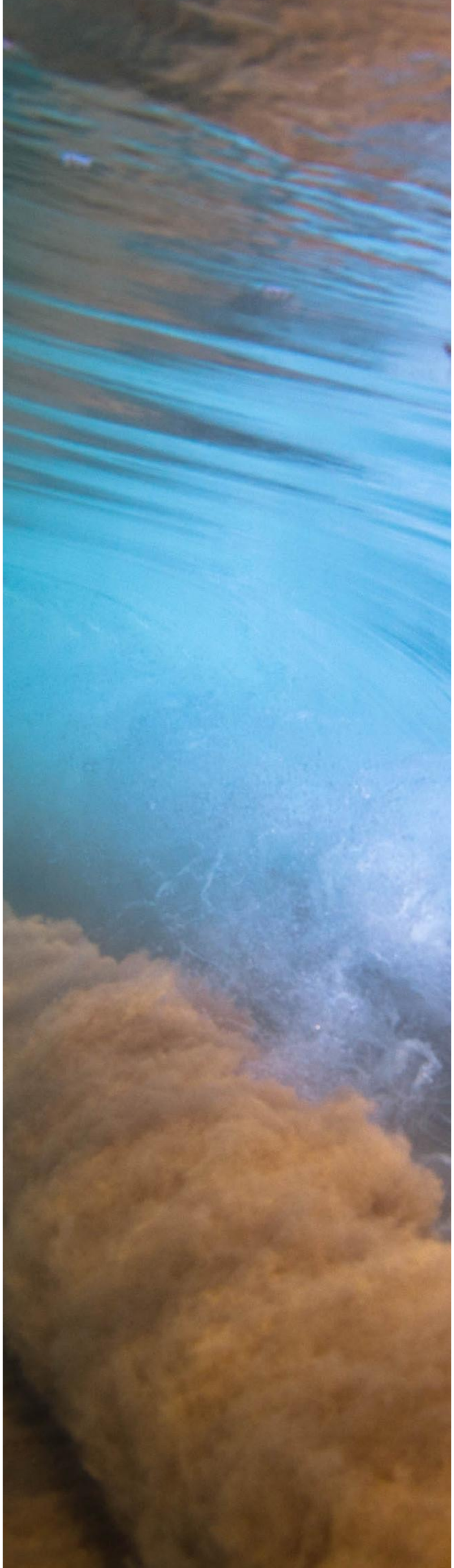

Modelling the influence of storm related processes and their frequencies of occurrence on sand wave dynamics in the North Sea

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UNIVERSITY OF TWENTE.

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Preface

With this report I complete my Master Civil Engineering and Management at the University of Twente. The study of sand waves was a completely new topic for me, and I have learned a lot from the research and the process itself.
I would like to thank Geert Campmans, Pieter Roos and Suzanne Hulscher for their understanding of the difficult situation I was in during this graduation project. From the beginning on you all took the situation into account and throughout the process kept a positive and hopeful attitude. In particular I would like to thank Geert for helping me understand the research subject, for answering all my questions and for keeping me enthusiastic about the research.
Furthermore I would like to thank my family and friends for their support. Arno, thank you for all your computer related help and support. Lidewij and Willeke, thank you both for the schnitzel dates and for being there for me at times when I needed distraction and some fun. Sylvie, thank you for the textual support and for being there for overall help and guidance during this graduation project and in the years before. Furthermore I would like to thank my parents for giving me the opportunity to study in Enschede without a care. Last, but not least, I would like to thank Hannie for all the times she was there for me at doctor appointments, during treatments and operations and on the phone.

Ellis Schrijen
Enschede, May 2017

Abstract

Large parts of the sea bed of shallow shelf seas, such as the North Sea, are covered with sand waves. Sand waves are medium-scale bedforms characterized by wave heights of several meters and migration rates up to tens of meters per year. Knowledge about the behavior of sand waves is of importance since they can form a hazard to pipelines, communication cables, offshore constructions and navigation. Campmans et al. (2017) state that waves and wind indeed can play a significant role in sand wave dynamics. However since storms occur only for a small fraction of the time during a year Campmans et al. (2017) have stated that “to assess the averaged model effect of storms on sand wave dynamics a statistical approach is required” (p14).

The goal of this thesis is therefore to investigate the influence of the wind- and wave climate and in particular storms, consisting of a combination of the storm related processes of wind waves and wind-driven flow and its frequencies of occurrence, on sand wave dynamics by applying a statistically combined wave and wind climate to the idealized sand wave model of Campmans et al. (2017) and analyzing its results.

This research aims to answer the following questions:

1. What is the wind- and wave climate at the research location?
2. Based on the idealized sand wave model of Campmans et al. (2017):
    a) what is the influence of the storm related processes and their frequencies of occurrence on the growth- and migration rate of sand waves?
    b) which storm related processes make the biggest contribution to the resulting growth- and migration rate?

The storm related processes that were focused on in this research are wind (wind speed and wind direction) and waves (wave height, wave period and wave direction). Wind- and wave data is obtained for a chosen location and timeframe, and desk research is carried out to obtain a general climate, storm climate and the frequencies of occurrence. The data is divided in bins and used as input values for the idealized model of Campmans et al. (2017). By dividing the data in these bins the correlation between the 5 parameters is taken into account.

The results show that including storm related processes and their frequencies of occurrence influence the sand wave dynamics in their formation stage by causing the total growth rate to decrease. The frequency of occurrence shows to be more important for the resulting growth rate than the actual growth rate associated with the parameters itself. The growth rate itself is however still of importance and can contribute to small differences in the growth rate values of the bins. The migration rate is determined by a combination of frequency of occurrence and the migration rate itself. For certain bins the migration rate itself is dominant over the frequency of occurrence whereas the opposite is true for other bins. The influence of storms (defined as a wind measuring 20.8 m/s or higher) on the growth- and migration rate of sand waves is only minimal because of their low frequencies of occurrence.

The biggest contribution to the resulting growth rate comes from a wind- and wave climate consisting of wind speeds between 0 and 10 m/s, wave heights between 0 and 2 meters, wave periods between 3 and 5 seconds, wind angles between -180 and -120, between -60 and 0 and between 120 and 180 degrees and wave angles between -30 and 60 degrees. A wind speed between 10 and 21 m/s combined with a wind angle between 0 and 180 degrees contributes most to the migration rate.

Recommendations for further research are to further investigate the vertical eddy viscosity by taking it into account as a variable and not as a constant, and to more elaborately investigate the influence of the hours surrounding storms. Together these could give more insight into the contribution of storm related processes and storms to the overall growth rate.

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1 Introduction

1.1 Sand waves

Large parts of the sea bed of shallow shelf seas, such as the North Sea (see Figure 1), are covered with sand waves. Sand waves are medium-scale bedforms that are characterized by wavelengths (i.e. the distance between two adjacent crests) of the order of hundreds of meters and a wave height of several meters (Terwindt, 1971). Furthermore sand waves have crests that are almost perpendicular to the direction of the tidal current (Knaapen, Hulscher, & De Vriend, 2001). Sand waves can migrate up to tens of meters per year, and are formed at a time scale of 1-10 years (Terwindt, 1971). Knowledge about the behavior of sand waves is of importance since they can form a hazard to pipelines, communication cables, offshore constructions and navigation.

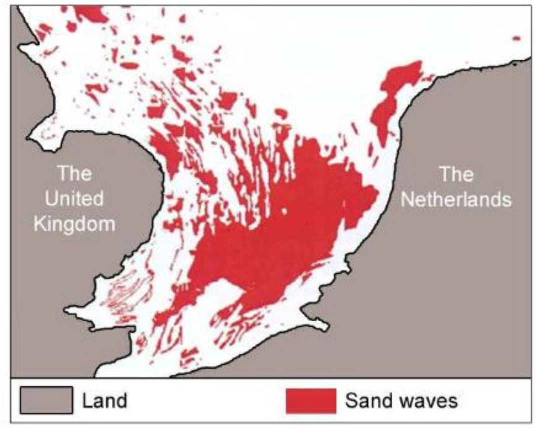


Figure 1: Locations of several tidal sand bank Systems in the North Sea. Adapted from “Comparison between predicted and observed sand waves and sand banks in the North Sea” by S. Hulscher and G. Van den Brink, 2001, *Journal of Geophysical Research, 106*, p. 9328. Copyright by AGU.

1.2 Sand wave dynamics

1.2.1 Sand wave formation

Hulscher (1996) demonstrated that sand waves can be explained as free instabilities, formed due to interactions between tidal flow and a sandy seabed. The interaction of the tidal current with a bottom perturbation leads to a tide-averaged residual circulation. This circulation is directed from the trough towards the crest of the sand wave and causes a net sediment flux towards the crest (see Figure 2 (Hulscher, 1996, p.20740)). This process leads to sand wave growth as long as the sediment transport overcomes the opposing effect of gravity (Borsje, Roos, Kranenburg, & Hulscher, 2013).

Together the tidal flow and the seabed create a feedback mechanism; the tidal flow changes the shape of the seabed through sand transport, in turn the shape of the seabed affects the tidal flow. Sand wave dynamics thus consist of a competition between residual current and gravity which creates the feedback mechanism consisting of water flow and sediment transport. The depth-averaged residual current can originate either from the tide, from a wind-induced current or from wave-induced current (Besio, et al., 2008).

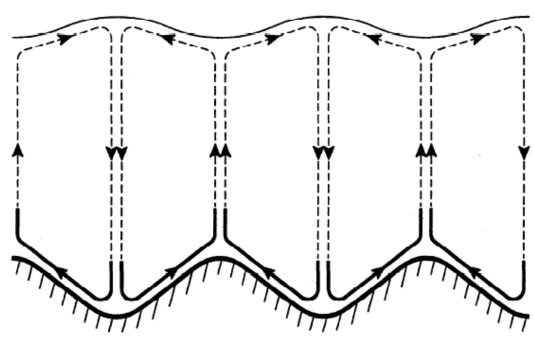
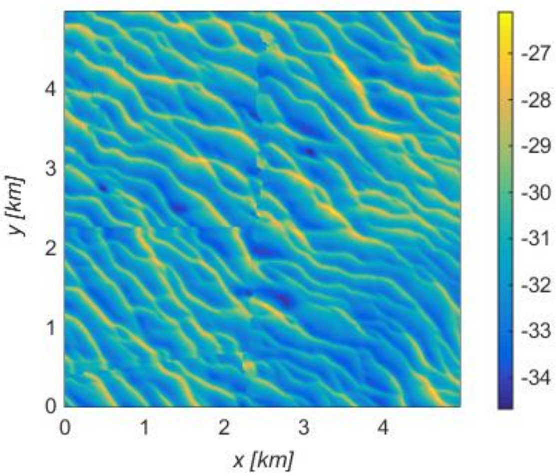


Figure 2: Strong near-bed circulation which supports the growth of the bottom perturbation. The backward circulation in the upper flow part uses a larger part of the water column and is weaker. Reprinted from “Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model” by S.J.M.H Hulscher, 1996, *Journal of geophysical research, 101*, p. 20740. Copyright 1996 by the American Geophysical Union.



The mode (wavelength and crest orientation) with the largest growth rate is the fastest growing mode (FGM) and is assumed to prevail. The FGM is considered the dominant bed form and its four key properties are wavelength, crest orientation, migration rate and growth rate. Studies have shown that the wavelength of the fastest growing sand wave is controlled by, among others, the water depth, the maximum depth-averaged tidal current, the ellipticity of the depth-averaged tidal current and sediment grain size (Van Santen, De Swart, & Van Dijk, 2011).

Figure 3: Sand wave pattern in the North Sea (location Europlatform) (J.M. Damen, personal communication, August 29, 2016). Colors indicate the bed level relative to LAT. The y-axis points northward.

1.2.2 Wind-induced current

Wind driven currents are currents that are created by the force of the wind exerting stress on the sea surface. This stress causes the surface water to move and this movement is transferred to the underlying water layers. However, a wind-driven current does not flow in exactly the same direction as the wind, but is deflected by the Coriolis force. Under ideal conditions, being a steady wind blowing across an ocean of unlimited depth and extent, the surface layer moves at an angle of 45 degrees from the direction of the wind, because of this Coriolis effect. As the surface layer moves, each successive layer of water is set in motion at a progressively slower velocity, and in a direction progressively to the right of the one above it (in the Northern Hemisphere). The net water movement, called the Ekman transport, is 90 degrees to the right from the wind direction in the Northern Hemisphere (see Figure 4). These conditions however rarely occur. The difference in direction between the wind and the surface current in real life varies from about 10 degrees in shallow coastal areas to as much as 45 degrees in some open ocean areas. In shallow coastal waters the Ekman transport can be nearly the same direction as the wind (Trujillo & Thurman, 2011), whereas the Ekman transport in the open ocean is typically around 70 degrees from the wind direction. In case the water is deep enough, friction will consume the wind energy and no motion will occur below that depth. Although dependent on wind speed and latitude, this typically occurs at a depth of about 100 meters.

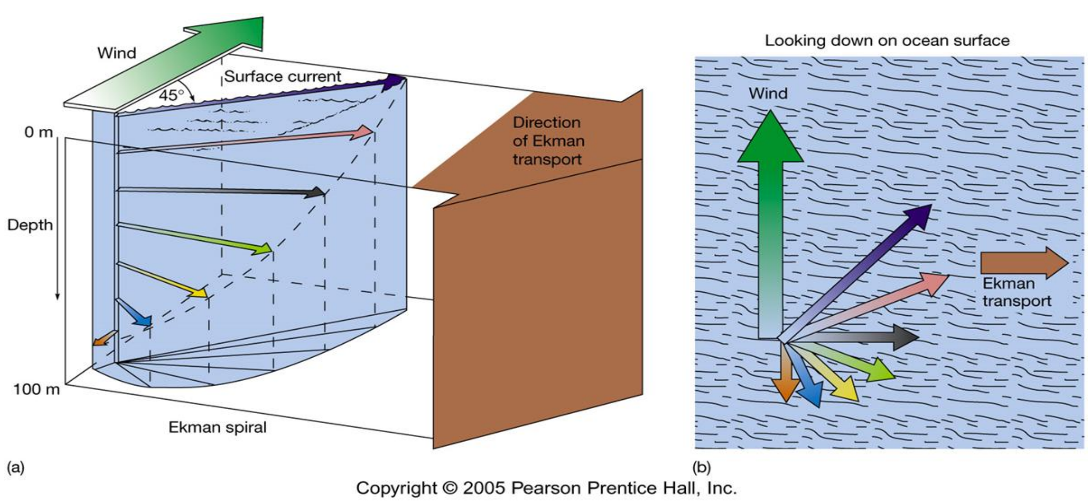


Figure 4: Perspective view (a) and top view (b) of Ekman spiral and Ekman transport. Wind drives surface water in a direction 45 degrees to the right of the wind in the Northern Hemisphere. Deeper water continues to deflect to the right and moves at a slower speed with increased depth, causing the Ekman spiral. Ekman transport which is the average water movement for the entire column, is at a right angle (90 degrees) to the wind direction. Reprinted from *Essentials of Oceanography 10th ed*. (p. 201), by A.P. Trujillo and H.V. Thurman, 2011, US: Prentice Hall. Copyright 2011 by Prentice Hall.

1.2.3 Wind waves & wave motion

As the wind blows over the ocean surface, it creates pressure and stress. The wind transfers its energy to the water and as more energy is transferred, waves develop. The energy from the wind increases the height, length, and speed of the wave. Waves have a variety of periods and wavelengths due to frequently changing wind speed and direction. As a wave travels, the water passes the energy along by moving in ellipses. This movement is called circular orbital motion. The forward movement of the water under a crest in shallow water is faster than the backward movement under its trough (Anthoni, Oceanography: waves, 2000).

1.2.4 Sand transport

Sand transport occurs due to a combination of wind, waves and currents. Sand can be transported by wind-, wave-, tide-and density-driven currents, by the oscillatory water motion caused by wave asymmetry (deformation of waves under the influence of decreasing water depth) or by a combination of currents and waves (Rijn, n.d.).
Sand waves are not steady, they can migrate, saturate and/or be suppressed. Sand wave migration occurs due to a residual current (Besio, et al., 2008). Sand waves saturate because of the nonlinearity in the competition between residual circulation directed from the trough towards the crest of the sand wave and the slope term, which reduces the net amount of sediment transported upward toward the crest (Németh, Hulscher, & Van Damme, 2007). Sand waves can also be suppressed. Research (Borsje, Kranenburg, Roos, Matthieu, & Hulscher, 2014) has shown that sand waves are only found at locations where bedload transport was the dominant transport mode. Sand waves are absent at locations where suspended load transport was the dominant transport regime. Model simulations show that suspended load transport has a damping effect due to the phase lag between the suspended sediment concentrations and the sand wave. This phase lag results in a tide-averaged divergence of suspended load transport at the sand wave crest and hence sand wave decay.

1.3 Storms

1.3.1 Storm characteristics and storm activity in the North Sea region

KNMI (n.d., d) states that the meteorological definition of a storm is a wind measuring 9 or higher on the Beaufort scale. This refers to a ten-minute average wind speed between 75 and 88 kilometers per hour (20.8-24.4 m/s). Large differences in temperature in the atmosphere generally create turbulent weather and storms. Therefore the heaviest storms generally occur in the fall and winter. When the atmosphere is unstable, storms occur shortly one after another (KNMI, n.d., c). Occasionally heavy storms occur soon after another, other times there can be years in between. The repetition time for a storm at sea is shorter than its repetition time in the midland.
Storm activity in the North Sea region is not constant, but has undergone considerable variations over the past decades. In the 20th century, storms with a wind measuring 10 or higher on the Beaufort scale during at least an hour occurred 35 times in the Netherlands. Nine of these occurred since 1990 (Meteolink, n.d.). In the last 30 years, a wind measuring 11 on the Beaufort scale only occurred in 1990 and 2013 (KNMI, n.d., f). Based on observations, the KNMI concluded that there were more storms above the North Sea area at the beginning and end of the twentieth century. Midway the century and in recent years the number of storms is lower. However they do point out that the Netherlands is too small and that its measurement series are too short to determine changes in the number of heavy storms (10 or 11 on the Beaufort scale) (KNMI, n.d., b). Weisse, Von Storch, Niemeyer and Knaack (2012) have

stated that research reveals considerable variability on inter-annual and on decadal time scales but shows no clear long-term trend concerning storms in the North Sea region.
A study on the evolution of extreme wind conditions, wave height and storm surge levels in the North Sea Region, especially in the Belgian part of the North Sea (van den Eynde, de Sutter, & Haerens, 2012), stated that no clear trend can be observed for the occurrence of higher wind speeds, higher waves, nor increased frequency or duration of storm winds over the Belgian part of the North Sea. All in all these studies conclude that there is no clear trend in the frequency and intensity of storms over the past centuries.

1.3.2 Storm related sand wave research

Multiple investigations into the influence of storm related processes and storms on sand wave dynamics have been executed over the years. The results of these investigations, among others, show that sand wave heights are reduced during stormy periods, state that the decreasing sand wave heights towards the coast can be explained by an increased importance of wind waves, suggest that storms may play a major role in the migration of sand waves and consist of observations showing significant migration speeds that reverse direction due to a change of wind direction during the monsoon season (Terwindt, (1971), Langhorne (1982), Houthuys et al. (1994), Van de Meene et al. (1996), Van Dijk and Kleinhans (2005), McCave (1971), Fenster et al. (1990), Harris (1989), as cited in Campmans, Roos, De Vriend, & Hulscher (2017).
Van der Molen (2002) has stated that the presence of waves during storm conditions causes an increase in the contribution of storms in the mean sand transport since waves stir up the sand while the wind-driven currents facilitate the transport. Furthermore the contribution of suspended load is larger at locations where storms dominate compared to where tides dominate because of the rougher conditions at the times that sand transport occurs. Campmans et al. (2017) have shown that their model results support the observations by Terwindt (1971), McCave (1971) and Fenster et al. (1990), who suggested that storms may be important factors in sand wave dynamics.

1.3.3 Model by Campmans et al. (2017)

Campmans et al. (2017) have pointed out that despite the observations and research mentioned in the previous paragraph “storm-related processes have not been investigated systematically in a process-based sand wave model” (p2). Therefore they address the question “to what extent wave and wind effects need to be taken into account in sand wave formation models and, if so, what are the most important mechanisms” (p2). The research includes three storm-related processes: (i) wind waves, (ii) wind-driven flow and (iii) suspended sediment transport. These processes are systematically analyzed (both separately and in combination) and wind and waves are allowed to come from an arbitrary direction with respect to the tidal current. Wind waves as modeled herein are unable to induce migration themselves but can enhance migration through other mechanisms. Wind-driven flow induces migration because it breaches tidal symmetry. The research of Campmans et al. (2017) concluded that “storms significantly influence sand wave dynamics and therefore need to be taken into account when attempting to explain the behavior of a sand wave field” (p1). Furthermore the research provided the following results and conclusions regarding growth rate, migration rate and the FGM:

Waves: Waves decrease the growth rate and in particular when they propagate in a direction roughly parallel to the sand wave crest (θ_{wave} = 90°). As wave action increases, the decrease of the bed slope effect outcompetes the increase of the bed flow effect. Wind waves increase the growth rate due to suspended load, however this increase is outcompeted by the reduction in growth rate by wind waves due to bed load transport.

Wind: The effect of wind on the total growth rate is the sum of the alternating increasing and decreasing growth rate of bed load and the decreasing growth rate due to suspended load, which results in a growth rate that is either unchanged or decreased for wind directed parallel to the tidal current. The angle at which the growth rate is reduced most is approximately $\theta_{wind} = 0°, 180°$. Due to the Coriolis effect the wind-driven flow component experiences Ekman veering through the water column.

Migration: The total migration rate due to wind-driven flow is predominantly generated by the perturbed concentration contribution. The wind direction at which maximum migration occurs and the magnitude of the maximum migration is affected by the Coriolis effect due to the veering of the flow.

Wind and waves combined, FGM: Storms tend to favor sand waves that have longer wavelengths than those generated during fair weather conditions. The combined effect of waves and wind reduces the growth rate, and increases the wavelength of the FGM even further. The combined effect of waves and wind perpendicular to the tide results in a slightly smaller wavelength and larger growth rate compared to the combined effect of waves and wind tangential to the tide. The effect of storms on the growth rate is dependent on the mode. The slope effect is more important for bed forms with small wavelengths. Therefore, especially small wavelength perturbations (large k^*) experience a reduction in growth rate by wave action. The maximum migration is observed for modes that are oriented in the direction of the veered near bed flow.

1.3.4 Limitations and follow-up study

Campmans et al. (2017) have pointed out that their study "investigated storm processes in the formation stage, implying that we cannot model properties of fully grown sand waves such as like migration rates, heights and shape which require a nonlinear approach" (p.12). However their results suggest that waves and wind-driven flow are also important processes in nonlinear sand wave models. The research furthermore points out that comparing its results to reality remains difficult since "sand waves in the field are fully grown, i.e. no small amplitudes, and storm processes are not isolated events between two field measurements" (p13). One storm can counteract sand wave developments due to a previous storm that had another wind direction. Furthermore the migration rates in the paper are large compared to field data. This is because storms occur only for a small fraction of the time during a year. Based on the modeled effects of specific storm conditions Campmans et al. (2017) have stated that waves and wind indeed can play a significant role in sand wave dynamics. However since storms occur only for a small fraction of the time during a year Campmans et al. (2017) have stated that "to assess the averaged model effect of storms on sand wave dynamics a statistical approach is required" (p14).

1.4 Research goal and questions

Sand waves can form a hazard to pipelines, communication cables, offshore constructions and navigation. The research of Campmans et al. (2017) concludes that "storms significantly influence sand wave dynamics" (p1), however since storms only occur occasionally the research states that "to assess the averaged model effect of storms on sand wave dynamics a statistical approach is required" (p14). The research carried out in this thesis builds on the research of Campmans et al. (2017) and therefore focuses on the North Sea and uses the sand wave model of Campmans et al. (2017) to investigate the influence of storm related processes on sand waves.

1.4.1 Research goal

The goal of this research is to investigate the influence of the wind- and wave climate and in particular storms, consisting of a combination of the storm related processes of wind waves and wind-driven flow and its frequencies of occurrence, on sand wave dynamics by applying a statistically combined wind- and wave climate to the idealized sand wave model of Campmans et al. (2017) and analyzing its results.

1.4.2 Research questions

1. What is the wind- and wave climate at the research location?
   a) What is the general climate?
   b) What is the storm climate?
   c) What are the frequencies of occurrence of the wind and wave conditions?

2. Based on the idealized sand wave model of Campmans et al. (2017):
   a) what is the influence of the storm related processes and their frequencies of occurrence on the growth- and migration rate of sand waves?
   b) which storm related processes make the biggest contribution to the resulting growth- and migration rate?

1.5 Methodology

The storm related processes that were focused on in this research are wind (wind speed and wind direction) and waves (wave height, wave period and wave direction). Wind- and wave data was obtained from the websites of The Royal Netherlands Meteorological Institute (KNMI) and Rijkswaterstaat (RWS), for a chosen location and timeframe. The secondary data collected will be cleaned for outliers and missing data. Desk research was carried out to obtain a general climate, storm climate and the frequencies of occurrence for the research location. Taking the limited amount of time and computer resources into account, the data will be divided in bins. The bin values and their calculated frequencies of occurrence are used as input values for the idealized model of Campmans et al. (2017).

To research the influence of the wind- and wave climate and its frequencies on sand wave dynamics, the model of Campmans et al. (2017) needs to be adjusted to the research location. This includes changes to parameters and settings, tidal current angle and wind- and wave direction adjustments and the inclusion of the frequencies of occurrence. To determine the influence of the storm related processes of wind waves and wind-driven flow and its frequencies on sand wave dynamics, the model is run and the growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^*, the growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^* per bin, and the growth rate and migration rate of a fixed mode are plotted.

1.6 Outline of the thesis

This thesis is structured as follows. In Chapter 2 the research location and timeframe is chosen, and the data is cleaned and analyzed to obtain the wind- and wave climate. Chapter 3 addresses the model and the adjustments and additions that have been made to research the influence of the storm related processes and its frequencies. The results of the model runs are given in Chapter 4. The discussion and conclusion can be found in respectively Chapter 5 and Chapter 6.

2 Data collection, -cleaning and -analysis

2.1 Wind- and wave data

The storm related processes that were focused on in this research are wind (wind speed and wind direction) and waves (wave height, wave period and wave direction). Wind- and wave data was obtained from the websites of The Royal Netherlands Meteorological Institute (KNMI) and Rijkswaterstaat (RWS). The KNMI is the Dutch national weather service. Its primary tasks are weather forecasting and monitoring of weather, climate, air quality and seismic activity. KNMI is also the national research and information center for meteorology, climate, air quality, and seismology (KNMI, n.d., a). In the Netherlands KNMI operates 33 automatic weather stations on land, 15 wind poles in coastal areas and 13 automatic weather stations on North Sea platforms (Dutch part of the Continental Shelf North Sea, see Figure 5 (KNMI, 2014)). These weather stations report meteorological parameters such as temperature, relative humidity, wind (speed, gust, direction), air pressure and visibility. The weather stations on North Sea platforms provide both hourly and daily data. RWS provides actual and historic water data on different topics from locations across the Netherlands. These topics are among others water level, water temperature, wave heights, eutrophication and drainage. This data is recorded every hour. For several reasons the hourly data was used in this research. First of all because both the wind and wave data are given in intervals of one hour. And secondly because, although the use of hourly data leads to lengthy data processing and longer calculation times, the more detailed data will give a more accurate and realistic estimation of the wind- and wave climate.
The hourly data of KNMI provides, among others, the following information:

- Mean wind direction (in degrees) during the 10-minute period preceding the time of observation (360=north, 90=east, 180=south, 270=west, 0=calm 990=variable);
- Hourly mean wind speed (in 0.1 m/s);
- Mean wind speed (in 0.1 m/s) during the 10-minute period preceding the time of observation.

The mean wind speed (in 0.1 m/s) during the 10-minute period preceding the time of observation was chosen instead of the hourly mean wind speed (in 0.1 m/s) since this coincides with the measurement of the mean wind direction.

2.2 Location choice

Before the data can be collected, first the location to be studied had to be chosen. When choosing a location the following demands and preferences were taken into account:

- Presence of sand waves;
- Preferably absence of major shipping lanes, sand banks, nearby coast lines, dredging channels or other large constructions or modifications. This is because the model is based on an ideal situation, consisting of a flat bottom on which perturbations are implemented;
- Presence of sand waves with and 'ideal' shape, thus no complicated shapes or large amounts of variation in the sand wave shapes. An 'ideal' shape is preferred since the model assumes a sand wave with an 'ideal' shape;
- Availability of both wind- and wave data for the specific location and for a significant time span.

The KNMI provides data for 13 locations and RWS for 6 locations. By comparing these locations it can be concluded that there are two corresponding locations; Europlatform and K13a platform. Figure 5 (Van der Veen, Hulscher & Knaapen, 2006, p. 229) shows the sand bank and sand wave occurrence in the North Sea.

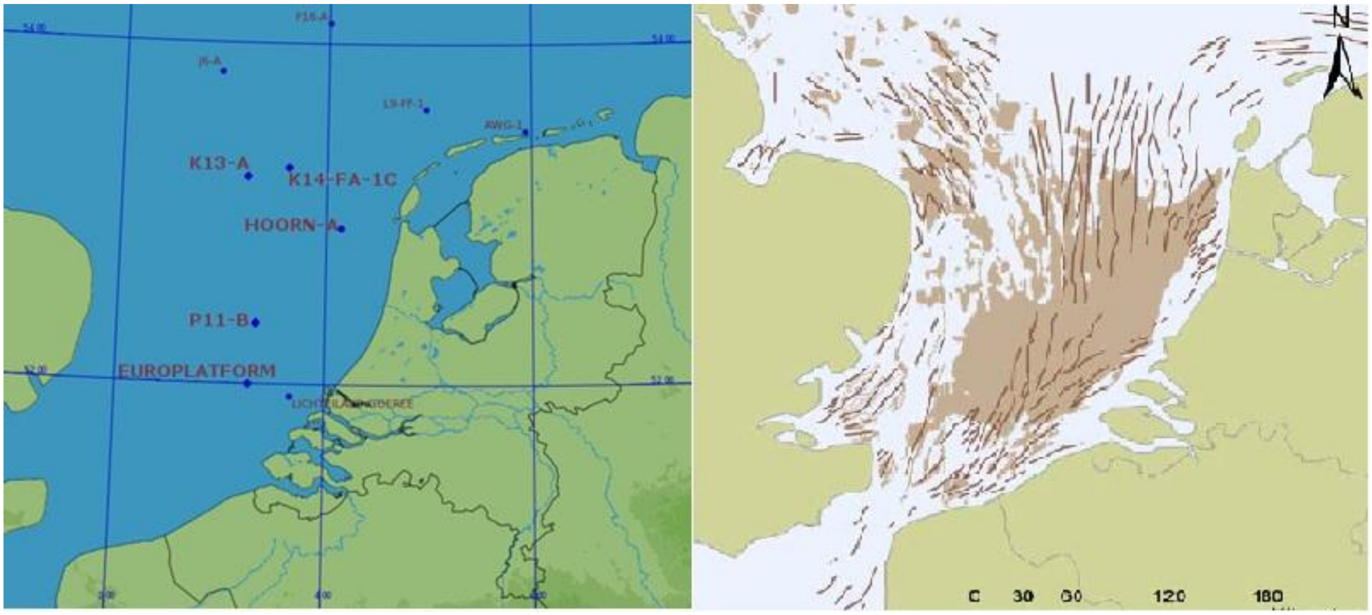


Figure 5: Observation points located along the coast and in the North Sea. Adapted from KNMI website, by KNMI, n.d., e retrieved from https://www.knmi.nl/nederland-nu/weer/actueel-weer/kust-en-noordzee/ Copyright by KNMI. (left) - Sand bank (lines) and sand wave (brown areas) occurrence in the North Sea. Reprinted from "Grain size dependency in the occurrence of sand waves", by H.H. van der Veen, S.J.M.H. Hulscher, and M.A.F. Knaapen, 2006, *Ocean Dynamics*, 56, p. 229. Copyright 2006 by Springer-Verlag. (right)

From this figure it can be concluded that the area of the K13a platform is scarce of sand waves whereas the Europlatform is located in an area rich of sand waves. Therefore, considering the scope of the research, the most fitting location to use for this research is the Europlatform. However, it should be noted that the area of the Europlatform is not ideal considering the demands and preferences as stated above. The Europlatform is located at a distance of about 30 km south-west from Hoek van Holland (ECN, n.d.). As can be seen in Appendix A, the platform is located next to the Eurogeul, a shipping lane. The area thus does not meet the preference of absence of major shipping lanes, sand banks, nearby coast lines, dredging channels or other large constructions or modifications. Furthermore the preference of presence of sand waves with and 'ideal' shape can also not be assured. This should be taken into account when analyzing the model results.

2.2.1 Possible use of data of nearby platforms

As indicated before, not every location offers data for both wind and wave conditions or data for a large time span. A possible solution for this could be to investigate whether nearby platforms have similar data values. If their data values are in line, an average value could be used for locations nearby where no wind or wave data is present. By doing this a location more suitable than Europlatform could be chosen for the research. In the case of wind data, the locations p11b, Hoorn-a and Europlatform were compared to one another for the timeframe January 1st 2010- December 31st 2014. These platforms were chosen because they all lie within or near the sand wave area.
When looking at the wind roses in Appendix B it can be seen that there are clear differences between the wind roses. Therefore no average value can be constructed and Europlatform will be taken as the single location.

2.3 Timeframe

When collecting the data a choice has to be made about the timeframe of data to be studied. There are however no clear rules concerning the length of this timeframe. The KNMI Europlatform data goes back to July 1996, RWS data goes back further, and both have data up to present day. As the information in Paragraph 1.3.1 about storms in the North Sea region states there is no clear trend in the frequency and intensity of storms. Based on observations the KNMI concludes that there were more storms above the North Sea area at the beginning and end of the twentieth century, and that in the last 30 years, a wind measuring 11 on the Beaufort scale only occurred in 1990 and 2013. Choosing a timeframe that includes both the end of the twentieth century and recent years, and would take into account at least one occasion where the wind measures 11 on the Beaufort scale would be preferred since this assures a sufficient representation of the variety that could be present in the wind- and wave climate. As there are no rules or trends present for choosing a timeframe, the aim was to gather as much data from as long a period as possible, to obtain a sufficient representation of the wind- and wave climate and its frequency distribution at the Europlatform. This led to a data timeframe of January 1st 1997 until December 31st 2015.

Sand waves are formed on a time scale of 1-10 years (see Paragraph 1.1). Therefore the timeframe of 19 years is, in all likelihood, long enough considering that the formation of at least one sand wave falls within this timeframe. Furthermore the research goal is to investigate the influence of storm related processes and their frequencies of occurrence on sand wave dynamics. As this research goal indicates, it is not yet clear what the influence of a wind- and wave climate is. Therefore applying a realistic timeframe is best suitable. Applying extreme- or predetermined values, as is the case with for example a “magnitude– frequency diagram”, is thus not suitable since it is not yet clear how the different storm related processes influence the sand wave dynamics and thus which values should be applied.

The next step is to check the data. Depending on the results this could alter the timeframe.

2.4 Data cleaning

2.4.1 Checking data on quality, continuity and correctness

Before using the data, it first needs to be checked on quality, continuity and correctness. The quality of the data can be assumed to be of a sufficient level considering the data is provided by the KNMI and RWS. The continuity can be checked by searching for missing data, being missing dates or missing storm related processes. The correctness can be assured by looking for outliers. An outlier is a value that appears to deviate considerably from other values in the sample in which it occurs. When an outlier occurs there are two possibilities (Grubbs, 1969), the outlying observation may be:

- an extreme manifestation of the random variability inherent in the data. If this is true, the values should be retained and processed in the same manner as the other observations in the sample.
- the result of gross deviation from the prescribed procedure or an error in calculating or recording the numerical value. In such cases, it may be desirable to investigate the reason for the deviating value. The observation could eventually be rejected.

The table below shows the amount of missing data and outliers present in the wind and wave data, including minimum and maximum length in hours, and the date at which the maximum gap and outliers take place. Outliers for the wind speed, wave height and wave period were sought by plotting these three variables. Extreme outliers will stand out immediately and their value and the associated values were removed. Subsequently the data was plotted again. If there was still an outlier, the data was looked at in detail and all data points under a certain value were removed. For the wind- and wave direction values above 360 degrees were sought after. This analysis led to the following results:

- Wind direction: 106 times a value of 990 (i.e. variable wind direction). These directions cannot be taken into account in the model and analysis. Therefore all these values and their associated values were removed.
- Wave direction: 4 times a value above 360. All these values and their associated values were removed.
- Wind speed: a minimum value of 0 m/s and a maximum value of 26 m/s. Plot shows no extreme outliers.
- Wave height: a minimum value of 0.17m and a maximum value of 6.36 m. Extreme values occur occasionally and this minimum and maximum value do not deviate. Thus no outliers are present.
- Wave period: In the period between the 18th and 22nd of December 2006 there are multiple distinct low values for the wave period. After examining the wave period values overall, the corresponding wave height and wind speed and researching literature for distinct weather related or other events during that period, it can be concluded that there is no clear reason for these values to be this low and that it is a single event. Also, based on linear wave theory, high frequent waves are not felt at the seabed so these low-period-waves are very unlikely to have any effect. Looking outside this timeframe, the lowest value measured is 2.03 s. A threshold of 2.0 s is chosen and all values below this threshold, and their associated values, were removed.
-

Type of data	Number of missing data points	Minimum gap (hour(s))	Maximum gap (hours)	Date of maximum gap	Outliers	Date of outlier
Wind speed	1645	2	562	18 Jan-10 febr 2015	-	-
Wind direction	1408	1	562	18 Jan-10 febr 2015	108	Value of 990 (i.e. variable wind direction) occurs almost every year
Wave height	5479	1	642	24 jan-20 febr 2001	-	-
Wave period	5481	1	642	24 jan-20 febr 2001	45	18, 19, 21 & 22 dec 2006
Wave direction	6875	1	642	20 jan-20 febr 2001	4	1,19 & 24 sept 2005

Table 1: Overview of the amount of missing data and outliers present in the wind and wave data of the location Europlatform during the timeframe 1997-2015, including minimum and maximum length in hours, and the date at which the maximum gap and outliers took place.

By combining both missing data and outliers, and their associated values, the total amount of data gaps can be obtained (see Figures 6 & 7 below and Tables C1 & C2 in Appendix C).

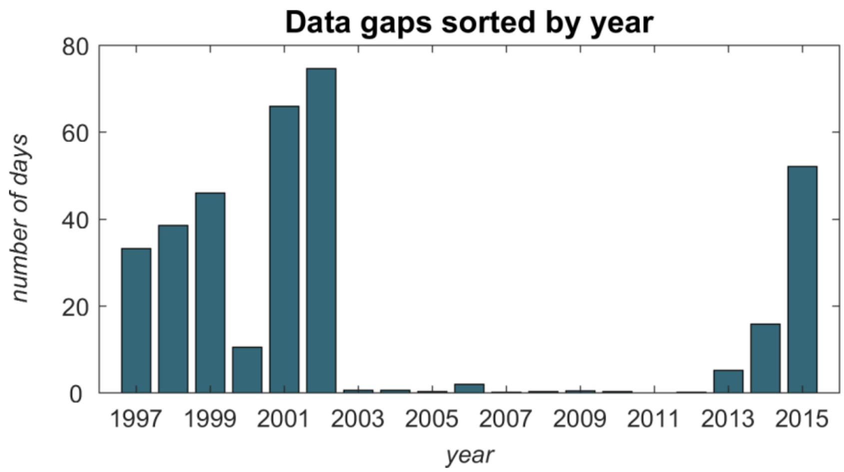


Figure 6: Data gaps (missing data & outliers) per year (in days) of the location Europlatform during the timeframe 1997-2015.

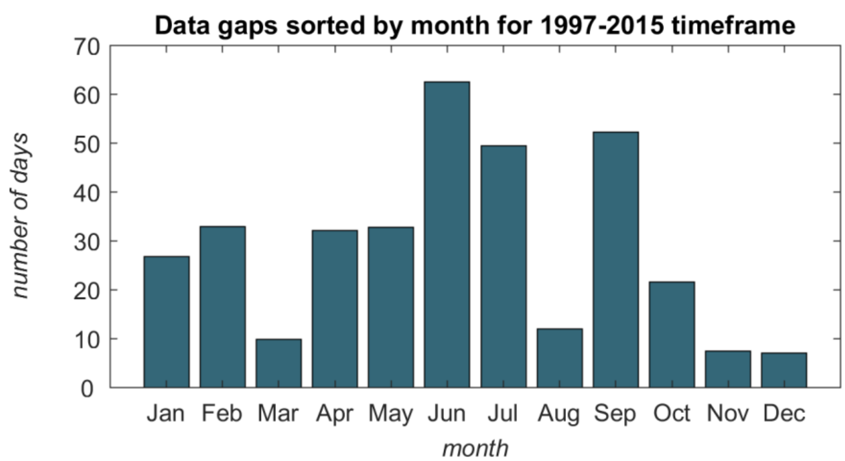


Figure 7: Data gaps (missing data & outliers) per month (in days) of the location Europlatform during the timeframe 1997-2015

The total amount of data gaps is 8324 hours during a period of 19 years, i.e. 5% of the data consists of missing data and outliers. The graphs and table show that the vast amount of data gaps is between 1997 and 2003, and between 2014 and 2015. The largest amount of data gaps are found in 1999, 2001, 2002 and 2015. The most data gaps are found in the months of June, July and September. March, August, November and December have the least amount of data gaps. Researching literature and analyzing the data provides no clear explanation for why the data gaps differ between the months and years.

2.4.2 Deleting missing data and outliers

Until recently, listwise deletion has been the most common way of dealing with missing data (Newsom, 2015). Listwise deletion means that any cases with missing data on one or more of the variables gets eliminated from the analysis. In the last few years research shows that when there is a lot of missing data, listwise deletion will have biased parameters and standard errors (Newsom, 2015) and researchers have begun to use data estimation techniques if values are missing in the data set. However then the question arises: What is a large amount of missing data? Schlomer, Bauman, & Card (2010) have stated that experts have not reached a consensus about the percentage of missing data that is acceptable. Their research also shows that there is yet no established cutoff as one research (Schafer (1999), as cited in Schlomer et al. (2010)) has recommended 5% as the cutoff whereas other research (Bennett, 2001) has suggested to use a maximum of 10% of missing data, and others have used 20% (Peng, Harwell, Liou, & Ehman, 2006). Dong & Peng (2013) however have stated that the amount of missing data is not the sole criterion by which a researcher assesses the missing data problem; the missing data mechanisms and the missing data patterns have greater impact on research results than does the proportion of missing data. There are three "missing data mechanisms" under which missing data can occur: missing at random (MAR), missing completely at random (MCAR), and missing not at random (MNAR). Newsom (2015) has explained their difference by stating that both MAR and MCAR require that the variable with missing data needs to be unrelated to whether there is missing data on that variable. MCAR indicates that there is "no relationship between whether a data point is missing and any values in the data set, missing or observed", whereas MAR indicates that the "propensity for a data point to be missing is not related to the missing data, but it is related to some of the observed data" (Grace-Martin, 2017). In all likelihood it seems to be the case for this research that the missing data is M(C)AR since, as shown in Paragraph 2.4.1, the data gaps in the storm related processes are fairly evenly distributed along the months. The months with the, in general, highest wind speeds, the months of fall and winter, do not show a significant larger amount of missing data.

2.4.3 Adjusting the timeframe

Based on the missing data and outliers and their distribution along the years, as found in the previous paragraph, and the information about deleting missing data and outliers, as mentioned above, the question arises whether data from the period 1997-2015 or 2003-2012 should be used. In first instance as much data from as long a period as possible was chosen, to obtain a sufficient representation of the wind- and wave climate and its frequency distribution at the Europlatform. The missing data and outliers could however distort this representation of the wind- and wave climate. To determine whether there is a significant difference between the wind-and wave climate of the periods 1997-2015 and 2003-2012, and thus whether the data gaps affect the wind-and wave climate, the mean and standard deviation of the storm related processes for both periods were calculated and compared (see Appendix D). The mean value and standard deviation have been calculated per year and per month. Furthermore the amount and intensity of storms in both periods were compared. Reducing the timeframe could cause a decrease in storm data which is, considering the research goal, not preferred. Also the top 3 most common wind- and wave climates were determined. These tables can also be found in Appendix D. Based on the data and facts that:

- There is no clear trend present in the wind climate (see Paragraph 1.3.1) and in the appearance of storms;
- There are no clear rules or guidelines regarding removing missing data and outliers;
- Within the 1997-2015 timeframe, a wind speed of a Beaufort scale of 10 or higher (≥ 24.5 m/s) occurred 87.5% of the time outside the 2003-2012 timeframe;
- The mean values of the storm related processes of both periods are close together and have large standard deviations. This makes it plausible that there are no significant differences between both periods.

The decision was made to take all 19 years of data (1997-2015), excluding the data gaps, into account.

2.5 General wind- and wave climate

The general wind and wave climate of the Europlatform during the period 1997-2015 was determined by plotting the wind- and wave roses, calculating the monthly and yearly mean values of the storm related processes, calculating the frequency and mean value per bin of each of the storm related processes, and calculating the top 3 most common wind- and wave climate combinations. This data is presented in the form of tables, graphs and wind- and wave roses. Figures 8 & 9 shows the wind- and wave roses. More detailed figures of the wind-and wave roses and the remaining figures and tables can be found in Appendices E & F.

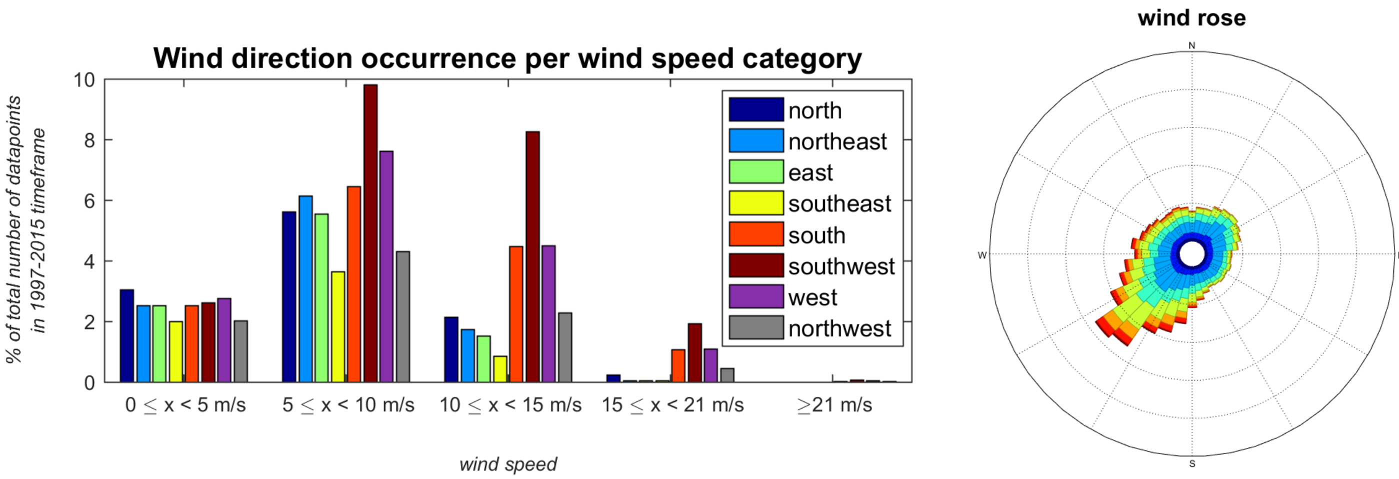


Figure 8: Wind direction occurrence per wind speed category and wind rose of the location Europlatform during the timeframe 1997-2015.

Based on the tables, graphs and wind- and wave roses, the wind- and wave climate at the Europlatform during the period of 1997-2015 is as follows:

<u>Wind:</u>

- The yearly mean wind speed is between 7.3 and 8.4 m/s. The yearly mean wind direction is between 180 and 211 degrees;
- The majority of the wind comes from a southwest (202.5-247.5 degrees) direction (approximately 23% of the time), followed by wind from a west (247.5-292.5) direction (approximately 16%) and south (157.5-202.5) direction (approximately 15%);
- A wind speed of 6-10 m/s occurs most often (approximately 48%), followed by wind speeds of 0-5 m/s (approximately 29 %) and wind speeds of 11-15 m/s (approximately 20 %);
- Wind speeds of 21m/s and up (storms) only occur 0.1% of the time.
- The majority of wind speeds of 12.5m/s or higher comes from a southwest direction;
- The wind speed is highest between October and February (autumn/winter). During the spring and summer (March-September) the average wind speed is 1-3 m/s lower than during the autumn/winter. The mean wind direction value differs from month to month. There is no trend depending on for example season;
- Between 190 and 280 degrees wind direction, the wind is measured with an occurrence of an approximate minimum of 2.8%. whereas the peaks occur up to 4.5% and the two largest peaks around the 6.5%;
- The remaining wind directions (290-180 degrees), with the exception of a few, do not get an occurrence above the 2.8% but mainly between 1.5% and 2.5%.

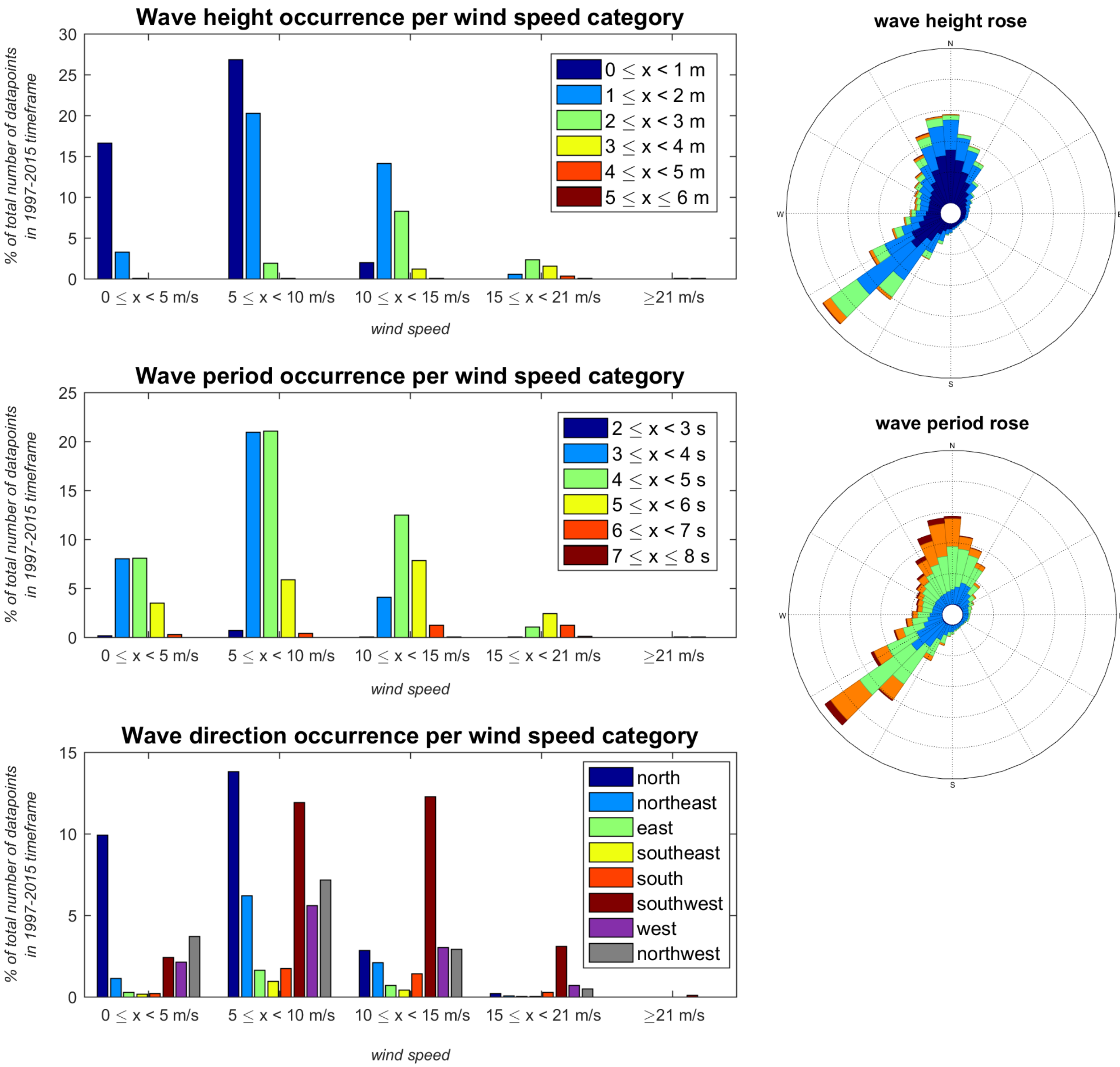


Figure 9: Occurrence of wave height, wave period and wave direction per wind speed category and the wave period rose of the location Europlatform during the timeframe 1997-2015.

Waves:

- The yearly mean wave height is between 1.1 and 1.4 m. The yearly mean wave period is between 4.2 and 4.5 s. The yearly mean wave direction is between 194 and 233 degrees;
- The most common wave direction is from the southwest (202.5-247.5 degrees, occurs approximately 30 % of the time), closely followed by a wave direction from the north (337.5-22.5 degrees, approximately 27%);
- Mainly wave heights between 0.5 and 1.5 m (approximately 55%) and between 1.5 and 2.5 m (approximately 23%);
- Wave heights, of 3 m and up, are mainly measured from the southwest (220 – 240 degrees);

- Mainly wave period between 3.5 and 4.5 seconds (occurs approximately 46% of the time), followed by wind periods between 4.5 and 5.5 seconds (approximately 32 % of the time);
- The wave height shows a difference between autumn/winter and spring/summer season. The average wave height is 0.2-0.7 m higher in the autumn/winter. The wave period also shows, even though it's only small, a difference between autumn/winter and spring/summer season. The average wave period is 0.1-0.6 s longer in the autumn/winter. The seasonal differences in wave height and -period can be explained by the fact that, as stated in Paragraph 1.2.3, as the wind blows over the ocean surface, waves develop. The energy from the wind increases the height, length, and speed of the wave. Waves have a variety of periods and wave heights due to frequently changing wind speed and direction;
- The mean wave direction value differs from month to month. There is no trend depending on for example season.

The most common wind-and wave climate has a wind- and wave direction between 202.5 and 247.5 degrees, a wind speed between 5 and 10 m/s, a wave height between 0.5 and 1.5 meter and a wave period between 3.5 and 4.5 seconds. This climate occurs 3.3% of the time.

2.6 Storm wind- and wave climate

The storm wind and wave climate of the Europlatform during the period 1997-2015 was determined by selecting the data with a wind speed of 20.8 m/s or higher and calculating the amount of storms (in hours) per year and per month, calculating the monthly and yearly mean values of the storm related processes, calculating the frequency and mean value per bin of each of the storm related processes, and calculating the top 3 most common wind- and wave climate combinations. This data is presented in the form of tables, graphs and wind- and wave roses. Figure 11 shows the wind- and wave roses. More detailed figures of the wind-and wave roses and the remaining figures and tables can be found in Appendices F & G.

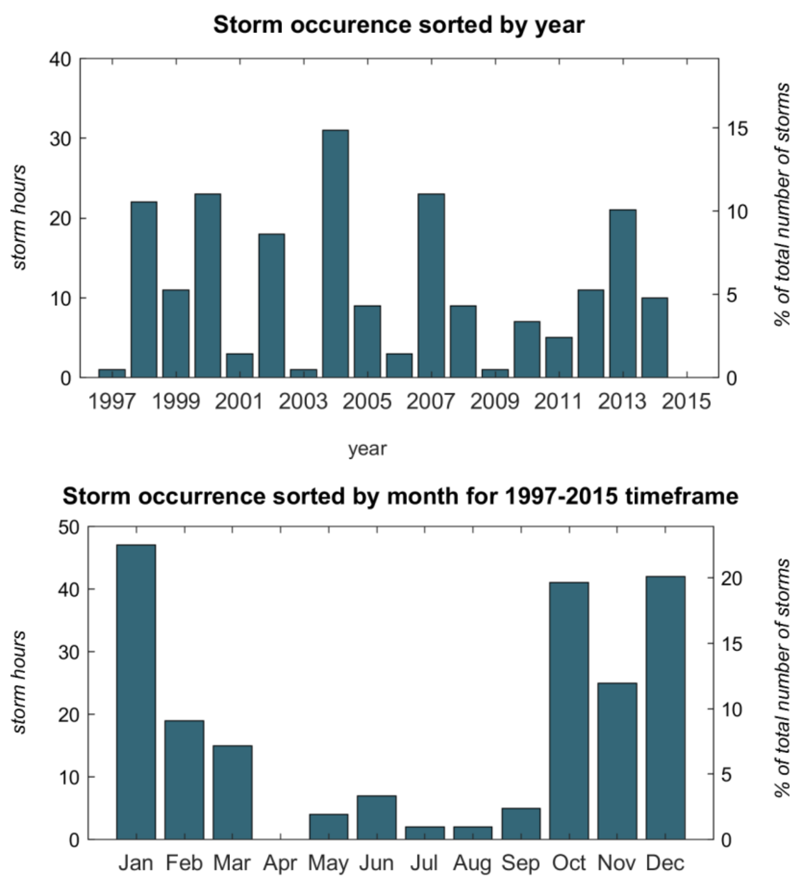


Figure 10: Storm occurrence sorted by year (in hours and percentage) of the location Europlatform during the timeframe 1997-2015.

Storms occur 0.1% of the time. Looking at the tables and figures there is no clear trend or pattern regarding storms. The most likely certainty is that in principle storms occur every year. The monthly results show storm peaks in January, October and December. The smallest amounts of storms occur in April, July and August. In conclusion, no clear trend about the amount of storms per year can be found, the most likely certainty is that storms occur in principle every year with a preference for the months of October-March. As can be seen from the data in Appendix G, storms are associated with a wave height between 2.5 and 5.5 m, comprising 92.3% of the data, with a peak at 3.5-4.5 m. This is a clear difference from the general wind- and wave climate where the wave height is between 0 and 2.5m, coincidentally also comprising 92.3% of the data, with a peak at 0.5-1.5 m. Whereas wave heights between 2.5 and 5.5m only make up 7.7% of the data.

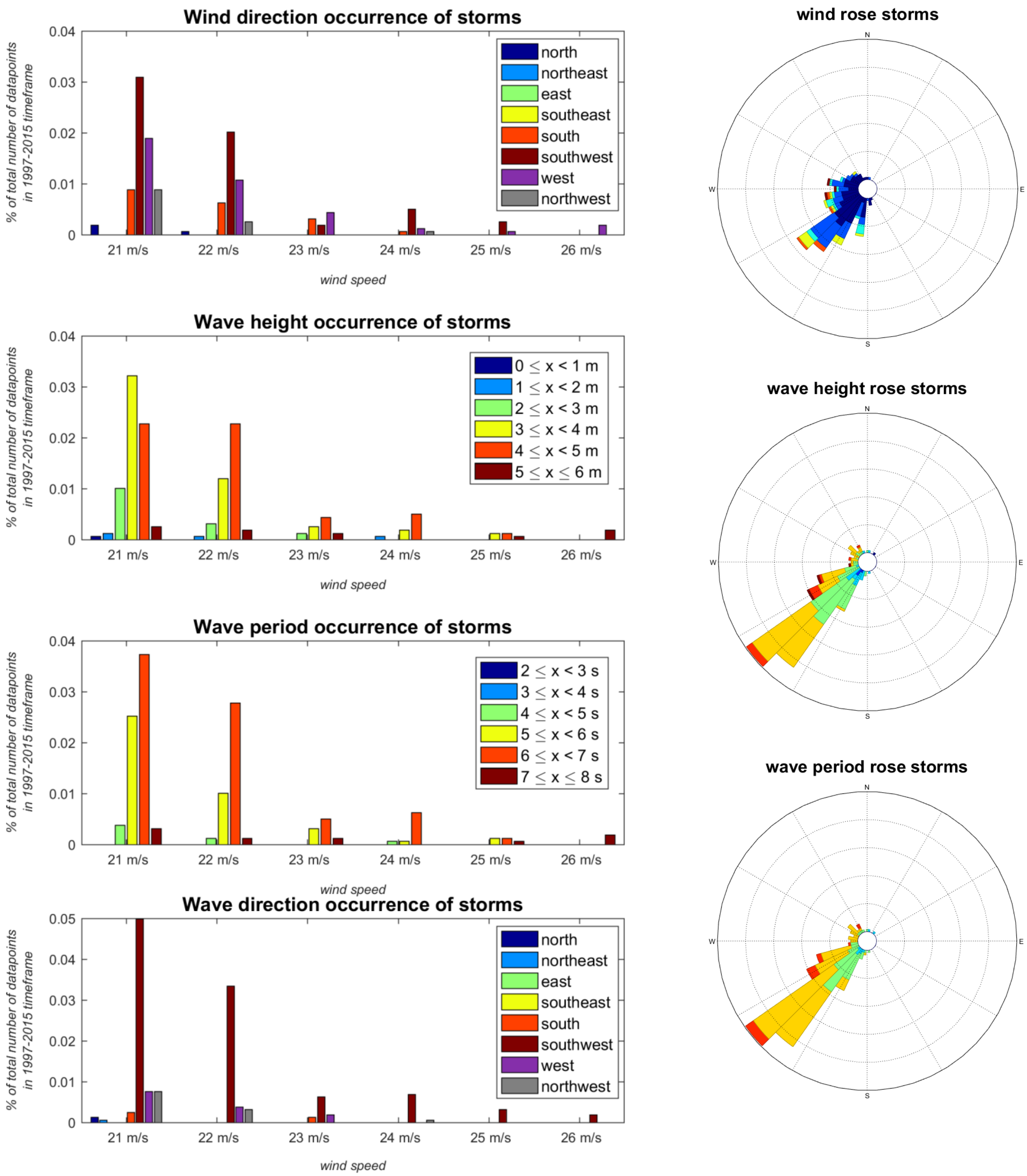


Figure 11: Occurrence of wind direction, wave height, wave period and wave direction per wind speed category and the wind rose, wave height rose and wave period rose of the location Europlatform during the timeframe 1997-2015.

Storms are mostly, but not exclusively, associated with the following values:

- A wind speed of 21 or 22 m/s. This makes sense considering these wind speeds are considered as 9 on the Beaufort scale (20.8-24.4 m/s) and as stated in Paragraph 1.3.1, wind speeds of 10 or higher on the Beaufort scale hardly occur in the Netherlands;
- A wind direction between 202.5 and 247.5 degrees (occurrence of approximately 46%), followed by a wind direction between 247.5 and 292.5 degrees (occurrence of approximately 29%). This resembles the general wind climate (Paragraph 2.5);
- A wave height between 3.5 and 4.5 meters (occurrence of approximately 44%), followed by a wave period between 2.5 and 3.5 meters (occurrence of approximately 25%) and 4.5 and 5.5 meters (occurrence of approximately 23%);
- A wave period between 5.5 and 6.5 seconds (occurrence of approximately 57%), followed by a wave period between 6.5 and 7.5 seconds (occurrence of approximately 30%);
- A wave direction between 202.5 and 247.5 degrees (occurrence of approximately 77%). This differs slightly from the conclusion made from the wave roses of the general wave climate (Paragraph 2.5), where the most common wave direction was divided amongst two directions being the southwest (202.5-247.5, occurs approximately 30 % of the time), closely followed by a wave direction from the north (337.5-22.5, occurs approximately 27% of the time).
- The most common storm wind-and wave climate has a wind- and wave direction between 202.5 and 247.5 degrees, a wind speed of 21 m/s, a wave period between 5.5 and 6.5 seconds and a wave height between either 2.5 and 3.5 meter or 3.5 and 4.5 meter. This climate occurs 6.2% of the time that storms occur.

2.7 Model bins

Preferably the model would be run by using small data steps, i.e. of 1 m/s or 10 degrees. However the smaller the steps, the larger the calculation time. Since there is only limited time and computer resources for this research, these small data steps are not achievable. Therefore the data used as input for the model was divided in bins of different sizes. The size of the bin was based on the scope of the research and results presented in Campmans et al. (2017). Campmans et al. (2017) show that for wave heights below approximately 3 m and wind speeds below approximately 15 m/s the growth rate shows only minor changes. Based on these results and the fact that the research goal of this thesis, as presented in Paragraph 1.4.1, focuses on storms and thus higher wind speeds, smaller bins were applied for higher wind speeds and larger bins for lower wind speeds.
When deciding on the bin sizes, a difference has to be made between the "gridded" and the "single mode" model run. The gridded model run calculates the growth and migration rates for the chosen wind- and wave parameters, as a function of the topographic wave numbers k_x^* and k_y^*. The single mode model run calculates the growth and migration rate for a chosen fixed mode (a chosen k_x^* and k_y^*). The calculation time per run for the gridded model run is higher than the single mode model run. Therefore the bin sizes for the gridded model run are larger than those of the single mode model run. This leads to the bins as given in Appendix H. The original data values that fall within the interval were replaced by the central value of the bin. These values were run in the model. For the gridded model this meant that there were 7776 different bins in which the data could be subdivided (wind speed bins x wind direction bins x wave height bins x wave period bins x wave direction bins = 6x6x6x6x6 = 7776). For the single mode model this meant that there were 46656 different bins in which the data could be subdivided.

By dividing the data in these bins the correlation between the 5 parameters is taken into account.

2.8 Wind- and wave climate occurrence plots

Figures 12, 13 & 14 show the occurrences of the wind- and wave climate as a function of respectively wind speed and wind angle, wave height and wave angle, and wave period and wave angle. To create these figures the bins for the gridded model run were used (see Appendix H2). These occurrences were determined by summing the number of times the combination of two storm related processes values occur (e.g. U= 5 m/s and θ_{wind}= 30°), and dividing this with the total number of combinations occurring in the 19 year time interval.

The occurrence plots can be used to get a clear indication of the more occurring wind- and wave climate combinations and as a visual aid when analyzing the results.

The plots show higher occurrences at wind speeds between 5 and 13 m/s and wind angles between 120 and 170 degrees, at wave heights between 0 and 2 meters and wave angles between -35 and -10, and 10 to 60 degrees, at wave periods between 3 and 5 seconds, with a wave angle between -35 and +35 degrees. When looking into detail at the low occurrences present at storm related wind speeds (>=20.8 m/s), the lowest values can be found at a wind angle between 0 and -50 degrees. The maximum occurrence at storm related wind speeds is $5.7*10^{-4}$.

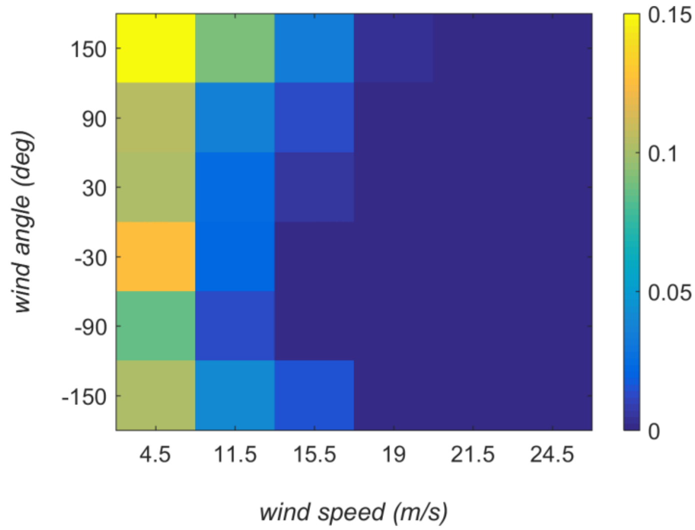


Figure 12: Wind climate occurrence plot as a function of wind speed and wind angle of the location Europlatform during the timeframe 1997-2015.

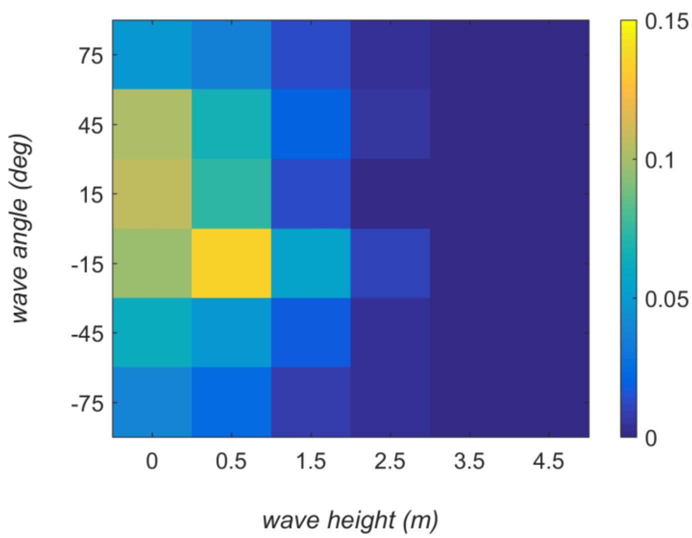


Figure 13: Wave climate occurrence plot as a function of wave height and wave angle of the location Europlatform during the timeframe 1997-2015.

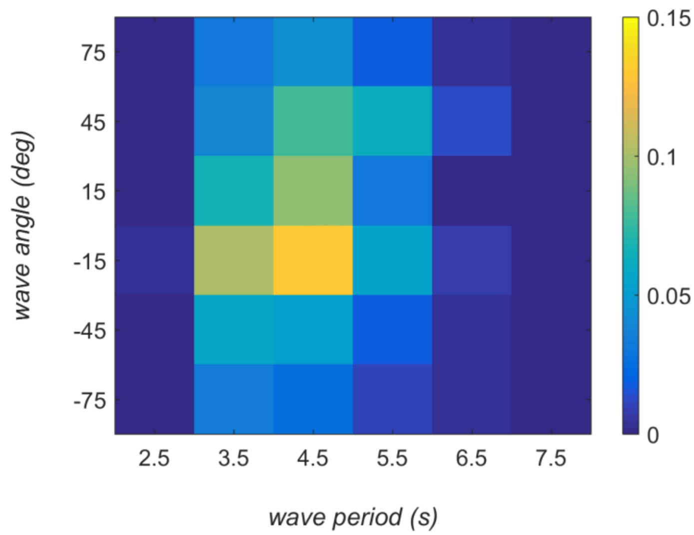


Figure 14: Wave climate occurrence plot as a function of wave period and wave angle of the location Europlatform during the timeframe 1997-2015.

3 Model

3.1 Model basics

To research the influence of the wind- and wave climate and its frequencies on sand wave dynamics, the model of Campmans et al. (2017) was used. This idealized sand wave model is a linear stability model and takes the model of Hulscher as a base and adds migration, wind driven current, wind waves and suspended load. Compared to other studies the main innovation is that the wave and wind conditions can be imported both separately and in combination. Furthermore it allows the wind and waves to come from an arbitrary direction with respect to the tidal current. By running the model, information can be gained on the migration rate, growth rate, orientation and wavelength of sand waves. The change in bed load and suspended load due to currents and waves can also be shown separately.

3.1.1 Stability analysis

Stability analyses are used to isolate a certain phenomenon or feature and assume a simplified geometry and simplified boundary and initial conditions, so that they can be solved efficiently using mathematical methods (Dodd, Blondeaux, Calvete, De Swart, & Falques, 2003). Because of the simplifications, the computational costs are less. The disadvantage of the linear stability analysis is that it cannot model properties of fully grown sand waves since sand waves have to be assumed small in order to do the linear analysis (Campmans, Modeling the effect of storm events and wind waves on sand wave dynamics, n.d.).

3.1.2 Bed load and suspended load

The growth and migration rate are the sum of the contributions of bed load and suspended load. The bed load consists of the sum of two contributions: the perturbed flow effect and the bed slope effect. The suspended load consists of the sum of three contributions: the perturbed flow, the perturbed sediment concentration and the perturbed bed. The third contribution only contributes to migration (Campmans et al., 2017). Rijn (n.d.) has explained that suspended transport can be subdivided into current-related (perturbed flow (c0u1) and perturbed bed (h1c0u0)) and wave-related transport components (perturbed sediment concentration (c1u0)). The current-related suspended transport component represents sediment transport by current velocities (i.e. the transport of sediment carried by the steady flow). The wave-related suspended sediment transport represents sediment transport by orbital motion. When waves and currents occur together, both the current velocities and the sediment concentrations will be affected by the wave motion. Wave motion reduces the current velocities near the bed while it increases the near-bed concentrations due to stirring. Bed load transport occurs for coarse sediment and/or small shear stresses, whereas suspended load transport occurs when sediment grains are small enough and/or shear stresses are large enough (Menninga, 2012).

3.2 Model adjustments

To research the influence of the wind- and wave climate and its frequencies on sand wave dynamics, the model of Campmans et al. (2017) had to be adjusted to the location of Europlatform. This included changes to the input values, tide angle and wind- and wave direction adjustments, and the inclusion of the frequencies of occurrence of the wind and wave conditions.

3.2.1 Input

The model consists of four different input sections; parameters, numerical setting, forcing and modes. These inputs remained largely the same. A few however were adapted to the location of Europlatform since the model of Campmans et al. (2017) assumes a representative value for the North Sea as a whole based on reference values.
The value for the slip parameter, slope correction factor, topographic wave number, gravitational acceleration, tidal frequency and wave friction factor remained the same as given in Campmans et al. (2017) (G.H.P. Campmans, personal communication, June 15 – August 31, 2016). The wind wave frequency is variable since it is based on the wave period. The Coriolis parameter is based on the latitude, and the settling velocity on the sediment grains size. This value is calculated by the model itself and does not need to be inserted separately. The values for water depth, sediment grain size, tidal ellipticity and tidal current velocity were all provided by J.M. Damen (personal communication, August 29, 2016). The value for the latitude of the Europlatform was taken from RWS (Rijkswaterstaat, n.d.).
The vertical eddy viscosity can be estimated via the method proposed by Davies and Xing (1999) (G.H.P. Campmans, personal communication, July 18 2016). This paper states that the equation

$$A_v = C_1(\bar{u}^2 + \bar{v}^2)^{0.5}\Delta\psi_m(\sigma)$$

has been used very successfully to model tidal currents in shallow regions. In this equation C1 is an observationally determined coefficient of the order of 0·0025, with $\bar{u}$ and $\bar{v}$ east and north components of the depth mean currents, Δ the thickness of the boundary layer, in shallow water taken as the water depth h, and $\psi m(\sigma)$the profile of eddy viscosity through the vertical. This can be simplified to:

$$A_v = CUH\psi$$

With ψ=1 (a constant profile)
Which can be simplified to CUH, with ψ=1;
This gives a value of 0.0025*0.51*31=0.039≈0.04

It should however be noted that the vertical eddy viscosity is dependent on numerous variables, making it sensitive to change. Considering the limited amount of time and computer resources, a simplification was applied and a constant vertical eddy viscosity was chosen.

Table 1 gives an overview of the model parameter values, their typical values and their reference values for the Europlatform. The parameters that changed compared to the research by Campmans et al. (2017)) are shown in the table, the other parameters did not change.

Model parameters	Symbol	Typical values	Reference value	Unit
Water depth	H*	15 - 40	31	m
Tidal current velocity (M2)	U*	0.3 - 0.8	0.5	m/s
Vertical eddy viscosity	A_v*	0.025 – 0.09	0.04	m^2/s
Latitude	Φ	-90 - 90	52.0	°N
Tidal ellipticity (M2)	ϵ_{M2}	0 – 1	0.2	-
Sediment grain size	d*	200 - 500	393	µm

Table 2: The model parameter values, their typical values and their reference values of the location Europlatform

The input forcing and input numerical setting remain the same since these values are adequate (G.H.P. Campmans, personal communication, June 2016). Input modes can be either a single mode or multiple modes. The value for the single mode will be adjusted further along in the research but the number of multiple modes will be altered before running the model. The higher the number of modes, the more detailed and accurate the model result will be. However a larger number of modes also causes a longer calculation time. Therefore a choice has to be made between details and calculation time. Different numbers of input modes have been used to run the model and calculate the growth rate as a function of topographic wave numbers k_x^* and k_y^* for a fair weather reference condition. These results have been compared and the number of input modes 2^3+1 was chosen, for both k_x^* and k_y^*.

3.2.2 Tidal current angle, and wind and wave direction correction

The wind and wave direction data had to be corrected for the angle of the tidal current since, as stated in Campmans et al. (2017), the depth averaged M2 tidal current is always chosen to be aligned with the x-axis (see Figure 15). Data from J.M. Damen (personal communication, August 10, 2016) was used to determine this angle (see Figure 3). This data shows sand waves present at the research location. Since sand waves have a crest that is almost perpendicular to the direction of the tidal current (Knaapen, Hulscher, & De Vriend, 2001), the angle of the sand wave crests can be used to determine the angle of the tidal current relative to the north. This led to an average tidal current angle of 28 degrees relative to the north. Campmans et al. (2017) Figures 5 and 6 show that a small change in degrees does not have a significant influence on the growth rate value. Therefore an average value for the tidal current angle is adequate.
Furthermore wave direction is only displayed by values between -90 and 90 degrees since waves have a back and fro motion and do not break the symmetry. Therefore wave directions beyond the -90 and 90 degrees can be seen as coming from the exact opposite direction (i.e. a 180 degrees difference) and were corrected to values between -90 and 90 degrees.

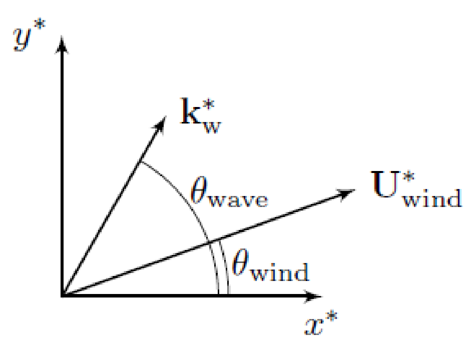


Figure 15: Definition sketch (top view) of the direction of the wind velocity vector U_{wind}^* and wave vector k_w^* (in the direction in which the waves propagate). Although the depth-averaged tidal flow can be in arbitrary direction, in our model simulations it is always chosen aligned with the x-axis. Reprinted from "Modeling the influence of storms on sand wave formation: A linear stability approach", by G.H.P. Campmans, P.C. Roos, H.J. de Vriend, S.J.M.H Hulscher, 2017, Continental Shelf Research, 137, p.105. Copyright 2017 by Elsevier.

3.3 Figures

In order to research the effect of the wind- and wave climate and its frequencies on the sand wave dynamics the following figures will be plotted:

- The growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^*;
- The growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^* per bin;
- The growth rate and migration rate of a fixed mode as a function of wind speed and angle;
- The growth rate of a fixed mode as a function of wave height and angle.
- The growth rate of a fixed mode as a function of wave period and angle.

Note that the fixed mode is determined by taking the wave numbers k_x^* and k_y^* of the fastest growing mode.

When plotting the growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^* the bins in Table H1 were used. This meant that there were 7776 different bins in which the data could be subdivided (wind speed bins x wind direction bins x wave height bins x wave period bins x wave direction bins = 6x6x6x6x6 = 7776). By subdividing the data in this way, the dependency between the 5 wind- and wave parameters is taken into account. When plotting the growth rate and migration rate of a fixed mode the bins in Table H2 were used. This meant that there were 46656 different bins in which the data could be subdivided. For each bin, its frequency of occurrence was calculated. These occurrences were determined by summing the number of times a certain combination of storm related processes values occurs in the data (e.g. the combination of parameter values U= 5 m/s, θ_{wind}= 30°, H= 1 m, T= 3 s, θ_{wave}= -75°), and dividing this with the total number of combinations occurring in the 19 year time interval.

When modelling the figures mentioned above and eventually when looking at the resulting figures, it is important to keep in mind that the data is made up of a combination of 5 different variables, being wind speed, wind angle, wave height, wave period and wave angle. The results are thus consisting of 6 variables (the 5 variables mentioned above and the growth rate or migration rate). However plotting 6D is not possible, therefore the figures are confined to 3D. It is therefore important to realize that behind the two variables and growth- or migration rate, there are actually 3 variables hidden.
To give an example, Figure 18 shows the growth rate as a function of the topographic wave numbers k_x^* and k_y^*. To obtain these figures, e.g. the figure of U= 5 m/s, θ_{wind}= 30°, the following steps were carried out:

1) Find the first data point that consists of U= 5 m/s and θ_{wind}= 30° (being e.g. U= 5 m/s, θ_{wind}= 30°, H= 0 m, T= 0 s, θ_{wave}= -75°);
2) Calculate the growth rate using the 5 variables;
3) Take the corresponding frequency of occurrence (taken from the Europlatform 1997-2015 data) and multiply it with the growth rate;
4) Repeat the step above for the second, third, fourth, etc combination of the 5 variables that consist of u= 5 m/s and θ_{wind}= 30° (being e.g. respectively U= 5 m/s, θ_{wind}= 30°, H= 0 m, T= 0 s, θ_{wave}= -45° ; U= 5 m/s, θ_{wind}= 30°, H= 0 m, T= 0 s, θ_{wave}= -15° ; U= 5 m/s, θ_{wind}= 30°, H= 0 m, T= 0 s, θ_{wave}= 15°);
5) Sum all these results to one overall plot.

This way the remaining 3 variables and the dependency between the 5 wind and wave parameters is still taken into account. This method is used for all figures, both for growth rate and migration rate. Figures where the frequencies of occurrence are not included skip step 3.

Since each growth rate plot is multiplied with its own frequency of occurrence, simply multiplying the figure of the growth rate (excluding the frequencies of occurrence) with the figure of the wind- and wave climate occurrence plots (as given in Figures 12, 13 & 14) does not lead to the figure of the growth rate including the frequencies of occurrence. Looking at the wind- and wave climate occurrence plots however does give a clear indication of the more occurring wind- and wave climate combinations and an explanation for variations in the growth rate.

4 Results

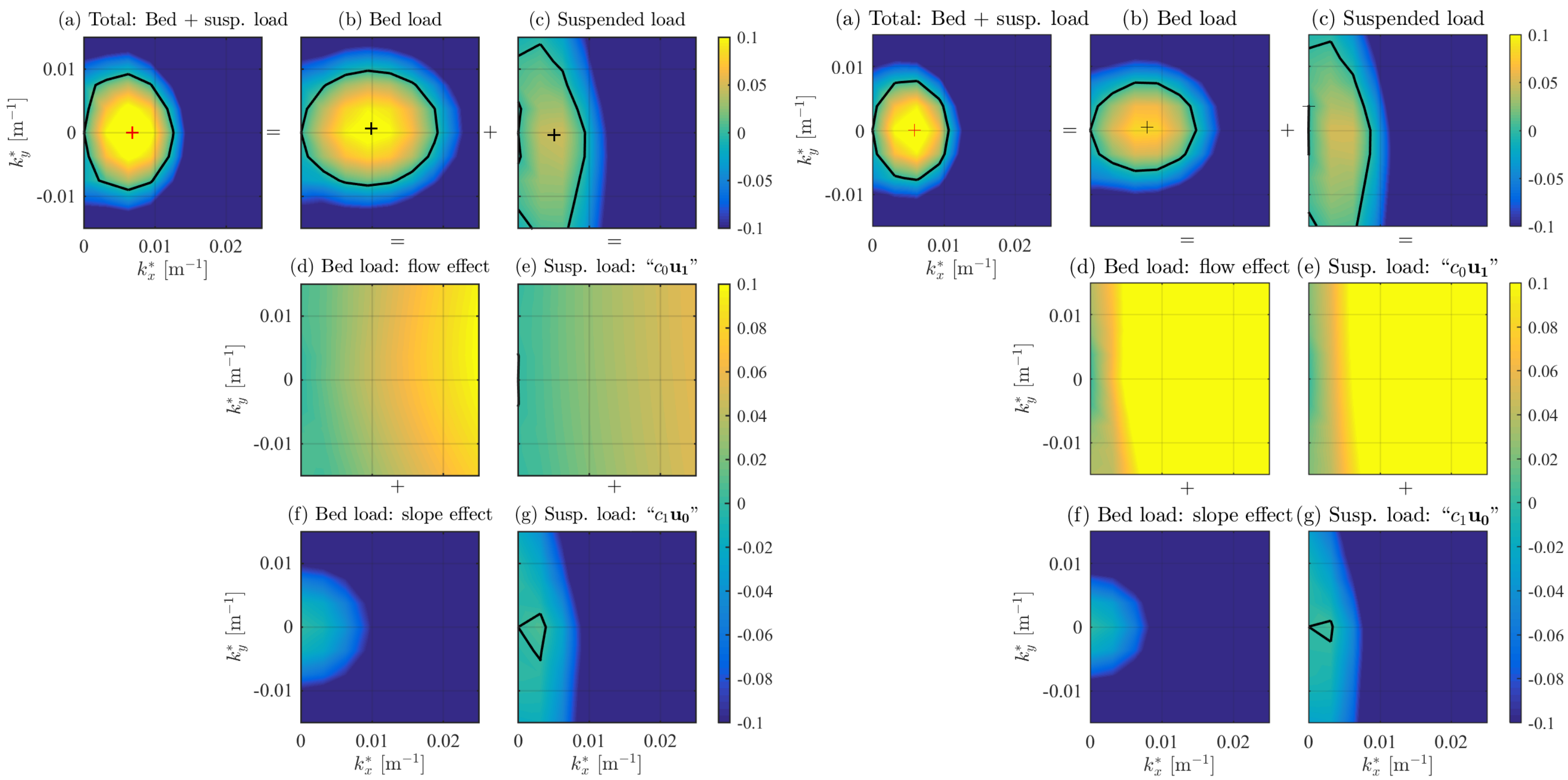
This chapter shows the results of the model runs. The results consists of plots of the growth rate and migration rate as a function of the topographic wave numbers k_x^* and k_y^* and as a function of the topographic wave numbers k_x^* and k_y^* per bin, the growth and migration rate of a fixed mode as a function of wind speed and angle, and the growth rate as a function of wave height and angle and as a function of wave period and angle. As the goal of the research is, among others, to investigate the influence of the wind- and wave climate frequencies of occurrence on sand wave dynamics, some of the plots described above are plotted both excluding and including the frequencies of occurrence. As mentioned in Paragraph 3.3 it is important to keep in mind that the data is made up of a combination of 5 different variables. Behind the 2 variables displayed on the axes, there are 3 variables hidden. Therefore when talking about the effect of e.g. changing wind speed, this means that the hidden wave parameters change together with these changing wind speeds. The thick black lines in the plots of the growth- and migration rate as a function of topographic wave numbers k_x^* and k_y^* denote the zero growth contours. The + denotes the FGM.

4.1 Growth rate; effect of storms and frequencies of occurrence

4.1.1 Growth rate as a function of the wave numbers k_x^* and k_y^*

Figure 16 shows the growth rate [yr-1] as a function of the topographic wave numbers k_x^* and k_y^* for the Europlatform 1997-2015, including tidal flow only (a symmetric M2 tidal current), leaving out any storm processes (left) and including tidal flow, storm processes and the frequencies of occurrence of the wind and wave climate (right) (see Appendix I for larger figures).
These figures show that including storm related processes, being wind speed, wind direction, wave height, wave period and wave direction, and their frequencies of occurrence influence the sand wave dynamics in their formation stage by causing the total growth rate to decrease.

Campmans et al. (2017) researched the total growth rate for four different storm conditions, being fair weather, waves only, wind only and waves+wind, and showed that the values and shape of the growth rate changes when adding wind and/or waves. Figure 16 also shows a change in value of the growth rate. These changes are however less extreme than the changes found in Campmans et al. (2017). This however could be explained by the fact that extreme conditions, being U= 20 m/s and H= 5 m, were being used in Campmans et al. (2017), causing more extreme changes in the growth rate. Smaller wind speed and wave height values would result in smaller changes in the growth rate. These smaller changes can also be an indication that the smaller values of the wind speed, wave height and wave period, and thereby more frequently occurring values (see Figure 12, 13 & 14), make a bigger contribution to the overall growth rate than the growth rate itself.



a) tide only

b) including tide, wind & waves, and frequencies of occurrence

Figure 16: Growth rate as a function of the topographic wave numbers k_x^* and k_y^*, for tide only (left) and including tide, wind &waves and the frequencies of occurrence (right) of the location Europlatform during the timeframe 1997-2015.

Figure 17 shows the difference in growth rate between including and excluding storms (wind speeds ≥ 20.8 m/s), while taking the frequencies of occurrence into account. This figure clearly shows that including storms has little influence on the growth rate. Considering that, when excluding the frequencies of occurrence, the growth rate shows a more significant difference between excluding and including storms (see Appendix J) these figures show that the frequencies of occurrence of storms are small and thus cause storms to have only a minimal influence on the overall growth rate.

The FGM based on the growth rate including storms and including the frequencies of occurrence as given in Figure 16b, has the following characteristics: wavelength L^*= 1068 m, orientation θ = -0.2°, growth rate ω^*= 0.123 yr^{-1} and migration rate c_{mig}^* = 45 m yr^{-1}.

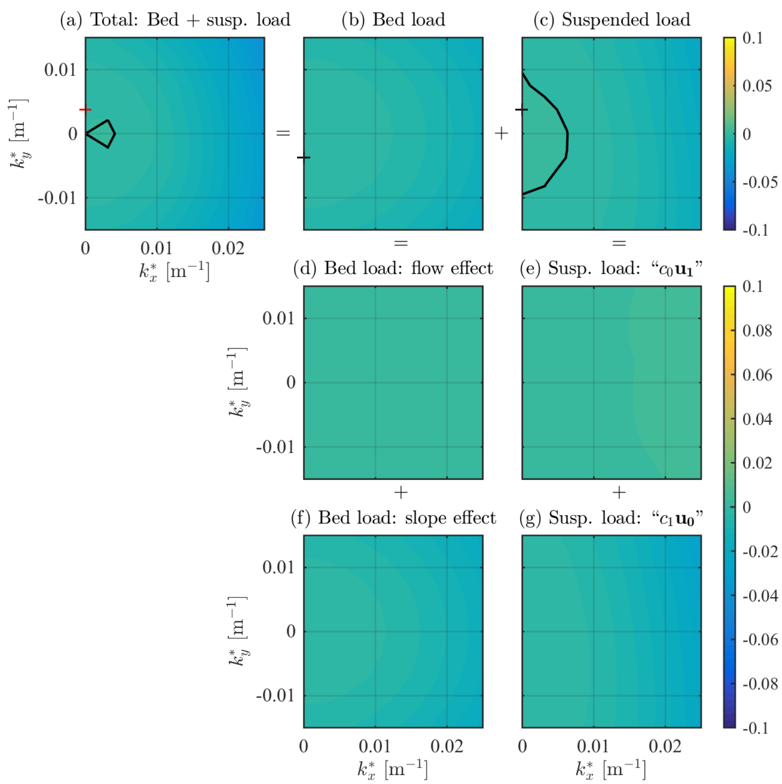
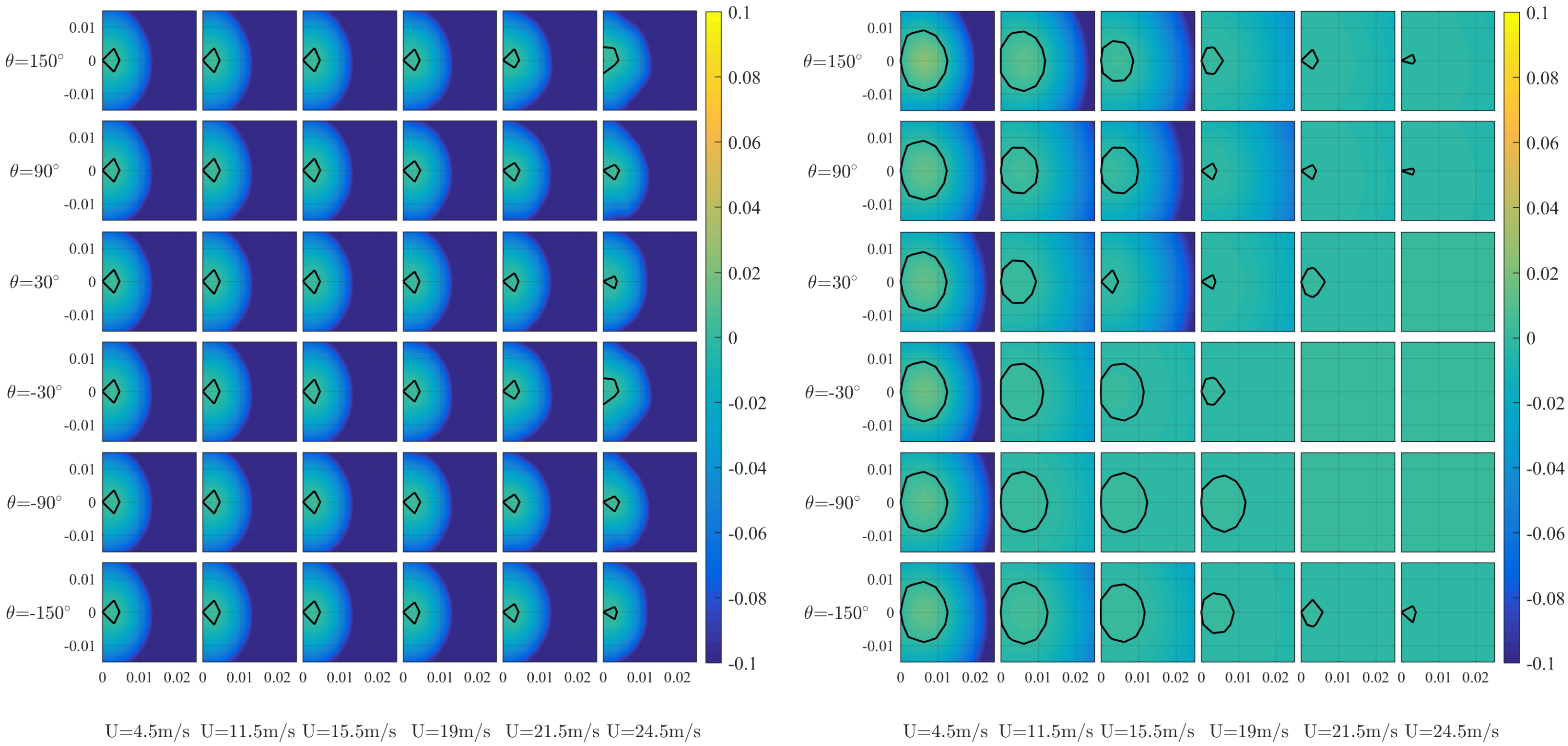


Figure17: Difference in growth rate [yr-1] between including and excluding storms (wind speeds ≥ 20.8 m/s), taking the frequencies of occurrence into account, as a function of the topographic wave numbers k_x^* and k_y^* of the location Europlatform during the timeframe 1997-2015.

To further investigate the influence of storms and the frequencies of occurrence on the growth rate of sand waves, Figure 16b is investigated in more detail by calculating and plotting the growth rate per bin. Excluding the frequencies of occurrence (Figure 18a) shows that as the wind speed increases, the growth rate slightly decreases (see Appendix K for larger figures). The wind angle only has a small influence on both the growth rate values and the shape of the figure. Including the frequencies of occurrence (Figure 18b) shows that increasing the wind speed causes the growth rate to variously decrease and increase. There is a clear difference in growth rate when changing the wind speed or wind angle. The change in wind angle however is less influential than the change in wind speed. For the positive wind angles, an increase in wind speed causes the growth rate to first decrease and then between bin 15.5 m/s and bin 19.5 m/s to variously decrease and increase and go towards zero. For the negative wind angles, an increase in wind speed causes the growth rate to almost immediately go towards zero.



a) excluding the frequencies of occurrence

b) including the frequencies of occurrence

Figure 18: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) of the location Europlatform during the timeframe 1997-2015.

The biggest contribution to the growth rate comes from wind speeds between 0 and 10 m/s, for all wind angles. The second largest, but significantly smaller, contribution comes from a combination of wind speeds between 14 and 18 m/s and positive wind angles (between 0 and 180 degrees) and a wind speed between 10 and 14 m/s and a wind angle between 120 and 180 degrees. Investigating the wind- and wave parameters within the bins that contribute most to the growth rate (see Appendix L) shows that these wind speeds are mostly accompanied by wave heights between 0 and 2 meters, wave periods between 3 and 6 seconds and a wave angle between -30 and 60 degrees.
Looking at the wind climate occurrence plot in Figure 12 and comparing it with the values mentioned above and with Figure 18, it shows that the bins that display the biggest contribution to the growth rate coincide with the bins with the highest occurrence. This shows that the overall growth rate is largely determined by the frequencies of occurrence. However, when looking more into detail it can be seen that, for example, bin 11.5 m/s & 90° has a higher occurrence than bin 15.5 m/s & 90°. The contribution of the latter bin is however larger than that of the former bin. This shows that the growth rate itself is still of importance and can contribute to small differences in the growth rate values of the bins.

4.1.2 Growth rate of the fixed mode

The fastest growing mode of Figure 16b is taken and used as an input to calculate the growth rate and migration rate contribution of a fixed mode as a function of wind speed (see Figure 19).

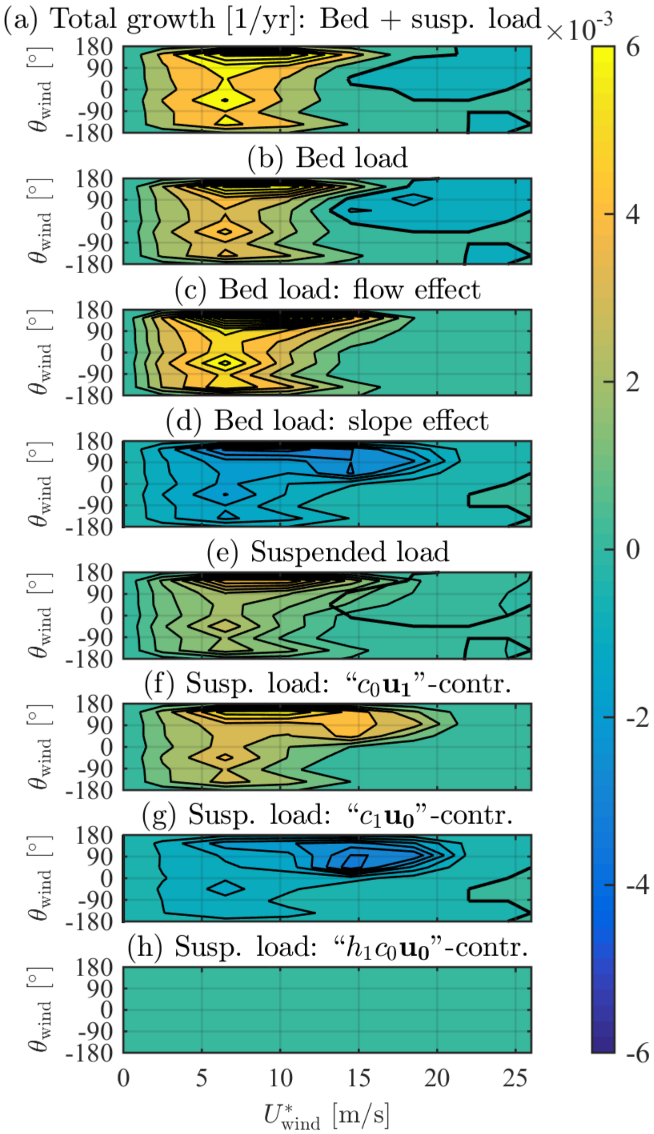


Figure 19: Growth rate contribution of the fixed mode as a function of wind speed and wind angle, including the frequencies of occurrence of the location Europlatform during the timeframe 1997-2015.

Dividing the wind speed in low-medium (<=15 m/s), high (15-21 m/s) and storm (21+), the following results are obtained:

Low-medium: Including the frequencies of occurrence causes wind speeds up to approximately 12 m/s to have a positive growth rate contribution, which varies for the wind angle. These variations are in agreement with the variations present in the occurrence plot (Figure 12). The growth rate is mainly determined by the bed flow effect.

High: Including the frequencies of occurrence causes wind speeds between 15 and 21 m/s to have a negative growth rate contribution at a wind angle between approximately -45 and 135 degrees, the remaining wind angles have a growth rate of approximately zero. The largest growth rates occur approximately between 45 and 90 degrees. These variations are in agreement with the variations present in the occurrence plot (Figure 12). The growth rate is determined by the both the bed and suspended load. Figure 19 shows that the bed slope effect becomes stronger with increasing wind speed and depends on the wind angle. As wind speed increases, the decrease of the bed slope effect outcompetes the increase of the bed flow effect.

Storm: Storm parameters hardly occur in the Europlatform 1997-2015 wind and wave climate and when they do occur, they results in a growth rate contribution close to zero because of their low frequencies of occurrence.

Looking at Figure 19 it can be seen that the positive growth rates outweigh the negative growth rates, resulting in a positive overall growth rate at the fixed mode.
Research by Campmans et al. (2017) showed that wind parallel to the tidal flow ($\theta_{wind} \approx 0°, 180°$) reduces the growth rates. Figure 19 shows that the largest growth rate contributions occur at a wind angle between 90 and 180 degrees, with a smaller peak between 0 and -90 degrees. These angles are in agreement with the angles at which higher frequencies of occurrence are present. The wind angles at which the highest growth rate contribution occurs is thus more dependent on the frequencies of occurrence than of the variables characteristics.

4.2 Growth rate; contribution of bed load and suspended load

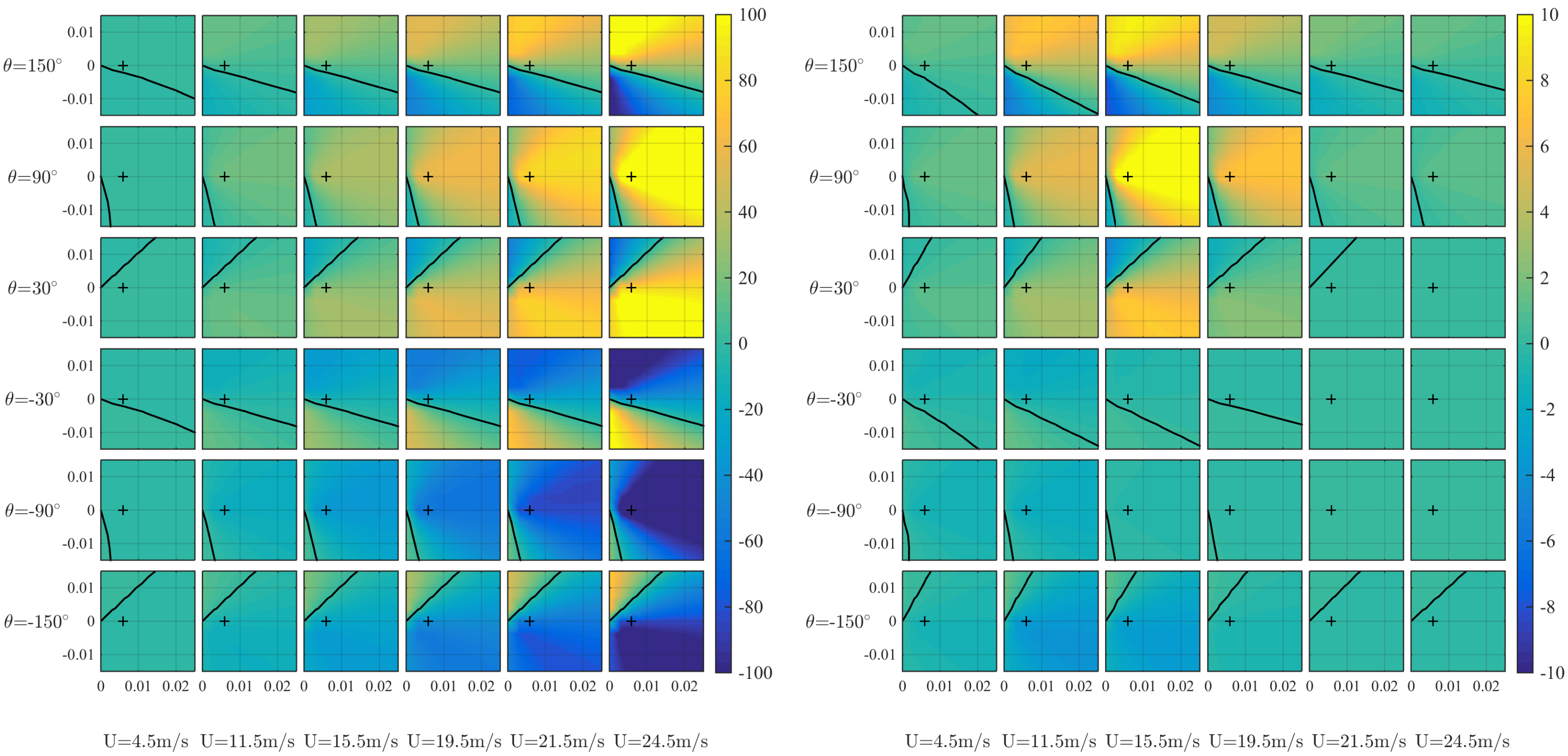
Based on Figure 19, the bed load makes a larger contribution to the total growth rate than the suspended load. As mentioned in Paragraph 1.3.2, Van der Molen (2012) states that the contribution of suspended load is larger at locations where storm dominate compared to where tides dominate because of the rougher conditions at the times that sand transport occurs. Looking at the figures in Appendix M, comparing the contributions of bed load and suspended load for storm related wind speeds (column 5 and 6) to the growth rate excluding the frequencies of occurrence, it can be seen that the contribution of suspended load does become larger as the wind speed increases. However its low frequencies of occurrence for large wind speeds and the larger contributions of the bed load in general cause the resulting effect of the suspended load for all wind speeds to be only small.

4.3 Migration rate

Figure 20a shows that the migration rate as a function of the topographic wave numbers k_x^* and k_y^* becomes more extreme (both for positive and negative values) as the wind speed increases. Taking the frequencies of occurrence into account (Figure 20b) causes the migration rate to become close to zero for a significant part of the presented bins (see Appendix N for larger figures). A wind speed between 10 and 21 m/s combined with a wind angle between 0 and 180 degrees contributes most to the migration rate, with its biggest contribution being a wind speed between 14 and 18 m/s and a wind angle between 60 and 180 degrees. This is different from the growth rate, where the biggest contribution to the growth rate comes from wind speeds between 0 and 10 m/s, for all wind angles.
Looking at the wind climate occurrence plot in Figure 12 and comparing it with the values mentioned above and with Figure 20, it shows that there are a few similarities. It shows that the migration rate is determined by a combination of frequency of occurrence and the migration rate itself. For certain bins the migration rate itself is dominant over the frequency of occurrence whereas the opposite is true for other bins. The main difference with the growth rate is that the migration rate shows almost no migration rate contributions for wind speeds between 0 and 10 m/s. The rest of the bins develop more

similar to the bins of the growth rate.

Positive wind angles cause both positive and negative migration rates, whereas negative wind angles mainly cause negative or zero migration rate. As indicated in Campmans et al. (2017), a symmetric M2 tidal current is imposed in the model, such that the migration rate of any bed perturbation is zero. Furthermore wind waves, as modeled herein, are unable to induce migration themselves, but can enhance migration through other mechanism. It is the wind-driven flow that induces migration as it breaches tidal symmetry.



a) excluding the frequencies of occurrence

b) including the frequencies of occurrence

Figure 20: Migration rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) of the location Europlatform during the timeframe 1997-2015. The + denotes the FGM of Figure 16b.

Figure 21 shows the migration rate contribution of the fixed mode as a function of wind speed and wind angle. When including the frequencies of occurrence, there is a positive migration rate contribution for a wind angle between approximately 0 and 180 degrees and wind speeds between approximately 9 and 21 m/s, with a peak at around 17 m/s and 90 degrees wind angle. For the wind angles between approximately 0 and -180 degrees, the negative migration rate contribution is present for almost all wind angles. Its value reaches its peak between 9 and 13 m/s and between -170 and -120 degrees. The remaining migration rates are approximately zero. The suspended load, foremost the c1u0 contribution (wave-related transport component), is the main contributor to the migration rate. The positive migration at positive wind angles and negative migration at negative wave angles is due to the Coriolis effect.

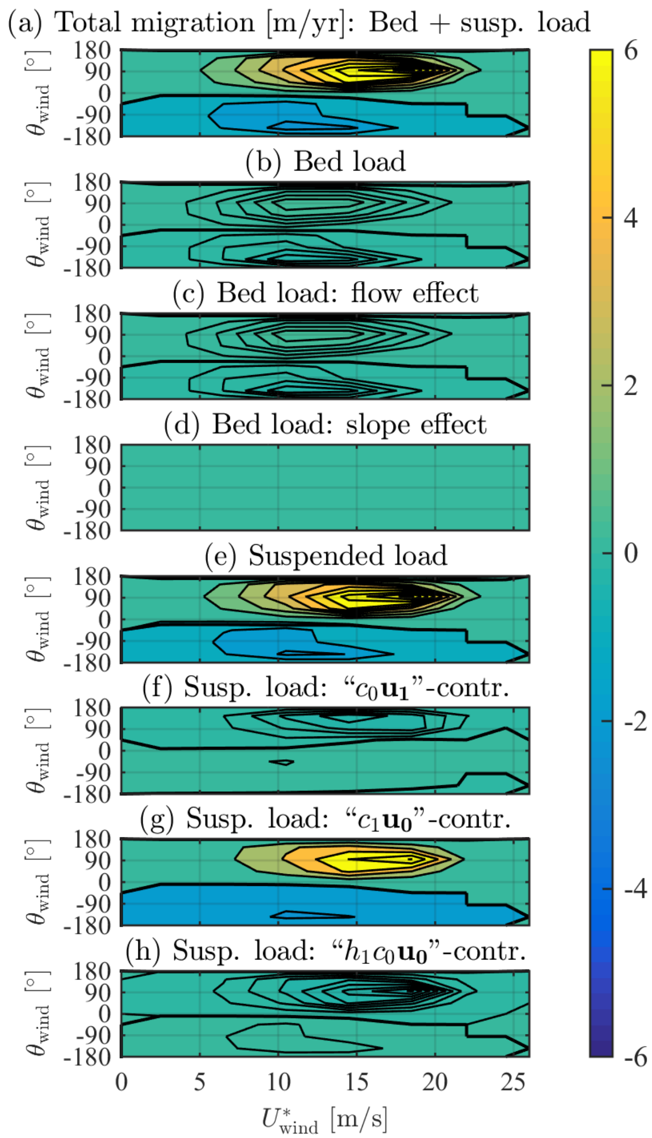


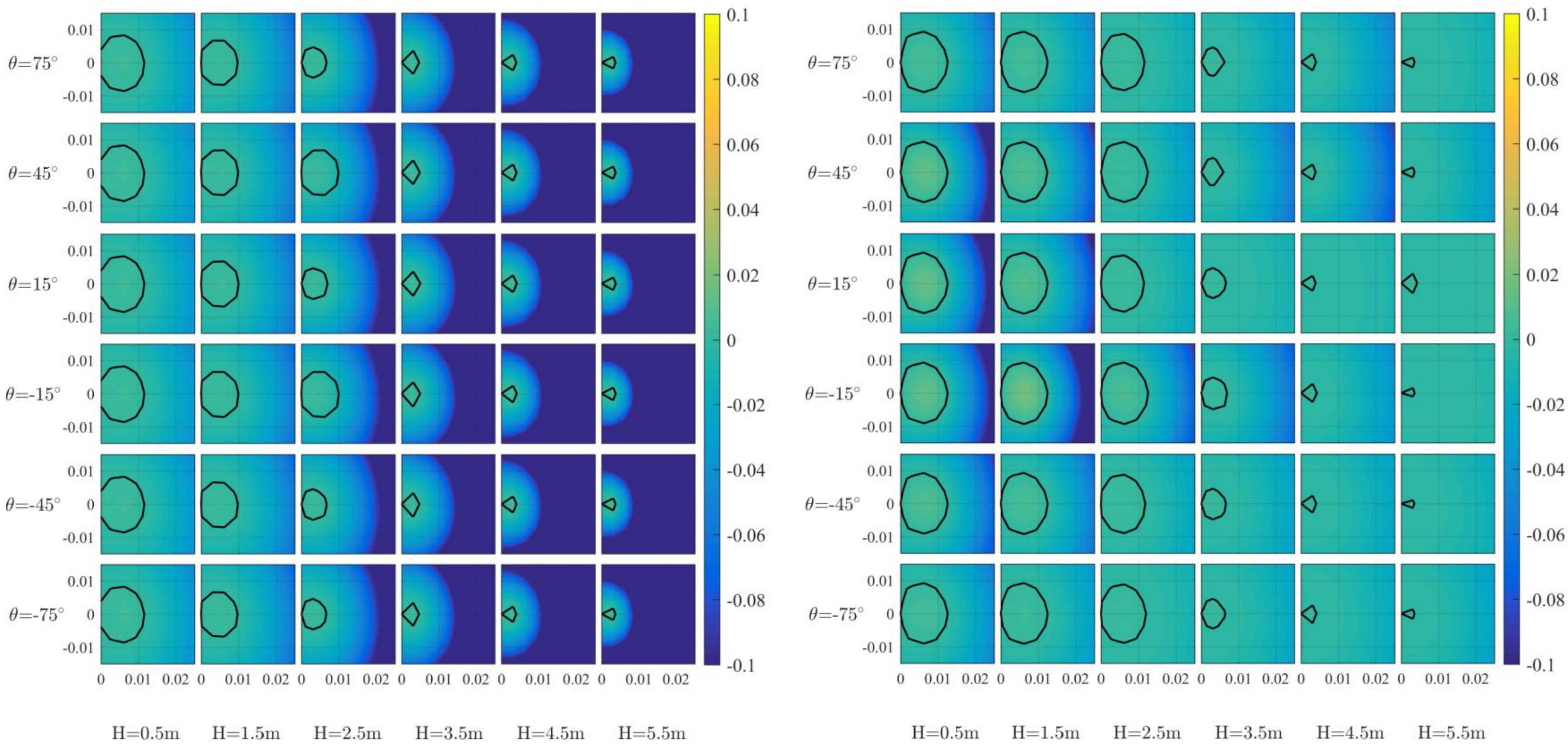
Figure 21: Migration rate contribution of the fixed mode as a function of wind speed and wind angle, including the frequencies of occurrence of the location Europlatform during the timeframe 1997-2015.

As already mentioned in Paragraph 4.1.1, the FGM based on the growth rate including storms and including the frequencies of occurrence as given in Figure 16b, has a migration rate of 45 m yr^{-1}. This migration rate is of the same order of magnitude as the migration rates common for sand waves, being up to tens of meters per year.

4.4 Growth rate; effect of wave height and – period

4.4.1 Wave height

Figure 22 shows the growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave height and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) (see Appendix O for larger figures). Excluding the frequencies of occurrence shows that increasing the wave height causes a decrease in growth rate. There is little variation in the wave angle. Including the frequencies of occurrence results in either an increase, decrease or variously a decrease and increase of the growth rate as the wave height increases. It leads to a growth rate distribution with more pronounced differences and extremes for lower wave heights (especially for -15 and 45 degrees wave angle), and less negative or even towards zero growth rate for the higher wave heights.



a) excluding the frequencies of occurrence

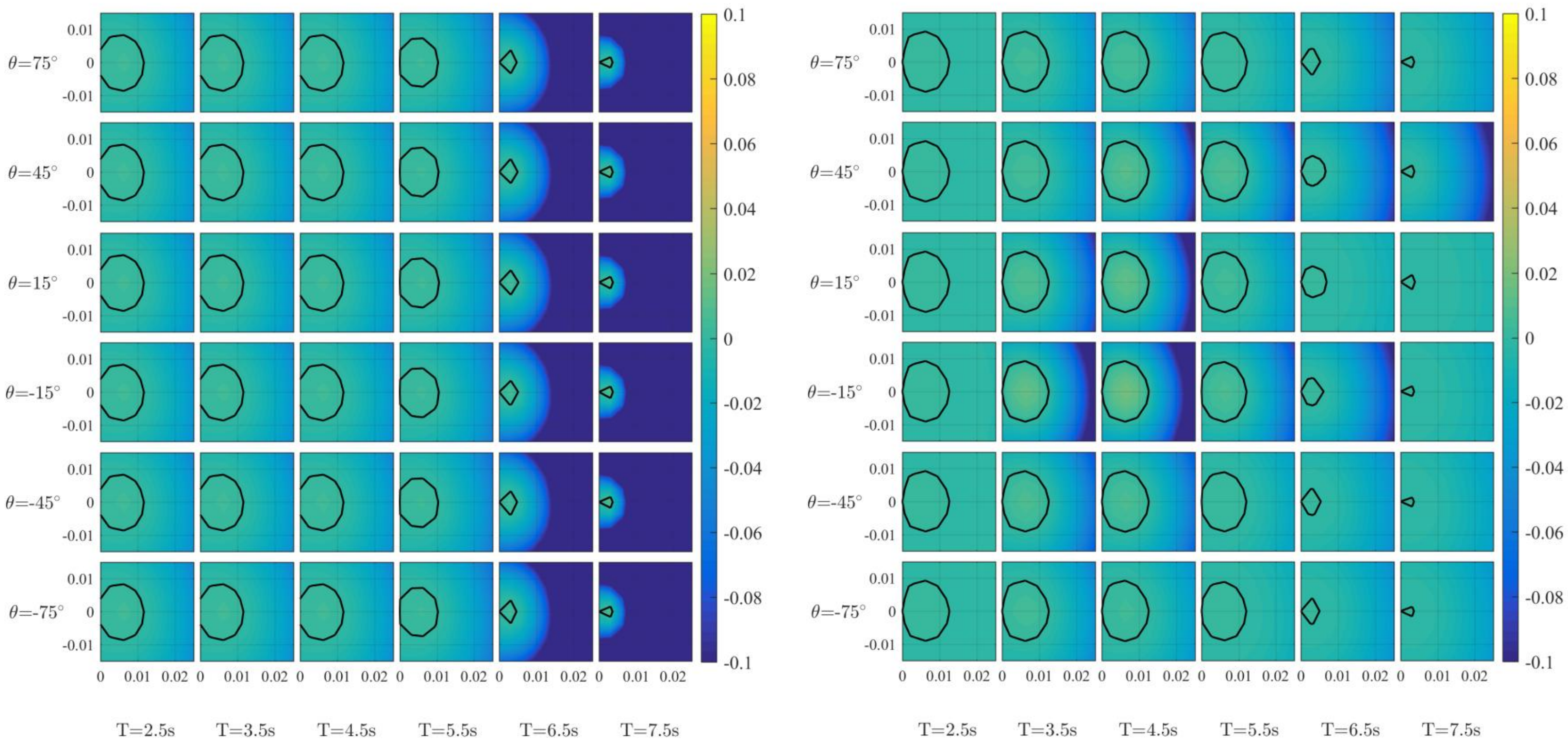
b) including the frequencies of occurrence

Figure 22: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave height and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) of the location Europlatform during the timeframe 1997-2015.

The biggest contribution to the growth rate comes from wave heights between 0 and 2 m, for all wave angles. With a larger contribution in general by wave angles between -30 and 60 degrees. Higher wave heights combined with a wave angle of -30 to 0 degrees and 30 to 90 degrees show a slightly higher growth rate than their surrounding bins. Investigating the wind- and wave parameters within the bins that contribute most to the growth rate (see Appendix L) shows that these wave heights are mostly accompanied by wave periods between 3 and 5 seconds, wind speeds between 0 and 14 m/s and a wind angle between -180 and -120, -60 and 60, and 12- and 180 degrees.

4.4.2 Wave period

Figure 23 shows the growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave period and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) (see Appendix O for larger figures). Excluding the frequencies of occurrence shows that increasing the wave period causes a decrease in growth rate. There is little variation in the wave angle. Including the frequencies of occurrence results in either a decrease or variously a decrease and increase of the growth rate as the wave period increases. It leads to a more negative growth rate for low to medium wave periods (for all wave angles), and a less but still significant negative growth rate for some of the medium to higher wave periods.



a) excluding the frequencies of occurrence

b) including the frequencies of occurrence

Figure 23: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave period and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) of the location Europlatform during the timeframe 1997-2015.

The biggest contribution to the growth rate comes from wave periods between 3 and 5 s, for wave angles between -30 and 60 degrees. Higher wave periods between 5 and 8 seconds combined with a wave angle of -30 to 0 degrees and 30 to 60 degrees show a slightly higher growth rate than their surrounding bins. Investigating the wind- and wave parameters within the bins that contribute most to the growth rate (see Appendix L) shows that these wave periods are mostly accompanied by wave heights between 0 and 3 meter, wind speeds between 0 and 14 m/s and a wind angle between -180 and -120, -60 and 60, and 12- and 180 degrees.

4.4.3 Influence of wave climate

Looking at the wave climate occurrence plots in Figure 13 and 14 and comparing it with the values mentioned above and with Figure 22 and 23, it shows that the bins that display the biggest contribution to the growth rate coincide with the bins with the highest occurrence. Just as in Paragraph 4.1.1 it shows that there are some bins with lower occurrences that have a higher contribution to the growth rate, e.g. bin H=4.5 s & θ=45° and bin T=7.5 s & θ=45°. This shows that the growth rate itself is still of importance and can contribute to small differences in the growth rate values of the bins.

Research by Campmans et al. (2017) showed that waves decrease the growth rate in particular when they propagate in a direction roughly parallel to the sand wave crest (θ_{wave} = 90°). Figure 22b and 23b shows that the largest growth rate contributions occur at a wave angles that are in agreement with the angles at which higher frequencies of occurrence are present. The wave angles at which the highest growth rate contribution occurs is thus more dependent on the frequencies of occurrence than of the variables characteristics.

The growth rate of the fixed mode as a function of wave height and angle and the growth rate of the fixed mode as a function of wave period and angle show the same variation in growth rate for different wave heights and wave periods as was found in Paragraph 4.4.1 and 4.4.2 (see Appendix P for larger figures).

4.5 Hours surrounding the storms

As mentioned in Paragraph 1.3.2, researches show that sand wave heights are reduced during stormy periods and suggest that storms may play a major role in the migration of sand waves. Campmans states that their model results support the observations by Terwindt (1971), McCave (1971) and Fenster et al. (1990), who suggested that storms may be important factors in sand wave dynamics. The results presented above however do not show this. Measuring the change in sand wave height and dimensions is, in all likelihood, not carried out immediately before and after a storm takes place but over a longer period of time. Therefore the question arises whether it are the storms themselves or the hours building up to and hours after the storm, that contribute to the sand wave dynamics. Extensively investigating this however would comprise a whole new research, therefore this is only researched broadly by determining the amount of hours before and after a storm where the consecutive wind speeds are higher than or equal to 17.2 m/s, and plotting the growth rate as a function of the topographic wave numbers excluding the storms and their surrounding hours. A wind speed of 17.2 m/s or higher was chosen since a wind speed between 17.2 and 20.8 m/s is indicated as 8 on the Beaufort scale. Words used to describe these wind speeds in literature and other resources are “stormy” and “gale”. These hours are therefore from hereon referenced as ”gale hours”.

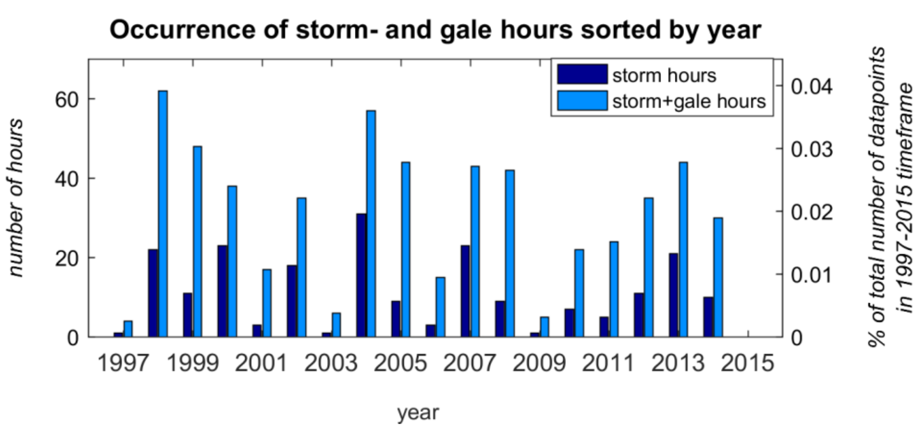


Figure 24: Occurrence of storms and gale hours sorted by year of the location Europlatform during the timeframe 1997-2015.

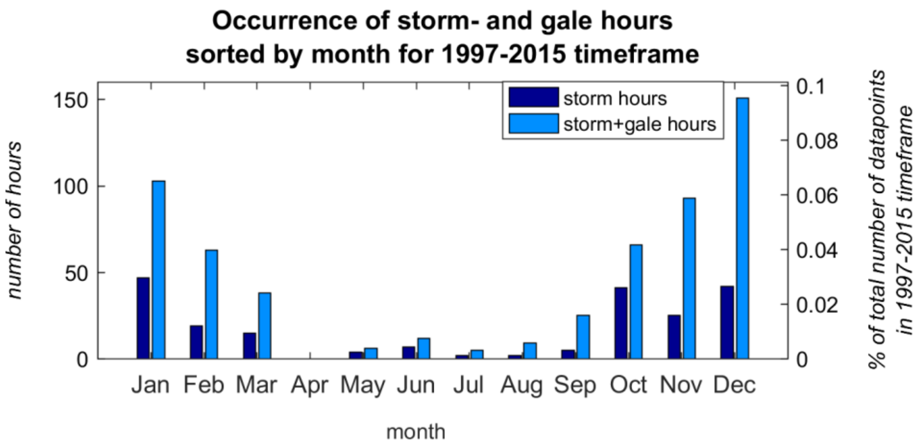


Figure 25: Occurrence of storms and gale hours sorted by month of the location Europlatform during the timeframe 1997-2015.

The analysis shows that on average 2.3 hours before and 2.5 hours after a storm, wind speeds consecutively between 17.2 and 20.8 m/s occur. The amount of hours varies from 0 to 12. In total 362 gale hours are removed on top of the 209 storm hours. Gale hours thus have higher frequencies of occurrence causing the eventual growth rate contribution to be larger than that of the storm hours and thus more significant. Figure 26 (see Appendix Q for larger figure) shows the difference in growth rate between including and excluding storm+gale hours, taking the frequencies of occurrence into account. This figure shows that excluding the storms and gale hours makes a small but, compared to excluding only the storm hours (see Figure 17), more significant difference for the growth rate.

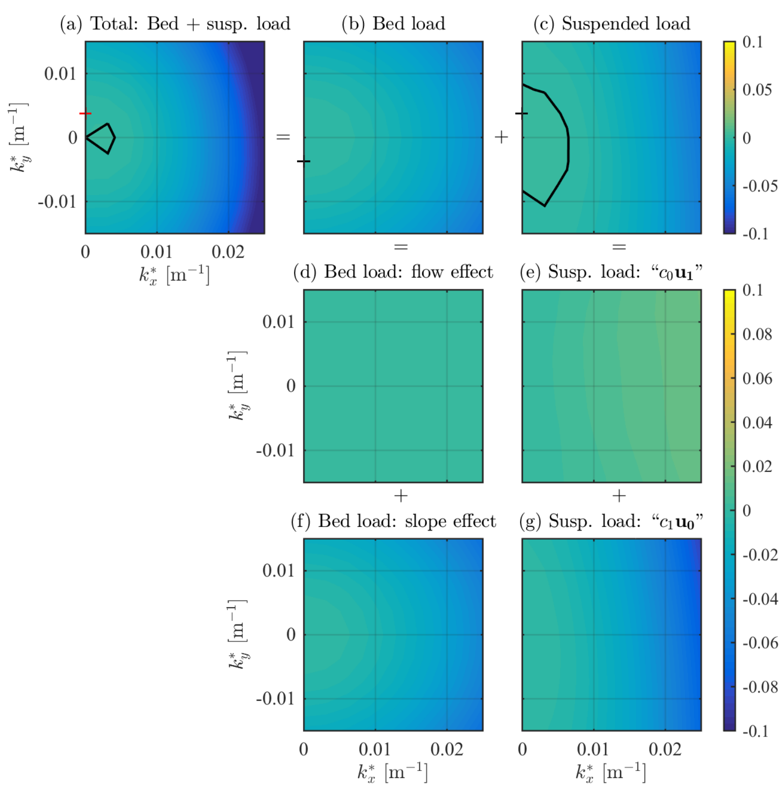


Figure 26: Difference in growth rate [yr-1] between including storms (wind speeds ≥ 20.8 m/s) and excluding storm+gale hours, taking the frequencies of occurrence into account, as a function of the topographic wave numbers k_x^* and k_y^* of the location Europlatform during the timeframe 1997-2015.

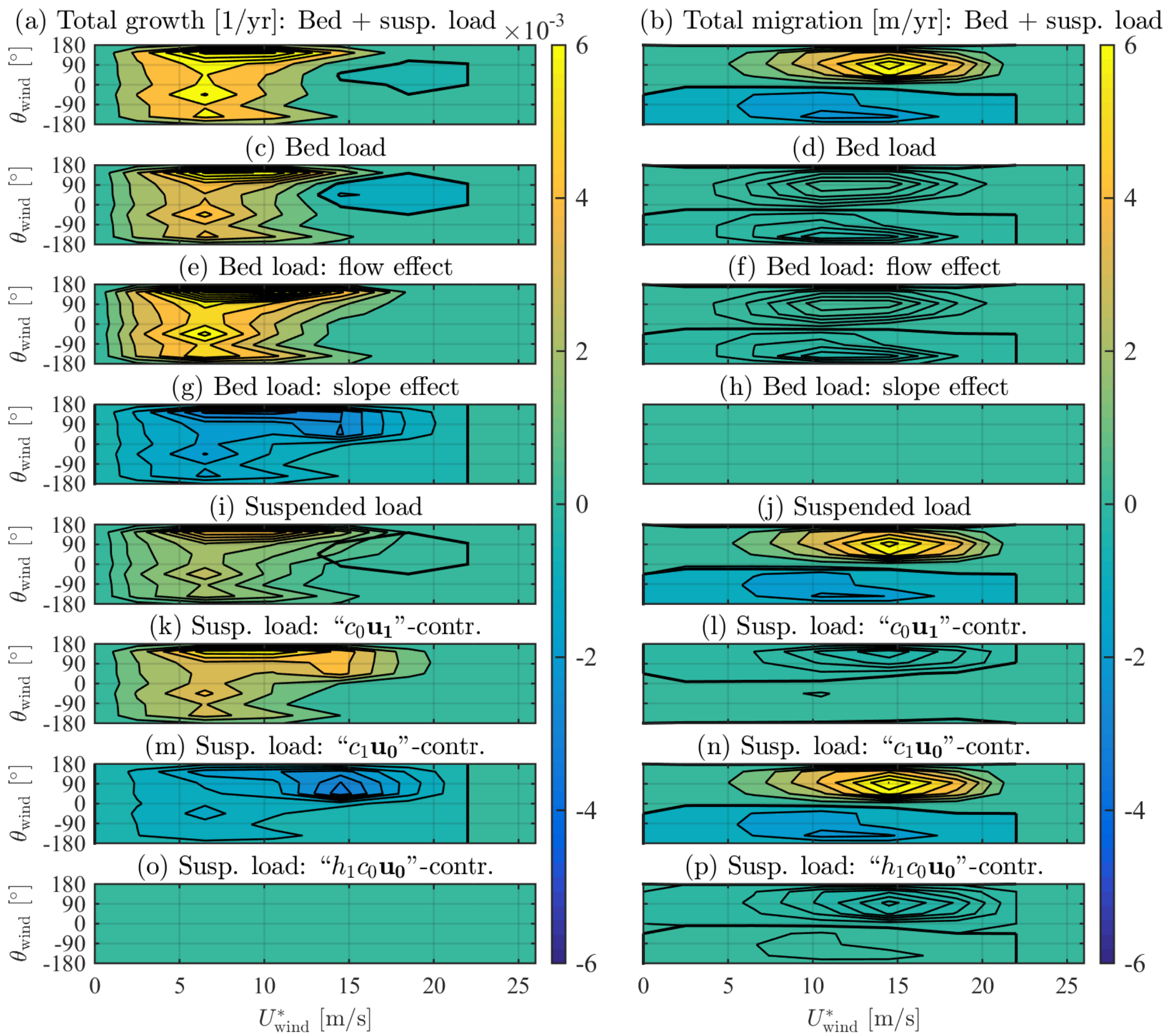


Figure 27: Growth- and migration rate contribution of the fixed mode as a function of wind speed and wind angle including the frequencies of occurrence, excluding the storm+gale hours of the location Europlatform during the timeframe 1997-2015.

4.6 Influence of the vertical eddy viscosity

As indicated in Paragraph 3.2.1 the vertical eddy viscosity is dependent on numerous variables, making it sensitive to change. In this research a simplification was applied and a constant vertical eddy viscosity was chosen. A question that arises when looking at the results is whether the vertical eddy viscosity has a significant influence on the growth rates and thus whether assuming a constant vertical eddy viscosity could distort the results. Extensively investigating this however would comprise a whole new research, therefore this is only researched broadly by varying the vertical eddy viscosity for the average general wind- and wave climate and for the storm wind- and wave climate. The general wind- and wave climate consists of the following values: U= 7.8 m/s, θ_{wind}= -166°, H= 1.3 m, T= 4.4 s, θ_{wave}= -4°. The storm wind- and wave climate consists of U= 21.8 m/s, θ_{wind}= 148°, H= 3.9 m, T= 6.1 s, θ_{wave}= -26°. As given in Table 1 Campmans et al. (2017) the vertical eddy viscosity has typical values of 0.025-0.09. The following variety of values to investigate was chosen: 0.025, 0.04, 0.055, 0.07 and 0.085.

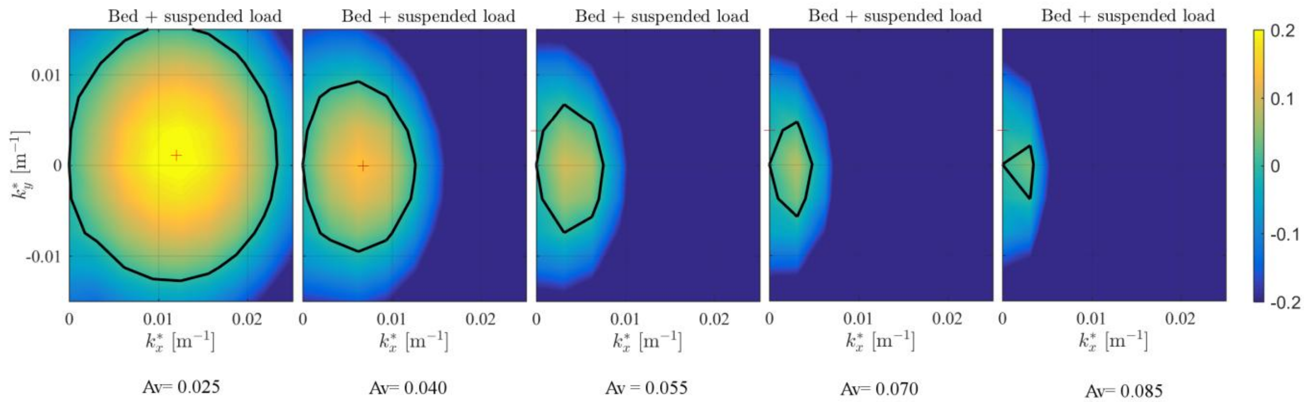


Figure 28: Growth rate of the general wind- and wave climate as a function of the topographic wave numbers k_x^* and k_y^* for varying vertical eddy viscosities of the location Europlatform during the timeframe 1997-2015.

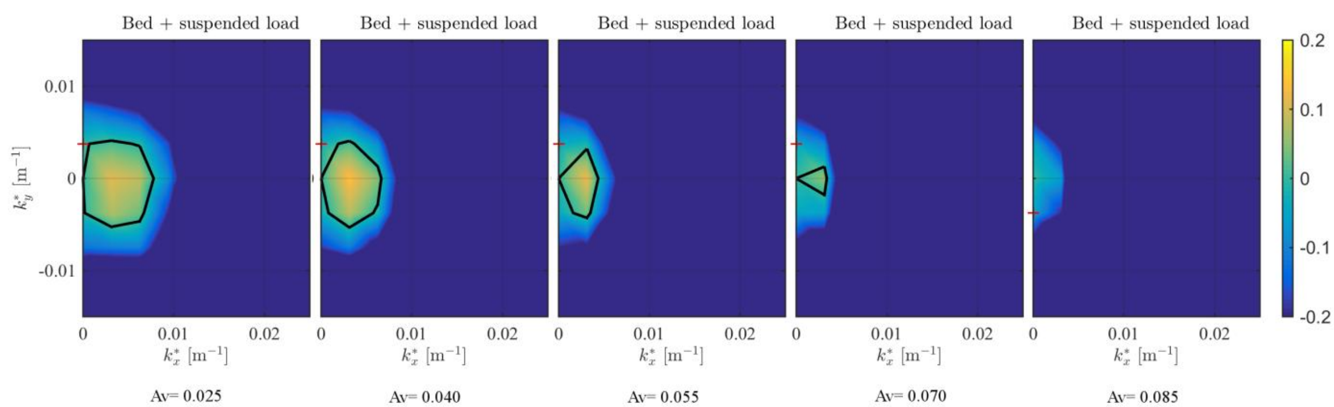


Figure 29: Growth rate of the storm wind- and wave climate as a function of the topographic wave numbers k_x^* and k_y^* for varying vertical eddy viscosities of the location Europlatform during the timeframe 1997-2015.

Figures 28 and 29 show the resulting growth rate for the varying vertical eddy viscosities. This shows that the vertical eddy viscosity has a significant effect on the growth rate. The growth rate value changes significantly when changing the vertical eddy viscosity, both for a general climate and for a storm climate. When changing the vertical eddy viscosity not only the growth rate value can change but also its sign (going from positive to negative or vice versa).

5 Discussion

In this research the model of Campmans et al. (2017) is used. This model uses a linear stability analysis meaning it cannot model properties of fully grown sand waves and thus investigates storm processes in the formation stage. However, Campmans et al. (2017) already mentioned that their “results in the linear regime suggest that waves and wind-driven flow are also important processes in nonlinear sand wave models” (p.12). Therefore the results attained in this research are still valid. Furthermore there were no clear rules for choosing the timeframe and removing the data gaps, and the research location was not ideal. Since there was only limited time and computer resources for this research, decreasing the ability to investigate the different wind- and wave climate values in detail, the use of bins was necessary. Despite these limitations and adjustments the resulting data can still be considered as valid since the timeframe is fitting to the time scale of 1-10 years on which sand waves are formed (see Paragraph 2.3), research in Paragraph 2.4.3 showed little change in means and standard deviations when decreasing the timeframe or when removing a fair amount of data gaps, reasonable size data bins were used and a fair amount of years with considerable variations in storm conditions were taken into account. Furthermore subdividing the data into bins may make it less detailed but it still encompasses the goal of the research, that is to investigate the influence of the storm related processes on sand wave dynamics.

The results of the research show that the influence of storms on the growth rate of sand waves is only minimal because of their low frequencies of occurrence. Based on previous research, it was expected that storms play a significant part in sand wave dynamics. The difference in results and expectation based on previous research can be due to multiple reasons. First of all, the model used is a linear model whereas fully grown sand waves require a nonlinear approach.
Furthermore, as pointed out in Paragraph 4.6, taking a variable vertical eddy viscosity causes the growth rate to change. Both an increase and a decrease of the growth rate is possible. This could possibly affect the overall growth rate and the importance of the frequency of occurrence. It could also change the contribution of storms to the overall growth rate and possibly explain the results found in previous research that storms play a significant part in sand wave dynamics.
Also, the conclusions and expectations mentioned in previous research were based on observations and/or measurements. Observing and/or measuring the change in sand wave dimensions is, in all likelihood, not carried out immediately before and after a storm takes place but over a longer period of time. Excluding the storms and their surrounding gale hours makes a small but, compared to excluding only the storm hours, more significant difference for the growth rate. Change in growth rates after periods of storms could thus be due to the hours before and after storms, that are associated with high wind speeds and more significant frequencies of occurrence, rather than due to the storm hours itself.

Recommendations for further research are to further investigate the vertical eddy viscosity. By taking the vertical eddy viscosity into account as a variable and not as a constant, its effect on the growth- and migration rate contribution can be determined. Furthermore the influence of the hours surrounding storms could be more elaborately investigated and be combined with a case study. This should give clear results on whether there is a significant difference after storm events or periods at which multiple storms occur such as previous research suggests, and whether storms+gale hours or low, middle or high wind speeds contribute to the differences measured.
In case the run time of the model needs to be decreased, without significantly affecting the results of the simulation, a model, similar to a program called 'Opti', could be developed. Opti consists of an iteration where the conditions that contribute the least to the end result are dropped and the weights for the remaining conditions are redistributed. The output is a reduced set of wind- and wave conditions

and their adjusted weight factors, which results in a shorter run time of the model without significantly affecting the results of the simulation (Mol, 2007).

6 Conclusion

The goal of this research is to investigate the influence of the wind- and wave climate and in particular storms, consisting of a combination of the storm related processes of wind waves and wind-driven flow and its frequencies of occurrence, on sand wave dynamics by applying a statistically combined wave and wind climate to the idealized sand wave model of Campmans et al. (2017) and analyzing its results.

The first research question focusses on determining the wind- and wave climate at the research location. At the research location, being the Europlatform during the timeframe January 1st 1997 - December 31st 2015, storms occur 0.1% of the time. These storms have the following overall mean values: U= 21.8 m/s, H= 3.9 m, T= 6.1 s, and a wind- and wave direction of respectively 240° and 234°. The general wind- and wave climate consists of the following overall mean values: U= 7.8 m/s, H= 1.3 m, T= 4.4 s, and a wind- and wave direction of respectively 194° and 212°.

The first part of the second research question consists of determining the influence of the storm related processes and their frequencies of occurrence on the growth- and migration rate of sand waves. The results show that including storm related processes, being wind speed, wind direction, wave height, wave period and wave direction, and their frequencies of occurrence influence the sand wave dynamics in their formation stage by causing the total growth rate to decrease. The frequency of occurrence shows to be more important for the resulting growth rate than the actual growth rate associated with the parameters itself. The growth rate itself is however still of importance and can contribute to small differences in the growth rate values of the bins. The migration rate is determined by a combination of frequency of occurrence and the migration rate itself. For certain bins the migration rate itself is dominant over the frequency of occurrence whereas the opposite is true for other bins. The influence of storms (defined as a wind measuring 20.8 m/s or higher) on the growth- and migration rate of sand waves is only minimal because of their low frequencies of occurrence.

Including the frequencies of occurrence for the fixed mode (wave numbers k_x^* and k_y^* of the fastest growing mode) causes wind speeds up to approximately 12 m/s to have a positive growth rate contribution, which varies for the wind angle. For wind speeds between 15 and 21 m/s it causes a negative growth rate contribution at a wind angle between approximately -45 and 135 degrees, the remaining wind angles have a growth rate of approximately zero. For storms (21 m/s and up) it results in a growth rate contribution close to zero.

The second part of the second research question looks at which storm related processes make the biggest contribution to the resulting growth- and migration rate. The biggest contribution to the resulting growth rate comes from a wind- and wave climate consisting of wind speeds between 0 and 10 m/s, wave heights between 0 and 2 meters, wave periods between 3 and 5 seconds, wind angles between -180 and -120, between -60 and 0 and between 120 and 180 degrees (these comprise a northeast, east, southeast, south, southwest and west direction) and wave angles between -30 and 60 degrees (these comprise a northwest, north, northeast, southeast, south and southwest direction).
A wind speed between 10 and 21 m/s combined with a wind angle between 0 and 180 degrees contributes most to the migration rate, with its biggest contribution being a wind speed between 14 and 18 m/s and a wind angle between 60 and 180 degrees.

Reference list

Anthoni, J. (2000). *Oceanography: waves*. Retrieved April 23, 2016, from http://www.seafriends.org.nz/oceano/waves.htm

Bennett, D. (2001). How can I deal with missing data in my study? *Australia and New Zealand journal of public health*, 464-469.

Besio, G., Blondeaux, P., Brocchini, M., Hulscher, S., Idier, D., & Knaapen, M. (2008). The morphodynamics of tidal sand waves: A model overview. *Coastal Engineering, 55*, 657–670.

Borsje, B. W., Kranenburg, W. M., Roos, P. C., Matthieu, J., & Hulscher, S. J. (2014). The role of suspended load transport. *Journal of Geophysical Research: Earth Surface, 119*.

Borsje, B., Roos, P., Kranenburg, W., & Hulscher, S. (2013). Modeling tidal sand wave formation in a numerical shallow water model: The role of turbulence formulation. *Continental Shelf Research, 60*, 17-27.

Campmans, G. (n.d.). *Modeling the effect of storm events and wind waves on sand wave dynamics*. Retrieved from utwente.nl: https://www.utwente.nl/en/et/wem/research/projects/campmans/

Campmans, G., Roos, P., De Vriend, H., & Hulscher, S. (2017). Modeling the influence of storms on sand wave formation: A linear stability approach. *Continental Shelf Research*, 103-116.

De Koning, M. (2007). *The stochastic characteristics of geometric properties of sand waves in the North Sea.* Enschede: University of Twente.

Dodd, N., Blondeaux, P., Calvete, D., De Swart, H., & Falque, A. (2003). Understanding Coastal Morphodynamics Using Stability Methods. *Journal of Coastal Research, 19*, 849-865.

Dong, Y., & Peng, C.-Y. J. (2013). Principled missing data methods for researchers. *Springerplus*.

Grace-Martin, K. (2017, April 11). *What is the difference between MAR and MCAR missing data?* Retrieved from The analysis factor: http://www.theanalysisfactor.com/mar-and-mcar-missing-data/

Grubbs, F. (1969). Procedures for Detecting Outlying Observations in Samples. *Technometrics*, 1-21.

Hulscher, S. (1996). Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. *Journal of geophysical research*, 20727-20744.

Knaapen, M., Hulscher, S., & De Vriend, H. (2001). A new type of sea bed waves. *Geophysical Research Letters, 28*(7), 1323–1326.

KNMI. (2014, March 5). *KNMI actual synoptic observations from NL land, coastal areas and North Sea stations per 10 minutes*. Retrieved from KNMI: https://data.knmi.nl/datasets/Actuele10mindataKNMIstations/1

KNMI. (n.d. a). *About KNMI*. Retrieved from KNMI: http://www.knmi.nl/over-het-knmi/about

KNMI. (n.d. b). *Stormen in Nederland*. Retrieved from KNMI: https://www.knmi.nl/kennis-en-datacentrum/uitleg/stormen-in-nederland

KNMI. (n.d. c). *Uitleg over storm*. Retrieved from KNMI: https://www.knmi.nl/kennis-en-datacentrum/uitleg/storm

KNMI. (n.d. d). *Waarnemingen Kust en Noordzee*. Retrieved from KNMI: https://www.knmi.nl/nederland-nu/weer/actueel-weer/kust-en-noordzee/

KNMI. (n.d. e). *Zware stormen in Nederland sinds 1910*. Retrieved from KNMI: https://www.knmi.nl/nederland-nu/klimatologie/lijsten/zwarestorm

Menninga, P. (2012). *Analysis of variations in characteristics of sand waves observed in the Dutch coastal zone: a field and model study.* Utrecht: Utrecht University.

Meteolink. (n.d.). *Stormen*. Retrieved from Meteolink: http://www.meteolink.nl/educatief/stormen/

Mol, A. (2007). *Schematisation of boundary conditions for morphological simulations.* R&D Kustwaterbouw.

Németh, A., Hulscher, S., & Van Damme, R. (2007). Modelling offshore sand wave evolution. *Continental Shelf Research, 27*, 713-728.

Newsom, J. T. (2015). *Missing Data and Missing Data Estimation*. Retrieved from web.pdx.edu: http://www.upa.pdx.edu/IOA/newsom/semclass/ho_missing.pdf

Peng, C., Harwell, M., Liou, S., & Ehman, L. (2006). Advances in missing data methods and implications for educational research. In S. Sawilowsky, *Real data analysis* (pp. 31-78). Charlotte, North Carolina: Information Age Pub.

Rijn, L. v. (n.d.). *Simple general formulae for sand transport in rivers, estuaries and coastal waters.*

Schlomer, G. L., Bauman, S., & Card, N. A. (2010). Best Practices for Missing Data Management in Counseling Psychology. *Journal of Counseling Psychology*, 1-10.

Terwindt, J. (1971). Sand waves in the southern bight of the North Sea. *Marine Geology, 10*(1), 51-67.

Trujillo, A. P., & Thurman, H. V. (2011). *Essentials of Oceanography* (Vol. 10th edition). United States: Prentice Hall.

van den Eynde, D., de Sutter, R., & Haerens, P. (2012). Evolution of marine storminess in the Belgian part of the North Sea. *Natural Hazards and Earth Systems Science*, 305-312.

Van der Veen, H., Hulscher, S., & Knaapen, M. (2006). Grain size dependency in the occurrence of sand waves", by H.H. van der Veen, S.J.M.H. Hulscher, and M.A.F. Knaapen, 2006, Ocean Dynamics, 56, p. 229. Copyright 2006 by Springer-Verlag. . *Ocean Dynamics*, 229.

Van Santen, R., De Swart, H., & Van Dijk, T. (2011). Sensitivity of tidal sand wavelength to environmental parameters: A combined data analysis and modelling approach. *Continental Shelf Research, 32*, 966–978.

Weisse, R., Von Storch, H., Niemeyer, H., & Knaack, H. (2012). Changing North Sea storm surge climate: An increasing hazard? *Ocean & Coastal Management, 68*, 58-68.

Appendix A. Overview Eurogeul and location of Europlatform

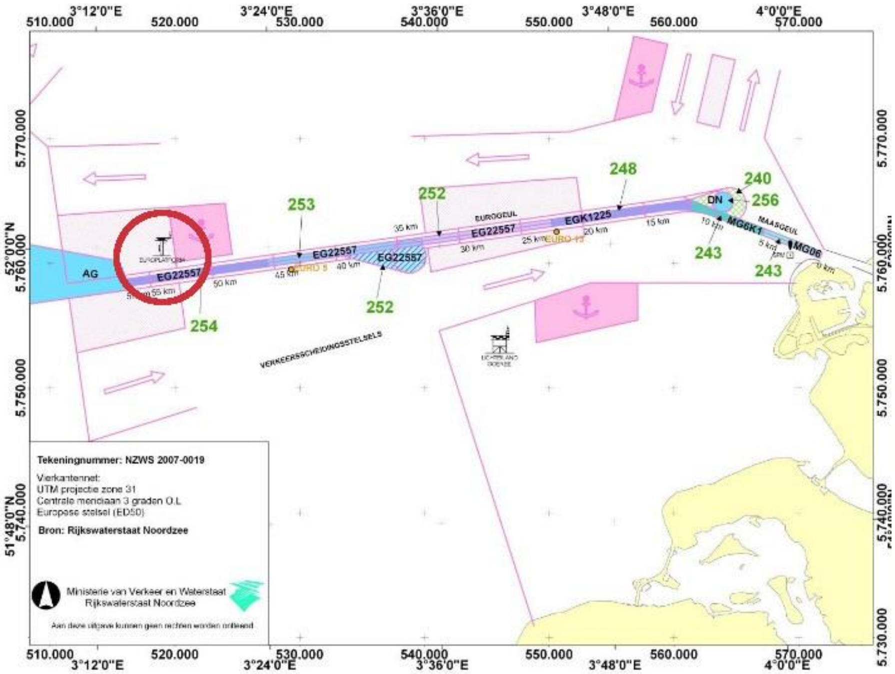


Figure A1: Overview Eurogeul. Reprinted from Tijpoort Regeling Euro-Maasgeul "Groene boekje 2007" (p. 15), by Ministerie van Verkeer en Waterstaat, 2007: Rijkswaterstaat Noordzee.

Appendix B. Windroses p11b, Hoorn-a and Europlatform

This appendix shows the windroses for the locations p11b, Hoorn-a and Europlatform for the timeframe January 1st 2010- December 31st 2014.
A wind rose is a graphic tool used by meteorologists to help visualize distribution of wind speed and -direction at a particular location for a specific period (Autodesk, n.d.). Presented in a circular format, the wind rose shows the frequency and value of winds blowing from particular directions (National Water and Climate Center, n.d.). Beside a wind rose, also two wave roses are made which represent the wave height and wave period distribution for the given wave direction.

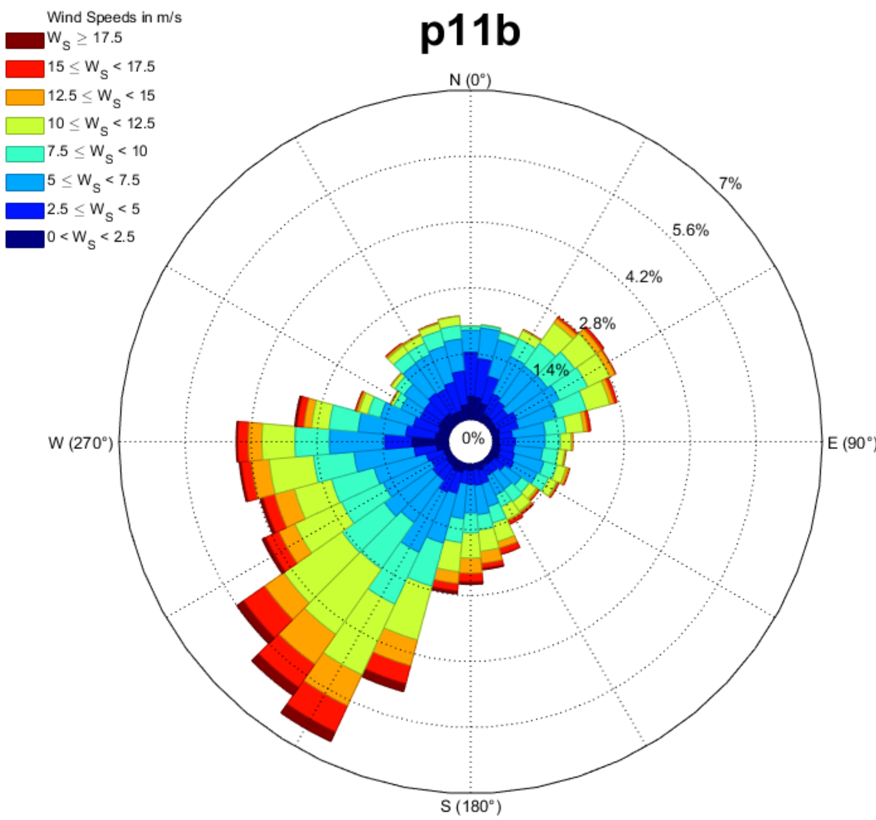
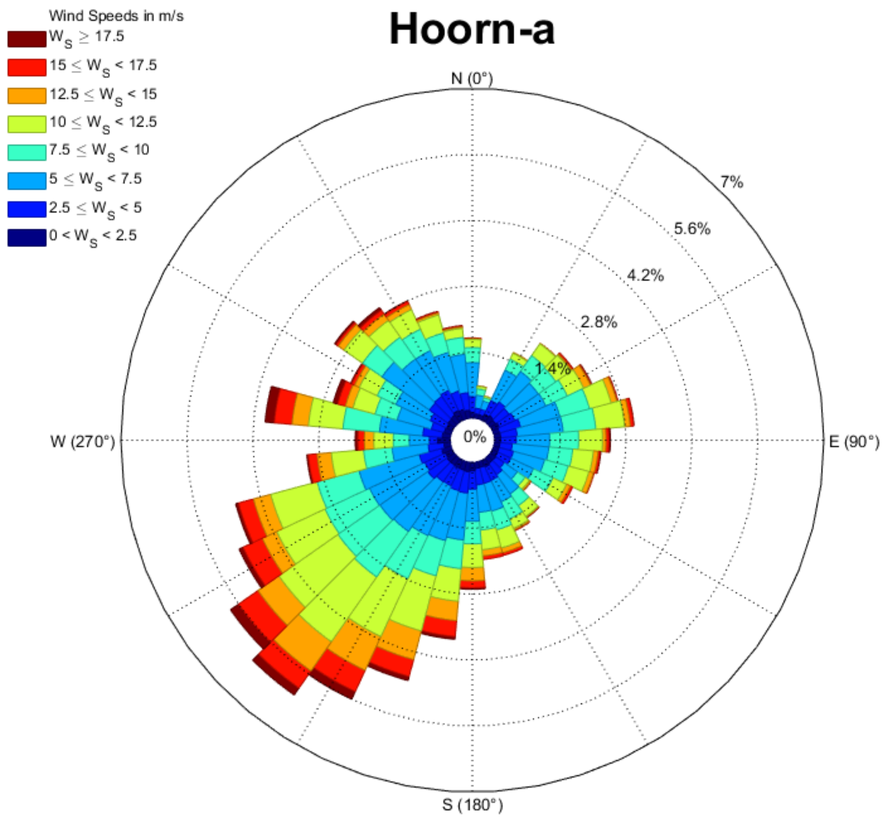
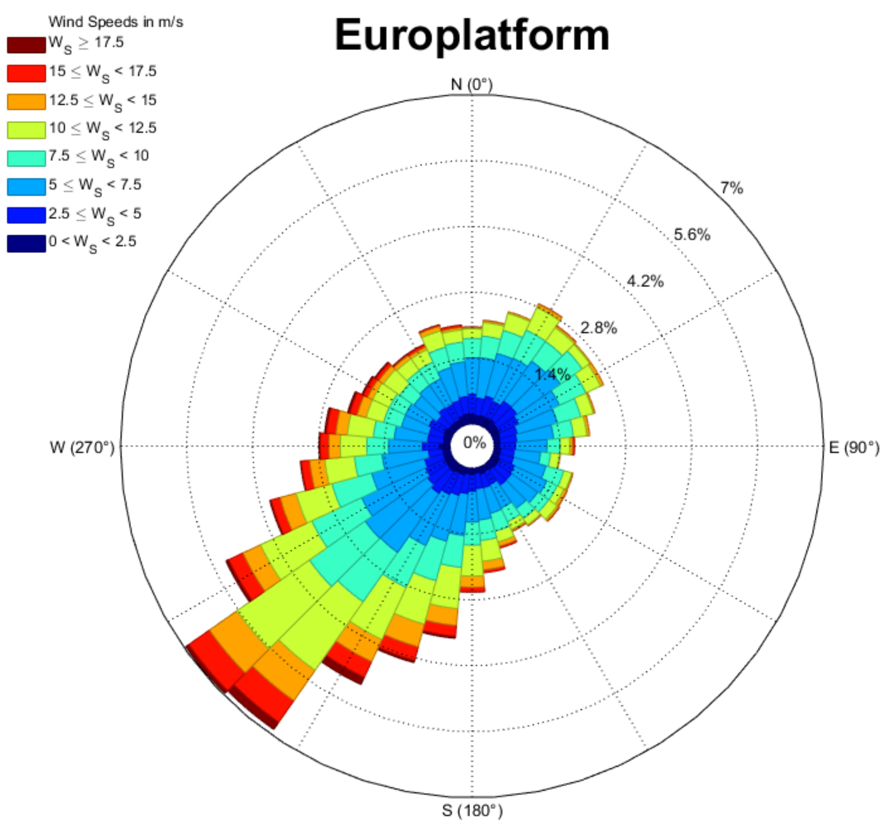


Figure B1: Wind rose of location p11b for 2010-2014 timeframe


Hoorn-a
Wind Speeds in m/s
$W_S \geq 17.5$
$15 \leq W_S < 17.5$
$12.5 \leq W_S < 15$
$10 \leq W_S < 12.5$
$7.5 \leq W_S < 10$
$5 \leq W_S < 7.5$
$2.5 \leq W_S < 5$
$0 < W_S < 2.5$
N (0°)
E (90°)
S (180°)
W (270°)
0%
1.4%
2.8%
4.2%
5.6%
7%


Europlatform
Wind Speeds in m/s
$W_S \geq 17.5$
$15 \leq W_S < 17.5$
$12.5 \leq W_S < 15$
$10 \leq W_S < 12.5$
$7.5 \leq W_S < 10$
$5 \leq W_S < 7.5$
$2.5 \leq W_S < 5$
$0 < W_S < 2.5$
N (0°)
E (90°)
S (180°)
W (270°)
0%
1.4%
2.8%
4.2%
5.6%
7%

Appendix C. Data gaps sorted by year and month

The tables below show the total amount and percentage of data gaps (missing dates+outliers) sorted by year and month for the location Europlatform during the timeframe January 1st 1997 – December 31st 2015

Year	Data gaps (hours)	% of data gaps (data gap hours/total hours in year)
1997	798	9.1
1998	925	10.6
1999	1103	12.6
2000	251	2.9
2001	1585	18.1
2002	1792	20.5
2003	15	0.17
2004	13	0.15
2005	6	0.07
2006	46	0.53
2007	2	0.02
2008	7	0.08
2009	11	0.13
2010	7	0.08
2011	1	0.01
2012	5	0.06
2013	124	1.42
2014	381	4.35
2015	1252	14.3

Table C1: Data gaps sorted by year of Europlatform.

Month	Data gaps (hours)	% of data gaps (data gap hours/total hours in year)
1	644	4.6
2	792	6.2
3	237	1.7
4	770	5.6
5	787	5.6
6	1500	11.0
7	1186	8.4
8	287	2.0
9	1254	9.2
10	518	3.7
11	180	1.3
12	169	1.2

Table C2: Data gaps sorted by month.

Appendix D. Data wind-and wave climate of the periods 1997-2015 and 2003-2012

The tables below consist of the data used to determine whether there is a significant difference between the wind-and wave climate of the periods 1997-2015 and 2003-2012 of the location Europlatform

Period	Data gaps (hours)	Hours of data gaps/total hours during period (%)	Average (+/-) data gaps per year (hours)
1997-2002	6454	12.3	1076
2003-2012	113	0.1	11
2013-2015	1757	6.7	586

Table D1: Total amount, percentage and average amount of data gaps (missing dates+outliers) per period.

Monthly mean value										
Month	Wind direction (deg)		Wind speed (m/s)		Wave height (m)		Wave period (s)		Wave direction (deg)	
	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012
1	199	200	9.4	9.5	1.59	1.65	4.57	4.64	208	209
2	201	189	8.8	8.1	1.45	1.34	4.51	4.43	215	199
3	184	184	7.6	7.6	1.17	1.15	4.38	4.34	205	205
4	170	170	6.7	6.5	0.96	0.90	4.27	4.24	201	202
5	176	181	7.0	6.9	1.02	1.01	4.26	4.24	193	194
6	189	188	6.5	6.4	0.98	0.95	4.29	4.25	210	212
7	203	206	6.6	6.6	0.98	0.99	4.16	4.15	223	230
8	208	216	6.6	6.9	0.99	1.08	4.11	4.17	228	233
9	198	199	7.2	7.4	1.16	1.22	4.27	4.33	213	217
10	193	190	8.7	8.4	1.42	1.37	4.40	4.36	208	206
11	207	209	9.1	9.1	1.56	1.60	4.54	4.56	224	225
12	203	205	9.6	9.2	1.69	1.64	4.67	4.62	215	217
Average value	194	195	7.8	7.7	1.25	1.24	4.37	4.36	212	212

Table D2: Comparison of the monthly mean values of the storm related processes.

Monthly standard deviation										
Month	Wind direction (deg)		Wind speed (m/s)		Wave height (m)		Wave period (s)		Wave direction (deg)	
	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012	1997-2015	2003-2012
1	84	88	4.0	3.9	0.83	0.83	0.82	0.81	101	103
2	89	96	3.9	3.7	0.85	0.82	0.83	0.83	105	115

3	101	102	3.6	3.5	0.74	0.75	0.77	0.79	126	127
4	107	107	3.1	3.0	0.59	0.55	0.73	0.73	132	133
5	108	109	3.2	3.2	0.60	0.61	0.69	0.68	131	131
6	106	107	3.2	3.2	0.57	0.59	0.72	0.71	131	132
7	96	90	3.2	3.2	0.61	0.62	0.72	0.73	113	106
8	96	94	3.2	3.3	0.61	0.64	0.72	0.75	111	106
9	96	95	3.6	3.7	0.73	0.76	0.79	0.80	118	116
10	86	90	3.8	3.5	0.79	0.72	0.82	0.78	105	109
11	84	86	3.9	3.9	0.83	0.85	0.83	0.85	96	96
12	88	91	4.0	4.1	0.86	0.87	0.85	0.86	103	106
Average value	96	97	3.8	3.7	0.77	0.77	0.79	0.79	115	116

Table D3: Comparison of the monthly standard deviations of the storm related processes.

Year	Number of storms per year (hours)	Percentage of total number of storms (%)
1997	1	0.5
1998	22	10.5
1999	11	5.3
2000	23	11.0
2001	3	1.4
2002	18	8.6
2003	1	0.5
2004	31	14.8
2005	9	4.3
2006	3	1.4
2007	23	11.0
2008	9	4.3
2009	1	0.5
2010	7	3.3
2011	5	2.4
2012	11	5.3
2013	21	10.0
2014	10	4.8
2015	0	0

Table D4: Amount and percentage of storms per year in hours.

Period	Total amount of storms (hours)	Average amount of storms per year (hours)
1997-2015	209	11
2003-2012	100	10

Table D5: Total and average amount of storms (in hours) per period.

Storms with a wind measuring 10 or higher on the Beaufort scale (>=24.5 m/s)		
	Number of storms per year (hours)	Percentage of total number of storms (%)
2000	1	12.5
2002	5	62.5
2007	1	12.5
2013	1	12.5

Table D6: Amount and percentage of storms with a wind measuring 10 or higher on the Beaufort scale (>=24.5 m/s).

Period	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)	Occurrence
1997-2015	202.5-247.5	10-15 m/s	1-2m	4-5s	202.5-247.5	4835
	202.5-247.5	5-10 m/s	0-1 m	3-4s	202.5-247.5	3751
	202.5-247.5	5-10 m/s	1-2m	4-5s	202.5-247.5	3139
2003-2012	202.5-247.5	10-15 m/s	1-2 m	4-5s	202.5-247.5	2676
	202.5-247.5	5-10 m/s	0-1 m	3-4s	202.5-247.5	2179
	202.5-247.5	5-10 m/s	1-2 m	4-5s	202.5-247.5	1692

Table D7: Top 3 most common storm wind- and wave climate combinations for the periods of 1997-2015 and 2003-2012.

Appendix E. General wind and wave climate Europlatform 1997-2015

The tables below provide the data that is used to determine the general wind and wave climate of the location Europlatform during the timeframe 1997-2015.

General, monthly and yearly mean values of the storm related processes

	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
Mean	194	7.8	1.3	4.4	212

Table E1: Mean values of the storm related processes.

Yearly mean value					
year	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
1997	181	7.39	1.10	4.30	203
1998	211	8.36	1.37	4.54	233
1999	196	8.18	1.32	4.47	218
2000	203	8.17	1.30	4.49	229
2001	190	7.89	1.25	4.35	210
2002	191	8.11	1.23	4.28	203
2003	180	7.29	1.10	4.21	200
2004	203	7.74	1.25	4.42	226
2005	200	7.61	1.26	4.43	218
2006	195	7.89	1.23	4.31	209
2007	203	8.06	1.37	4.48	216
2008	195	8.19	1.33	4.39	215
2009	195	7.56	1.20	4.30	210
2010	182	7.25	1.20	4.38	197
2011	194	7.88	1.24	4.30	212
2012	201	7.68	1.24	4.37	223
2013	185	7.77	1.26	4.31	194
2014	190	7.67	1.22	4.34	204
2015	193	8.24	1.31	4.37	208

Table E2: Yearly average value of the storm related processes..

Monthly mean value					
Month	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
1	199	9.40	1.59	4.57	208
2	201	8.81	1.45	4.51	215
3	184	7.57	1.17	4.38	205
4	170	6.69	0.96	4.27	201

5	176	6.98	1.02	4.26	193
6	189	6.47	0.98	4.29	210
7	203	6.56	0.98	4.16	223
8	208	6.59	0.99	4.11	228
9	198	7.23	1.16	4.27	213
10	193	8.69	1.42	4.40	208
11	207	9.12	1.56	4.54	224
12	203	9.62	1.69	4.66	215

Table E3: Monthly average value of the storm related processes..

Frequency and mean value per bin of each of the storm related processes

Wind direction Bin values (degrees)		Frequency	Percentage of total (%)	Mean (deg)
North	(337.5 – 22.5)	17491	11.06	349
North-East	(22.5-67.5)	16540	10.45	45
East	(67.5-112.5)	15286	9.66	88
South-East	(112.5-157.5)	10370	6.55	135
South	(157.5-202.5)	22977	14.52	185
South-West	(202.5-247.5)	35872	22.67	225
West	(247.5-292.5)	25345	16.02	268
North-West	(292.5-337.5)	14331	9.06	314

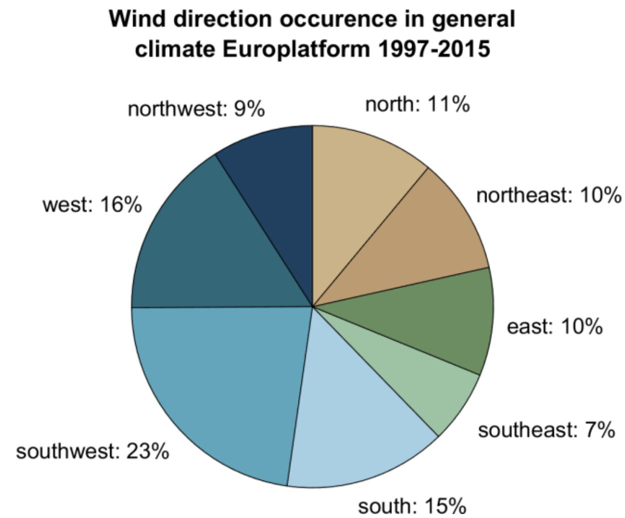


Table E4 & Figure E1: Frequency, percentage and mean value of the wind direction per bin.

Wind speed Bin values (m/s)	Frequency	Percentage of total (%)	Mean (m/s)
0-5	46145	29.17	3.57
6-10	75280	47.58	7.87
11-15	31983	20.22	12.47
16-20	4595	2.90	16.98
21+	209	0.13	21.79

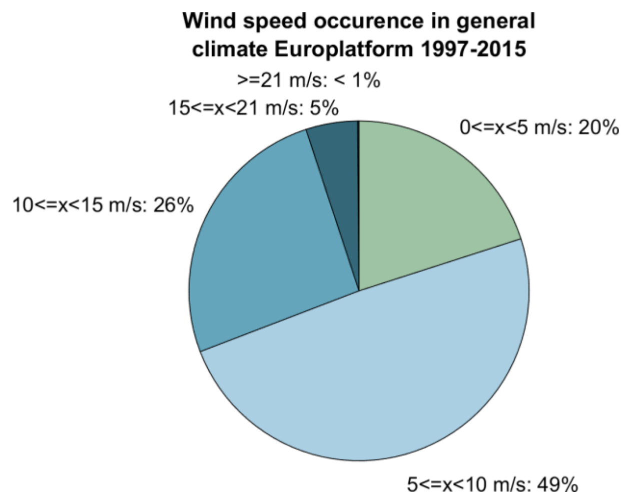


Table E5 & Figure E2: Frequency, percentage and mean value of the wind speed per bin.

Wave height Bin values (m)	Frequency	Percentage of total (%)	Mean (m)
0 <=x<0.5;	22869	14.45	0.37
0.5<=x<1.5;	86938	54.95	0.95
1.5<=x<2.5;	36226	22.90	1.91
2.5<=x<3.5;	9940	6.28	2.88
3.5<=x<4.5;	1941	1.23	3.86
4.5<=x<5.5;	285	0.18	4.80
5.5<=x<6	13	0.008	5.81

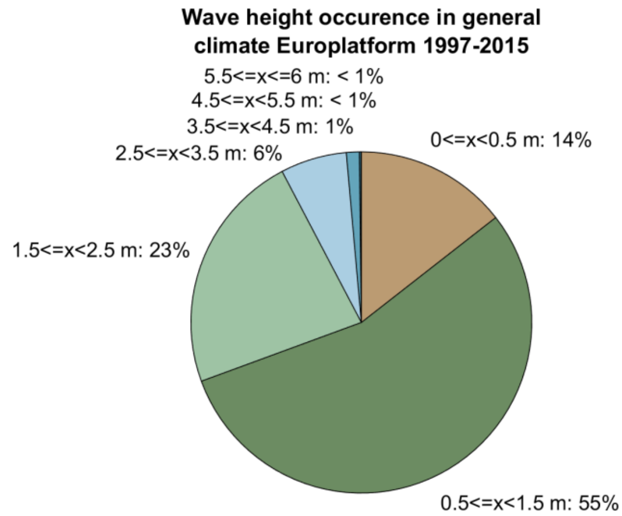


Table E6 & Figure E3: Frequency, percentage and mean value of the wave height per bin.

Wave period Bin values (s)	Frequency	Percentage of total (%)	Mean (s)
2 <=x<2.5;	13	0.008	2.28
2.5<=x<3.5;	18672	11.8	3.22
3.5<=x<4.5;	72352	45.7	3.96
4.5<=x<5.5;	51029	32.3	4.89
5.5<=x<6.5;	14777	9.3	5.81
6.5<=x<7.5;	1340	0.85	6.73
7.5<=x<8	29	0.018	7.61

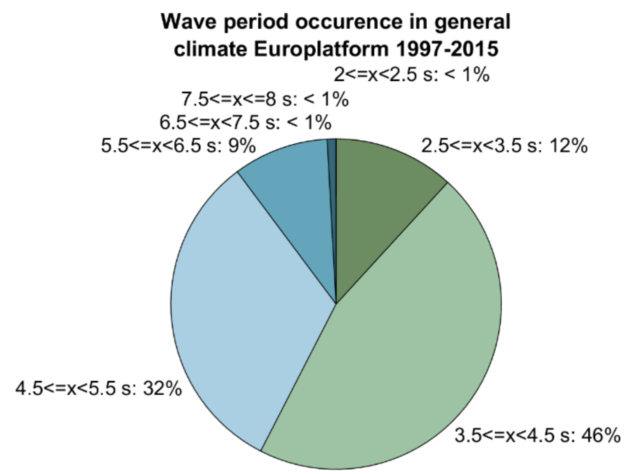


Table E7 & Figure E4: Frequency, percentage and mean value of the wave period per bin.

Wave direction Bin values (deg)		Frequency	Percentage of total (%)	Mean (deg)
North	(337.5 – 22.5)	42431	26.82	354
North-East	(22.5-67.5)	15087	9.54	38
East	(67.5-112.5)	4255	2.69	88
South-East	(112.5-157.5)	2503	1.58	134
South	(157.5-202.5)	5813	3.67	186
South-West	(202.5-247.5)	47225	29.85	227
West	(247.5-292.5)	18201	11.50	267
North-West	(292.5-337.5)	22697	14.346	319

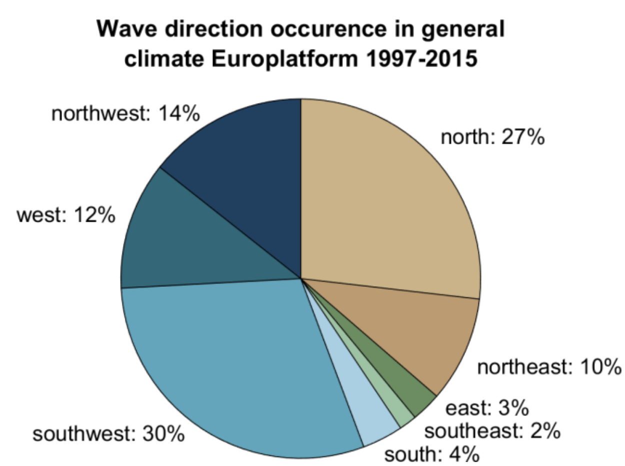


Table E8 & Figure E5: Frequency, percentage and mean value of the wave direction per bin.

Top 3 most common wind- and wave climate combinations

Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)	Occurence	Percentage of total occurences (%)
202.5<=x<247.5	5<=x<10 m/s	0.5<=x<1.5	3.5<=x<4.5	202.5<=x<247.5	5276	3.3
202.5<=x<247.5	10<=x<15 m/s	1.5<=x<2.5	4.5<=x<5.5	202.5<=x<247.5	4556	2.9
157.5<=x<202.5	5<=x<10 m/s	0.5<=x<1.5	3.5<=x<4.5	202.5<=x<247.5	2942	1.9

Table E9: Top 3 most common wind- and wave climate combinations.

Appendix F. Wind- and wave roses of the general wind- and wave climate and of the storm wind- and wave climate

This appendix consists of the wind- and wave roses of the general wind- and wave climate and of the storm wind- and wave climate of the location Europlatform during the timeframe 1997-2015.

General wind- and wave climate

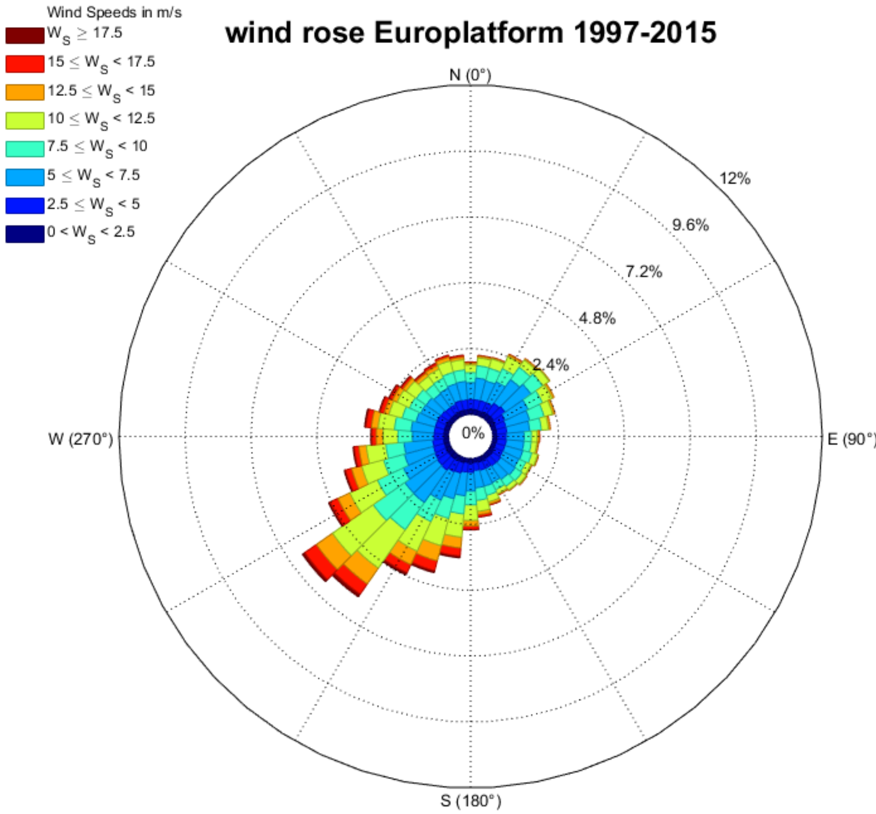


Figure F1: Wind rose of the general climate.

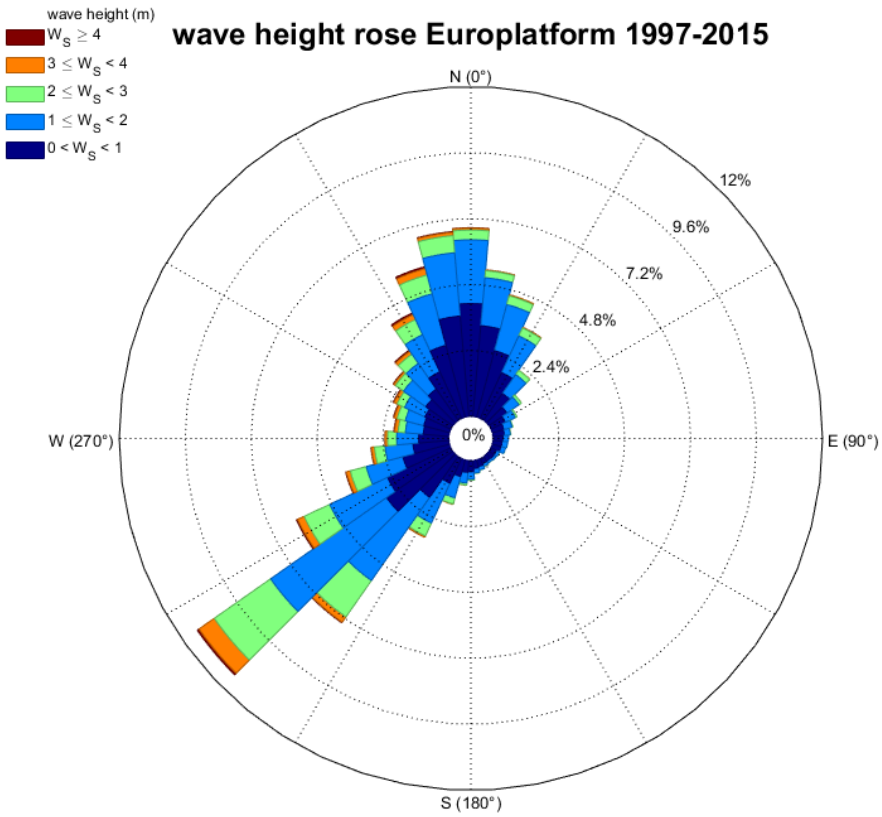


Figure F2: Wave height rose of the general climate.

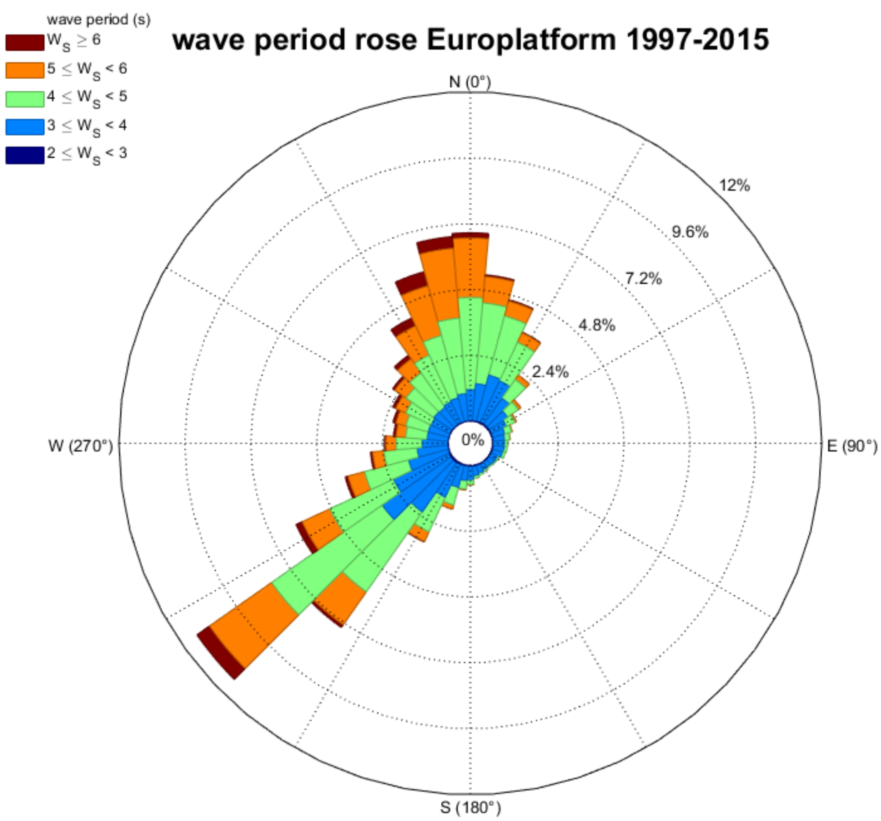


Figure F3: Wave period rose of the general climate.

Storm wind- and wave climate

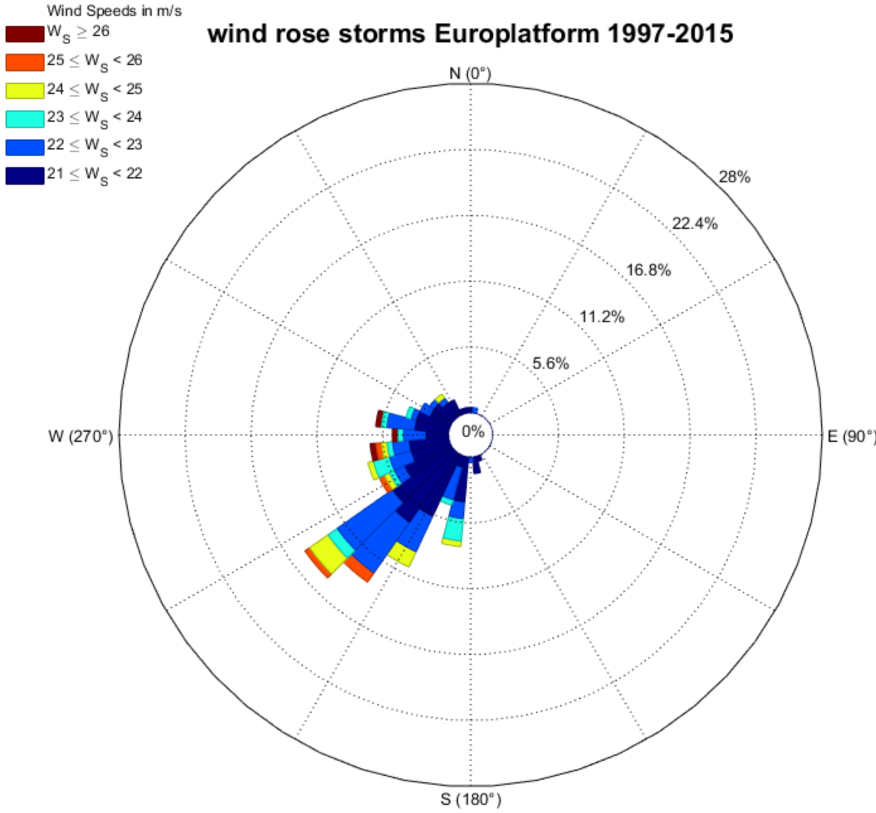


Figure F4: Wind rose of the storm climate.

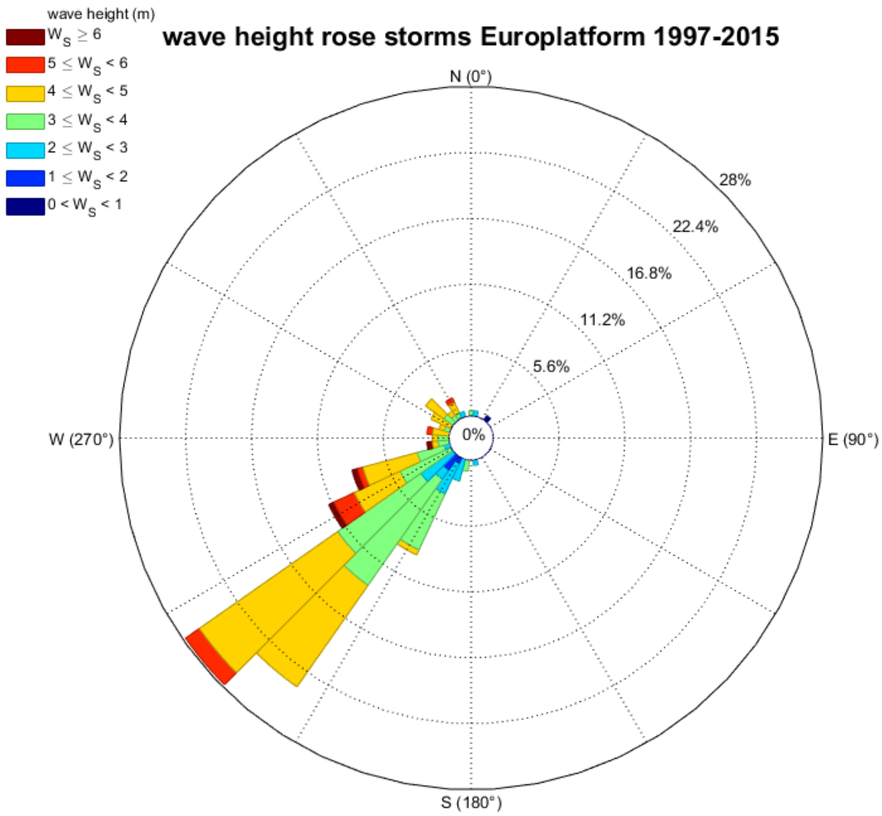


Figure F5: Wave height rose of the storm climate.

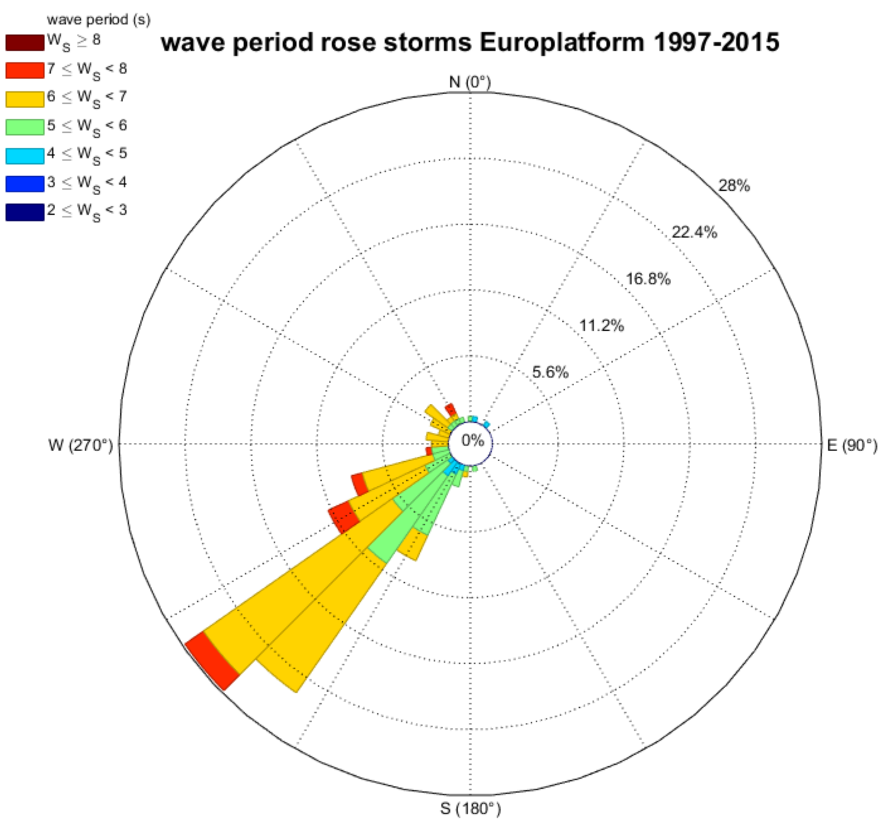


Figure F6: Wave height rose of the storm climate.

Appendix G. Storm wind and wave climate Europlatform 1997-2015

The tables below provide the data that is used to determine the storm wind and wave climate of the location Europlatform during the timeframe 1997-2015.

Number of storms and their percentage

Year	Number of storms (hours)	Percentage of total hours of storms (%)	Percentage of total hours per year (%)
1997	1	0.5	0.01
1998	22	10.5	0.25
1999	11	5.3	0.13
2000	23	11.0	0.26
2001	3	1.4	0.03
2002	18	8.6	0.21
2003	1	0.5	0.01
2004	31	14.8	0.35
2005	9	4.3	0.10
2006	3	1.4	0.03
2007	23	11.0	0.26
2008	9	4.3	0.10
2009	1	0.5	0.01
2010	7	3.3	0.08
2011	5	2.4	0.06
2012	11	5.3	0.13
2013	21	10.0	0.24
2014	10	4.8	0.11
2015	0	0	0

Table G1: Yearly amount and percentages of storms.

Month	Number of storms (hours)	Percentage of total hours of storms (%)	Percentage of total hours per year (%)
1	47	22.5	0.33
2	19	9.1	0.15
3	15	7.2	0.11
5	4	1.9	0.028
6	7	3.3	0.051
7	2	1.0	0.014
8	2	1.0	0.014
9	5	2.4	0.037
10	41	19.6	0.29
11	25	12.0	0.18
12	42	20.1	0.30

Table G2: Monthly amount and percentages of storms.

General, monthly and yearly mean values of the storm related processes

	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
Mean	240	21.8	3.9	6.1	234

Table G3: Mean values of the storm related processes for the storm climate.

Yearly mean value					
year	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
1997	220	22	3.0	6.1	226
1998	265	21.7	4.0	6.3	246
1999	237	21.3	3.9	6.3	240
2000	217	22.5	3.9	6.1	219
2001	213	21.3	3.2	5.8	284
2002	253	23.1	4.3	6.3	236
2003	260	21	3.8	6.1	247
2004	244	21.4	3.8	6.1	239
2005	288	21.7	4.5	6.7	281
2006	240	21	3.5	6.0	222
2007	257	22.0	4.0	6.0	218
2008	229	21.3	3.6	5.9	236
2009	230	21	3.0	5.5	214
2010	223	21.4	4.1	6.4	234
2011	228	21.2	3.9	6.2	242
2012	235	21.3	3.6	6.0	214
2013	223	21.9	3.9	6.2	229
2014	210	21.4	3.4	5.7	222
2015					

Table G4: Yearly average value of the storm related processes.

Monthly mean value					
Month	Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)
1	235	21	2.4	4.8	228
2	253	21	2.6	5.1	252
3	235	22.5	3.2	5.5	225
4	258	21.2	3.4	6.0	196
5	224	21.1	4.0	6.4	227
6	345	21.3	3.4	5.8	5
7	225	21.4	3.9	6.0	213
8	304	21.5	4.1	6.3	271
9	233	22.8	4.2	6.4	229
10	259	21.4	3.8	6.2	266
11	228	21.9	4.0	6.1	232
12	235	21	2.4	4.8	228

Table G5: Monthly average value of the storm related processes.

Frequency and mean value per bin of each of the storm related processes

Wind direction			
Bin values (deg)	Frequency	Percentage of total (%)	Mean
North (337.5 – 22.5)	4	1.9	355
North-West (292.5-337.5)	19	9.1	313
South (157.5-202.5)	30	14.4	190
West (247.5-292.5)	60	28.7	268
South-West (202.5-247.5)	96	45.9	224

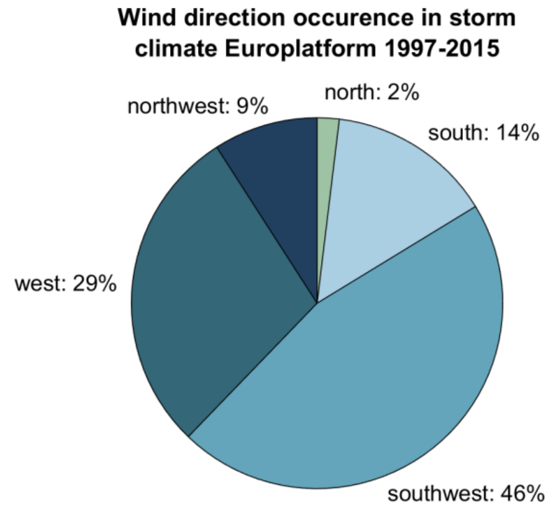


Table G6 & Figure G1: Wind direction frequencies in storm climate.

Wind speed		
Bin values (m/s)	Frequency	Percentage of total (%)
21	110	52.6
22	64	30.6
23	15	7.2
24	12	5.7
25	5	2.4
26	3	1.4

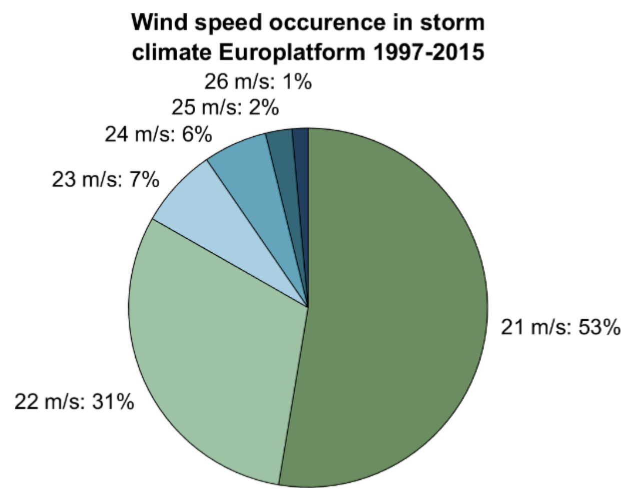


Table G7 & Figure G2: Wind speed frequencies in storm climate.

Wave height			
Bin values (m)	Frequency	Percentage of total (%)	Mean
0.5<=x<1.5;	2	1.0	1.1
1.5<=x<2.5;	9	4.3	2.1
2.5<=x<3.5;	53	25.4	3.1
3.5<=x<4.5;	92	44.0	4.0
4.5<=x<5.5;	48	23.0	4.8
>=5.5	5	2.4	6.1

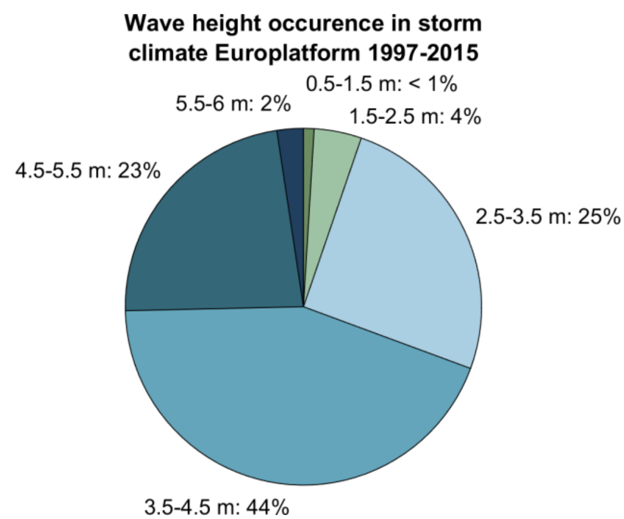


Table G8 & Figure G3: Wave height frequencies in storm climate.

Wave period			
Bin values (s)	Frequency	Percentage of total (%)	Mean
3.5<=x<4.5;	3	1.4	4.2
4.5<=x<5.5;	22	10.5	5.1
5.5<=x<6.5;	119	56.9	6.0
6.5<=x<7.5;	63	30.1	6.8
7.5<=x<8	2	1.0	7.6

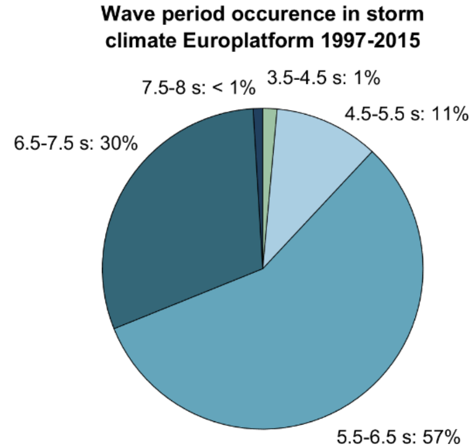


Table G9 & Figure G4: Wave period frequencies in storm climate.

Wave direction			
Bin values (deg)	Frequency	Percentage of total (%)	Mean
North-East (22.5-67.5)	1	0.5	39
North (337.5 – 22.5)	2	1.0	5
South (157.5-202.5)	6	2.9	190
North-West (292.5-337.5)	18	8.6	313
West (247.5-292.5)	21	10.0	262
South-West (202.5-247.5)	161	77.0	227

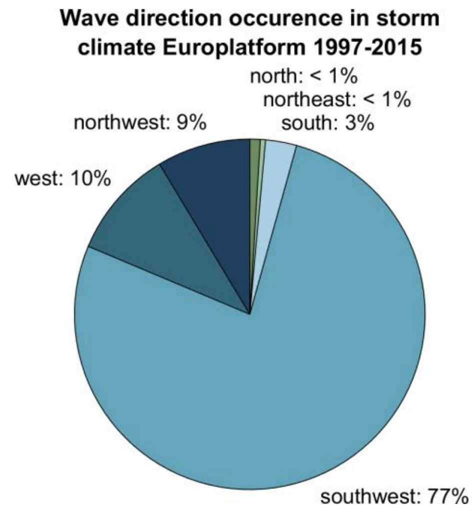


Table G10 & Figure G5: Wave direction frequencies in storm climate.

Top 3 most common wind- and wave climate combinations

Wind direction (deg)	Wind speed (m/s)	Wave height (m)	Wave period (s)	Wave direction (deg)	Occurence	Percentage of total occurences (%)
202.5-247.5	21m/s	2.5-3.5m	5.5-6.5s	202.5-247.5	13	6.2
202.5-247.5	21 m/s	3.5-4.5 m	5.5-6.5s	202.5-247.5	13	6.2
202.5-247.5	22m/s	3.5-4.5 m	5.5-6.5s	202.5-247.5	12	5.7

Table G11: Top 3 most common storm wind- and wave climate.

Appendix H. Bin sizes for the gridded and single model run

	Wind direction	Wind speed	Wave height	Wave period	Wave direction
Bin 1	-180 <= x <-120	0 <= x < 10	0 <= x < 1	2 <= x < 3	-90 <= x <-60
Bin 2	-120 <= x <-60	10 <= x < 14	1 <= x < 2	3 <= x < 4	-60 <= x <-30
Bin 3	-60 <= x <0	14 <= x < 18	2 <= x < 3	4 <= x < 5	-30 <= x <0
Bin 4	0 <= x <60	18 <= x < 21	3 <= x < 4	5 <= x < 6	0 <= x <30
Bin 5	60 <= x <120	21 <= x < 23	4 <= x < 5	6 <= x < 7	30 <= x <60
Bin 6	120 <= x <180	23 <= x < 26	5 <= x < 6	7 <= x < 8	60 <= x <90

Table H1: Bins used in the gridded model run

	Wind direction	Wind speed	Wave height	Wave period	Wave direction
Bin 1	-180 <= x <-170	0	0	2	-90 <= x <-85
Bin 2	-170 <= x <-120	1 <= x < 5	0 < x < 1	2 < x < 3	-85 <= x <-60
Bin 3	-120 <= x <-70	5 <= x < 9	1 <= x < 2	3 <= x < 4	-60 <= x <-35
Bin 4	-70 <= x <-20	9 <= x < 13	2 <= x < 3	4 <= x < 5	-35 <= x <-10
Bin 5	-20 <= x <20	13 <= x < 17	3 <= x < 4	5 <= x < 6	-10 <= x <10
Bin 6	20 <= x <70	17 <= x < 21	4 <= x < 5	6 <= x < 7	10 <= x <35
Bin 7	70 <= x <120	21 <= x < 24	5 <= x < 6	7 <= x < 8	35 <= x <60
Bin 8	120 <= x <170	24 <= x < 26	6	8	60 <= x <85
Bin 9	170 <= x <180	26			85 <= x <90

Table H2: Bins used in the single mode model run

Appendix I. Growth rate including the frequencies of occurrence, including and excluding storms

The figures below show the growth rate [yr-1] as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015, including tidal flow only, leaving out any storm processes (Figure I1), including tidal flow, storm processes and the frequencies of occurrence of the wind and wave climate (Figure I2) and the difference between including and excluding storms (Figure I3).

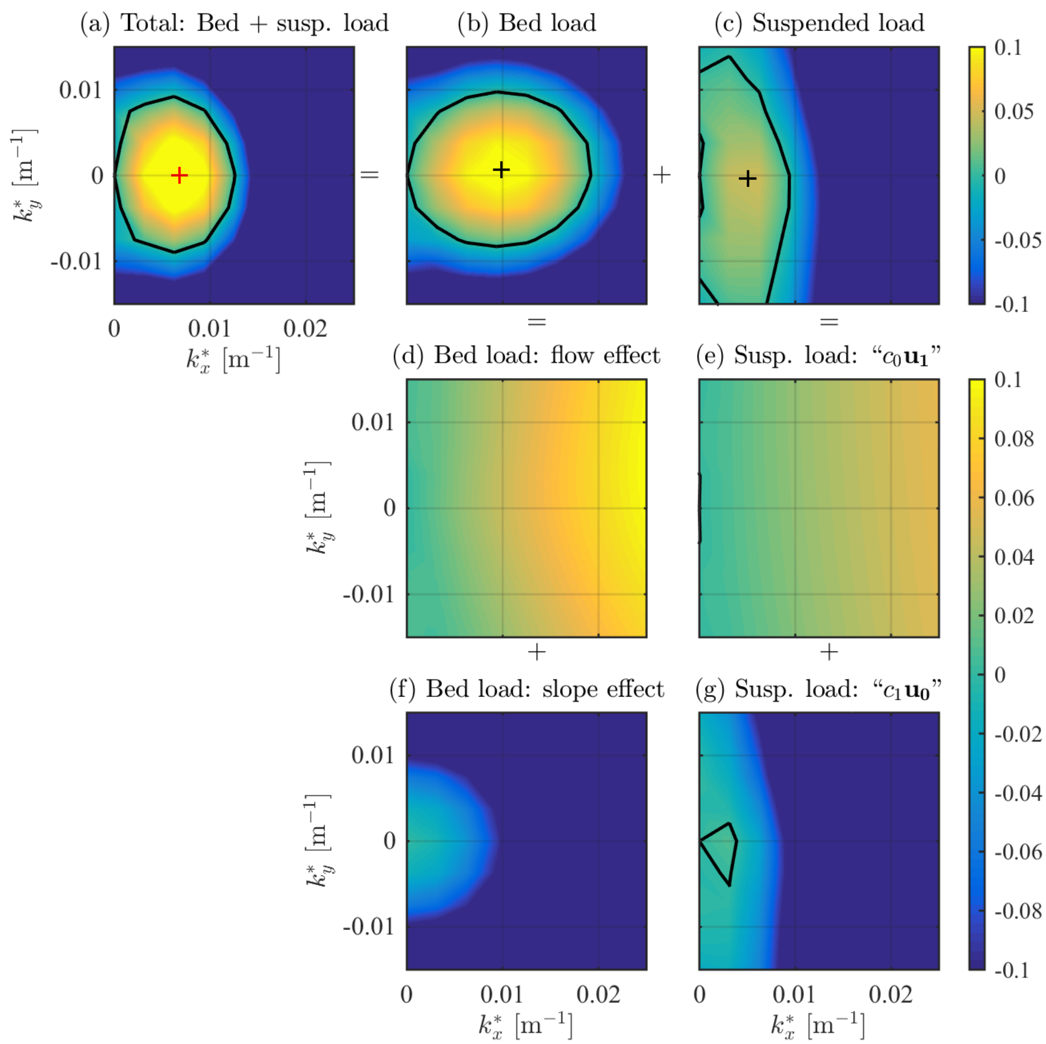


Figure I1: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for tide only.

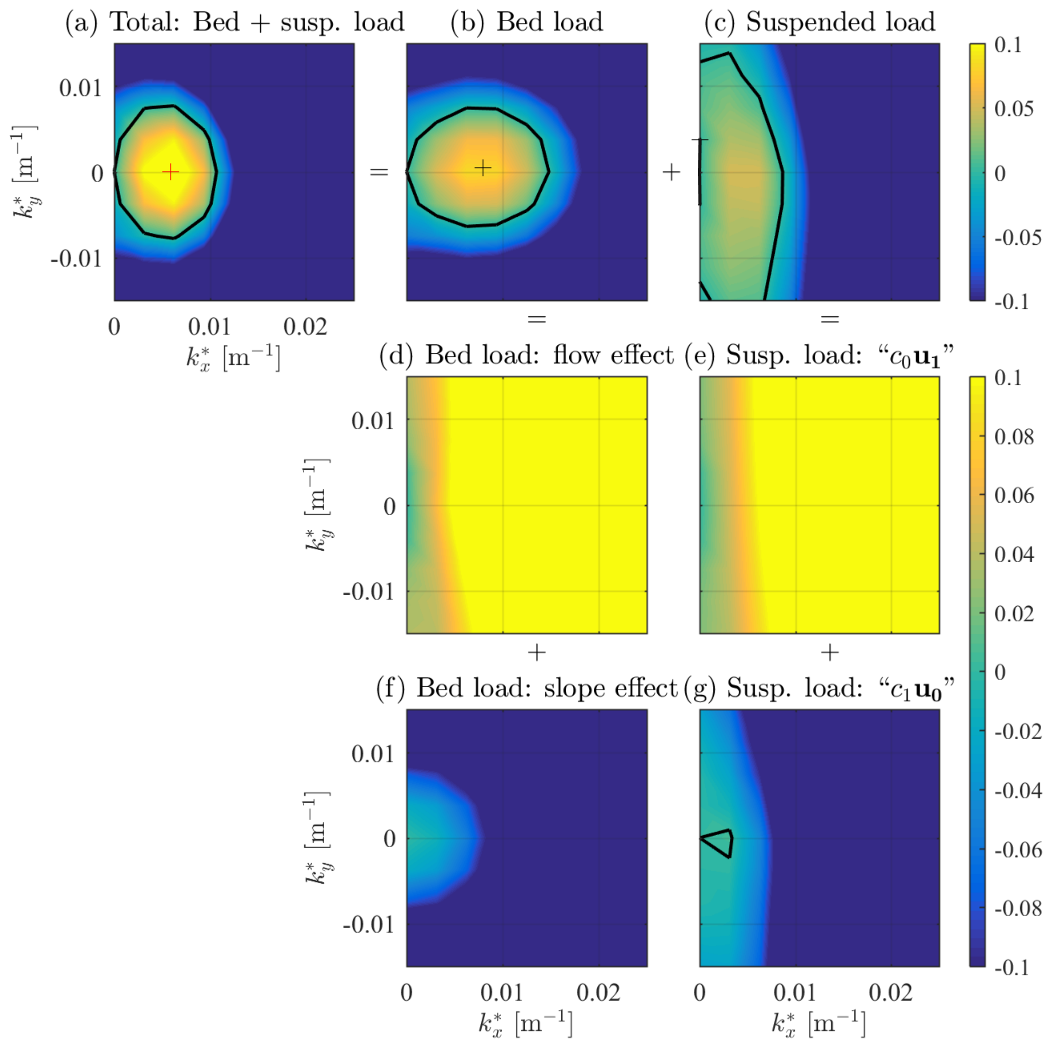


Figure I2: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* including tide, wind &waves and the frequencies of occurrence.

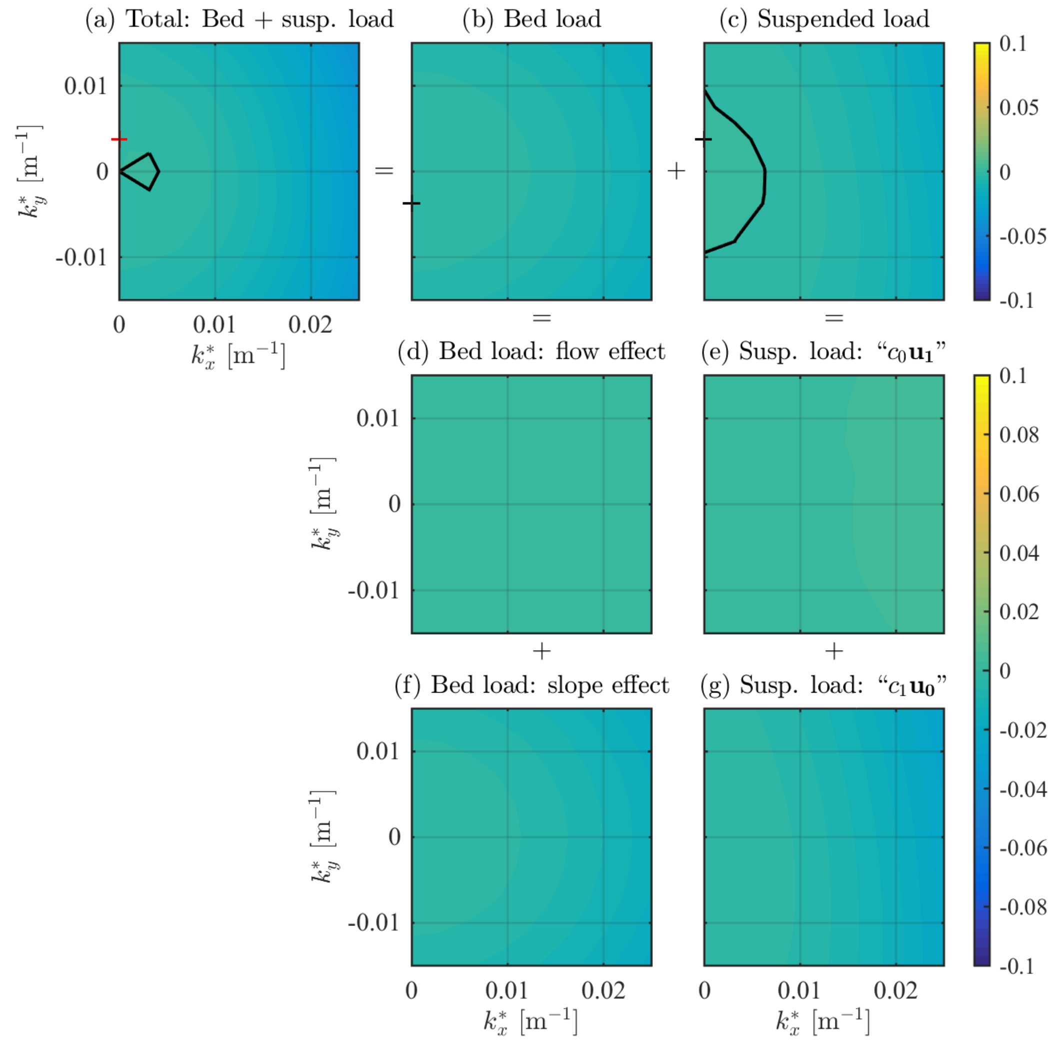


Figure I3: Difference in growth rate [yr-1] between including and excluding storms (wind speeds ≥ 20.8 m/s), taking the frequencies of occurrence into account, as a function of the topographic wave numbers k_x^* and k_y^*.

Appendix J. Growth rate excluding the frequencies of occurrence excluding and including storms

The figures below show the growth rate [yr-1] excluding the frequencies of occurrence as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015 wind and wave climate, excluding (Figure J1) and including (Figure J2) storm conditions (wind speed >= 21m/s).

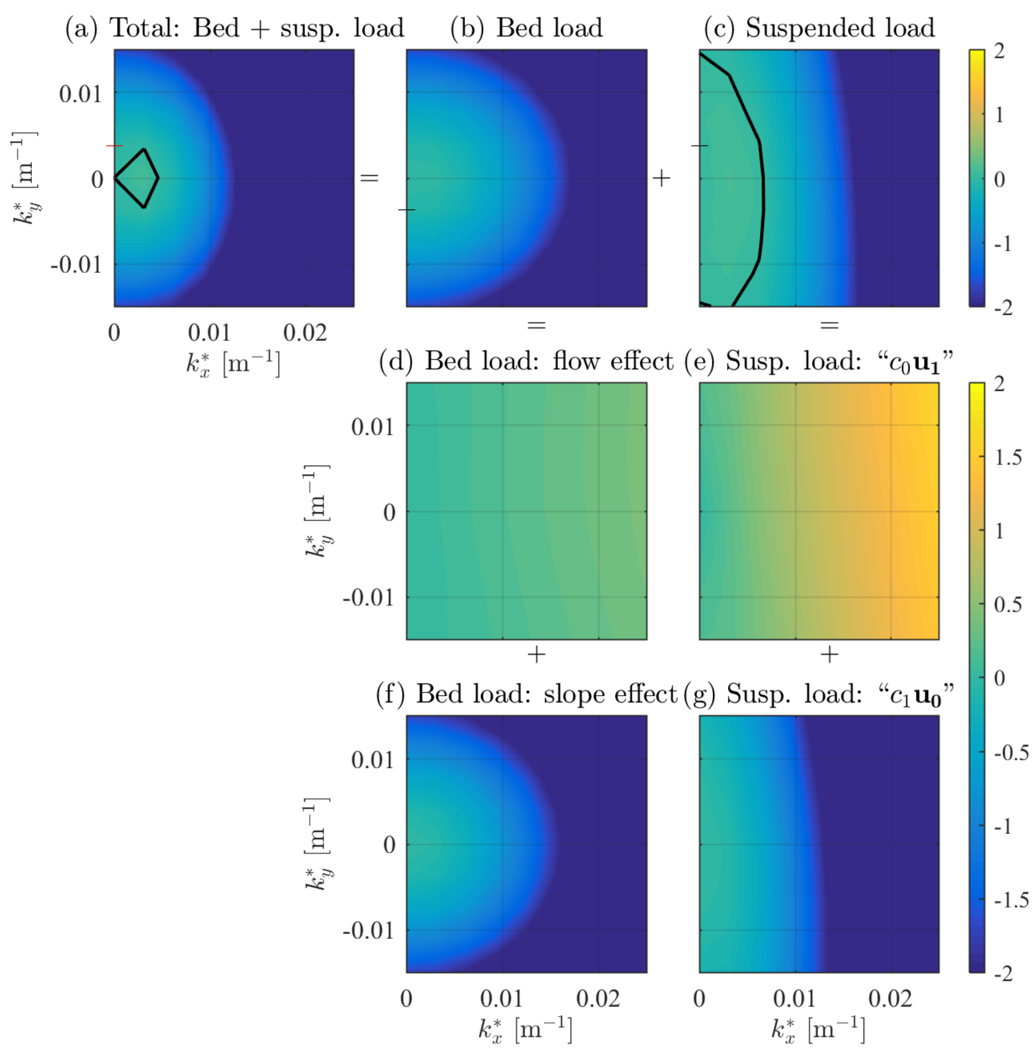


Figure J1: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* excluding the frequencies of occurrence, excluding storms.

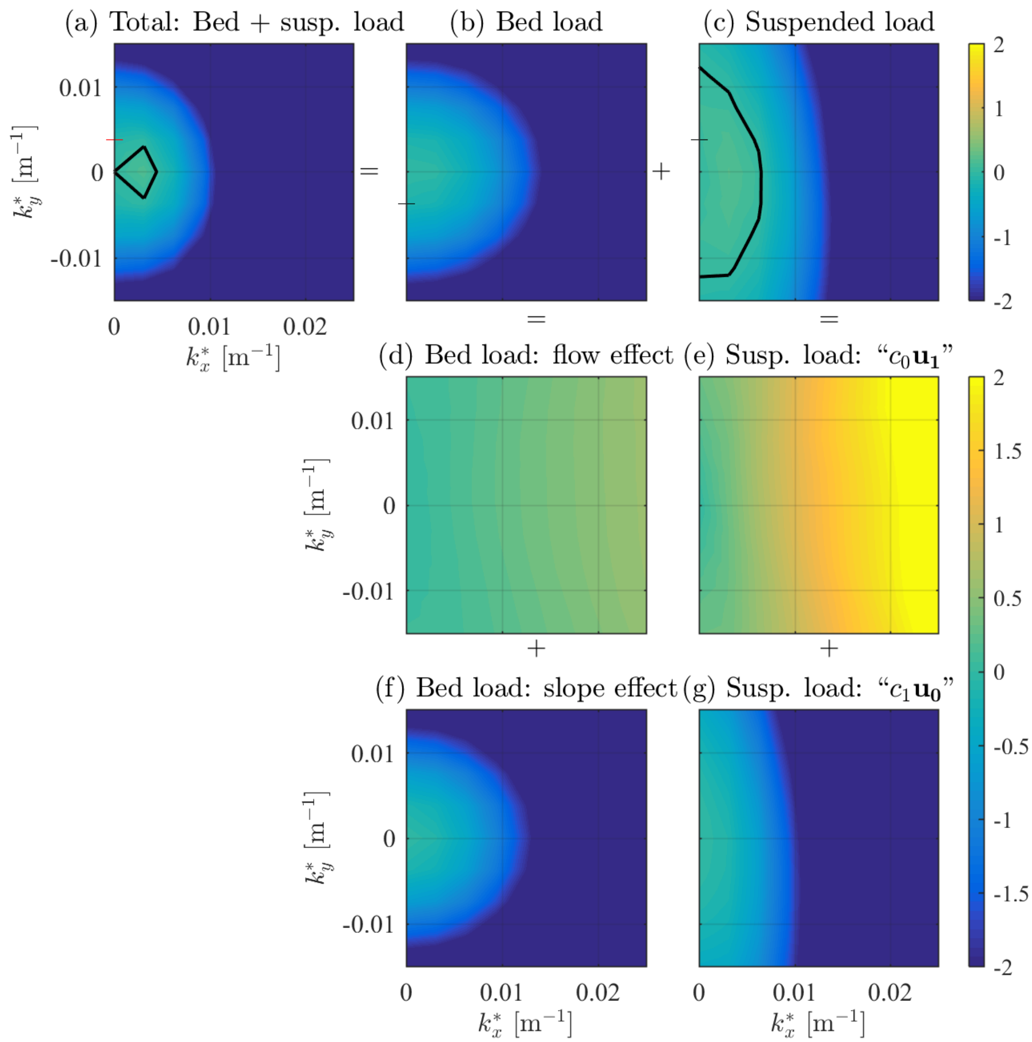


Figure J2: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* excluding the frequencies of occurrence, including storms.

Appendix K. Growth rate per wind speed and wind angle bin, excluding and including the frequencies of occurrence

The figures below show the growth rate [yr-1] as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015 per wind speed and wind angle bin, excluding the frequencies of occurrence (Figure K1) and including the frequencies of occurrence (Figure K2).

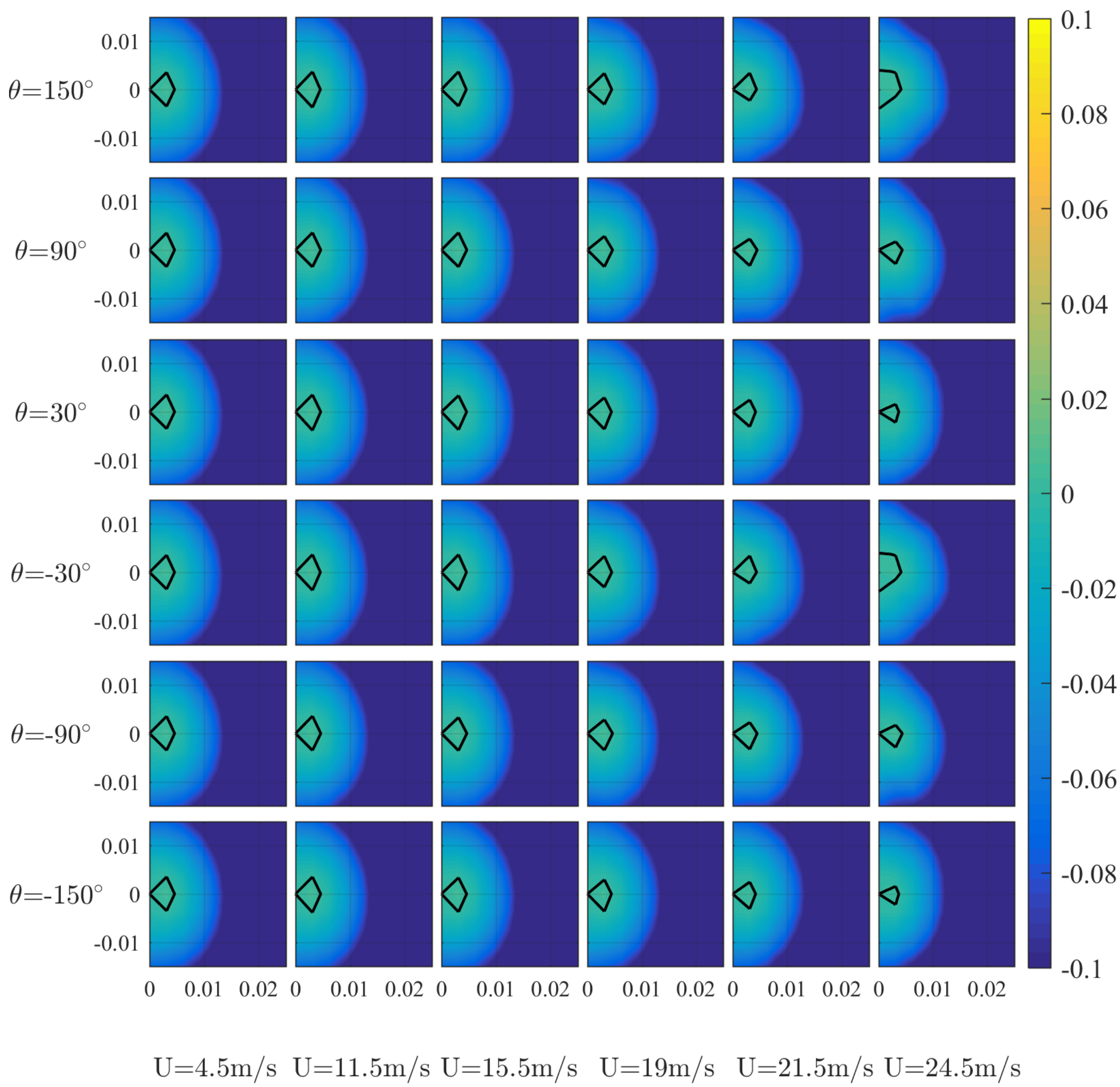


Figure K1: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence.

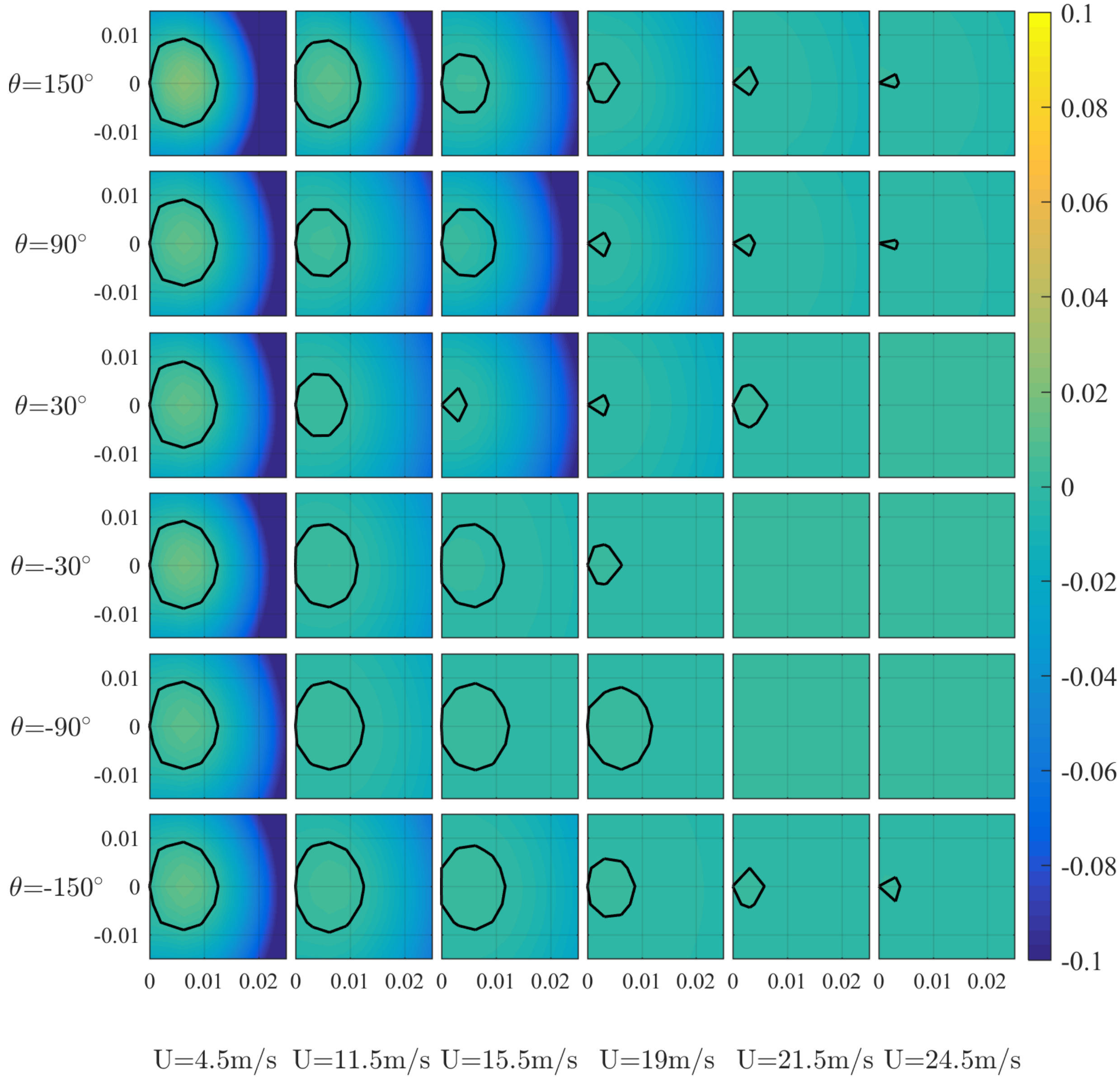


Figure K2: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, including the frequencies of occurrence.

Appendix L. Wind- and wave parameters that contribute most to the growth rate

In Paragraph 4.1.1 the values of wind speed and wind angle that contribute most to the overall growth rate are mentioned. The wave parameters that are associated with these wind speeds and wind angles are taken from the data (see Table L1). These values are used to determine the mostly accompanied wave parameters.

Wave height (m)	%	Wave period (s)	%	Wave angle (degrees)	%
0.5	53	2.5	1	-75	8
1.5	36	3.5	37	-45	14
2.5	9	4.5	42	-15	29
3.5	2	5.5	18	15	19
4.5	0.3	6.5	2	45	20
5.5	0.02	7.5	0.1	75	10

Table L1: Wave parameters accompanied with the wind parameters that contribute most to the overall growth rate.

In Paragraph 4.4.1 the values of wave height and wave angle that contribute most to the overall growth rate are mentioned. The wind- and wave parameters that are associated with these wind speeds and wind angles are taken from the data (see Table L2). These values are used to determine the mostly accompanied wind- and wave parameters.

Wind angle (degrees)	%	Wind speed (m/s)	%	Wave period (s)	%	Wave angle (degrees)	%
-150	19	4.5	79	2.5	1	-15	40
-90	10	11.5	19	3.5	36	15	31
-30	21	15.5	2	4.5	48	45	29
30	16	19	0.05	5.5	14		
90	8	21.5	0.004	6.5	0.7		
150	25	24.5	0.001	7.5	0.002		

Table L2: Wind- and wave parameters accompanied with the wave height and wave angle that contribute most to the overall growth rate.

In Paragraph 4.4.2 the values of wave period and wave angle that contribute most to the overall growth rate are mentioned. The wind- and wave parameters that are associated with these wind speeds and wind angles are taken from the data (see Table L3). These values are used to determine the mostly accompanied wind- and wave parameters.

Wind angle (degrees)	%	Wind speed (m/s)	%	Wave height (m)	%	Wave angle (degrees)	%
-150	17	4.5	65	0.5	37	-15	54
-90	8	11.5	25	1.5	45	15	17
-30	17	15.5	8	2.5	14	45	28
30	14	19	1	3.5	3		
90	9	21.5	0.1	4.5	0.4		
150	33	24.5	0.03	5.5	0.03		

Table L3: Wind- and wave parameters accompanied with the wave period and wave angle that contribute most to the overall growth rate.

Appendix M. Growth rate per wind speed and wind angle bin of the bed load and suspended load

The figures in this appendix show the growth rate [yr-1] as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015 per wind speed and wind angle bin of the bed load (Figure M1) and suspended load (Figure M2)

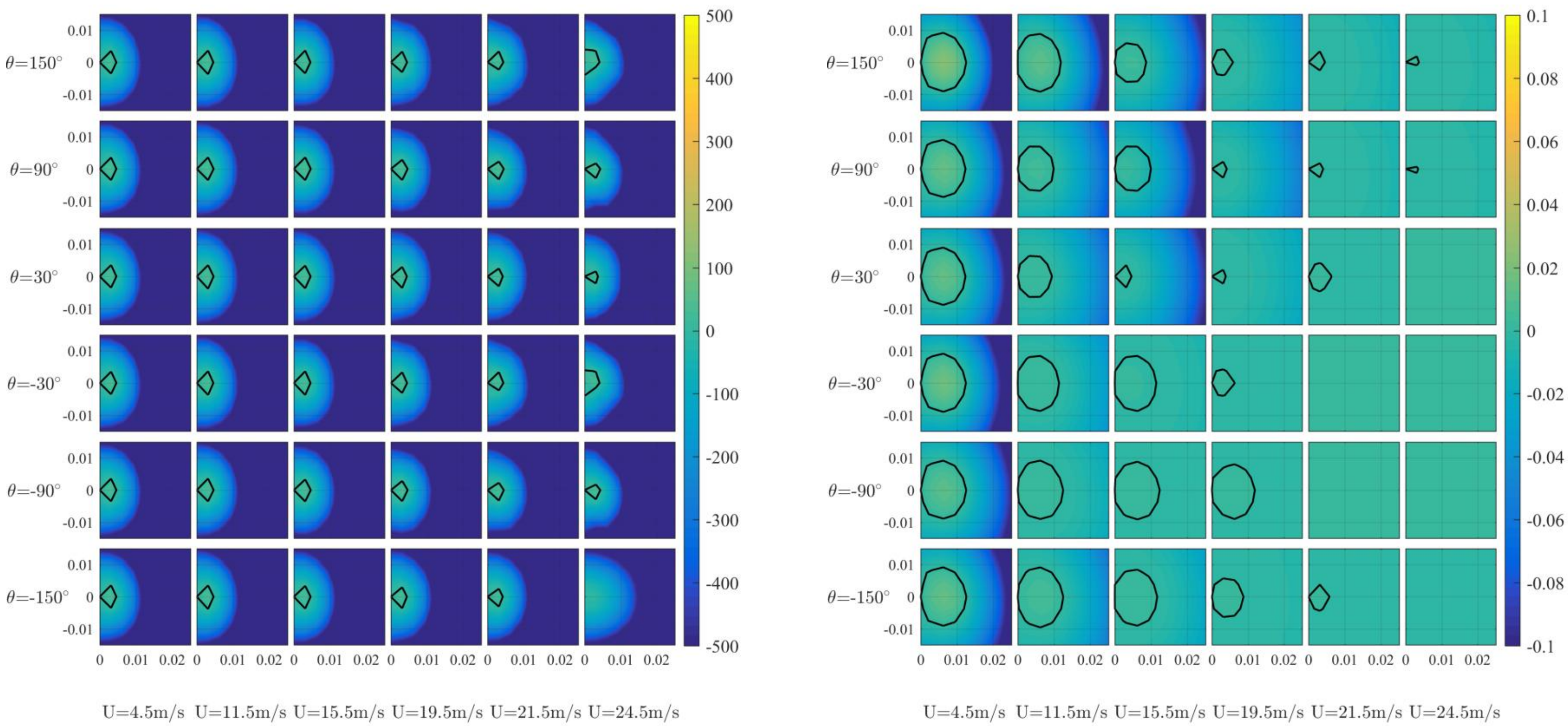


Figure M1: Bed load growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right)

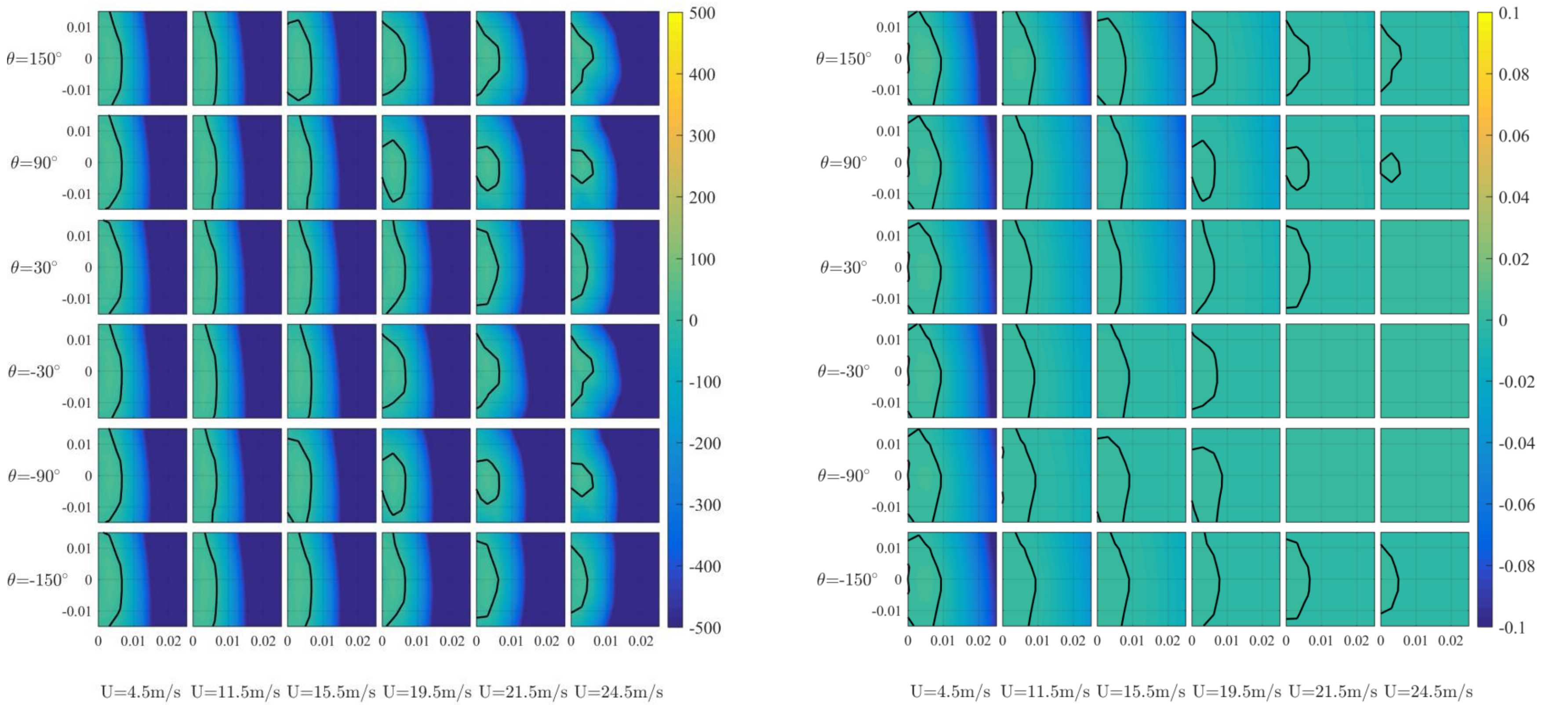


Figure M2: Suspended load growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right)

Appendix N. Migration rate for wind speed and wind angle bins, excluding and including the frequencies of occurrence

The figures below show the migration rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right) for the location Europlatform during the timeframe 1997-2015.

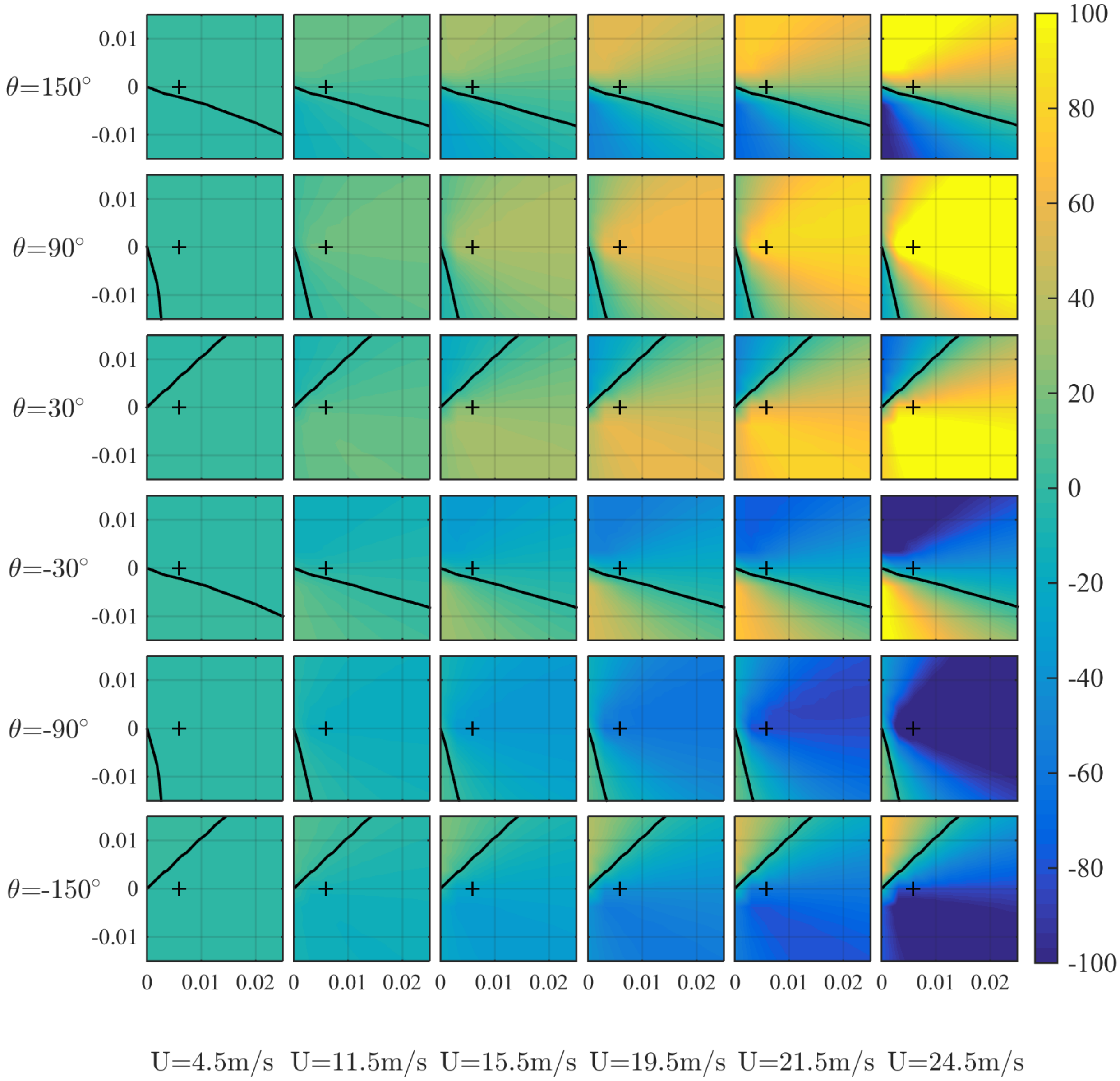


Figure N1: Migration rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, excluding the frequencies of occurrence. The + denotes the FGM of Figure 16b.

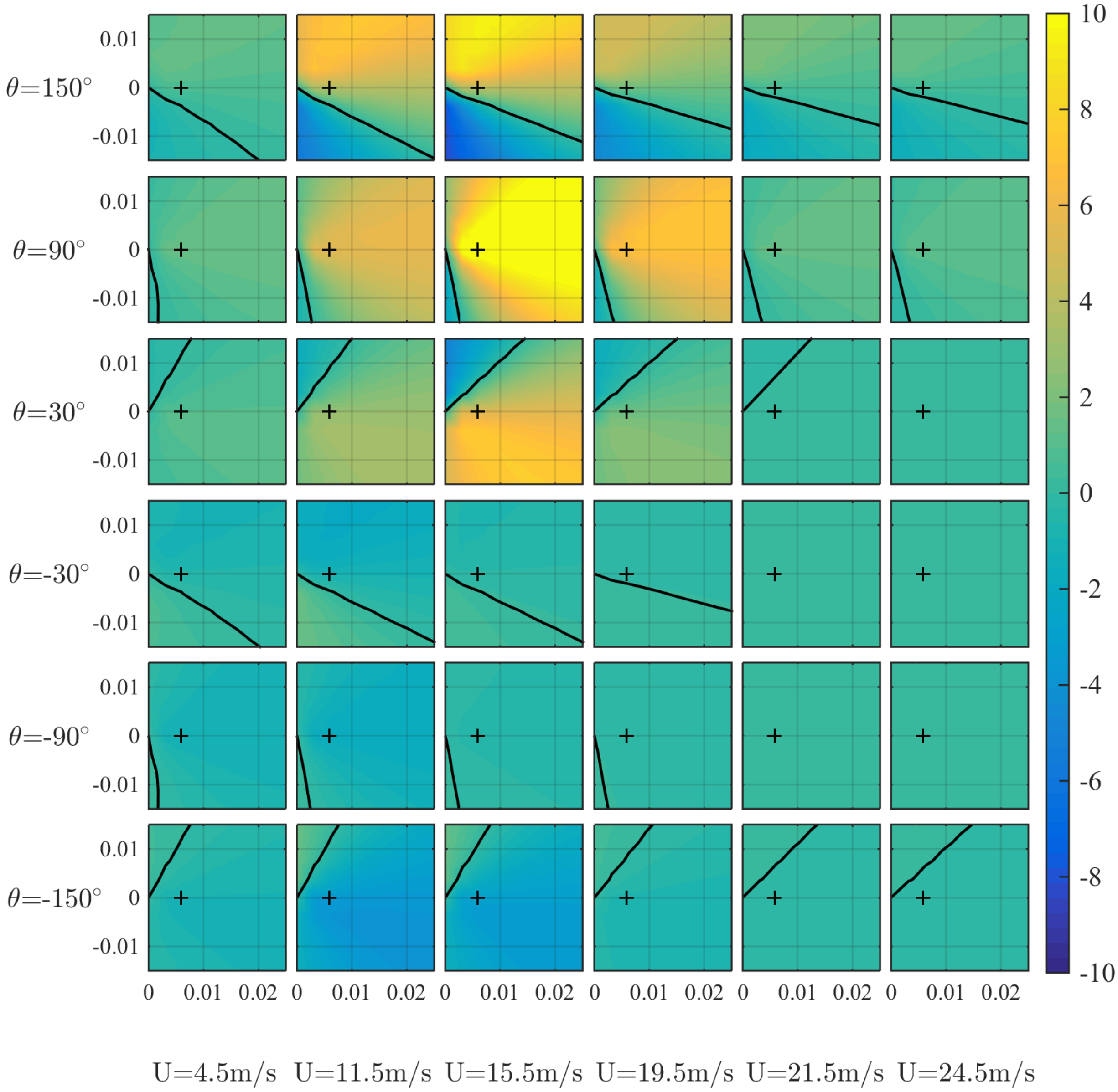


Figure N2: Migration rate as a function of the topographic wave numbers k_x^* and k_y^* for wind speed and wind angle bins, including the frequencies of occurrence. The + denotes the FGM of Figure 16b.

Appendix O. Growth rate including the frequencies of occurrence per wave height and wave angle bin and per wave period and wave angle bin

The figures below show the growth rate [yr-1] including the frequencies of occurrence as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015, per wave height and wave angle bin (Figure O1) and per wave period and wave angle bin (Figure O2).

Wave height

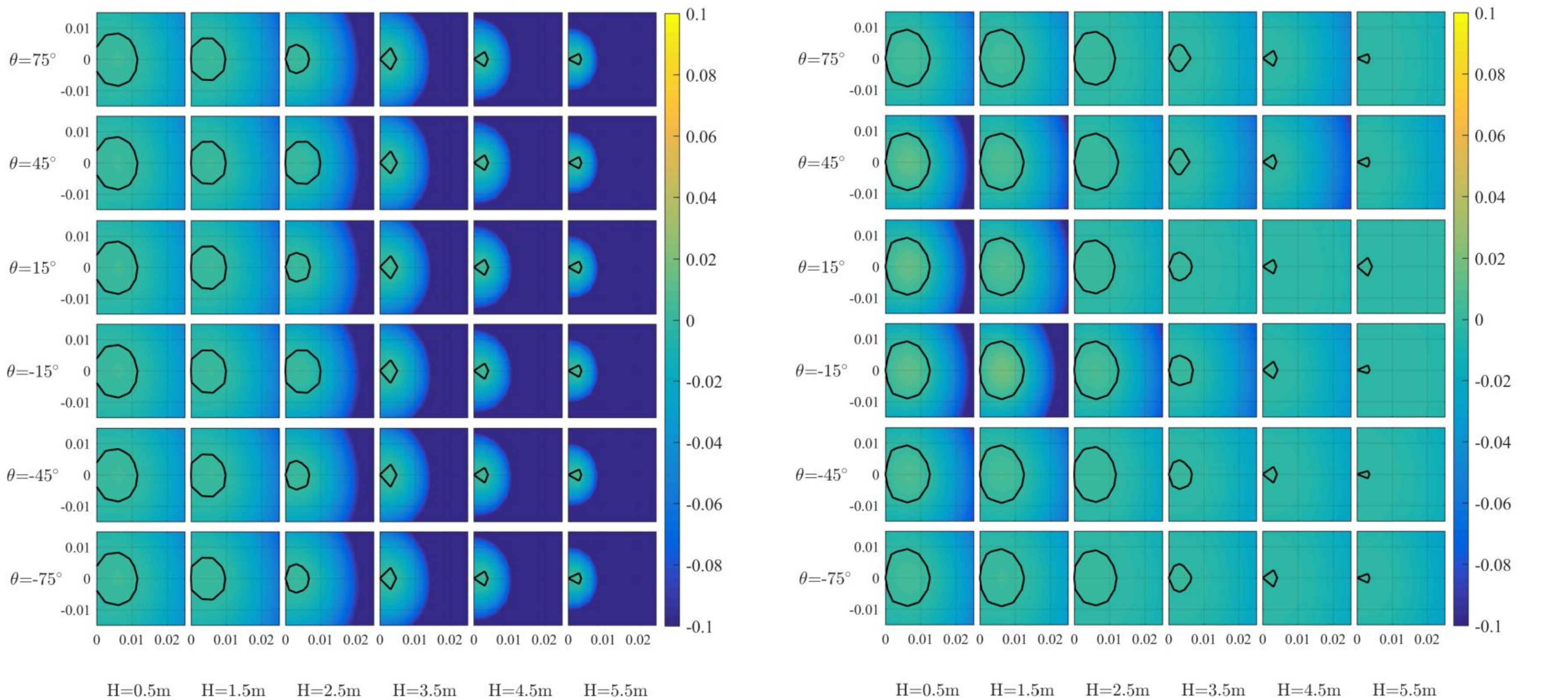


Figure O1: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave height and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right).

Wave period

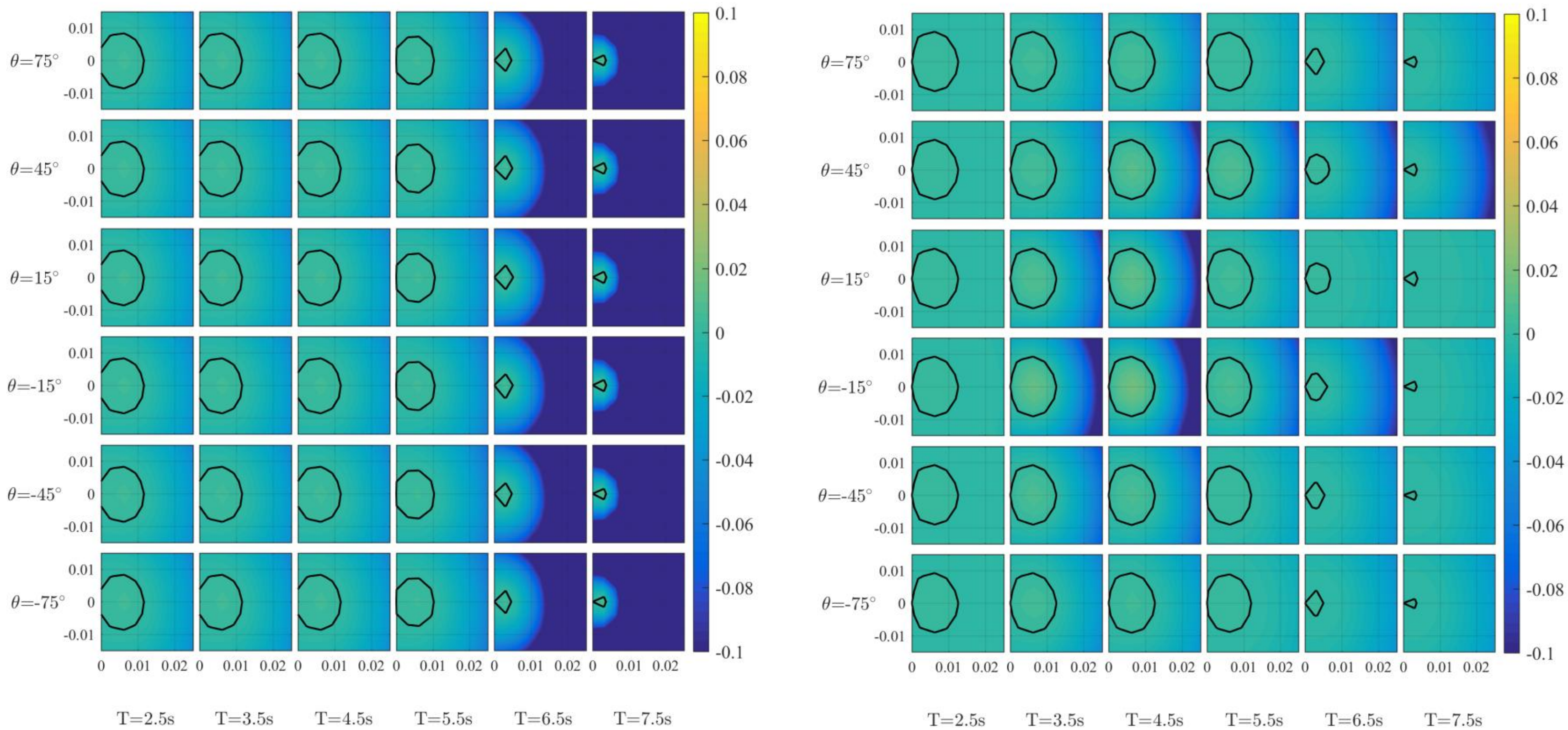


Figure O2: Growth rate as a function of the topographic wave numbers k_x^* and k_y^* for wave period and wave angle bins, excluding the frequencies of occurrence (left) and including the frequencies of occurrence (right).

Appendix P. Growth rate of the fixed mode as a function of wave height and –angle and as a function of wave period and – angle

The figures in this appendix show the growth rate contribution of the fixed mode as a function of wave height and –angle (Figure P1), and as a function of wave period and – angle (Figure P2) for the location Europlatform during the timeframe 1997-2015.

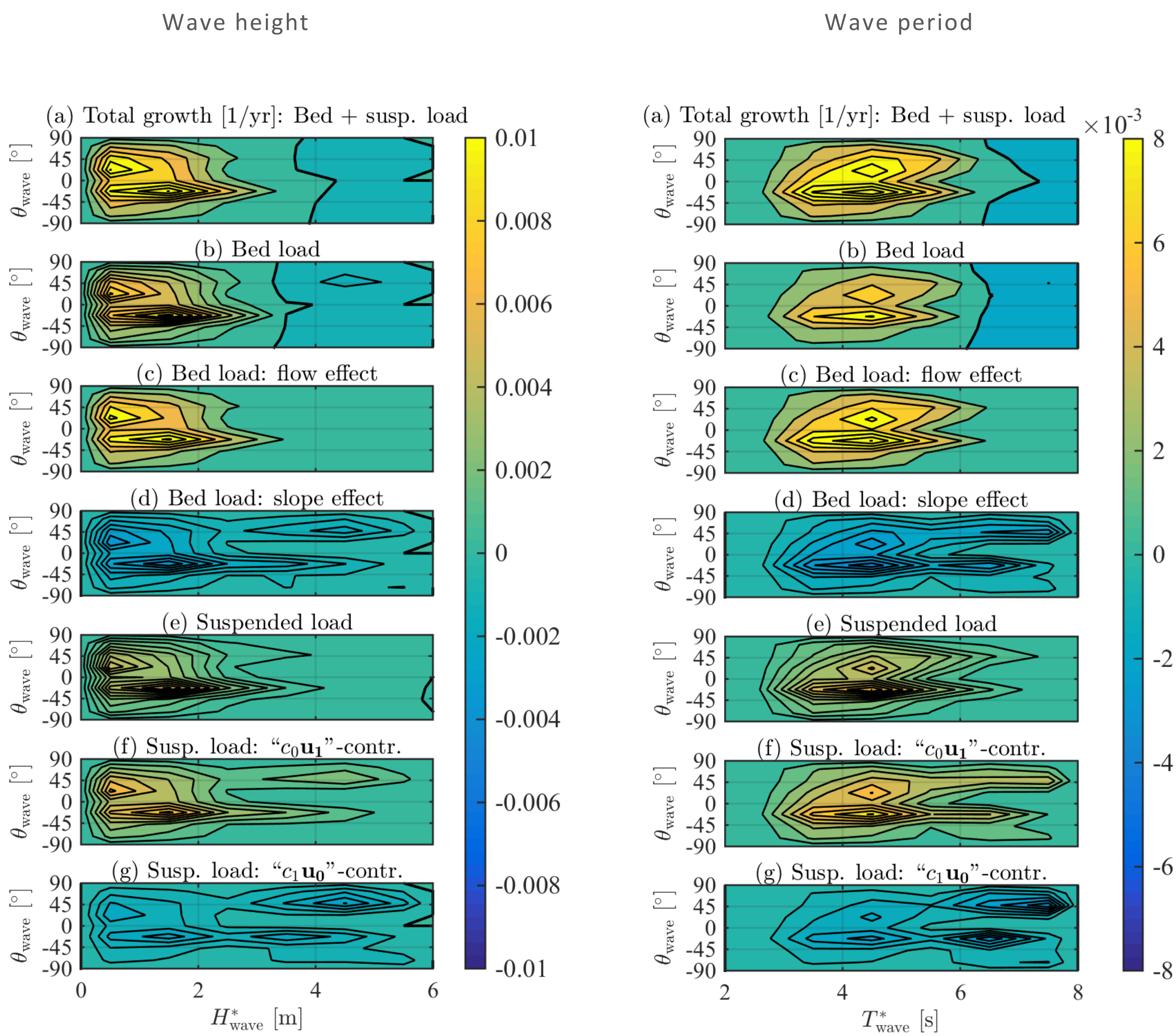


Figure P1: Growth rate contribution of the fixed mode as a function of wave height and wave angle (left), and as a function of wave period and wave angle (right), including the frequencies of occurrence.

Appendix Q. Difference in growth rate between including and excluding storm+gale hours

The figures below show the difference in growth rate [yr-1] between including and excluding storm+gale hours, taking the frequencies of occurrence into account, as a function of the topographic wave numbers k_x^* and k_y^* for the location Europlatform during the timeframe 1997-2015.

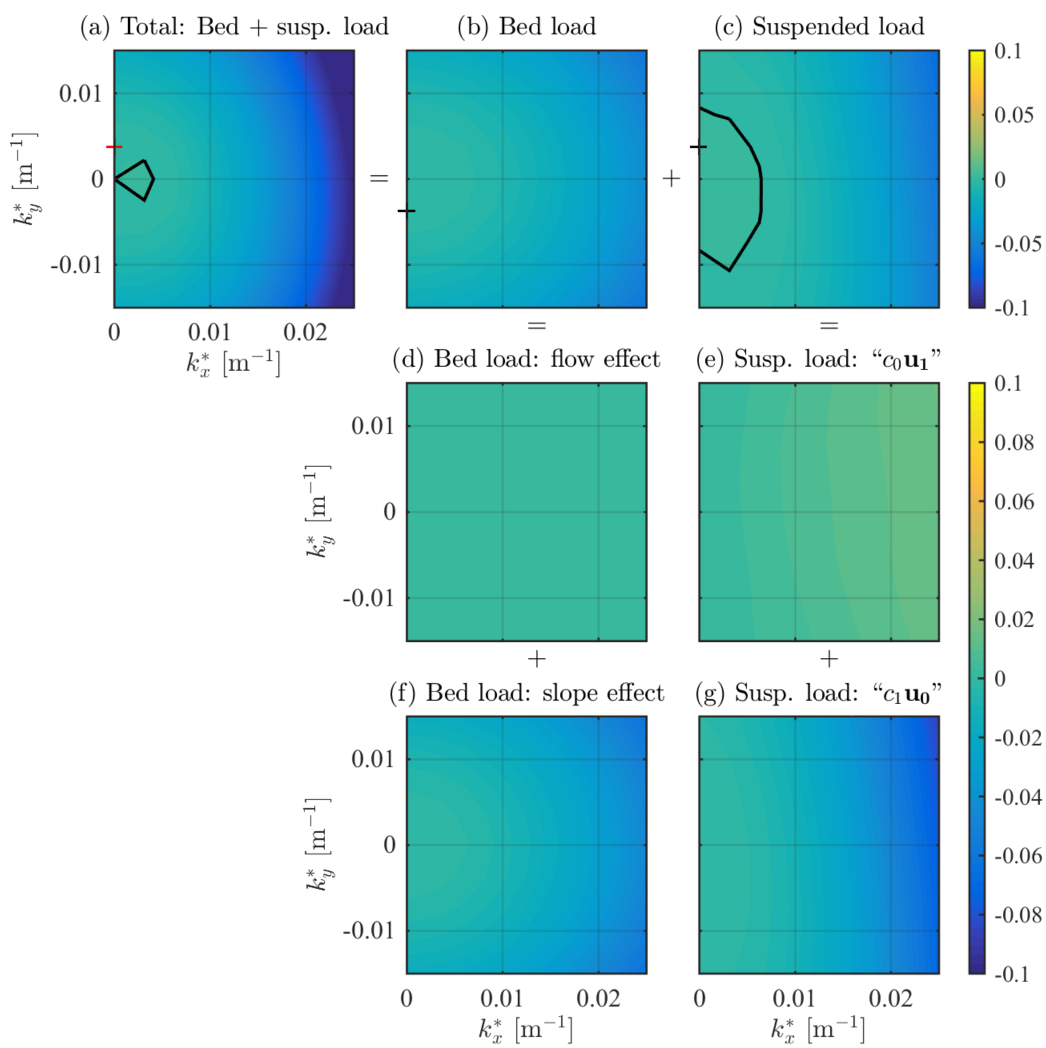


Figure Q1: Difference in growth rate [yr-1] between including storms (wind speeds ≥ 20.8 m/s) and excluding storm+gale hours, taking the frequencies of occurrence into account, as a function of the topographic wave numbers k_x^* and k_y^*.