Mid Wind, LHW = Low High Wind, HLS = High Low Surge, MMS = Mid Mid Surge, LHS = Low High Surge)

In figure 3.25 the results are shown for storms at Hoek van Holland. A few observations here are:

- Twin storms from direction 210 degrees give more dune erosion than single storms for a return period of 1000 years, but for return periods of 3000 years and 10000 years, the single storms give more dune erosion.
- Most storms can be found for wind direction 240 degrees as is indicated by the large green bars.
- Only a few twin storm clusters give more dune erosion than the corresponding single storm cluster.
- The percentage of dune erosion induced by a twin storm, normalised to the dune erosion of the corresponding single storm, does not increase for larger return periods.

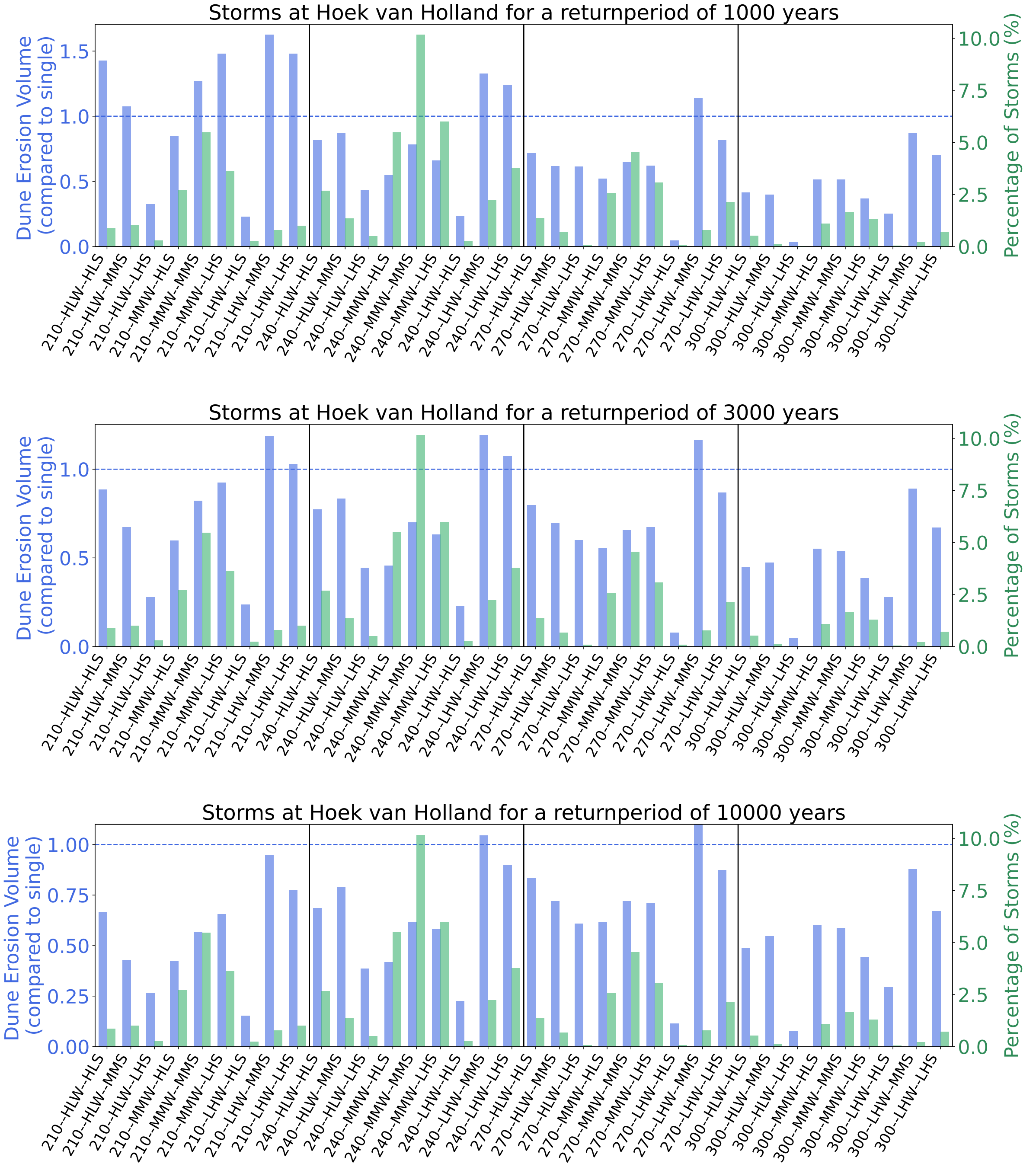


Figure 3.25: Dune erosion volumes per cluster for storms at Hoek van Holland with different return periods.The dashed line indicates the dune erosion volume of the single storm corresponding to the same wind direction. (HLW = High Low Wind, MMW = Mid Mid Wind, LHW = Low High Wind, HLS = High Low Surge, MMS = Mid Mid Surge, LHS = Low High Surge)

3.4.5. Dune erosion compared to BOI

In this section, a comparison will be made between dune erosion volumes found in this report and the dune erosion volume calculated in the Dutch safety assessment (BOI). In figure 3.26 it is shown what the dune erosion volumes are for single storms from different directions. The BOI category indicates the dune erosion volume that is found using the Dutch safety assessment.

It can be seen that the dune erosion predicted by the BOI for single storms is much larger than the dune erosion found using the schematisations in this report. Interpretation of the differences can be found in section 4.6.

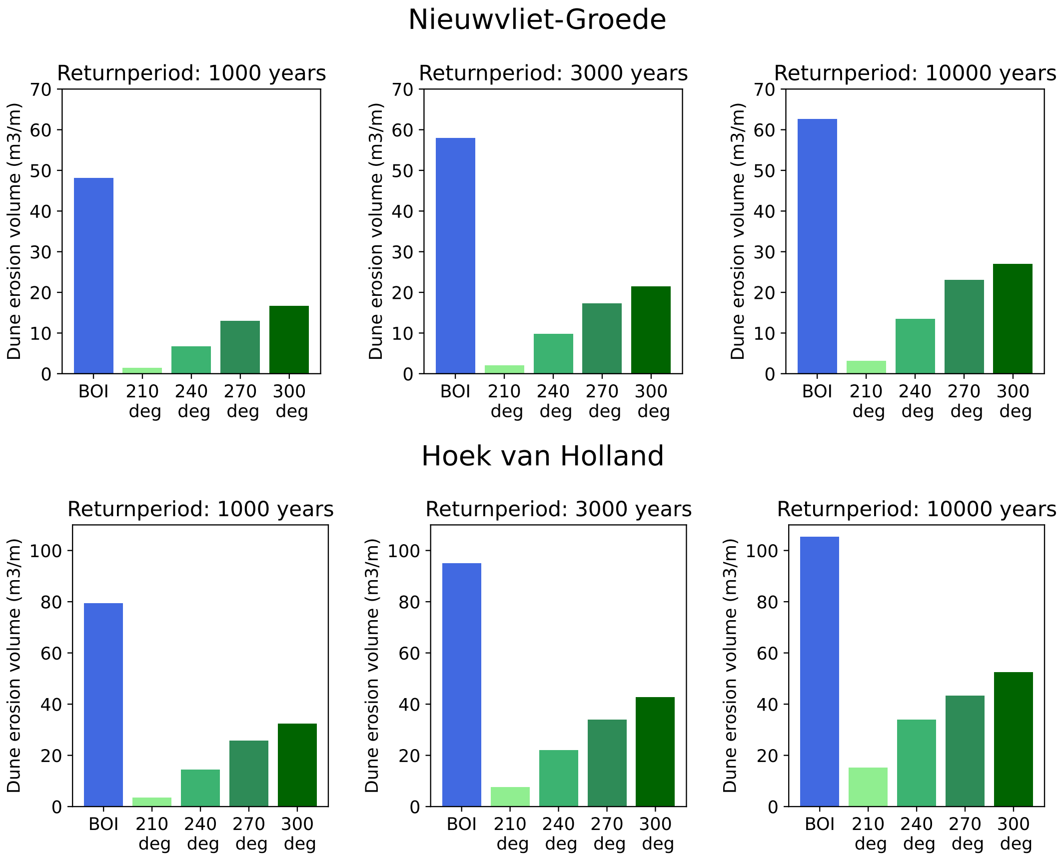


Figure 3.26: Dune erosion volumes for single storm schematisations compared to dune erosion volume of BOI

4

Discussion

4.1. Data collection

Uncertainties in simulated data

In this research, data from several sources was combined. From the ECMWF dataset, a period of 8000 years simulated wind speed and wind direction were available. The water levels corresponding to the same weather conditions were calculated by the KNMI using a model called WAQUA. The ECMWF data is simulated weather data, modelled given the current climate conditions. It should be taken into account that it is hard to validate the dataset as measurements go back only a hundred years. Thus, the extreme values in the dataset cannot be compared to observed data. Although there are model uncertainties, those do not weigh out the advantages of using this dataset to predict wind speeds and surge heights with very high return periods along the Dutch coast (van den Brink, 2020).

Estimation of wave parameters

As no wave data is modelled with either the ECMWF or WAQUA dataset, the waves were estimated using another method. In this report, this was done using relations from WTI 2011 (Stijnen and Kallen, 2010). In the WTI 2011, the wave periods with the highest probability of occurrence where estimated given a certain wind direction and wind speed. Thereafter, the wave period was coupled to the wave height and peak periods. The estimations from the report where compared to empirical formulations and showed a good agreement. Also an observed reference storm showed a similar relation between the wind speed and wave height. It should be noted that in reality there is way more variability in wave heights, given the same wind speed and wind direction. Therefore, the wave height in this report might both under- and overestimate wave heights observed during a storm.

4.2. Storm frequency

Storm definition

In this research, the frequency of single- and twin storms according to simulated weather data is described. When considering literature, twin storms can be considered a ’storm group’. The definition of storm group varies according to the location, and circumstances. A definition was constructed based on the features that are used to define storm groups (Eichentopf, Karunarathna, and Alsina, 2019). In this research it was decided to use the following definition:

- The wind speed should exceed 20.8 m/s to be considered a storm.
- The wind speed peaks should be spaced at least 24 hours and at most 120 hours apart.

While this definition is suitable for this project, another definition might be more appropriate for other research. Also, the number of twin storms found is largely dependent upon this definition. Choosing another wind speed threshold or another interval period might have lead to more storms and possibly more extreme twin storms.

Selection of storms

In this research it was assumed that the storms can be selected using a peak-over-threshold method on the wind speeds. However, a selection on storms based on a certain surge height might have lead to another selection of storms. In other literature, often the wave height is used for the storm selection. As in this research the wave height is based on the wind speed, this would have given similar results.

4.3. Storm characteristics

Clustering of single storms

Storm clusters were made to categorise the single- and twin storms. For single storms, the storms were divided solely on location and direction. This implies that the storm clusters for single storms contain a lot of storms. As a large number of storms falls in the cluster, the schematisation made can be considered a good approximation as it is based on a large number of storms. The downside is that the variability of single storms within a cluster is not accounted for.

Clustering of twin storms

For twin storms, two features are added for constructing the storm clusters: wind evolution and surge evolution. For both there are three types: high-low, mid-mid and low-high. High-low refers to a high peak followed by a lower peak, low-high to a low peak followed by a higher peak and mid-mid by two peaks with a comparable height. The threshold to determine in which of the categories a storm is placed is chosen manually, for two reasons. First, the clusters should be chosen such that there are enough storms in all clusters to be able to make a representative storm schematisation. On the other hand, when the threshold is chosen too low, the high-low and mid-mid storm do only show very little difference. The threshold was set such that the variability in the storms remained. An effect of this is, that some of the storm clusters represent more storms than other storm clusters. Some clusters only represent a few percent of the storms. Although the amount of storms per cluster could have been divided more equally, this would have lead to storm clusters that have more-less comparable storm evolutions.

4.4. Storm schematisation

Averaging procedure

Within this research, an averaging procedure was proposed to construct the evolution of storm parameters. After normalising the storms, all storms are defined on the same interval both in time and height. For each moment in time, the percentile value for all storms within the cluster can be computed. After doing this for each moment in time, the schematisation is a line through the percentile values. It was found that the constructed storm schematisations represent storm durations and the evolution in time well. However, due to the averaging procedure, the schematisations give very smooth evolutions of the storm parameters. Observed storms in reality would show more irregularities; those irregularities might have an effect on the amount of dune erosion that is found for each storm.

Estimating surge height with copulas

A copula is used to determine the surge height that belongs to a certain wind speed and wind direction. Copulas where compared using the Cramer-von-Mises test, the Kolmogorov-Smornov test and semi-correlations. Eventually, the Gumbel copula was chosen to estimate the surge heights. The semi-correlations test shows that the upper-tail correlation of the Gumbel copula is too strong and thereby the surge height might be overestimated for the most extreme wind speeds.

From the copula, the 50th percentile can be taken as an estimation of the surge height given a certain wind speed and wind direction. It should be taken into account though, that a large spread is observed. Estimating surge height by only using wind direction and wind speed comes with uncertainties; the model might under- or overestimate the expected surge height. Figure 4.1 shows the 50th percentile lines for storms from four directions and at both locations. It can be seen that the surge height is largely dependent upon the wind direction. The colored dots indicate the 1000, 3000 and 10000 year values for single storms.

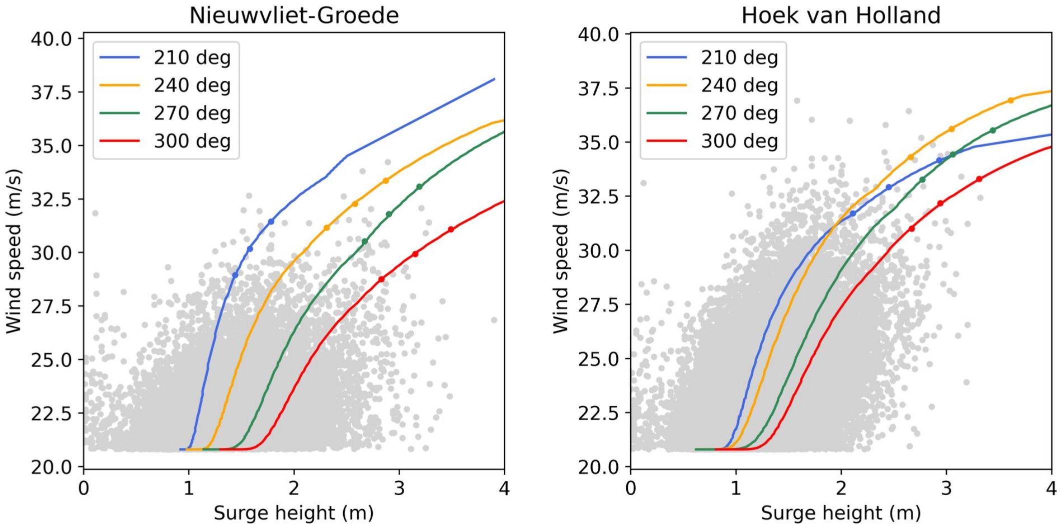


Figure 4.1: The grey dots indicate the combinations of peak wind speed and peak surge height for all storms. The colored lines indicate the 50th percentiles computed from the Gumbel copula for storms from different directions.

Tidal phase

It was found that the tidal peak shows a phase difference with the surge peak. It was determined that for both locations there are 4 distinct phases that occur. For all storm clusters, the phase with highest probability of occurrence was chosen. It is important to note that this choice can have large implications: due to a difference in tidal phase, the storm with the highest surge height is not per definition also the storm with the highest water level. In figure 4.2 it is shown how for storms at Nieuwvliet-Groede from 270 degrees, the schematisation differs for the two most frequently occurring tidal phases. Besides the difference in water level, a smaller tidal phase also means that the peak water level is closer to the peak wave height.

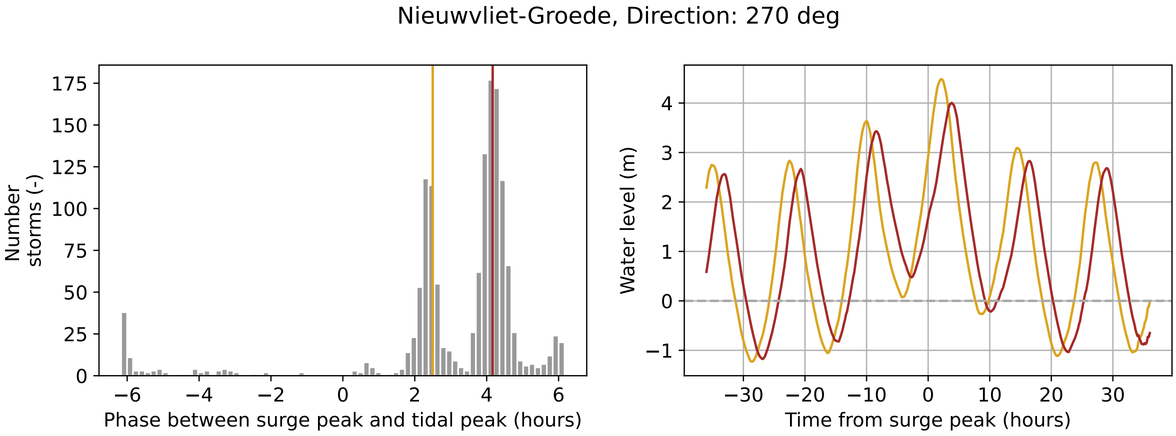


Figure 4.2: Left: histogram of the tidal phase for storms with a direction of 270 degrees at Nieuwvliet Groede. Right: time evolution of the water level for different tidal phases.

4.5. Dune erosion

Quantifying dune erosion

To quantify the dune erosion as a consequence of a single storm or a twin storm, several methods exist. In this report it is chosen to calculate the dune erosion volumes. Another way of quantifying dune erosion might give different results and conclusions. Furthermore, in this research a simplified definition is chosen to determine the dune foot. Only erosion above the dune foot is taken into account when calculating the dune erosion volume. Choosing another height of the dune foot can lead to different dune erosion volumes.

Wave direction
For the modelling of dune erosion, the wave direction is implemented in the XBeach model. In this thesis, the wave direction is assumed equal to the wind direction. Although this assumption holds well during the most extreme parts of the storm, there might be deviations for weaker wind speeds. This can have consequences for the computation of dune erosion volumes. Within the XBeach model, only waves that approach the coast under an angle in between -90 degrees to +90 degrees with respect to the shore normal are taken into account. It is assumed that waves that have a larger wave angle won't reach the coast, even when taking wave refraction into account. Therefore, deviations in the wave angle can lead to less wave impact and therewith less dune erosion.

Anomalies in dune erosion volumes
In this paragraph, some elaboration is given on anomalies in the observed dune erosion volumes. On the basis of figures 3.22 and 3.23, explanation is given on deviations for certain storm clusters.

- Storms from 210 degrees at Nieuwvliet-Groede
  When looking at figure 4.1, it can be seen that the copula that relates wind speed and surge height for storms from direction 210 degrees at Nieuwvliet-Groede is, in the region of interest (indicates with the colored dots), much steeper than for the other directions. This means that the surge height increases only by a small amount for a large increase in wind speed. Although the schematisation of the single storm has a wind speed that's much higher than that of the schematised twin storms, the surge height is therefore minimally higher. However, when looking at the return lines of the surge height (figure 3.4), it can be seen that single storms are expected to have a surge height that is significantly higher than that of a twin storm for the same return period.
  It was shown that the water level, and thus the surge height, have a large influence on the amount of dune erosion. It can be seen that most of the twin storm clusters from direction 210 degrees at Nieuwvliet-Groede give more dune erosion than the single storm cluster. This is due to the fact that the difference in surge height is relatively small.
- Storms from 270 degrees at Nieuwvliet-Groede
  Storms from direction 270 degrees at Nieuwvliet-Groede also often give more dune erosion than the same representing single storm. The difference observed is largely due to a difference in tidal phase. For the single storm, the phase between the tide and surge peak is estimated as 4.167 hours. Although the tidal phase of 4.167 is most frequent, there is also a large amount of storms from direction 270 degrees that exhibit a phase of 2.5 hours. As for the single storms, there is only one schematisation per direction, the water level is underestimated for storms from 270 degrees. Most of the twin storms have a tidal phase of only 2.5 hours. A shorter tidal phase gives larger water level peaks as the surge peak is closer to the tidal peak. A larger water level leads to a larger dune erosion volume.
- Storms with Low-High Wind evolution and Mid-Mid Surge evolution
  At Hoek van Holland it can clearly be seen that for all directions, the storm cluster that gives most erosion is the LHW-MMS (Low High Water - Mid Mid Surge) cluster. Due to certain choices made in the schematisation procedure, the surge heights for this cluster are overestimated with approximately 10%. For the same storm cluster at Nieuwvliet-Groede, the surge height is also overestimated with about 10

4.6. Applicability of results

Spatial applicability
In this research, only two locations are considered. For both locations one cross-shore profile is chosen so in total two bottom profiles have been evaluated. In (van Santen, 2021) it is described how the Dutch coast can be divided into 26 representative cross shore profiles. The profiles used in this research are therefore representative for approximately 10 kilometers of the Dutch coast.

Model compared to BOI
The Dutch safety assessment (BOI) gives much larger dune erosion volumes than the schematisations used within this report. Therefore the numbers found in this report cannot directly be compared to the BOI assessment. The differences can be accounted for by the following reasons:

- Wave-/storm direction
  In BOI, it is assumed that the governing wave direction is always perpendicular to the coast. Within this report, the wave direction is taken equal to the wind direction. The wind direction has a certain time evolution that is taken into account. For both, the wave directional spread is set to 30 degrees.
- Extreme value statistics
  In this report, the dataset from the ECMWF is used to determine statistics about the extreme values. For the BOI, other statistics are used to determine the maximum expected surge heights and wave heights.
- Phase difference surge and wave height
  In this report, a phase difference between surge height and wave height is determined. For the BOI, the peak of the surge height and of the wave height are assumed to occur simultaneously.
- Profile of time evolution of surge height
  The time evolution of surge height is different in the schematisation used in this report compared to BOI. In figure 4.3 it is shown how the schematisation of the surge compares to BOI for both locations. It can be seen that the BOI doesn't take into account the secondary peaks. Also, the duration at the top is longer for BOI than for the schematisation used here.

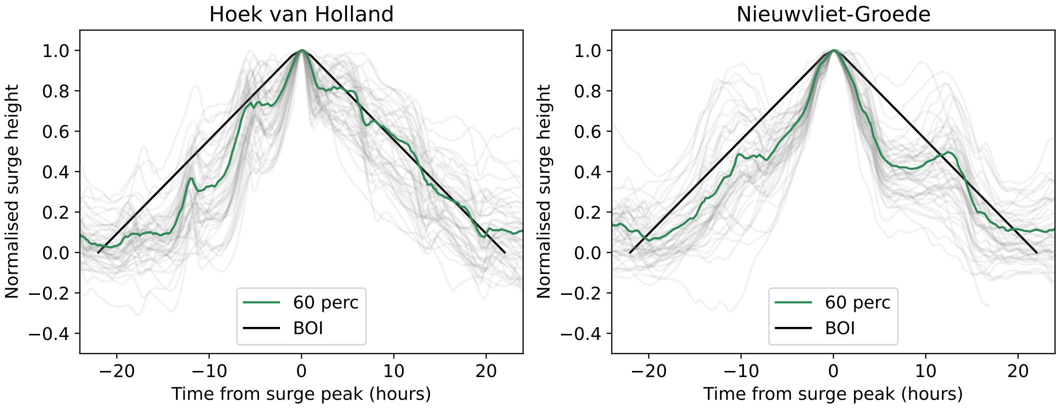


Figure 4.3: Time evolution of the normalized surge height for storms from direction 270 degrees compared to BOI.

- Duration of wave height evolution
  In figure 4.4 it is shown how the schematisation of the wave height is different for the BOI and the model in this report. In this report, the wave height is estimated based on the wind direction and wind speed.
  In the left subplot it is shown how the evolution of wind speed is estimated for the 60th (used in this report) and 90th percentile. The middle figure shows, using boxplots, the duration of the peak of all storms (assuming symmetrical storm peaks) and the duration of the peak of the schematisation. It can be seen that the 60th percentile is close to the median of all storms and the 90th percentile is much broader. In the right figure the calculated wave height evolution is shown for both the 60th and 90th percentile and the BOI schematisation. The wave height of the 60th and 90th percentile is scaled to have the same extreme value as the BOI. It can be seen that the BOI schematisation is close to the 90th percentile.

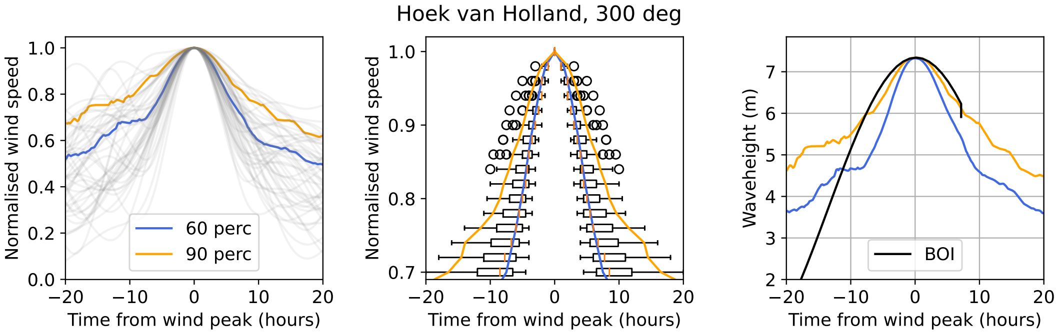


Figure 4.4: Subfigure 1&2: Time evolution of normalised wind speed.
Subfigure 3: Time evolution of wave height.

5

Conclusion

In this chapter the conclusions of this research are described. This is done by answering the four sub-research questions first, followed by answering the main research question.

RQ1: What is the frequency of occurrence of single- and twin storms?

The frequency of occurrence of single- and twin storms described here, is valid under two assumptions. First, a storm is defined as a wind speed higher than 20.8 m/s. The second assumption states that a twin storm consists of two storms with a time interval of at least 24 hours between the wind speed peaks and at most 120 hours between the wind speed peaks.

For both the locations Nieuwvliet-Groede and Hoek van Holland, it was found that almost all single- and twin storms have westerly peak wind directions. Considering only storms from those westerly directions, for Hoek van Holland it was found that approximately 25 - 30% of the storms can be labelled a twin storm. For Nieuwvliet-Groede the number is a bit lower; approximately 15-20% can be identified as a twin storm.

The probability that a storm is part of a twin storm is, to some extent, correlated with the peak wind speed of that storm. The probability that a storm is part of a twin storm is larger if the peak wind speed is larger. For storms with a wind speed peak in the range 20.8 m/s to 26 m/s, the probability that the storm is part of a twin storm increases for increasing peak wind speed. For storms with a peak wind speed even higher than 26 m/s, there is no evident increase or decrease of the probability anymore. When considering the peak surge height, storms with a higher peak surge height are more often part of a twin storm. The probability that a storm is part of a twin storm increasing for increasing peak surge heights up to 1.8 m. For storms with a peak surge height that is even higher than 1.8 m, the probability doesn't show a clear increase anymore.

RQ2: How can single- and twin storms be categorised according to their characteristics?

When considering storm characteristics that are relevant for dune erosion, three types of storm parameters can be identified: wind, water level and waves. When considering the wind, both the wind speed and wind direction are of importance. The water level consists of two components: the surge height and tidal height. The tidal height is equal for all storms, the surge height varies for different storms. The waves have three attributes: wave height, wave peak period and wave direction.

It was found that the peak wind direction of a storm has a large influence on the observed wind speed, surge height and wave parameters. Therefore, wind direction is one of the storm characteristics that can be used for categorisation of storms. Furthermore, the storms at both locations (Nieuwvliet-Groede and Hoek van Holland) showed significant differences. Thus, location is another characteristic taken into account.

Clustering single storms based on their location and wind direction results in representative clusters. For twin storms, the variety in storms is larger and two additional features are required: the wind speed evolution and the surge height evolution. These are meant to make a distinction between different time evolutions; e.g. a large storm can follow a smaller one or the other way around. This can be accounted for by defining both the type of time evolution of the wind speed an that of the surge height.

RQ3: How can the storm-evolution of single- and twin storms be schematised?

For each storm cluster, a representative storm schematisation can be made. The schematisation consists of time evolutions of storm parameters. It was found that the percentile averaging method is suitable for constructing normalised time evolutions of storm parameters for both single- and twin storms.

The created normalised time evolutions can be scaled by the extreme values that belong to a certain return period. For the single storms, the Generalised Pareto Distribution shows a good fit to the extreme wind speeds. For twin storms, the wind speeds of the peaks show a very low correlation and can be considered independent. Thus, an independent copula can be used to model the joint probability of a combination of wind speeds. The wind speeds observed during the single storm are higher than the wind speeds observed during twin storms. The expected extreme surge height can be approximated by a copula that relates the wind speed to the surge height. The single storms have higher surge heights than the twin storms.

Almost all storms exhibit both a surge phase (phase between wind and surge peak) and a tidal phase (phase between surge and tide peak). The surge phase for storms from direction 270 and 300 degrees can be considered normally distributed. For storms from direction 210 and 240 degrees, the normal distribution does not provide a good fit to the data. Regarding the tidal phase, four distinct phases can be identified at both locations.

RQ4: How can the dune erosion volumes of single- and twin storms be estimated?

The constructed storm schematisations consist of the time evolutions of wind speed, wind direction and surge height. To calculate the dune erosion, also the time evolution of the wave characteristics is required. Both the wave height and wave peak period can be estimated based on the wind direction and wind speed. This way, also the time evolution of the relevant wave parameters is known.

The storm schematisation, that now includes wave parameters, can serve as input for modelling software. In this report it's chosen to use XBeach, which is a model that can be used to model dune behaviour during extreme storms. As XBeach is a process-based model it's able to model both the storm conditions but also the calmer periods during a twin storm. From the dune profiles before and after the storm, the loss of sand above +3m NAP can be calculated as an indicator of the dune erosion volume.

How does the amount of dune erosion caused by a twin storm compare to the amount of dune erosion due to a single storm that has the same probability of occurrence for storms along the Dutch coast?

For all of the 240 storm schematisations, the dune erosion volume was calculated using XBeach. It was found that for both single- and twin storms, the peak wind direction of the schematisation has a large influence on the amount of dune erosion. Storms from direction 210 degrees give little erosion and storms from 270 and 300 degrees clearly give the most erosion.

For storms at Hoek van Holland it was found that twin storms, in most of the cases, do not give more dune erosion than single storms do. For the return periods 1000, 3000 and 10000 years, twin storms give more erosion only for 19.5%, 8.6%, and 3.0% of the time respectively. At Nieuwvliet-Groede it is observed that much more of the twin storms give more dune erosion than a single storm. Considering return periods of 1000, 3000 and 10000 years, the twin storms give more dune erosion in 38.3%, 27.6% and 23.5% of the cases respectively.

The results show that the observed amount of dune erosion is largely correlated with the surge height; the correlation found is approximately 0.9. At Nieuwvliet-Groede there is also a large correlation between maximum wave height and dune erosion, although for Hoek van Holland this is not the case. This can be explained by the fact that for storm schematisations at Nieuwvliet-Groede there is a large correlation between maximum surge height and maximum wave height. Therefore, all schematisations that have a large surge height also have a large wave height.

At Nieuwvliet-Groede twin storms give more dune erosion than single storms for approximately 30% of the time. For Hoek van Holland this is only 10%. The large difference is due to certain assumptions made in the model schematisation. At Nieuwvliet-Groede, the difference in surge height for single storms and twin storms is too small for storms from directions 210 and 270 degrees. For these directions, the dune erosion volumes of single and twin storms are therefore very comparable. Furthermore, it’s concluded that far most of the twin storms that give more dune erosion than single storms, are the effect of deviations in the schematisation procedure.

6

Recommendations

6.1. Storm frequency

According to recent research, the wind direction and wind speed at the Dutch coast do not significantly change in the future climate (KNMI, 2023a). In other words, the frequency and intensity of storms do not seem to increase due to climate change. However, a warmer climate might lead to more hurricanes over Western Europe (Haarsma et al., 2013). Hurricanes can have very high wind speeds and might lead to more extreme storm conditions (KNMI, 2021). More research is needed to verify whether hurricanes will happen more often and if so, what the conditions are during such a hurricane.

In this research, storms were selected by using a peak-over-threshold on the wind speed. Although wind speed often is a good indicator for storm conditions, there are also other parameters that can be used to indicate storms. Within this research it was found that the water level is important for dune erosion. Therefore, for further research it is recommended to not only select storms on wind speed but also on surge height.

6.2. Storm characteristics

In this research, single storms are only categorised by their wind direction and location. More categories should be added to better predict the storm evolution of a single storm. Parameters that might be considered are tidal phase, duration of wind speed and duration of surge height. Having more variation in the storm categorisation will lead to more representative storm schematisations and therewith a better estimation of the dune erosion volumes for single storms.

6.3. Storm schematisation

In this research, a deterministic approach was used. This means that for each parameter (e.g. tidal phase) one value is chosen, rather than sampled from a certain distribution. Although various combinations of parameters are possible, only one combination is chosen within this deterministic approach. Using a probabilistic method would give a range of outcomes, based on the distributions prescribed for all parameters. Knowing the variation of outcomes would increase the robustness of the predictions.

Furthermore, as the water levels are of large importance for the dune erosion volume, it should be better estimated what surge height is expected during a certain storm. There are several ways to improve the estimation of the surge height. Three possible ways are:

1. Investigating other bivariate distributions (e.g. t-distribution) to couple wind speed with surge height.
2. Using wind fields rather than wind direction and wind speed.
3. Constructing more storm clusters so that all storms within the cluster have similar characteristics.

In this report, the wave parameters were estimated using simplified relations. It should be further investigated how well these simplified relations are able to calculate the time evolution of the wave parameters during a storm.

6.4. Dune erosion

Although not explicitly considered in this research, climate change might have an effect on the results. As the sea level is rising, the water levels during storms will increase. As was seen in this research, higher water levels generally lead to a larger dune erosion volume. The surge height during storms won't increase due to climate change so the water level for future storms will only increase due to sea level rise (KNMI, 2023a).

For research into twin storms (and storm groups) it is advised to investigate the time scales and dynamics of dune growth. If XBeach is able to reproduce the observed dune growth after and between storms, longer interval times between storms can be considered. Increasing the interval time might lead to a larger number of twin storms and possibly more extreme twin storms. Also considering the effect of storm groups with more than two storms within a larger period could be investigated.

Only two locations are considered within this research. For both locations, one cross shore profile is selected. According to (van Santen, 2021), the Dutch coast can be divided into 26 representative cross shore profiles. Therefore, the conclusions drawn in this report hold for about 10 kilometers of the coast. It should be further looked into whether the conclusions also hold for other locations at the coast.

6.5. Dutch dune safety assessment (BOI)

The schematisation used in this report differs from the one used in the Dutch dune safety assessment (BOI). The most important differences are the time evolutions of the storm parameters and the implementation of surge- and tidal phase. Further research should help identify whether the approach in this report can lead to more realistic storm schematisations.

For further research into twin storms it is advised to consider a twin storm as a combination of two single storms and schematise it in that way. After schematising two single storms they can be merged to form a twin storm. There are two objectives that lead to this recommendation. First, it turns out that for most twin storms within the dataset, there is no clear correlation between the peak values of the two observed storms. Therefore, the storms can be modelled independently. Second, with the schematisation procedure used in this report it is not possible to change the shape or height of one of the two storms without changing the characteristics of the other storm. By considering two single storms, they can be constructed one by one. Yet, it is recommended to use the statistics from the ECMWF dataset to calculate the expected extreme values. Due to the long duration of the dataset, it is well applicable to derive the combinations of surge heights and wind speeds during a twin storm.

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A

Storm frequency

A.1. Wind speed threshold

In figure A.1 and A.2 it is shown how the number of twin storms varies for different wind speed thresholds. The number of twin storms seems to behave like an exponential distribution in the considered range of wind speed thresholds.

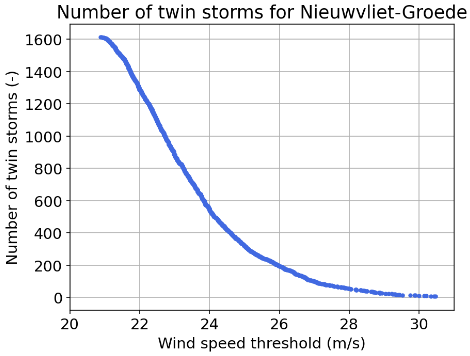


Figure A.1: Number of twin storms at Nieuwvliet-Groede for different wind speed thresholds

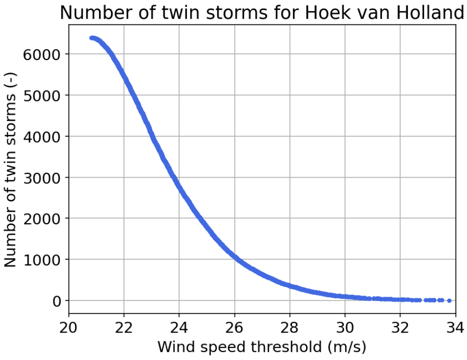


Figure A.2: Number of twin storms at Hoek van Holland for different wind speed thresholds

A.2. Interval duration

In figure A.3 and A.4 it is shown how the number of twin storms varies for changing the interval duration between the storms. The minimum interval between the peaks is fixed at 24 hours, the maximum interval duration is shown on the x-axis.

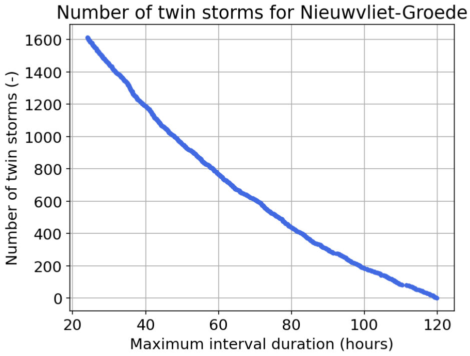


Figure A.3: Number of twin storms at Nieuwvliet-Groede for different maximum interval durations

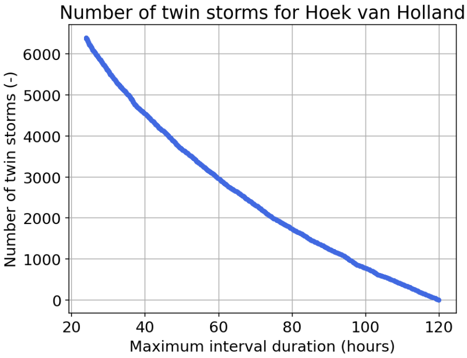


Figure A.4: Number of twin storms at Hoek van Holland for different maximum interval durations

B

Characteristics

In the table below it is shown how much storms are within each defined cluster. For each line in the table, three storms are constructed for different return periods. As the same combination of storms is used to make these three storms, the return period is not defined here.

Table B.1: Number of storms per storm cluster

Locatie	Richting	Wind speed evolution	Surge height evolution	Number
hoekvanholland	210	single	-	9977
hoekvanholland	210	high-low	high-low	75
hoekvanholland	210	high-low	mid-mid	87
hoekvanholland	210	high-low	low-high	25
hoekvanholland	210	mid-mid	high-low	233
hoekvanholland	210	mid-mid	mid-mid	472
hoekvanholland	210	mid-mid	low-high	312
hoekvanholland	210	low-high	high-low	21
hoekvanholland	210	low-high	mid-mid	68
hoekvanholland	210	low-high	low-high	86
hoekvanholland	240	single	-	18051
hoekvanholland	240	high-low	high-low	231
hoekvanholland	240	high-low	mid-mid	117
hoekvanholland	240	high-low	low-high	43
hoekvanholland	240	mid-mid	high-low	473
hoekvanholland	240	mid-mid	mid-mid	877
hoekvanholland	240	mid-mid	low-high	517
hoekvanholland	240	low-high	high-low	23
hoekvanholland	240	low-high	mid-mid	192
hoekvanholland	240	low-high	low-high	326
hoekvanholland	270	single	-	8229
hoekvanholland	270	high-low	high-low	118
hoekvanholland	270	high-low	mid-mid	58
hoekvanholland	270	high-low	low-high	7
hoekvanholland	270	mid-mid	high-low	221
hoekvanholland	270	mid-mid	mid-mid	392
hoekvanholland	270	mid-mid	low-high	265
hoekvanholland	270	low-high	high-low	7
hoekvanholland	270	low-high	mid-mid	67
hoekvanholland	270	low-high	low-high	185
hoekvanholland	300	single	-	3542
hoekvanholland	300	high-low	high-low	45
hoekvanholland	300	high-low	mid-mid	10
hoekvanholland	300	high-low	low-high	1

hoekvanholland	300	mid-mid	high-low	94
hoekvanholland	300	mid-mid	mid-mid	143
hoekvanholland	300	mid-mid	low-high	112
hoekvanholland	300	low-high	high-low	4
hoekvanholland	300	low-high	mid-mid	18
hoekvanholland	300	low-high	low-high	61
Nieuwvliet-Groede	210	single	-	2753
Nieuwvliet-Groede	210	high-low	high-low	5
Nieuwvliet-Groede	210	high-low	mid-mid	17
Nieuwvliet-Groede	210	high-low	low-high	13
Nieuwvliet-Groede	210	mid-mid	high-low	44
Nieuwvliet-Groede	210	mid-mid	mid-mid	58
Nieuwvliet-Groede	210	mid-mid	low-high	64
Nieuwvliet-Groede	210	low-high	high-low	8
Nieuwvliet-Groede	210	low-high	mid-mid	7
Nieuwvliet-Groede	210	low-high	low-high	9
Nieuwvliet-Groede	240	single	-	7281
Nieuwvliet-Groede	240	high-low	high-low	43
Nieuwvliet-Groede	240	high-low	mid-mid	55
Nieuwvliet-Groede	240	high-low	low-high	9
Nieuwvliet-Groede	240	mid-mid	high-low	147
Nieuwvliet-Groede	240	mid-mid	mid-mid	284
Nieuwvliet-Groede	240	mid-mid	low-high	164
Nieuwvliet-Groede	240	low-high	high-low	10
Nieuwvliet-Groede	240	low-high	mid-mid	35
Nieuwvliet-Groede	240	low-high	low-high	55
Nieuwvliet-Groede	270	single	-	3245
Nieuwvliet-Groede	270	high-low	high-low	24
Nieuwvliet-Groede	270	high-low	mid-mid	9
Nieuwvliet-Groede	270	high-low	low-high	2
Nieuwvliet-Groede	270	mid-mid	high-low	77
Nieuwvliet-Groede	270	mid-mid	mid-mid	112
Nieuwvliet-Groede	270	mid-mid	low-high	76
Nieuwvliet-Groede	270	low-high	high-low	2
Nieuwvliet-Groede	270	low-high	mid-mid	22
Nieuwvliet-Groede	270	low-high	low-high	47
Nieuwvliet-Groede	300	single	-	1711
Nieuwvliet-Groede	300	high-low	high-low	7
Nieuwvliet-Groede	300	high-low	mid-mid	3
Nieuwvliet-Groede	300	high-low	low-high	2
Nieuwvliet-Groede	300	mid-mid	high-low	26
Nieuwvliet-Groede	300	mid-mid	mid-mid	37
Nieuwvliet-Groede	300	mid-mid	low-high	45
Nieuwvliet-Groede	300	low-high	high-low	2
Nieuwvliet-Groede	300	low-high	mid-mid	4
Nieuwvliet-Groede	300	low-high	low-high	19

C

Schematisation

C.1. Wind duration storms

The duration of the peak of the simulated storm should be a good representation of all selected storms. To check whether this is the case, the duration at several relative levels will be determined. The duration of the selected storms and of the created storm evolution will be compared. To do so, first the duration at several relative levels is determined. Figure C.1 and C.2 show how the wind duration at a normalised level of 0.8 is determined for each peak.

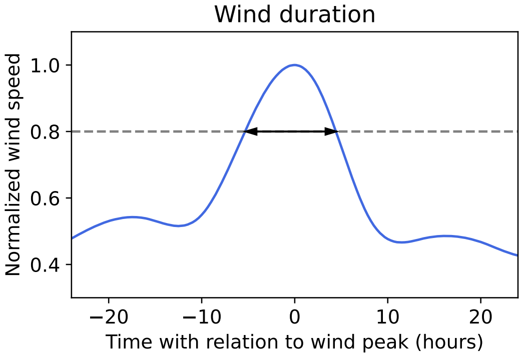


Figure C.1: Wind duration at a normalized level of 0.8 for single storms

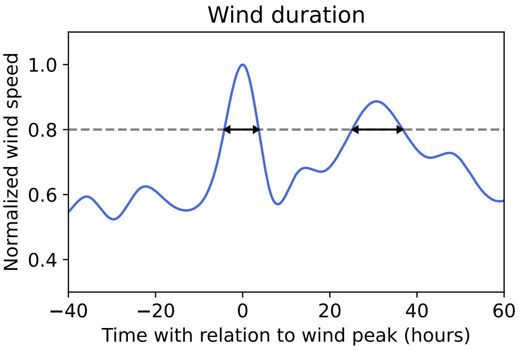


Figure C.2: Wind duration at a normalized level of 0.8 for both storms of a twin

This way, the duration at several normalised can be determined. A comparison can be made between the created wind speed evolution and the evolution of the storms that were used to create the representative wind speed evolution. In figure C.3 and figure C.4 it is shown for both Nieuwvliet-Groede and Hoek van Holland how the schematisation compares to the real storms. The boxplots shows the variation of all storms within the cluster. The line indicates what the schematisation of the peak looks like. It can be seen that the 60th percentile gives a representative estimation for the duration of the peak.

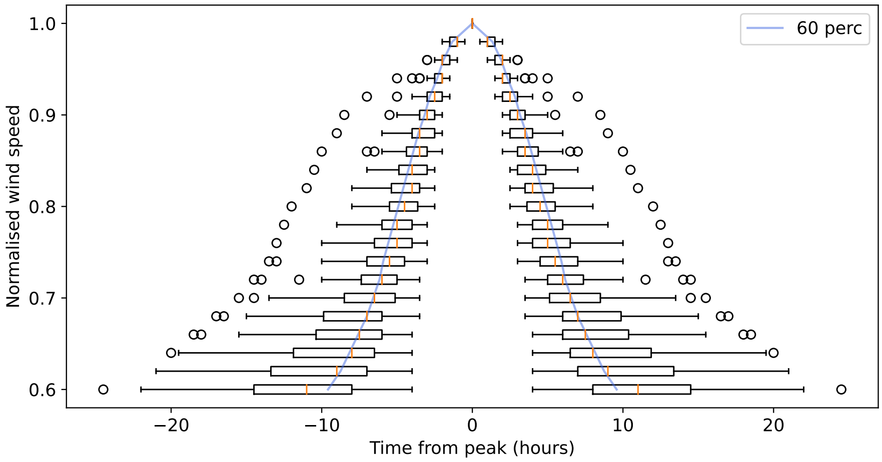


Figure C.3: Wind duration at relative level for single storms at Nieuwvliet-Groede

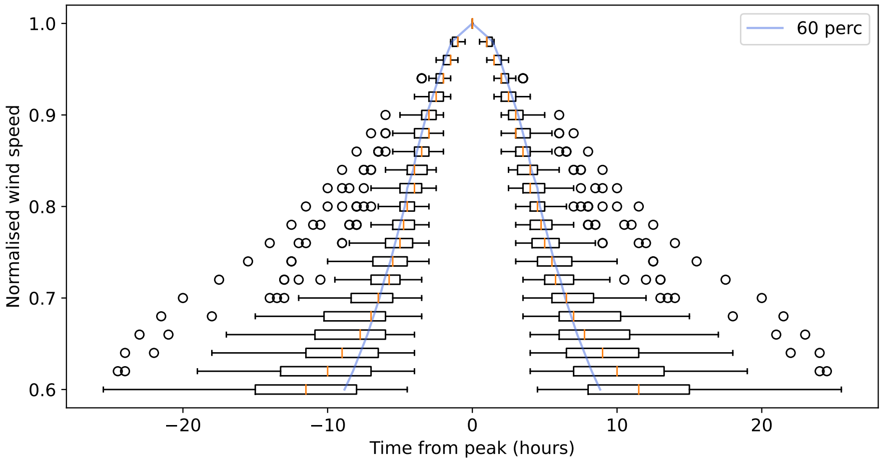
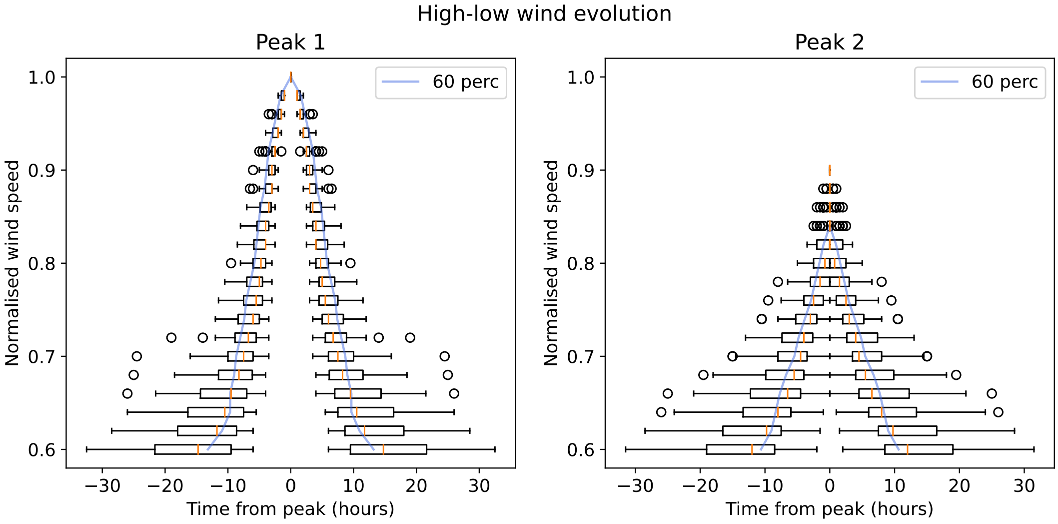


Figure C.4: Wind duration at relative level for single storms at Hoek van Holland

The same figure can be made for the twin storms. A distinction is made between the different wind evolutions: High-Low, Mid-Mid and Low-High. Figure C.5 shows the results for Nieuwvliet-Groede. For all figures, the left side shows peak one and the right figure shows peak two. Again the boxplots show the variation of durations for all storms and the blue line indicates the storm schematisation that was made.



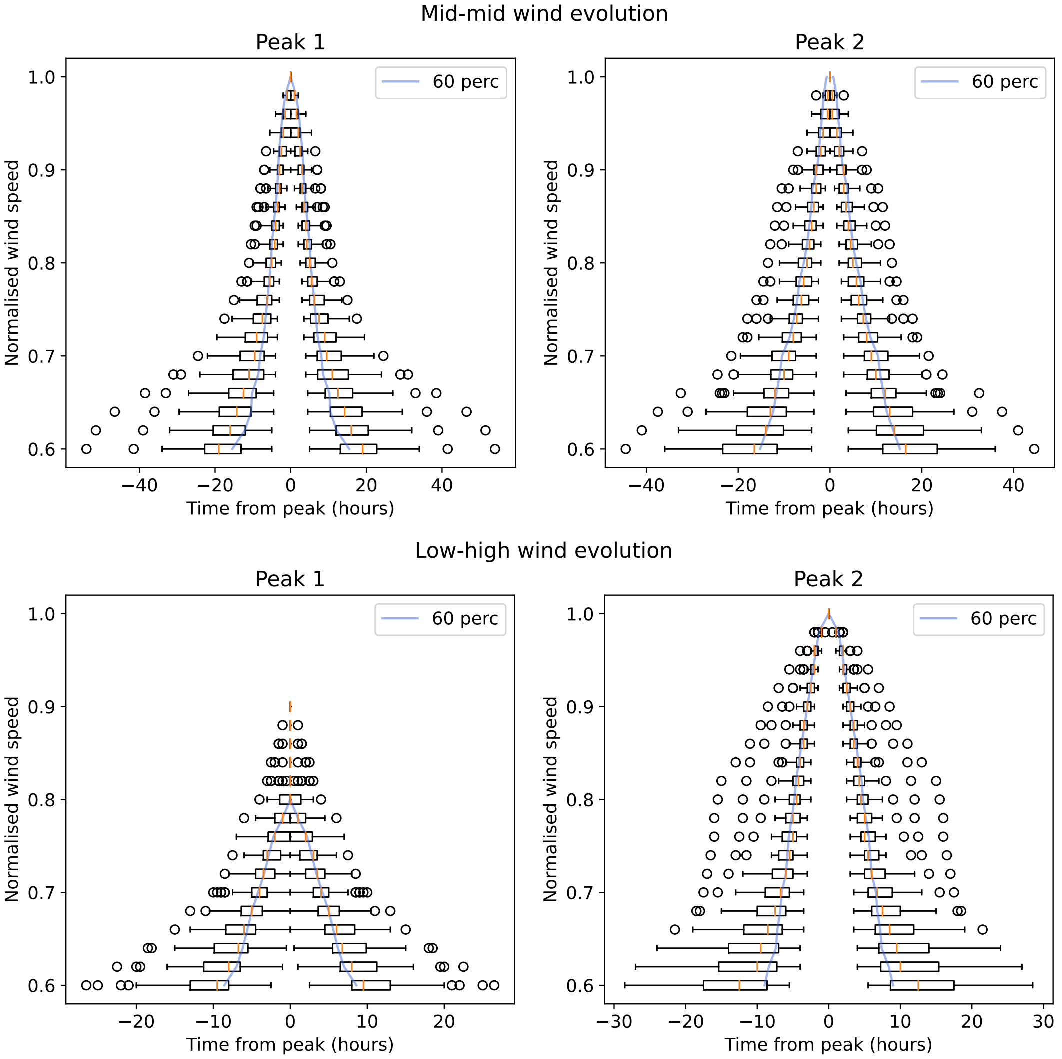


Figure C.5: Wind duration at relative level for twin storms for different wind evolutions at Nieuwvliet-Groede

C.2. Surge duration storms

The percentile chosen should well represent the surge height evolution. To check whether this is the case, the duration at several relative levels of the constructed surge evolution is compared with the duration at certain relative levels for the real storms. Figure C.6 shows how the duration at a relative level of 0.8 is determined for all the peaks.

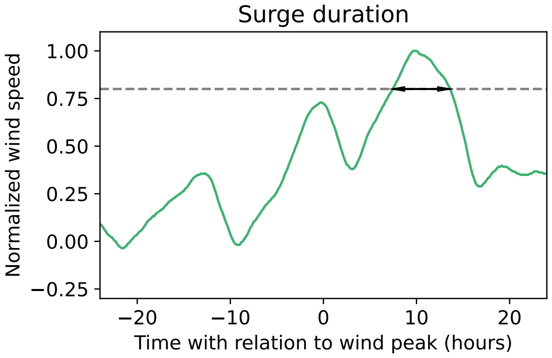


Figure C.6: Duration of the surge height for single storms

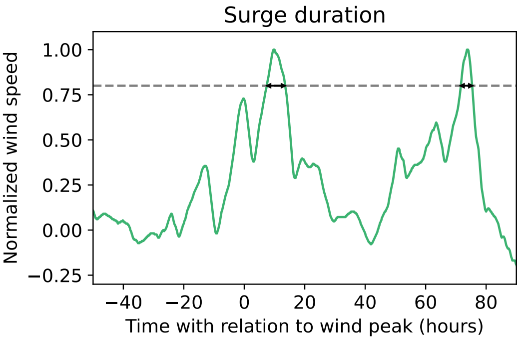


Figure C.7: Duration of the surge height for twin storms

Figures C.8 and C.9 show the durations at relative levels for the 60th percentile combined with boxplots that represent the duration for all storms that are in the selected cluster. The first figure shows the situation at Hoek van Holland, the second figure is for Nieuwvliet-Groede. It is assumed that for the surge duration, the 60th percentile gives a good estimation.

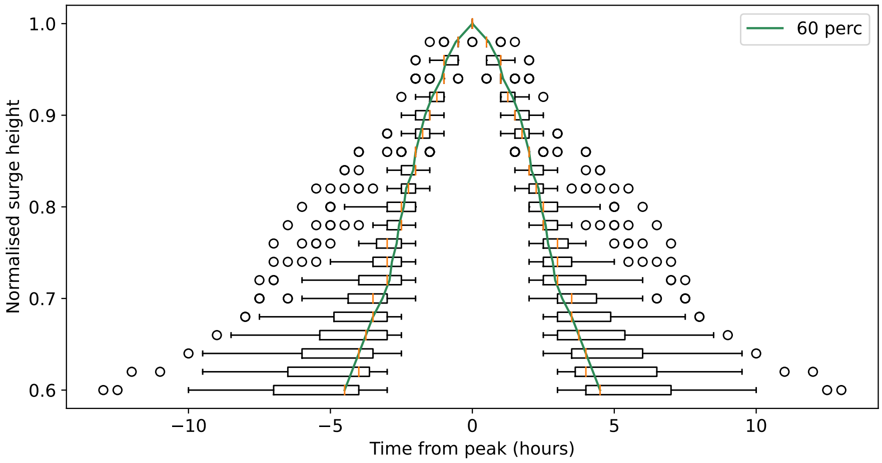


Figure C.8: surge duration at relative level for single storms at Nieuwvliet-Groede

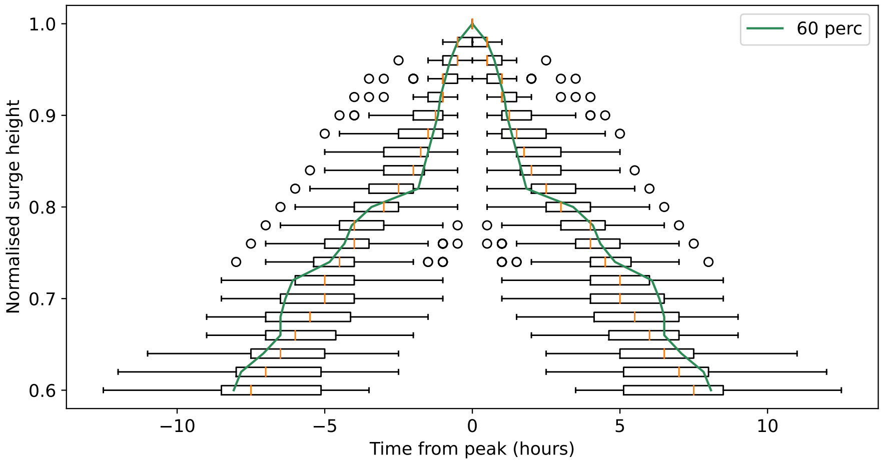


Figure C.9: surge duration at relative level for single storms at Hoek van Holland

The same figures can be constructed for twin storms. A distinction is made between the three surge evolutions: high-low, mid-mid and low-high. In each figure, the left plot shows the first peak and the right figure shows the second peak.

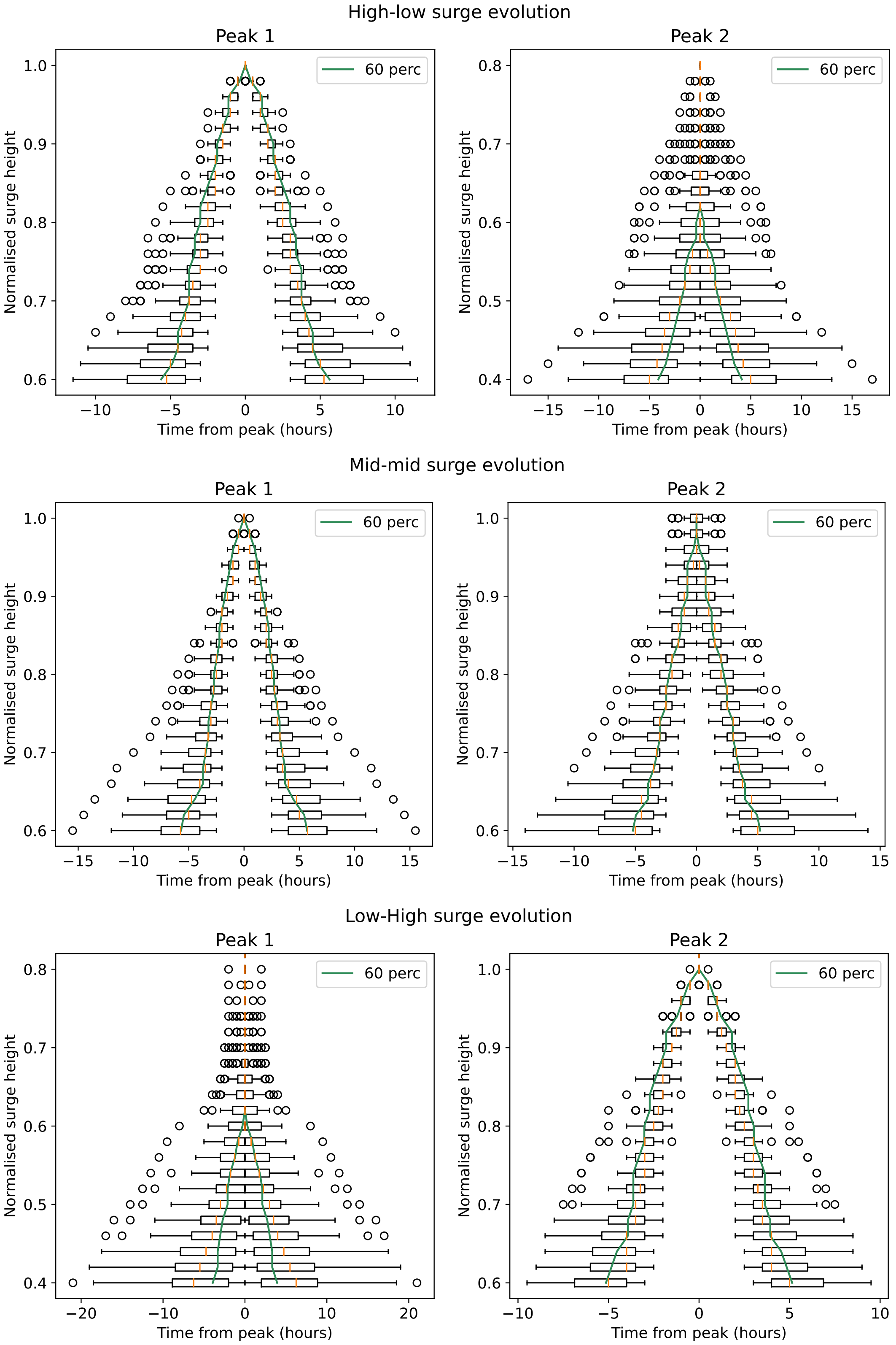


Figure C.10: Surge duration at relative level for twin storms with different surge evolutions at Nieuwvliet-Groede

C.3. Duration for extreme storms

In figure C.10 it is shown how the time evolution of the most extreme storms compares to the time evolution of less extreme storms.

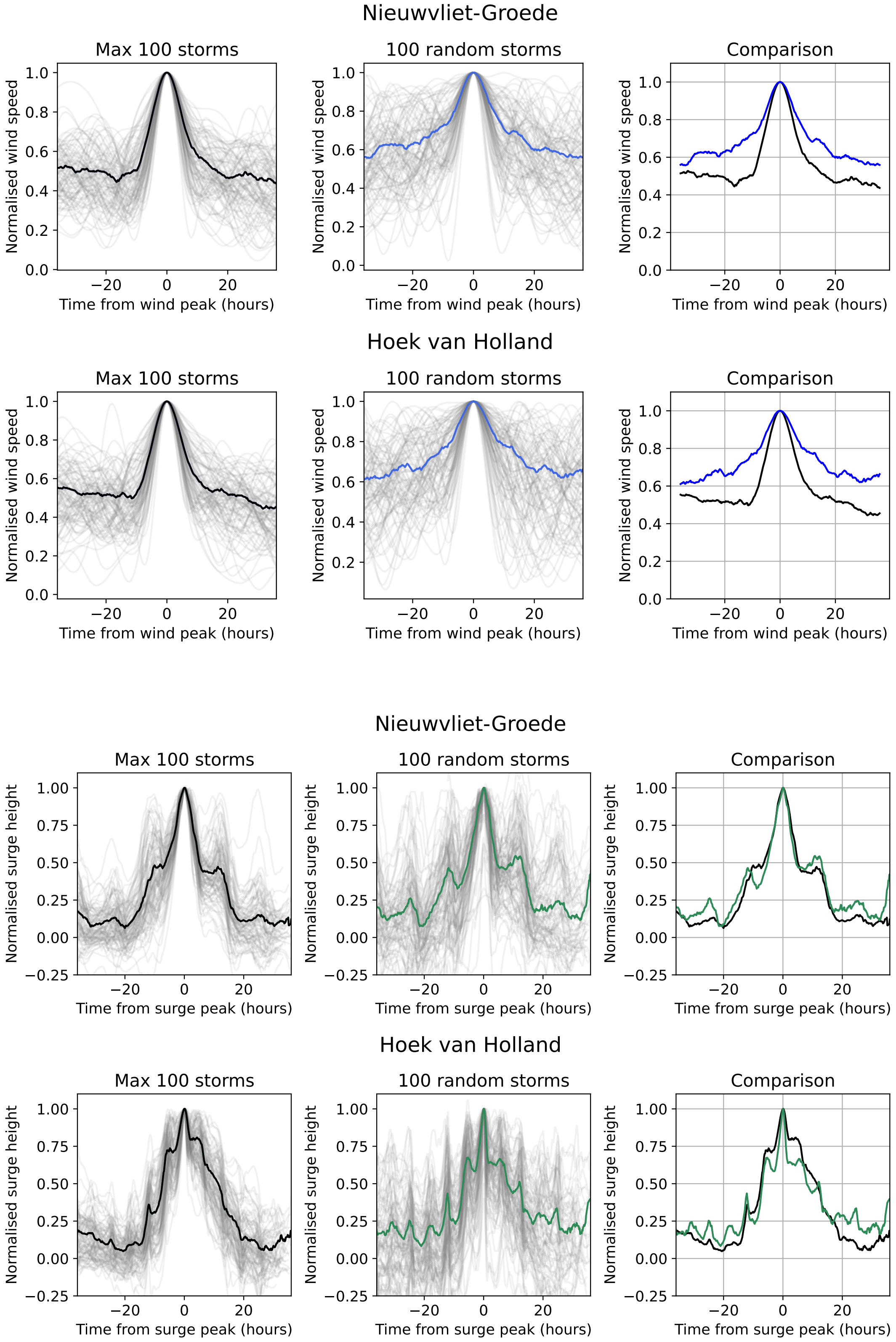


Figure C.10: Duration for extreme storms

C.4. Extreme wind speeds

Figure C.11 shows the fit of the Generalised Pareto Distribution for the wind speed peaks from different directions at Nieuwvliet-Groede.

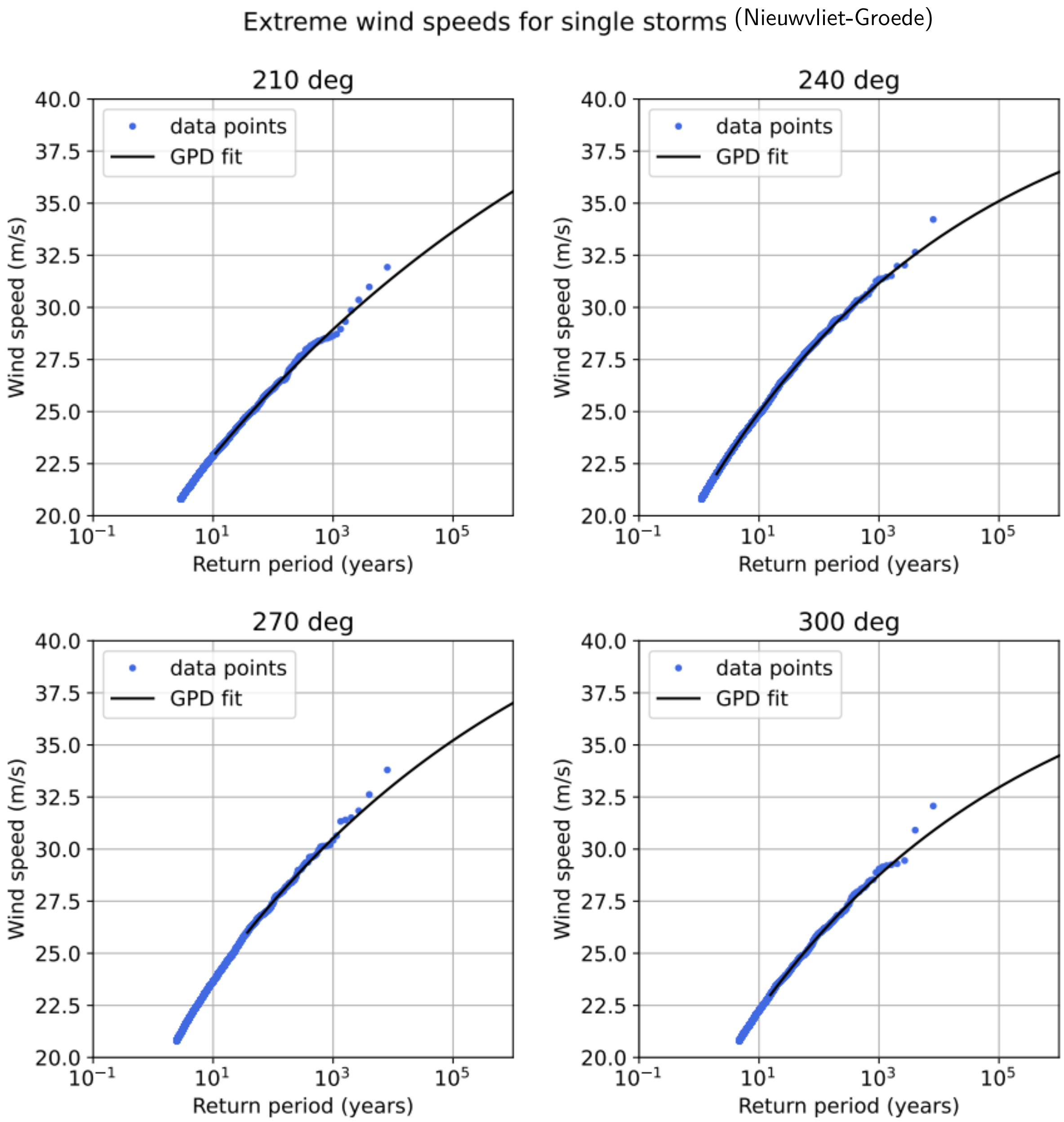


Figure C.11: Extreme wind speeds for single storms at Nieuwvliet-Groede

Figure C.12 shows the fit of the Generalised Pareto Distribution for the wind speed peaks from different directions at Hoek van Holland.

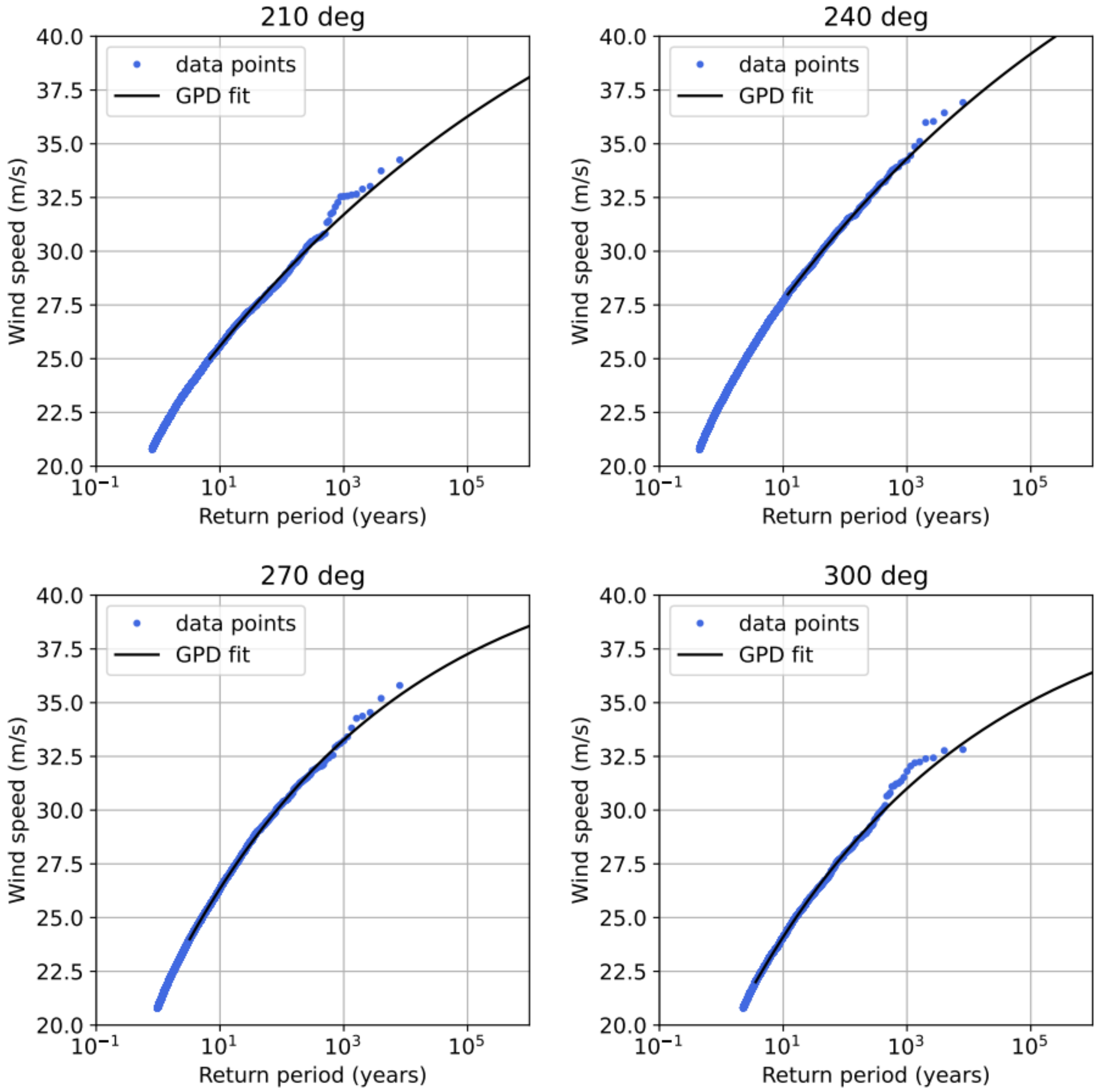


Figure C.12: Extreme wind speeds for single storms at Hoek van Holland

The two left columns in figure C.13 show the fit of the GPD to both wind peaks for twin storms from different directions. The right column shows the computed return period lines.

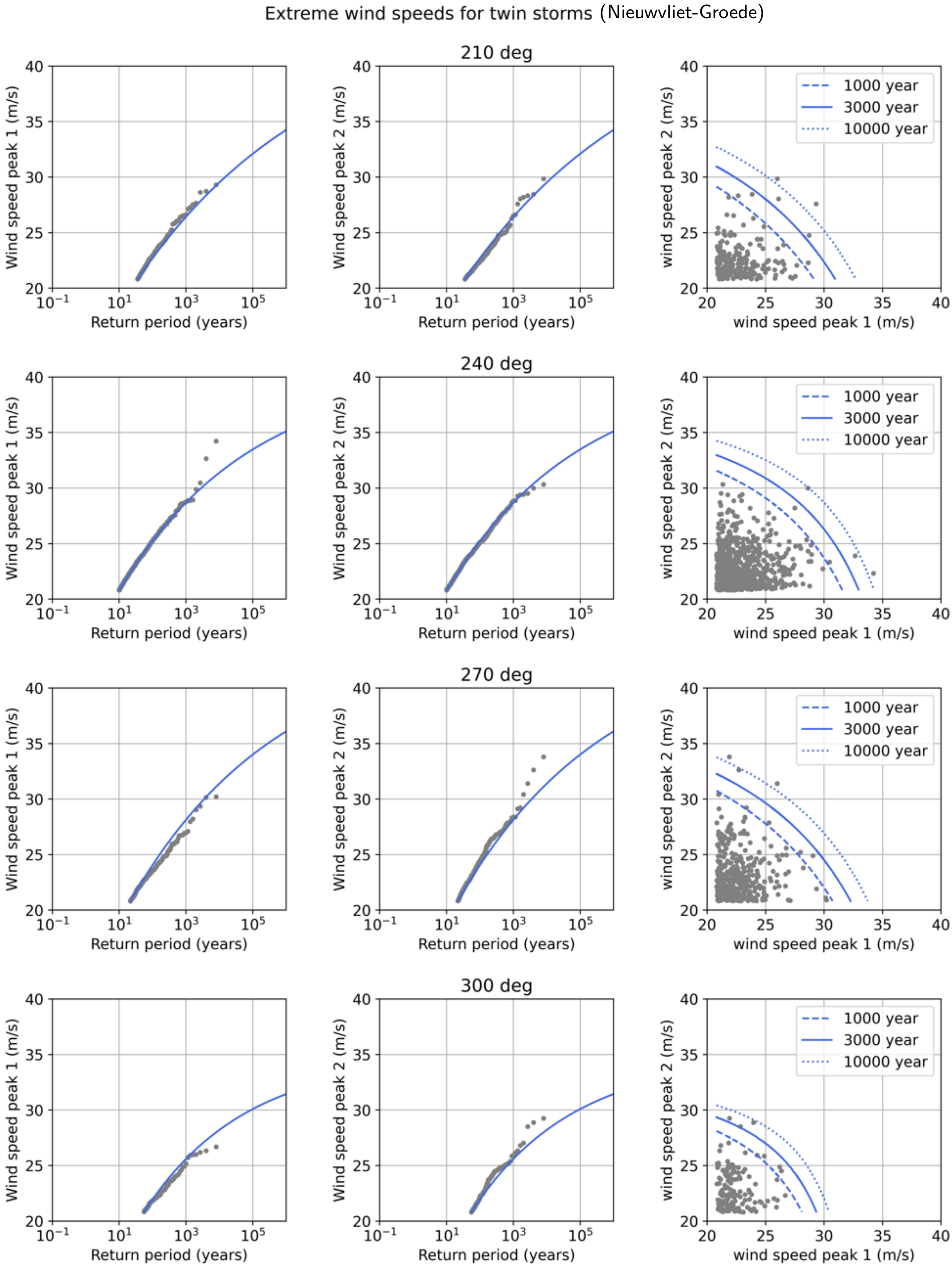


Figure C.13: Extreme wind speeds for twin storms at Nieuwvliet-Groede

The two left columns in figure C.14 show the fit of the GPD to both wind peaks for twin storms from different directions. The right column shows the computed return period lines.

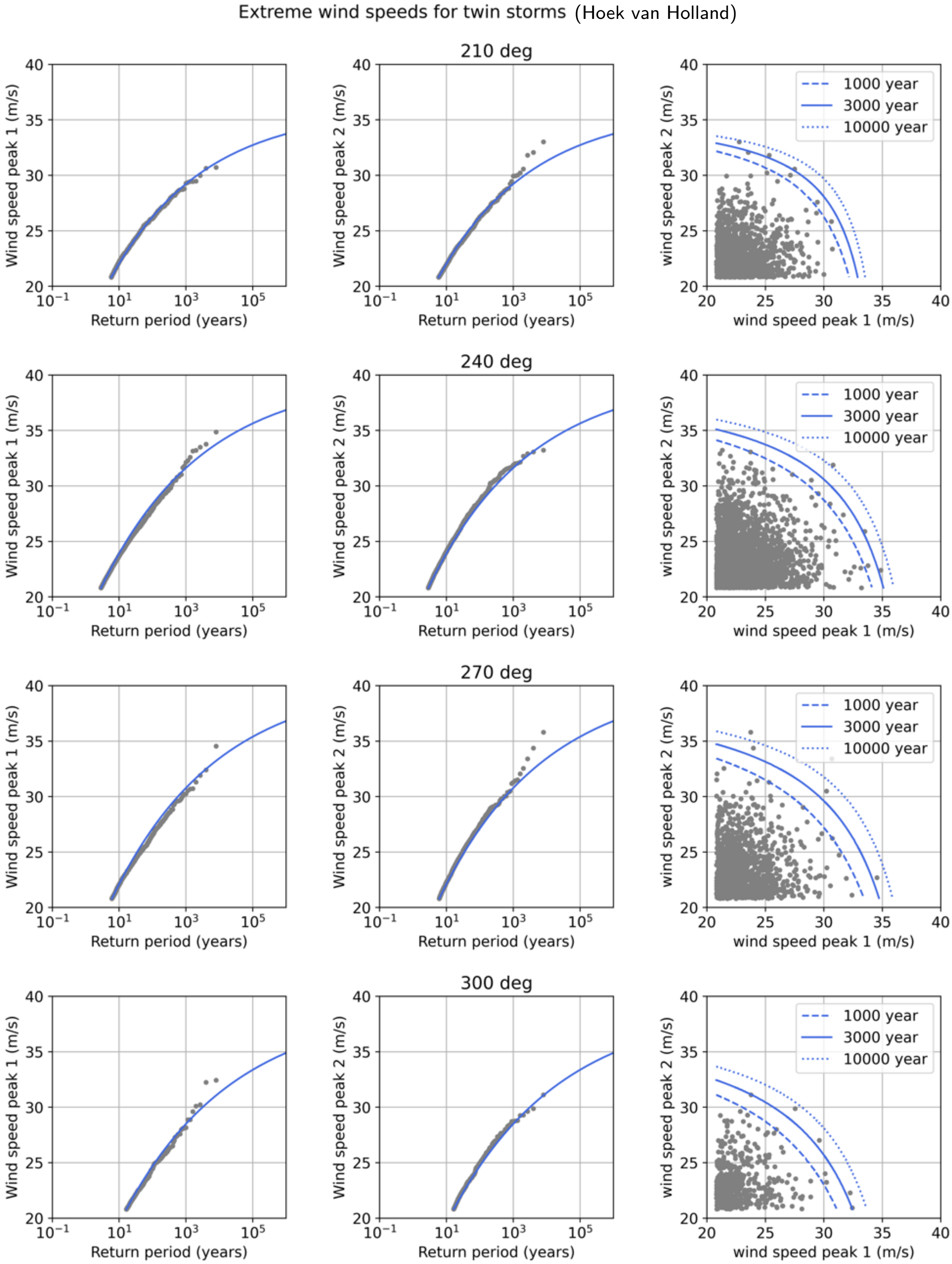


Figure C.14: Extreme wind speeds for twin storms at Hoek van Holland

C.5. Copulas

Bivariate correlations

In the model the correlation between parameters like wind speed and surge height should be described. This is done by applying copulas. A copula is a multivariate distribution function that can describe the correlation of two parameters over their marginal. According to Sklar's theorem (Sklar, 1959), the cumulative distribution function of two parameters can be written as:

$$F(x,y) = C(F(x),F(y)) \tag{C.1}$$

In this formula, $C(F(x),F(y))$ is the cumulative distribution function (CDF) of a copula. The probability density function (PDF) can be found by differentiating the CDF. This gives:

$$f(x,y) = f(x)f(y)c(F(x),F(y)) \tag{C.2}$$

If a copula is chosen, $c(F(x),F(y))$ is known as that is the PDF from the chosen copula. The functions $f(x)$ and $f(y)$ represent the PDF's from the considered variables. Multiplying the PDF from the copula with the PDF's from the variables yields the bivariate PDF in the physical space.

Copula families

There exist multiple copula families that all have their own characteristics. A copula should be chosen that represents the data parameters best. Figure C.15 shows two examples of copulas for different parameters: the Gaussian (or Normal) copula and the Gumbel copula.

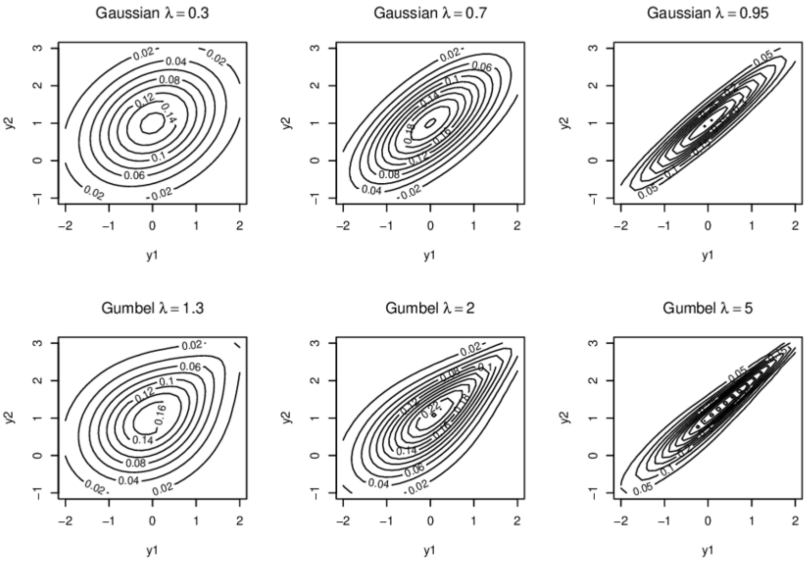


Figure C.15: Copula families (Calabrese, Osmetti, and Zanin, 2019)

Cramér-von Mises and Kolmogorov-Smornov tests

A large range of methods are available to indicate the goodness of the fit for a certain copula. Here, the Cramér-von Mises and Kolmogorov-Smornov criteria are computed to compare the different copula families (Genest, Rémillard, and Beaudoin, 2009). The equations below show the calculation procedure for the Cramér-von Mises and Kolmogorov-Smornov respectively.

$$CvM = \Sigma_{i=1}^{n} \left(F_{emp}\left(u_i,v_i\right) - C\left(u_i,v_i\right)\right)^2 \tag{C.3}$$

$$KS = max_i |F_{emp}(u_i,v_i) - C(u_i,v_i)| \tag{C.4}$$

The Cramér-von Mises calculates the sum of the squared differences for the empirical cdf value and the cdf value computed based on the copula. The Kolmogorov-Smornov criteria calculates the differences between the empirical cdf and the computed cdf and chooses the maximum value. In the formulas, F_{emp} indicates the empirical cdf value and C indicates the predicted cdf value.

Table C.1: Criteria scores for copula that relates wind speed to surge height

		Nieuwvliet-Groede			
		210 deg	240 deg	270 deg	300 deg
CvM	Gaussian	0.040	0.180	0.131	0.092
	Gumbel	0.048	0.104	0.039	0.039
KS	Gaussian	0.011	0.012	0.017	0.020
	Gumbel	0.014	0.011	0.011	0.014

		Hoek van Holland			
		210 deg	240 deg	270 deg	300 deg
CvM	Gaussian	0.215	0.729	0.426	0.244
	Gumbel	0.198	0.26	0.111	0.052
KS	Gaussian	0.012	0.015	0.018	0.019
	Gumbel	0.015	0.010	0.010	0.011

Semi-correlation

Semi-correlation is the Pearson correlation in each of the quadrant: upper-left, upper-right, lower-left and lower-right. To compute the semi-correlation, first the parameter values are converted to pseudo-observations ($F_{X,N}(X_i)$,$F_{Y,N}(Y_i)$). The functions $F_{X,N}$ and $F_{Y,N}$ are the empirical distribution functions. These can be described with (Charpentier, Fermanian, and Scaillet, 2007):

$$F_{X,T}(x) = \frac{1}{N+1}\sum_{i=1}^{T} \mathbb{1}(X_i \leq x) \qquad \text{and} \qquad F_{Y,T}(y) = \frac{1}{N+1}\sum_{i=1}^{T} \mathbb{1}(Y_i \leq y) \tag{C.5}$$

Next, the pseudo-observations are converted to standard normal variables. Then, the correlation in each quadrant can be determined by calculating pearson's correlation coefficient:

$$r_{xy} = \frac{s_{xy}}{s_x s_y} = \frac{\Sigma_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\Sigma_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\Sigma_{i=1}^{n}(y_i - \overline{y})^2}} \tag{C.6}$$

For each combination of location and wind direction, a table is given below. In the tables the correlation within the lower left (ll), upper left (ul), lower right (lr) and upper right (ur) are given. The empirical column indicates the correlations that are found based on the dataset. For four different copulas (Gumbel, Gaussian, Survival Clayton and Frank), the correlations are also shown. The most important correlation is the upper right quadrant as the most extreme wind speeds and surge heights are found in this quadrant.

Nieuwvliet-Groede, 210 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.053	0.043	0.074	0.009	0.034
ul	0.055	0.015	0.05	0.027	0.019
lr	0.004	0.02	0.054	0.033	0.032
ur	0.069	0.216	0.07	0.22	0.033

Nieuwvliet-Groede, 240 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.056	0.091	0.142	0.024	0.098
ul	0.061	0.038	0.086	0.043	0.064
lr	0.083	0.047	0.098	0.053	0.055
ur	0.213	0.348	0.137	0.376	0.091

Nieuwvliet-Groede, 270 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.058	0.137	0.199	0.041	0.12
ul	0.076	0.037	0.108	0.064	0.077
lr	0.094	0.048	0.111	0.061	0.066
ur	0.362	0.424	0.198	0.462	0.122

Nieuwvliet-Groede, 300 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.017	0.134	0.204	0.046	0.122
ul	0.003	0.05	0.111	0.054	0.057
lr	0.08	0.046	0.119	0.071	0.058
ur	0.31	0.412	0.194	0.468	0.124

Hoek van Holland, 210 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.082	0.106	0.168	0.025	0.12
ul	0.058	0.043	0.103	0.061	0.049
lr	0.05	0.056	0.106	0.061	0.052
ur	0.177	0.392	0.179	0.43	0.104

Hoek van Holland, 240 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.118	0.177	0.26	0.062	0.17
ul	0.066	0.059	0.135	0.068	0.079
lr	0.088	0.051	0.138	0.083	0.063
ur	0.353	0.484	0.248	0.552	0.156

Hoek van Holland, 270 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.155	0.222	0.316	0.08	0.205
ul	0.092	0.067	0.145	0.069	0.079
lr	0.026	0.061	0.148	0.08	0.083
ur	0.405	0.55	0.313	0.618	0.2

Hoek van Holland, 300 deg					
	Empirical	Gumbel	Gaussian	Survival Clayton	Frank
ll	0.121	0.196	0.276	0.068	0.178
ul	0.037	0.047	0.133	0.073	0.093
lr	0.167	0.051	0.145	0.069	0.062
ur	0.419	0.497	0.271	0.582	0.165

Choice of copula

A copula is used to relate the wind speed to the surge height. In table C.1 the CvM and KS criteria are calculated for the relation between wind speed and surge level for both locations and storms from four directions. A low score indicates a better fit. It can be seen that the differences found are relatively small. For Nieuwvliet-Groede, the Gaussian copula gives a better fit but for Hoek van Holland the Gumbel copula gives better results.

As the dataset for Hoek van Holland is larger than the dataset for Nieuwvliet-Groede, it is expected that the fit for Hoek van Holland is better than the one for Nieuwvliet-Groede. Furthermore, for consistency it is decided to use one copula family that holds at both locations. As the differences between the Gumbel and Gaussian copula are small, the Gumbel copula is chosen to define the relation between surge level and wind speed.

Fitted copulas

The fitted Gumbel copulas are shown in figure C.16 and C.17.

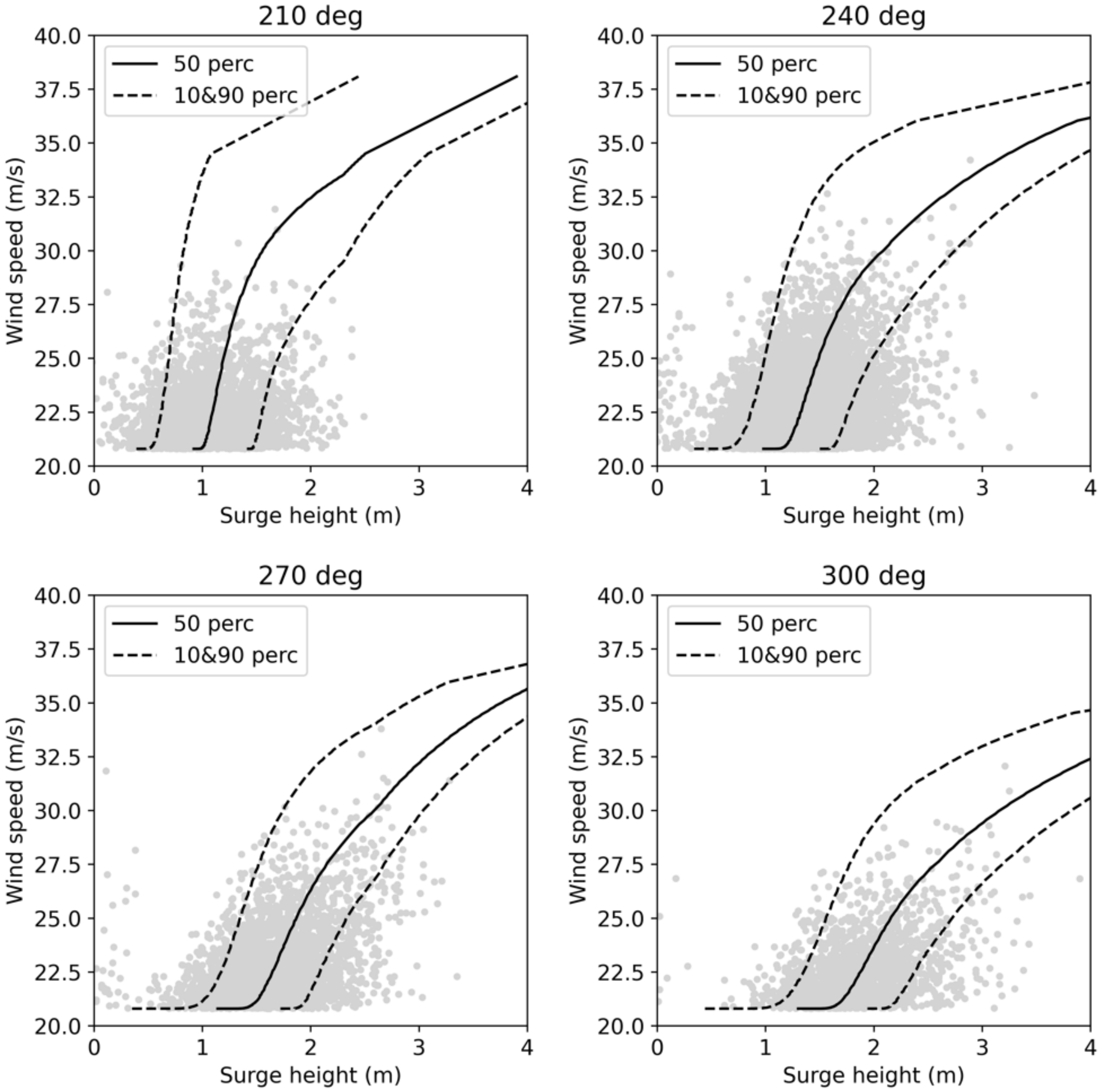


Figure C.16: Fitted Gumbel copula on wind speed related to surge height at location Nieuwvliet-Groede

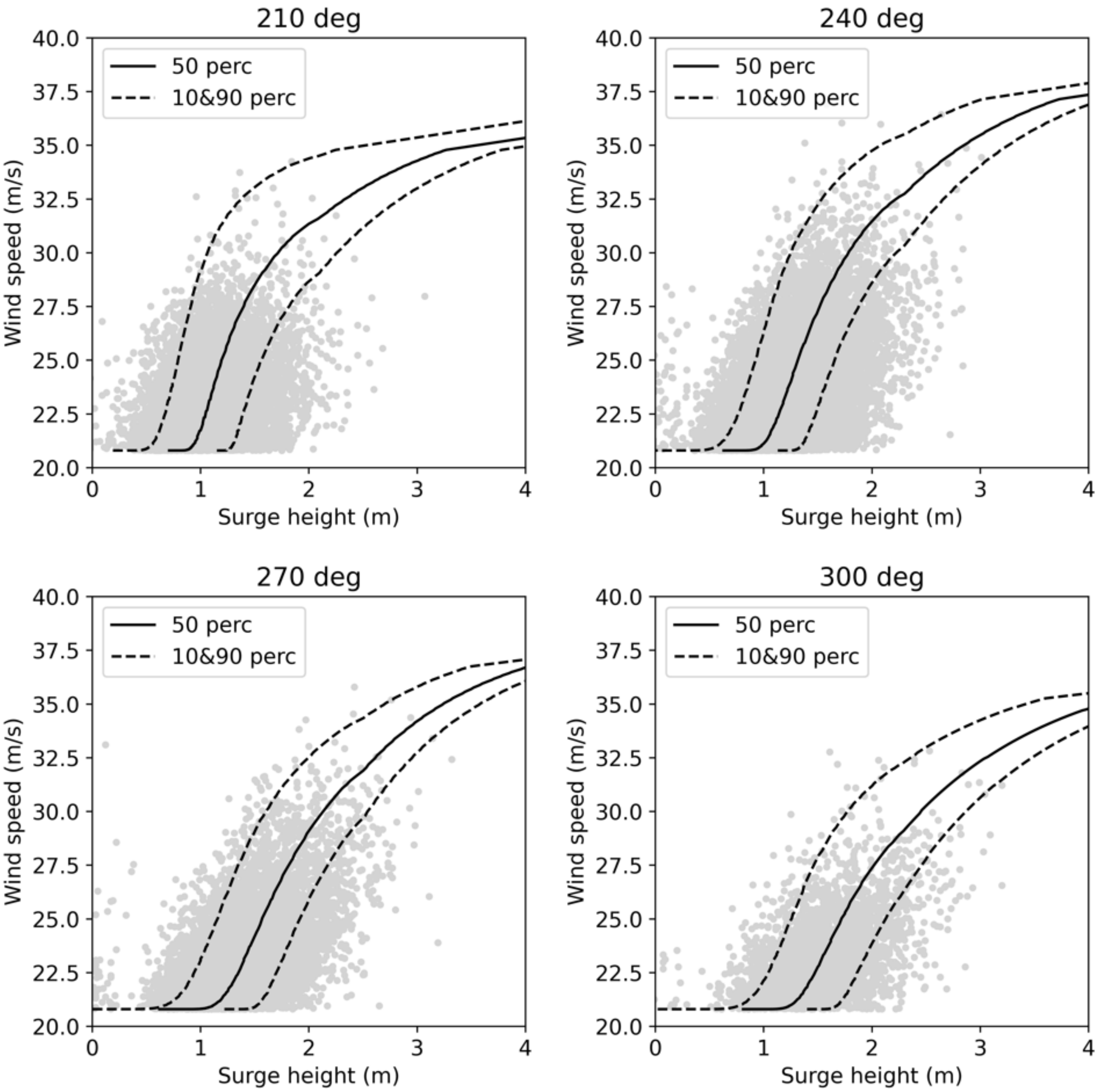


Figure C.17: Fitted Gumbel copula on wind speed related to surge height at location Hoek van Holland

C.6. Time scaling

For choosing an appropriate multiplication value, it should be taken into consideration how the interval duration influences the normalised pattern of the storms. It is assumed that the duration of the storms is not influenced by the interval duration between the storms. Thus, storms with a larger interval duration between the peaks give narrower normalised peaks than storms with a shorter interval duration as they are divided by a larger number. This is graphically shown in figure C.18.

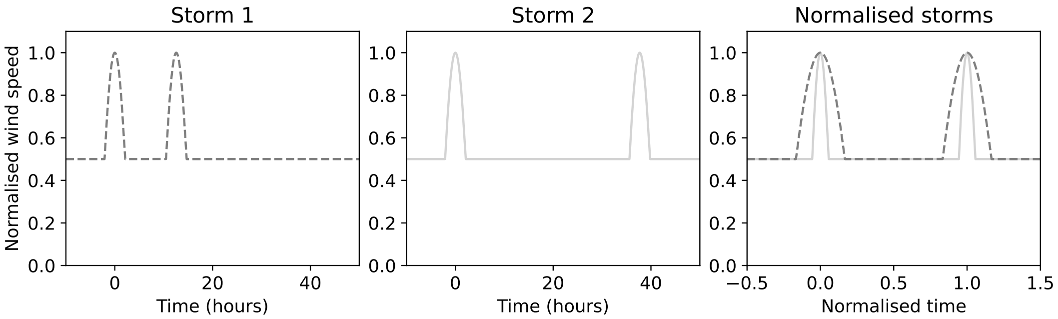


Figure C.18: Example of normalisation in time for storms with different wind speed intervals

The storm with a larger interval duration clearly gives a shorter normalised duration than the storm with a shorter interval duration. The consequences of this scaling property can be better illustrated with an example. Figure C.18 shows on the left an example of a wind peak from a storm. The right figure shows normalised wind peaks for several interval durations and the 50 percentile line that can be fitted.

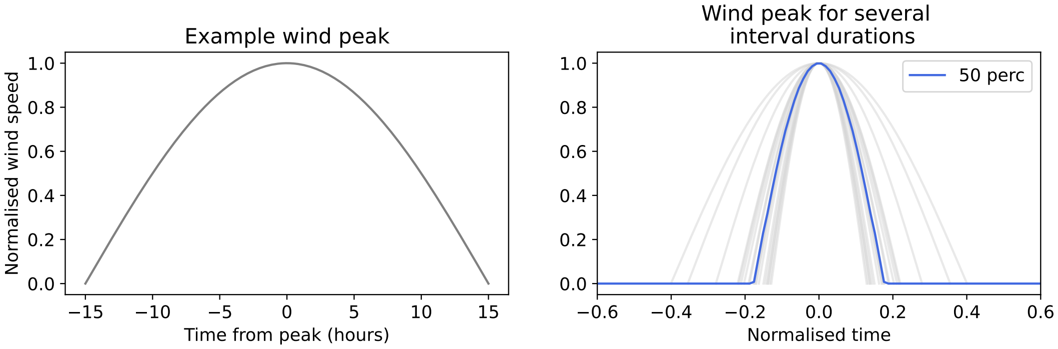


Figure C.19: Normalised time evolution of the normalised wind speed for different wind speed interval durations.

Upscaling is done by multiplying the percentile line with a time duration. As in the example all peaks in the beginning had the same duration, the upscaled duration should resemble the example wind peak. In figure C.20 it is shown how different scaling intervals give different results. It is shown that choosing a scaling interval that is too small gives a peak that is too narrow. Choosing a scaling interval that is too large gives a peak that is too broad. The middle figure shows a scaling interval of 67 hours which is the median of all storms shown in figure C.19. It can clearly be seen that choosing the median interval duration gives a good approximation of the storm.

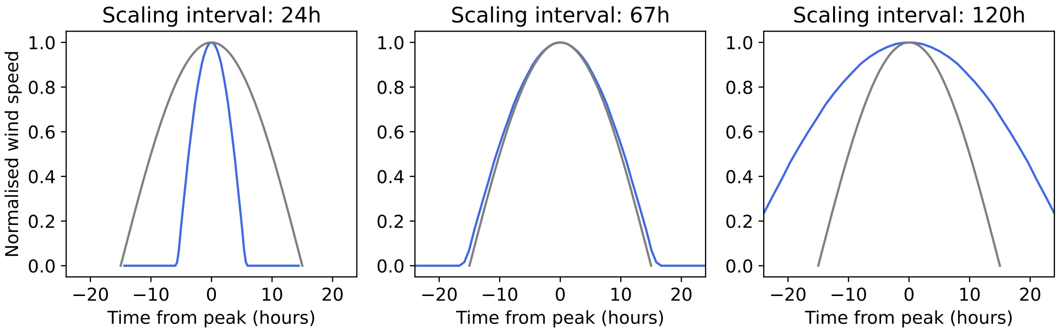


Figure C.20: Time evolution of normalised wind speed for different scaling intervals

C.7. Surge phases

In figure C.21, the surge phases are shown for all storms, divided per location and direction.

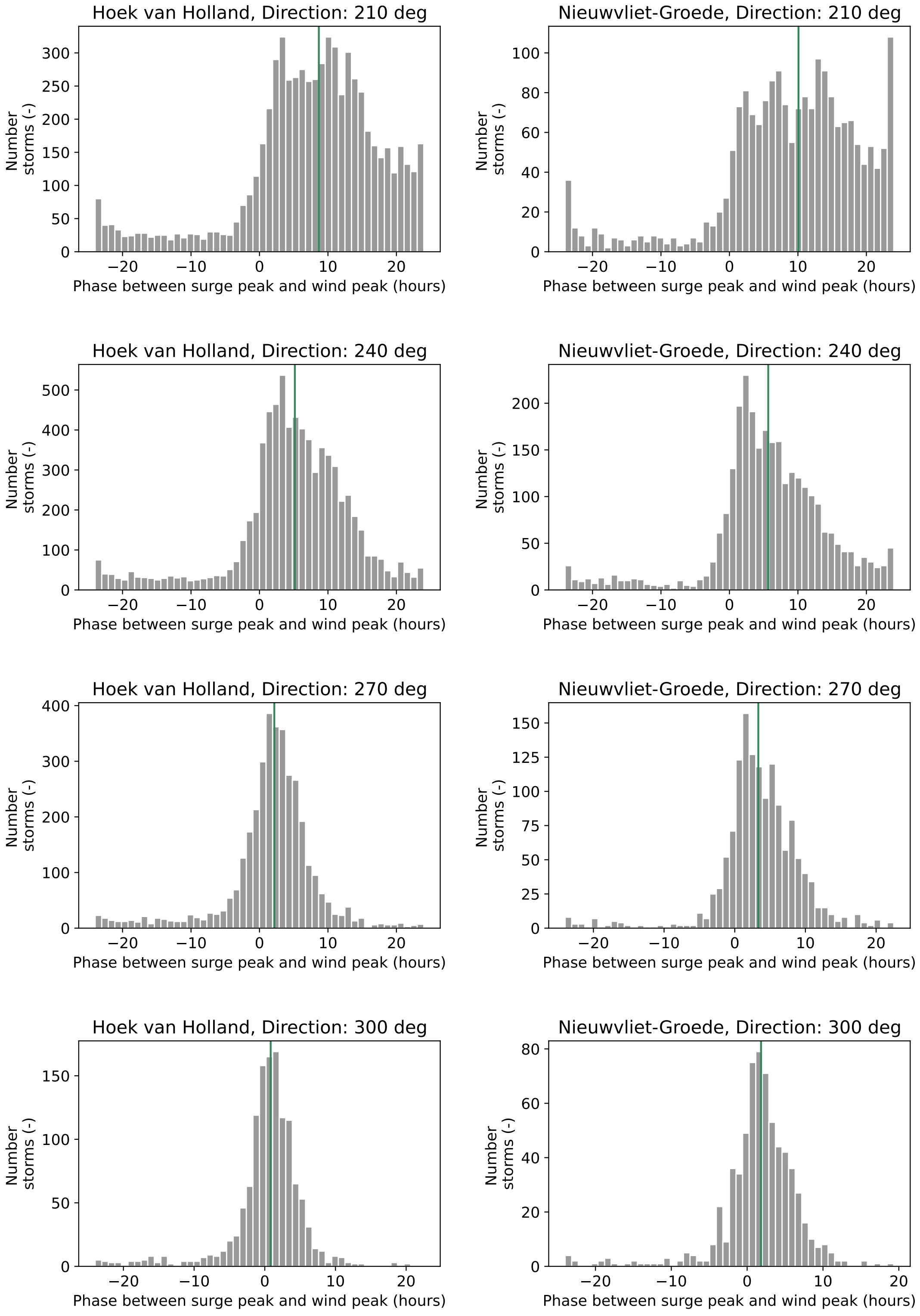


Figure C.21: Distribution of phase between wind speed peak and surge height peak for both locations and for storm from all directions. The green line indicates the median value.

C.8. Tidal phases

In figure C.22, the tidal phases are shown for all storms, divided per location and direction.

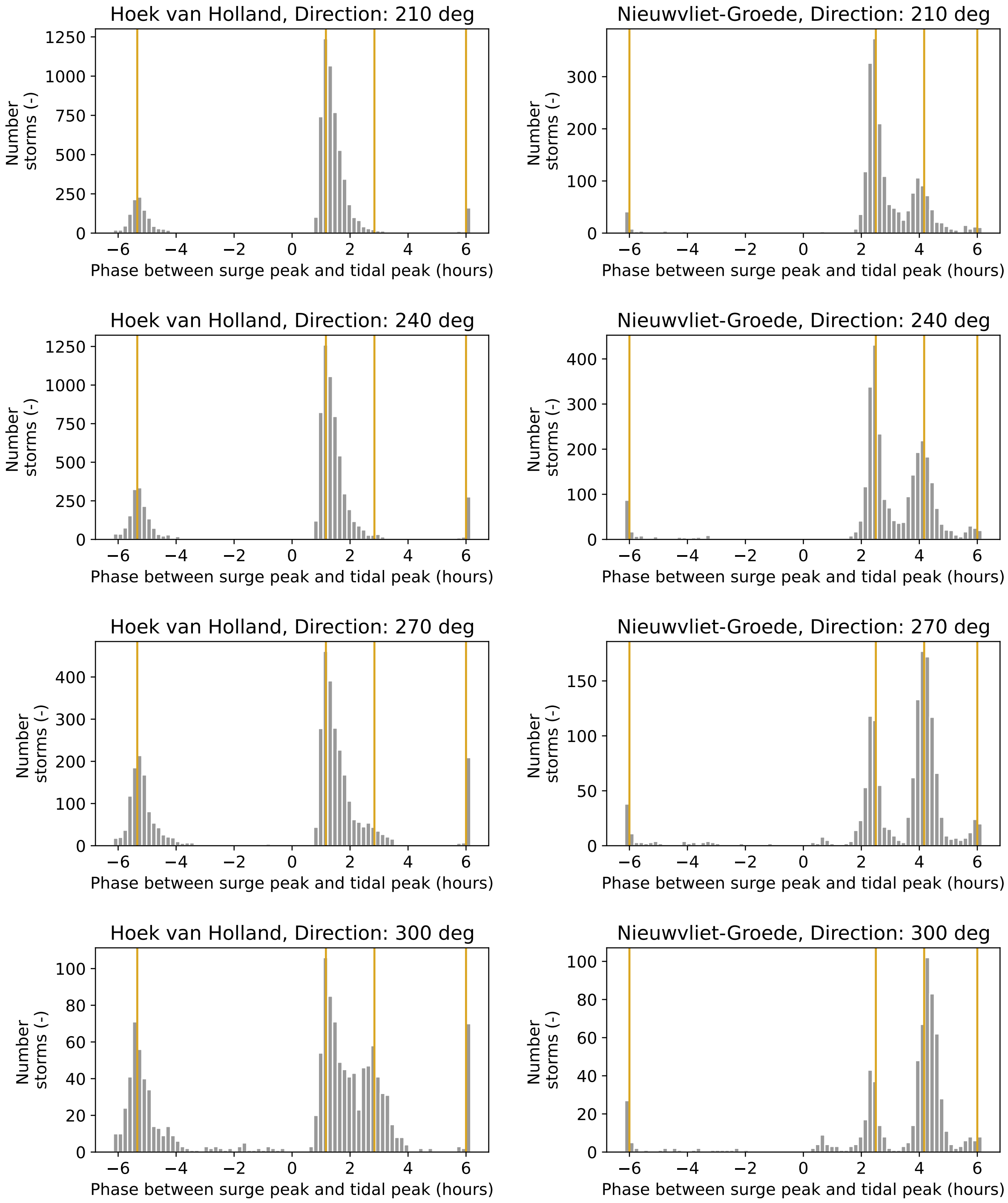


Figure C.22: Distribution of tidal phases for all storms at both locations and for storms from all directions. The orange lines indicate the most frequently occurring phases.

C.9. Wave parameters of reference storm

Figure C.23 shows the wind speed and wave height observed for the storms Eunice and Franklin in February 2022.

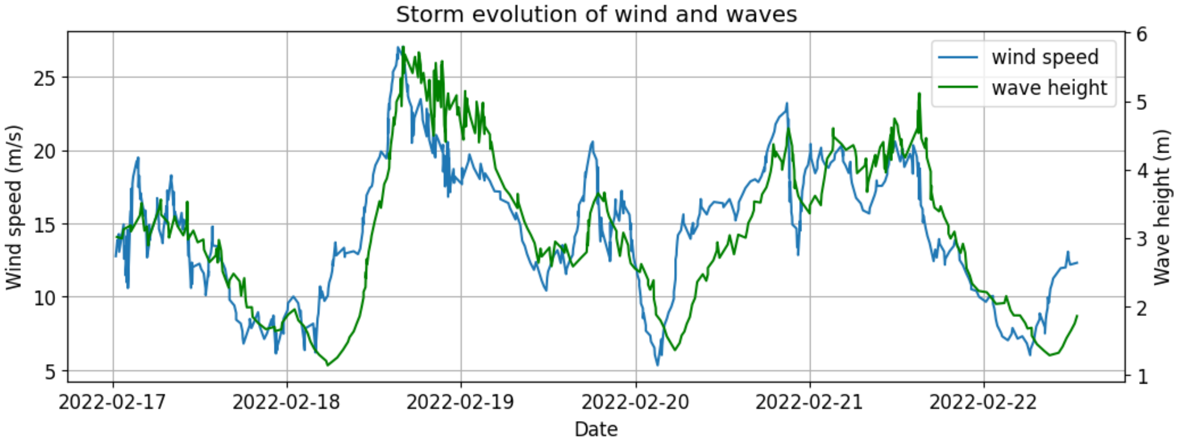


Figure C.23: Wind speed and wave height for storms of February 2022 at the Europlatform

Figure C.24 shows the wind direction and wave direction observed for the storms Eunice and Franklin in February 2022.

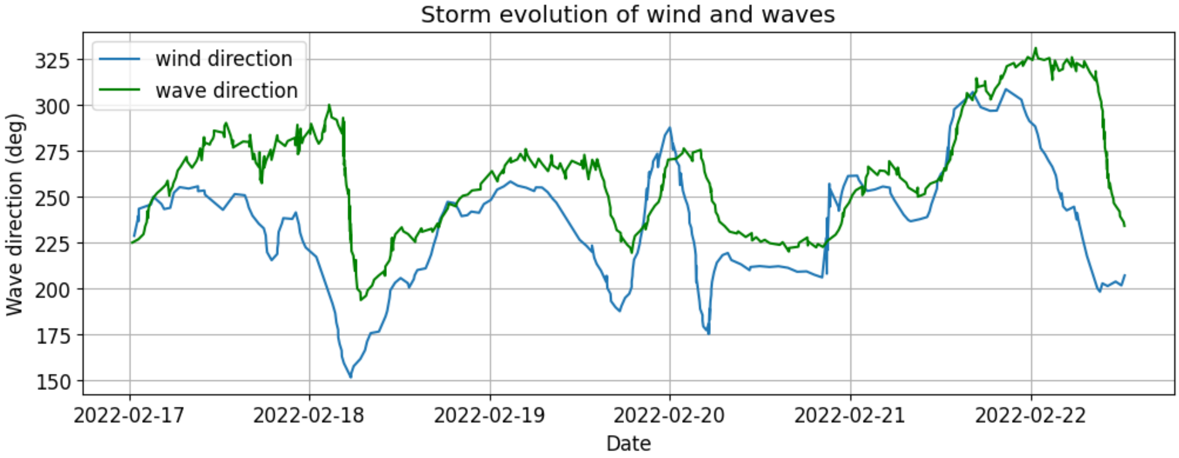


Figure C.24: Wind- and wave direction for storms of February 2022 at the Europlatform

D

Dune erosion

D.1. Cross shore profile locations

Considerations location Nieuwvliet-Groede

The location of Nieuwvliet-Groede is located on the island of Walcheren. Between the islands of Walcheren and Zeeuws-Vlaanderen, a tidal inlet can be found. Tidal inlets often form a very dynamic and complex morphological system. The same holds, for the inlet between Walcheren and Zeeuws-Vlaanderen. In figure D.1 the bathymetry around Nieuwvliet-Groede is shown. It can clearly be seen that there are a lot of bars and gullies, as a consequence of the tidal inlet. The sand bars can lead to dissipation of large amounts of wave energy. Furthermore, the coastline around the island of Walcheren is quite curved. Curvature of coastlines also influence the amount of dune erosion.

The modelling of dune erosion for curved coastlines and complex bathymetries, falls outside the scope of this work. Therefore, it is chosen to select a bottom profile on the island of Zeeuws-Vlaanderen as these locations are less prone to effects due to curvature of the coastline and wave dissipation due to sand bars.

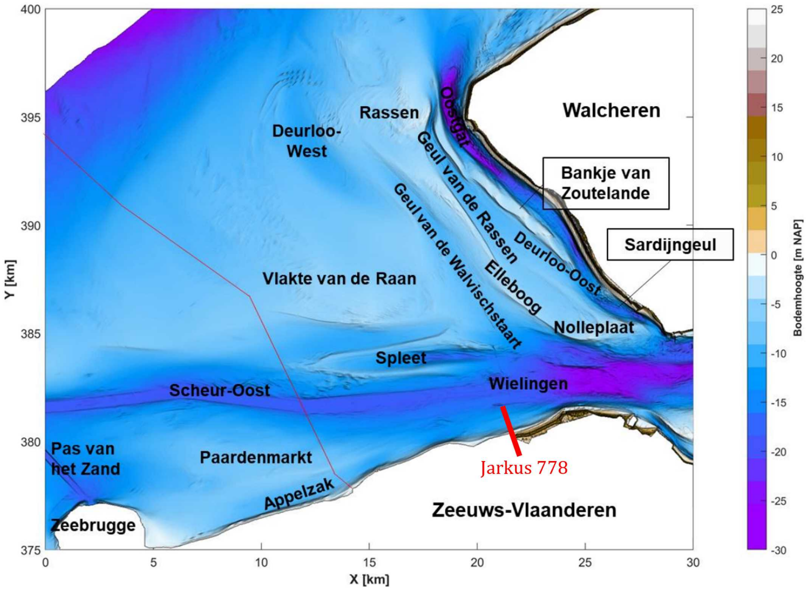


Figure D.1: Morphology Nieuwvliet-Groede (Vermeer and van der Werf, 2022)

Considerations location Hoek van Holland

The chosen bottom profile for Hoek van Holland is located directly behind the Maasvlakte as can be seen in figure D.2. For storms from South-Westerly directions, Hoek van Holland most probably experiences conditions that are less extreme than locations further to the North due to the sheltered position behind the Maasvlakte. In this research, sheltering effects are not taken into account.

Figure D.2: Location of Maasvlakte and cross shore profile of Hoek van Holland

D.2. XBeach input file

The params file used to initiate the XBeach calculation is shown below:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%        XBeach parameter settings input file        %%%
%%%                                                    %%%
%%%             date:    06-Oct-2023 13:36:03          %%%
%%%                 Delta-Shell XBeach plugin          %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Physical processes %%%

morphology = 1
wavemodel = surfbeat
sedtrans = 1
snells = 0

%%% Grid parameters %%%

thetanaut = 0
thetamin = -90
thetamax = 90
dtheta = 180
alfa = 322.2
xfile = x.grd
yfile = y.grd
vardx = 1
nx = 478
ny = 0
depfile = bed.dep
posdwn = -1

%%% Morphology parameters %%%

morfac = 4
morstart = 0
wetslp = 0.15
struct = 0

%%% Sediment transport parameters %%%

turbadv = none
facSk = 0.15
facAs = 0.2

%%% Flow boundary condition parameters %%%

front = abs_1d
left = wall
right = wall
back = abs_1d
epsi = -1
```

```
%%% Bed composition parameters %%%

D50 = 0.000214
D90 = 0.000321
rhos = 2650

%%% Physical constants %%%

rho = 1025

%%% Output variables %%%

rugdepth = 0.01
tstart = 0
tintg = 3600
tintp = 3600
tintm = 3600

%%% Model time %%%

CFL = 0.95
tstop = 463800

%%% Wave breaking parameters %%%

fw = 0
gammax = 2
alpha = 1.38
gamma = 0.46

%%% Roller parameters %%%

beta = 0.08
wbctype = jonstable
bcfile = waves.lst

%%% Randvoorwaarden verticaal getij %%%

tideloc = 2
zs0file = tide.txt
```