Description of the relation of Wind, Wave and Current Characteristics

at the Offshore Wind Farm Egmond aan Zee (OWEZ) Location in 2006

S. Barth, P.J. Eecen

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Abstract

NoordzeeWind carries out an extensive measurement and evaluation program as part of the Offshore Wind Farm Egmond aan Zee (OWEZ) project.

The technical part of the measurement and evaluation program considers topics as climate statistics, wind and wave loading, detailed performance monitoring of the wind turbines, etc.

The datasets are available in the public domain. The data that are analyzed in this report to characterize wind, wave and currents, are taken from a $116m$ height meteorological mast, located $18km$ offshore for the coast of Egmond aan Zee, the Netherlands.

According to the measurement and evaluation program the measured data should be reported periodically. This report represents the first of those periodic reports on wave measurements. Since from June 2005 to December 2006 only little data are available this report includes all available data for that period.

Principal

NoordzeeWind

2e Havenstraat 5b

1976 CE IJMuiden

Project Information

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A	Weibull scale parameter	
E	East	
$E(f)$	spectral density	
H_s	significant wave height	m
N	number of data points or North	
S	South	
S_E	standard error of the mean	
T	absolut temperature	K
T_z	wave period	s
W	West	
f	frequency	s^{-1}
h	height	m
k	Weibull shape parameter	
m_n	nth moment	
p	probability density	
u	wind speed	ms^{-1}
ϱ	correlation coefficient	
σ	standard deviation	

1 Introduction

NoordzeeWind carries out an extensive measurement and evaluation program (NSW-MEP) as part of the OWEZ project. NoordzeeWind contracted Bouwcombinatie Egmond (BCE) to build and operate an offshore meteorological mast at the location of the OWEZ wind farm. BCE contracted Mierij Meteo to deliver and install the instrumentation in the meteorological mast. After the data have been validated, BCE delivers the measured 10 minutes statistics data to NoordzeeWind.

A $116m$ high meteorological mast has been installed to measure the wind conditions. This mast is in operation since the summer of 2005. The measurements from the $116m$ high mast have been made available by Noordzeewind. This report intents to fulfill requirements which are specified in the measurement and evaluation program [1]. One of the requirements is to report periodically the wave conditions combined with the measured wind conditions at the met mast. During the period summer 2005 to December 2006 wave data are only available for the period 5 May 2006 to 30 October 2006. Those data are here reported graphically and tabularly. Note that during this period the wind farm has been installed, but has not been operational yet. Therefore the measured wind conditions at the mast are not disturbed by wakes.

In section 2 definitions used in this report are given.

In section 3 the measured signals are described and the instrument codes are given. From the measurements with several anemometers and vanes at each measurement level, a wind speed and wind direction is constructed that reduces the effect of flow distortion due to the mast and neighboring sensors. The definitions of derived wind speed and derived wind direction are described.

In section 4 the wind and wave climate during the period under consideration is described.

In section 5 the time series of water level and temperature, wave height, period and direction and current velocity and direction are shown.

2 Definitions

Unless mentioned differently the following definitions have been used in this report.

2.1 Standard error of the mean

The standard error of the mean of a sample from a population is the standard deviation of the sample divided by the square root of the sample size

$$S_E = \frac{\sigma}{\sqrt{N}}, \tag{1}$$

with N being the number of observations [2].

Note that all error bars within this report refer to this standard error, unless mentioned differently.

2.2 Significant wave height

Wave heights are given as significant wave heights, which are defined by the energy spectrum [3]

$$H_s = 4\sqrt{\int E(f)df}. \tag{2}$$

As not mentioned differently within this report, wave height always means significant wave height.

2.3 Zero upcrossing wave period

Wave periods are given as zero upcrossing periods, which are defined by [3]

$$T_z = 2\pi \cdot \sqrt{\frac{m_0}{m_2}}, \quad m_n = \int f^n E(f)df, \quad n = 0, 2. \tag{3}$$

As not mentioned differently within this report, wave period always means zero upcrossing wave period.

2.4 Stability

The stability or instability of a layer of the atmosphere or of the atmosphere as a whole is a state with respect to the reaction of a volume of air to a vertical displacement. The atmospheric stability determines the probability of convection, atmospheric turbulence and mixing. During highly unstable conditions a lifted parcel of air will be warmer than the surrounding air. It will continue to rise upward, away from its original position. Therefore a lot of atmospheric turbulence is likely to occur, which goes a along with strong mixing.

For highly stable conditions a lifted volume of air will be cooler than the surrounding air. It will sink back to its original vertical position. Distortions to the vertical position of an air volume will therefore be damped, which can lead to decoupled layers within the atmosphere.

During conditionally unstable conditions saturated air volumes can still rise due to moisture.

Note that there exists a large variety of methods to estimate atmospheric stability from measurements and that this topic is still ongoing research. Four different methods are tested to estimate atmospheric stability:

- the relation between water surface temperature and air temperature
- the ratio of potential to kinetic energy [5]
- best fit of the velocity profile [4]
- environmental lapse rate (variation of temperature with height)

The environmental lapse rate turned out to be the method that coincides best with the analyses. Therefore stability within this report is based on the variation of temperature with height:

$$\begin{aligned} -dT/dh < 6K/km &\equiv \text{stable atmospheric conditions} \\ 6K/km < -dT/dh < 10K/km &\equiv \text{conditionally unstable atmospheric conditions} \\ -dT/dh > 10K/km &\equiv \text{unstable atmospheric conditions.} \end{aligned} \tag{4}$$

3 Measured data

3.1 Measured signals

The instrumentation codes of the sensors in the $116m$ high meteorological mast at the offshore wind farm location OWEZ are indicated in the following table. The instrumentation is described in [6].

Channel	Instrumentation Code	Parameter	Unit
0	3D WM4/NW/21	wind direction	$^\circ$
1	3D WM4/NW/21	horizontal wind speed	ms^{-1}
2	3D WM4/NW/21	vertical wind speed	ms^{-1}
3	3D WM4/NW/116	wind direction	$^\circ$
4	3D WM4/NW/116	horizontal wind speed	ms^{-1}
5	3D WM4/NW/116	vertical wind speed	ms^{-1}
6	3D WM4/NW/70	wind direction	$^\circ$
7	3D WM4/NW/70	horizontal wind speed	ms^{-1}
8	3D WM4/NW/70	vertical wind speed	ms^{-1}
9	WS 018/NW/116	wind speed	ms^{-1}
10	WS 018/NE/116	wind speed	ms^{-1}
11	WS 018/S/116	wind speed	ms^{-1}
12	WS 018/NW/70	wind speed	ms^{-1}
13	WS 018/NE/70	wind speed	ms^{-1}
14	WS 018/S/70	wind speed	ms^{-1}
15	WS 018/NW/21	wind speed	ms^{-1}
16	WS 018/NE/21	wind speed	ms^{-1}
17	WS 018/S/21	wind speed	ms^{-1}
18	RHTT 261/S/116	ambient temperature	$^\circ C$
19	RHTT 261/S/70	ambient temperature	$^\circ C$
20	RHTT 261/S/21	ambient temperature	$^\circ C$
21	RHTT 261/S/116	relative humidity	$\%$
22	RHTT 261/S/70	relative humidity	$\%$
23	RHTT 261/S/21	relative humidity	$\%$
24	DP910	ambient air pressure	$mbar$
25	PD 205/NW/70	precipitation	$boolean$
26	PD 205/NE/70	precipitation	$boolean$
27	ST 808/NW/-3.8	sea water temperature	$^\circ C$
28	AC SB2i/T/116	acceleration (north - south)	ms^{-2}
29	AC SB2i/T/116	acceleration (west - east)	ms^{-2}

30	WD 524/NW/116	wind direction	$^\circ$
31	WD 524/NE/116	wind direction	$^\circ$
32	WD 524/S/116	wind direction	$^\circ$
33	WD 524/NW/70	wind direction	$^\circ$
34	WD 524/NE/70	wind direction	$^\circ$
35	WD 524/S/70	wind direction	$^\circ$
36	WD 524/NW/21	wind direction	$^\circ$
37	WD 524/NE/21	wind direction	$^\circ$
38	WD 524/S/21	wind direction	$^\circ$
50	ADCP	water level	m
51	ADCP	water temperature	$^\circ C$
52	ADCP	wave height	m
53	ADCP	wave period	s
54	ADCP	wave direction	$^\circ$
55	ADCP	current velocity 7m	ms^{-1}
56	ADCP	current velocity 11m	ms^{-1}
57	ADCP	current direction	$^\circ$
58	ADCP	current direction	$^\circ$
Channel	Instrumentation Code	Parameter	Unit

3.2 Measurement sectors

3.2.1 Meteorological mast

The meteorological mast is a lattice tower with booms at three heights: $21m$, $70m$ and $116m$ above mean sea level (MSL). At each height, three booms are installed in the directions north-east (NE), south (S) and north-west (NW). Sensors attached to the meteorological mast are described in [6]. The location of the meteorological mast is given in the following table.

	UTM31 ED50	WGS 84
x	594195	$4^\circ 23' 22,7''$ Longitude East
y	5829600	$52^\circ 36' 22,9''$ Latitude North

3.2.2 Derived wind data

The wind speeds and wind directions at each height are measured with more than one sensor. For certain wind directions the wind vanes and cups are in the wake of the mast or neighboring sensors or are otherwise significantly disturbed. It is necessary to select one of the cup anemometers and wind vanes depending on the actual wind direction in order to establish a wind speed that minimizes the distortion. The constructed wind speed and wind direction are used within this report. The selection of signals is indicated in the following table.

Wind direction	Selected sensors
330 to 30 °	average of wind vanes NW and NE boom
30 to 90 °	average of wind vanes S and NW boom
90 to 150 °	average of wind vanes S and NE boom
150 to 210 °	average of wind vanes NW and NE boom
210 to 270 °	average of wind vanes NW and S boom
270 to 330 °	average of wind vanes NE and S boom
0 to 120 °	cup anemometer in NE boom
120 to 240 °	cup anemometer in S boom
240 to 360 °	cup anemometer in NW boom

Averaging over two vanes reduces the effect of the distortion by the mast on the wind direction measurement.

For the selection of the wind speed sensor it is important that at the direction where the wind speed sensor is changed from one sensor to the other, the ratio of the wind speeds is close to one. Furthermore, the wind speed may not be measured in the wake of the mast or a neighboring sensor.

3.2.3 Wave and current data

Seen from the monopile of the measurement mast the ADCP is placed in a distance of $13.75m$ in the direction of $280°$. As it can be seen in Figure 1 the monopile stands in a sector seen from the ADCP where almost no wave or current data have been measured. Therefore the influence of the monopile on the measurements can be neglected.

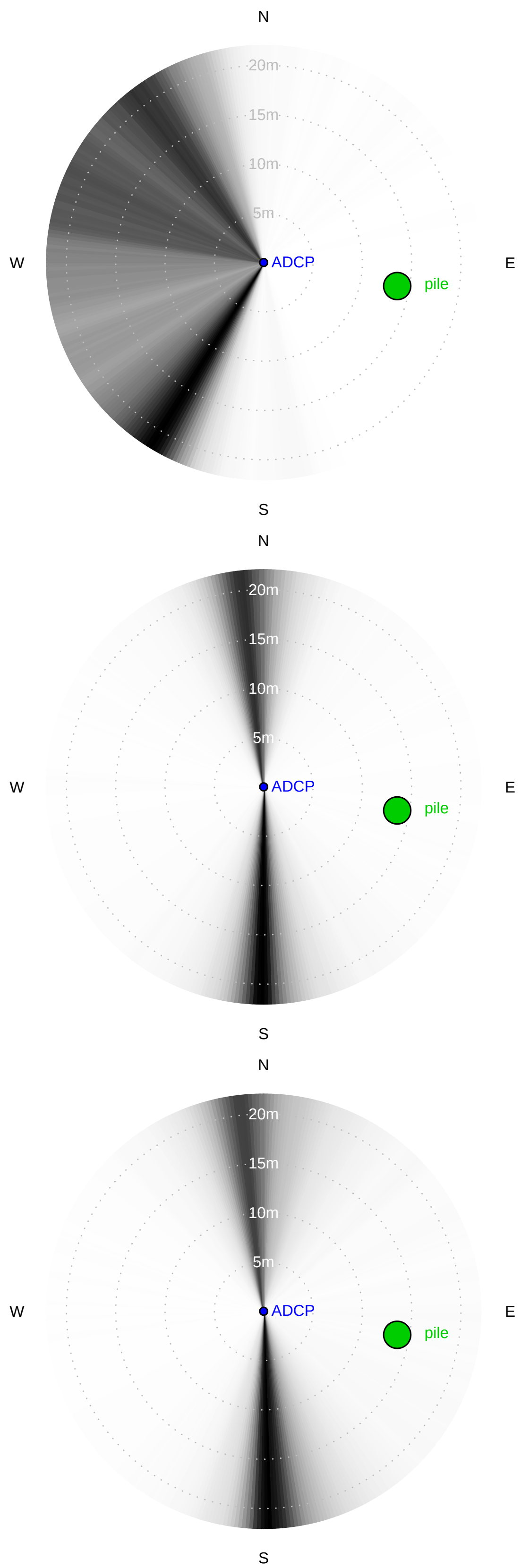


Figure 1: Angular frequency distribution of observations of wave directions (top), current directions in a depth of $7m$ (middle) and current directions in a depth of $11m$. Darker means larger number of observations, white corresponds to zero observations. The green circle marks the position and diameter of the monopile. The blue circle marks the position of the ADCP.

4 Wind and wave climate in the reporting period

The intention of this report is to describe the measured wave conditions at the measurementmast of NSW periodically. During a limited period from 5 May 2006 to 30 October 2006 wave data are available. In the following subsections the wind conditions during this period are described. The long-term wind climate will be reported in a separate report.

4.1 Wind speed frequency distributions

In this subsection the wind speeds are depicted for the period which coincides with the availability of wave date.

Figure 3 shows the wind speed frequency distributions for the three measurement heights $h = 116m$, $h = 70m$ and $h = 21m$, together with a fitted Weibull distribution

$$p(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^{k}\right), \tag{5}$$

with u being the horizontal wind speed, k the shape parameter and A the scale parameter.

According to the distributions and the fitting parameters, the scale parameter increases (exponentially) with height, while the shape parameter decreases with height, see Figure 2.

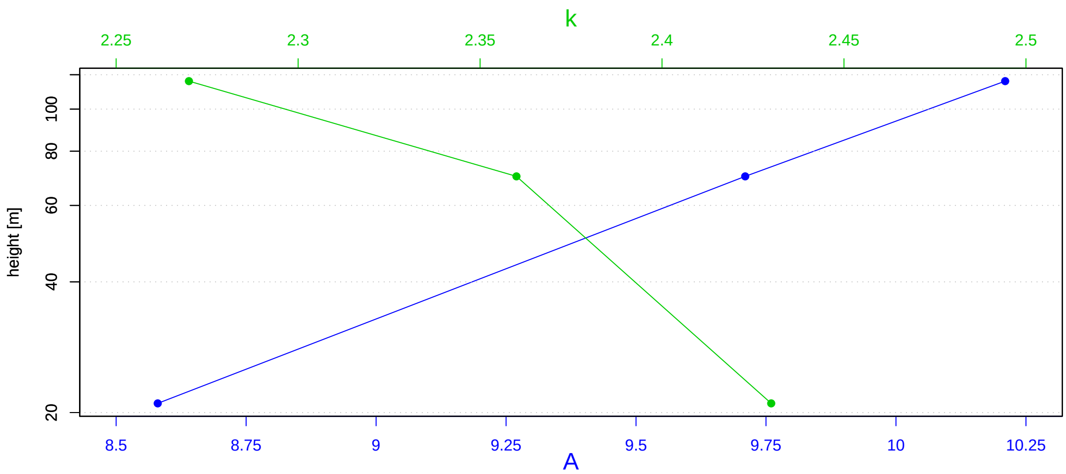


Figure 2: Weibull scale parameter (blue) and Weibull shape parameter (green).

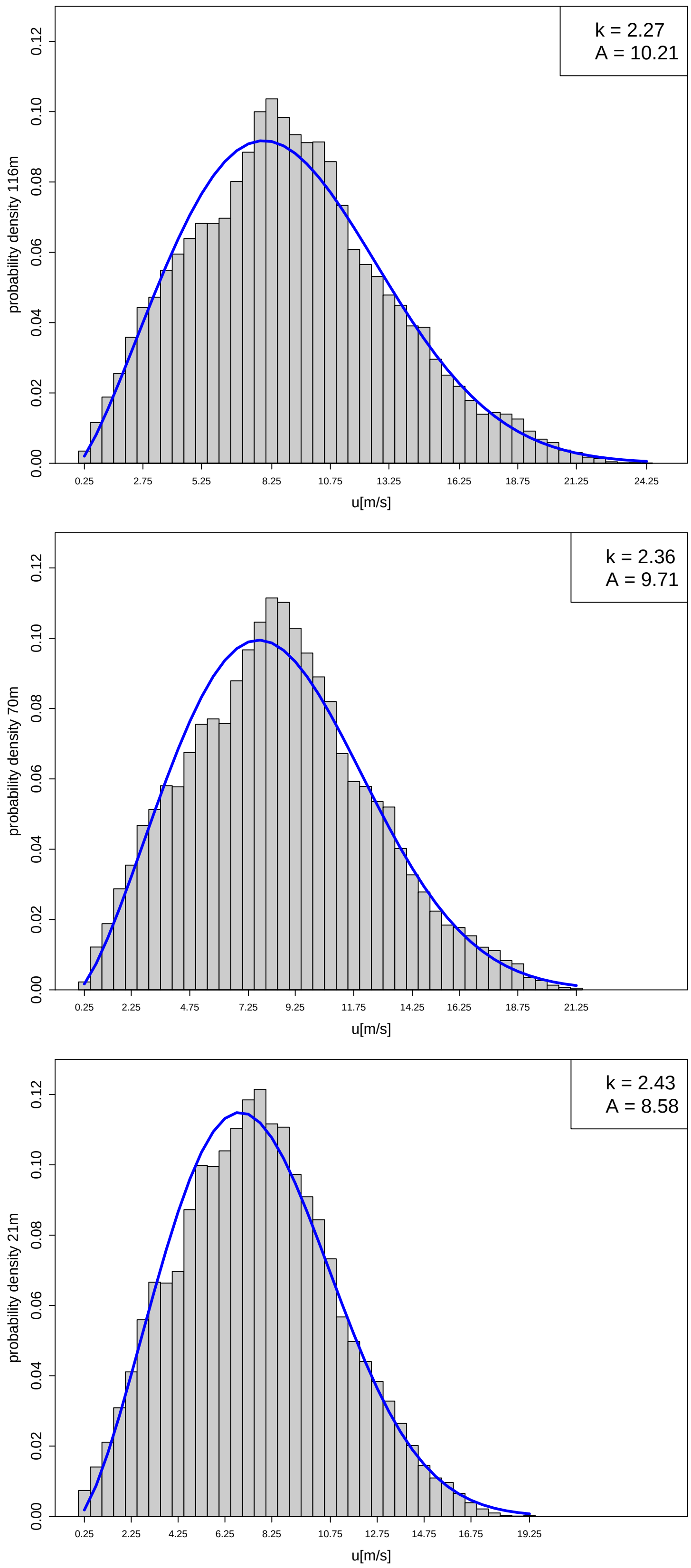


Figure 3: Wind speed frequency distribution at the height of $116m$ (top), $70m$ (middle) and $21m$ (bottom) for the period from 5 May 2006 to 30 October 2006. The blue lines show fitted Weibull distributions. Fitting parameters are given in the top right corner, respectively.

4.2 Wind direction frequency distributions

In this subsection the wind directions are depicted for the period which coincides with the availability of wave date.

Figure 4 shows the wind direction frequency distributions for the three measurement heights $h = 116m$, $h = 70m$ and $h = 21m$. The prevailing wind direction is south west.

As expected a change in orientation of the prevailing wind direction to the West can be observed with increasing height (Ekman spiral). Furthermore, the variation in wind directions increases with height, meaning that a prevailing wind direction is less pronounced for high altitudes.

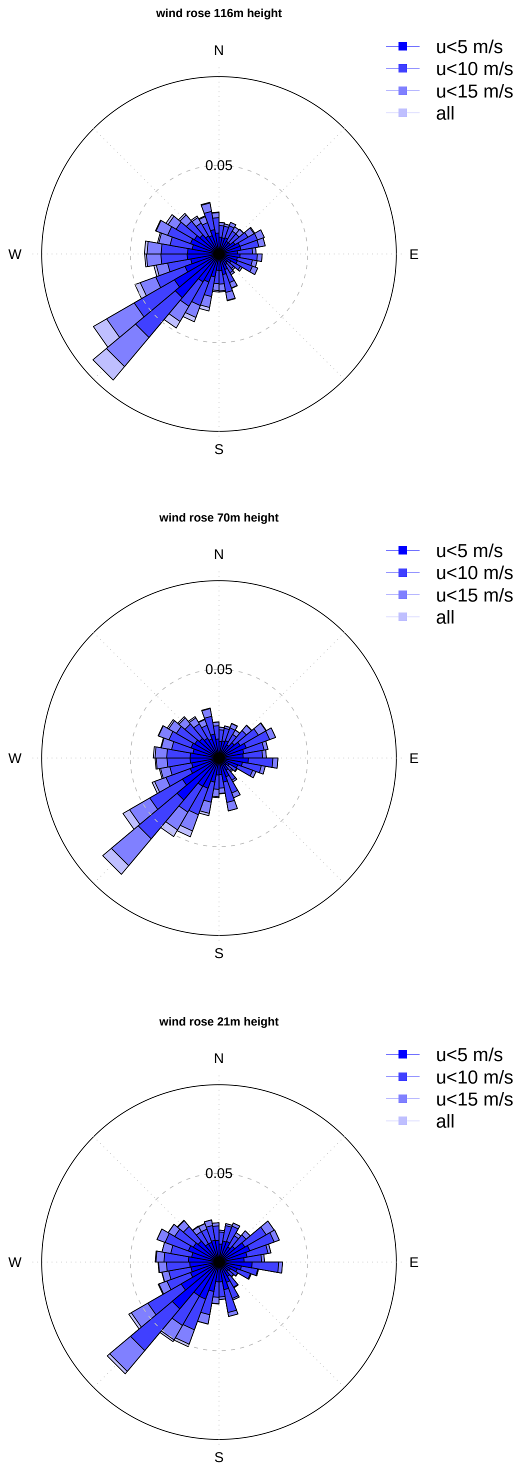


Figure 4: Wind direction frequency distribution at the height of $116m$ (top), $70m$ (middle) and $21m$ (bottom) for the period from 5 May 2006 to 30 October 2006. Radial units are given in probability densities (center is zero).

4.3 Wave height comparison with measurements from IJmuiden

As a first order check on the quality of the wave data the significant wave heights measured by OWEZ have been compared with those measured at the same time at the ammunition dump of IJmuiden. That station is located in a distance of $23km$ in $254.5°$ direction with respect to the OWEZ location, see Figure 5. Further information on that station can be found at [7].

Figure 5: Map of the wave measurement locations of the National Institute for Coastal and Marine Management. The ammunition dump of IJmuiden and the OWEZ location are marked with a red bullet.

Figure 6 shows the scatter plot of both measurements, together with a linear fit and the quantile-quantile plot. Quantile-quantile plots (also called q-q plots) are used to determine if two data sets come from populations with a common distribution. In such a plot, points are formed from the quantiles of the data. If the resulting points lie roughly on a line with slope 1, then the distributions are the same.

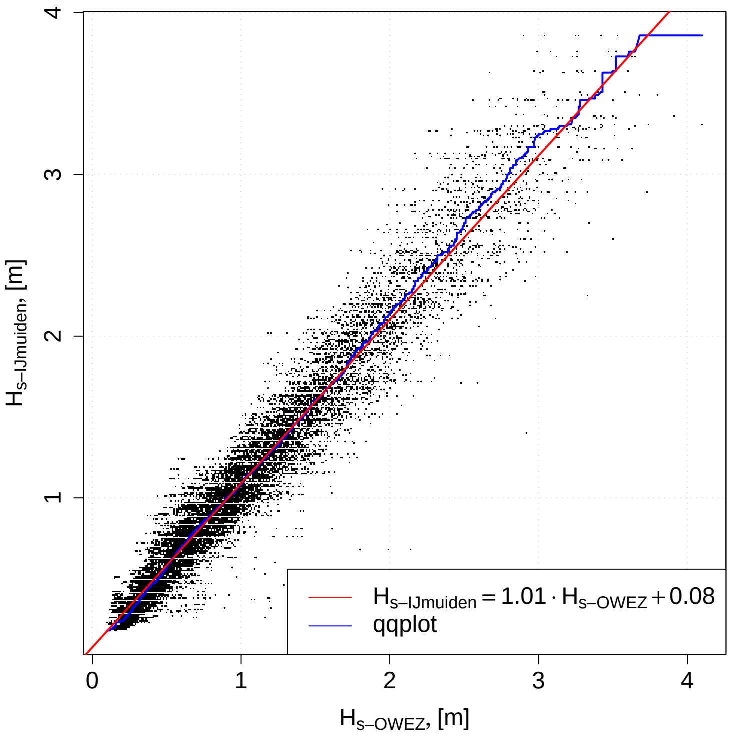


Figure 6: Scatter plot of the significant wave height measured by OWEZ and at IJmuiden, together with a linear fit (red) and the q-q plot (blue)

The correlation coefficient ϱ between both signals has been found to be 0.97. This means that the significant wave heights at OWEZ are quite similar to the significant wave heights measured at IJmuiden. Also a linear fit and the quantile-quantile plot provide evidence in the validity of the measurements.

4.4 Wave height frequency distributions

Figure 7 shows the frequency distribution of significant wave heights. The large probability for small ($< 0.5m$) wave heights correspond to stable atmospheric conditions[1], where due to the decoupling of different air layers the friction on water surface is expected to be reduced.

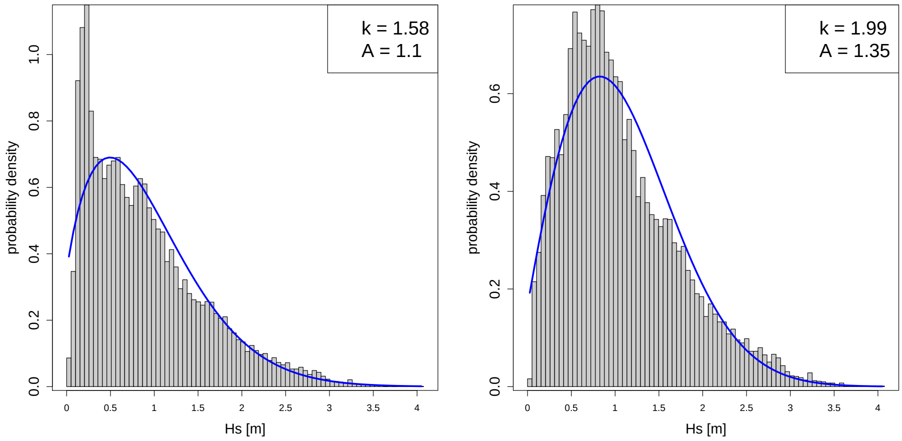


Figure 7: Wave height frequency distributions for all atmospheric conditions (left) and without stable conditions (right). Blue lines show a fitted Weibull distribution. Fitting parameters are given in the top right corner respectively.

[1] for the definition of stability see section 2.4

4.5 Wave direction frequency distributions

In Figure 8 the wave direction frequency distribution is shown. Due to the presence of the coast in the east, waves generally come from the west. This can easily be seen in Figure 8. The largest waves predominantly come from Noth-West or South-West directions.

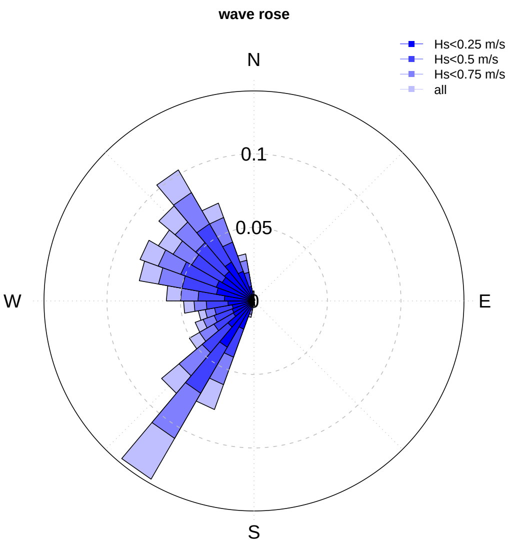


Figure 8: Wave direction frequency distribution. Radial units are given in probability densities.

4.6 Misalignment between wave and wind direction

Offshore wind turbines are exited by wave loads acting on the tower and wind loads mainly acting on the rotor. Therefore it is important to gain knowledge on the relative alignment of these forces.

Figure 9 shows histograms of misalignments between wind direction at the height of 21m and the measured wave direction

$$misalignment = |direction_{wind_{21m}} - direction_{wave}|. \quad (6)$$

It can clearly be seen that the misalignment depends on stability[2] of the atmospheric boundary layer, as it is predicted by theory.

For unstable periods the misalignment is found to be the smallest, since due to the turbulent mixing a coupling between different heightsexists.

For stable situations the misalignment is almost equally distributed, which is due to the fact that layers in different heightscan be decoupled and therefore winds in higher altitudes have no direct impact on winds above sea level, which are driving the waves.

[2]for the definition of stability see section 2.4

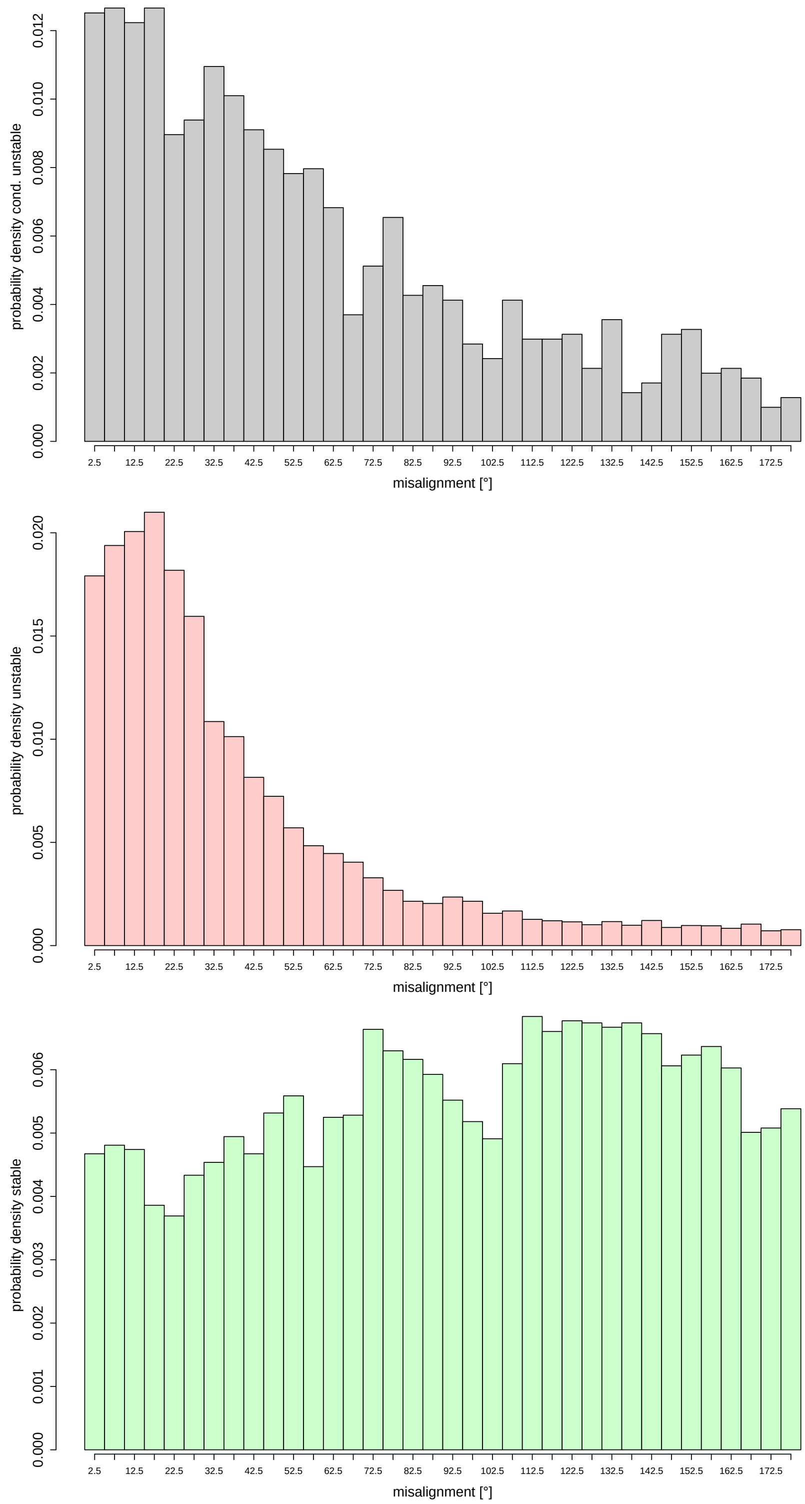
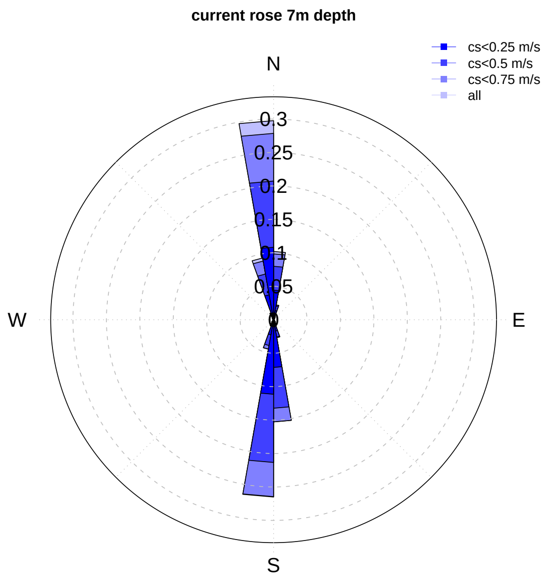


Figure 9: Histograms of misalignments between wind direction at the height of 21m and the measured wave direction for conditionally unstable, unstable and stable atmospheric conditions (from top to bottom).

4.7 Current direction frequency distributions

Another force on the turbines originates from the water current. Although of limited effect the information is essential for a proper description. In Figure 10 the current direction frequency distributions are shown for the depth of $7m$ as well as $11m$. A strong confinement of current directions along the North-South axis is observed and coincides with the knowledge on currents along the Dutch North Sea coast.



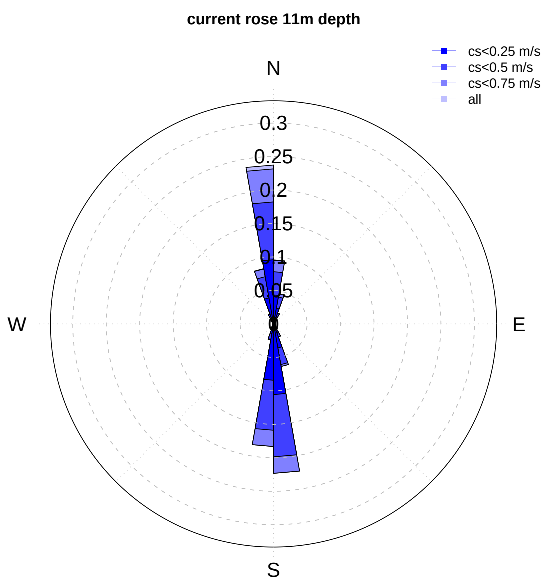


Figure 10: Current direction frequency distribution for $7m$ water depth (top) and $11m$ water depth (bottom). Radial units are given in probability densities.

4.8 Relation between wave height, wave period and wind speed

In figure 11 the 3D scatter plot of wave height, wave period and wind speed is shown.

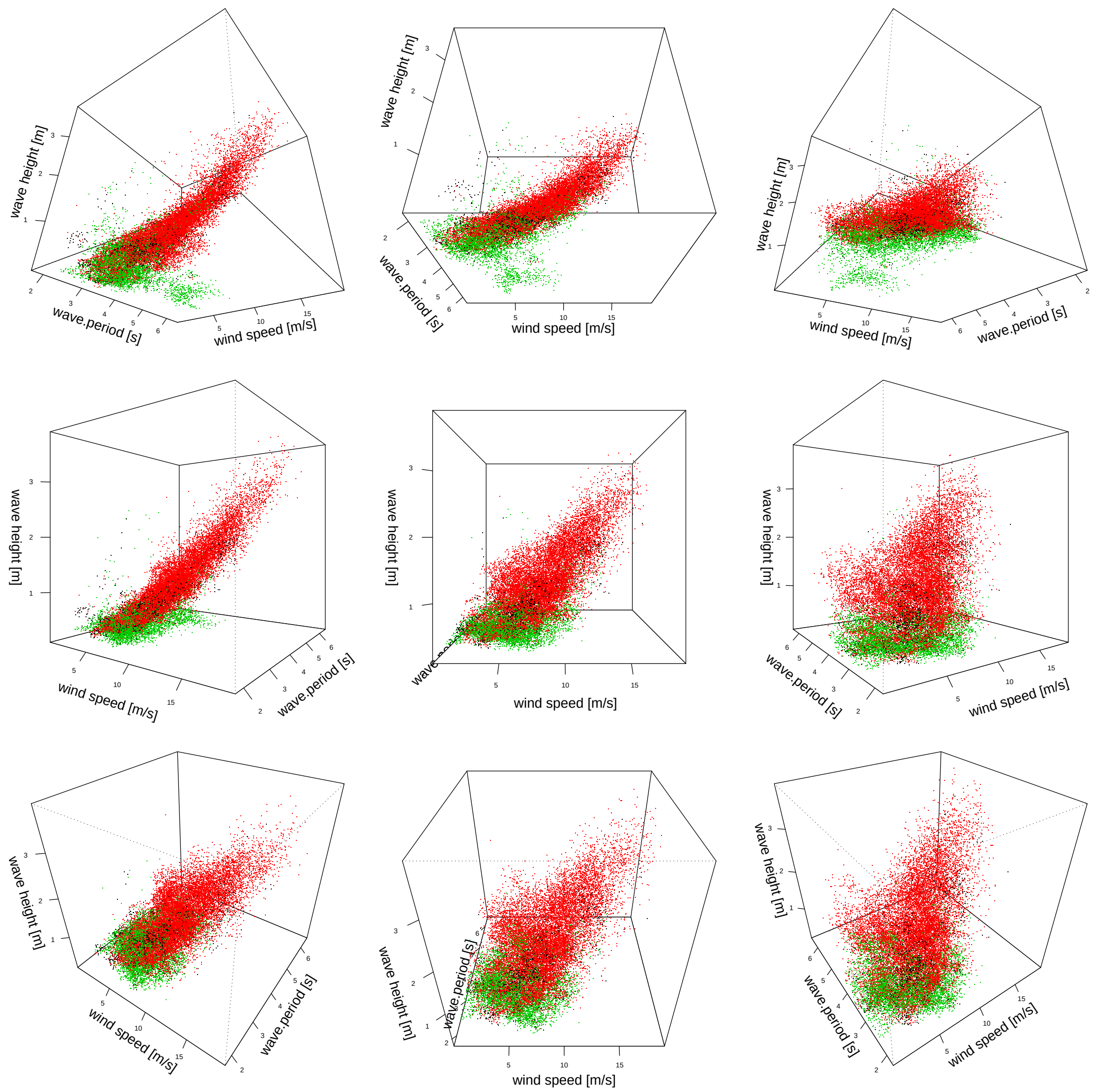


Figure 11: Different view angles of the 3D scatter plot of wave height, wave period and wind speed at $21m$. The colors black, red and green refer to conditionally unstable, unstable and stable atmospheric conditions respectively.

A detailed view of the dependence of wave height and wave period as well as wave height and wind speed can be found in Figure 12.

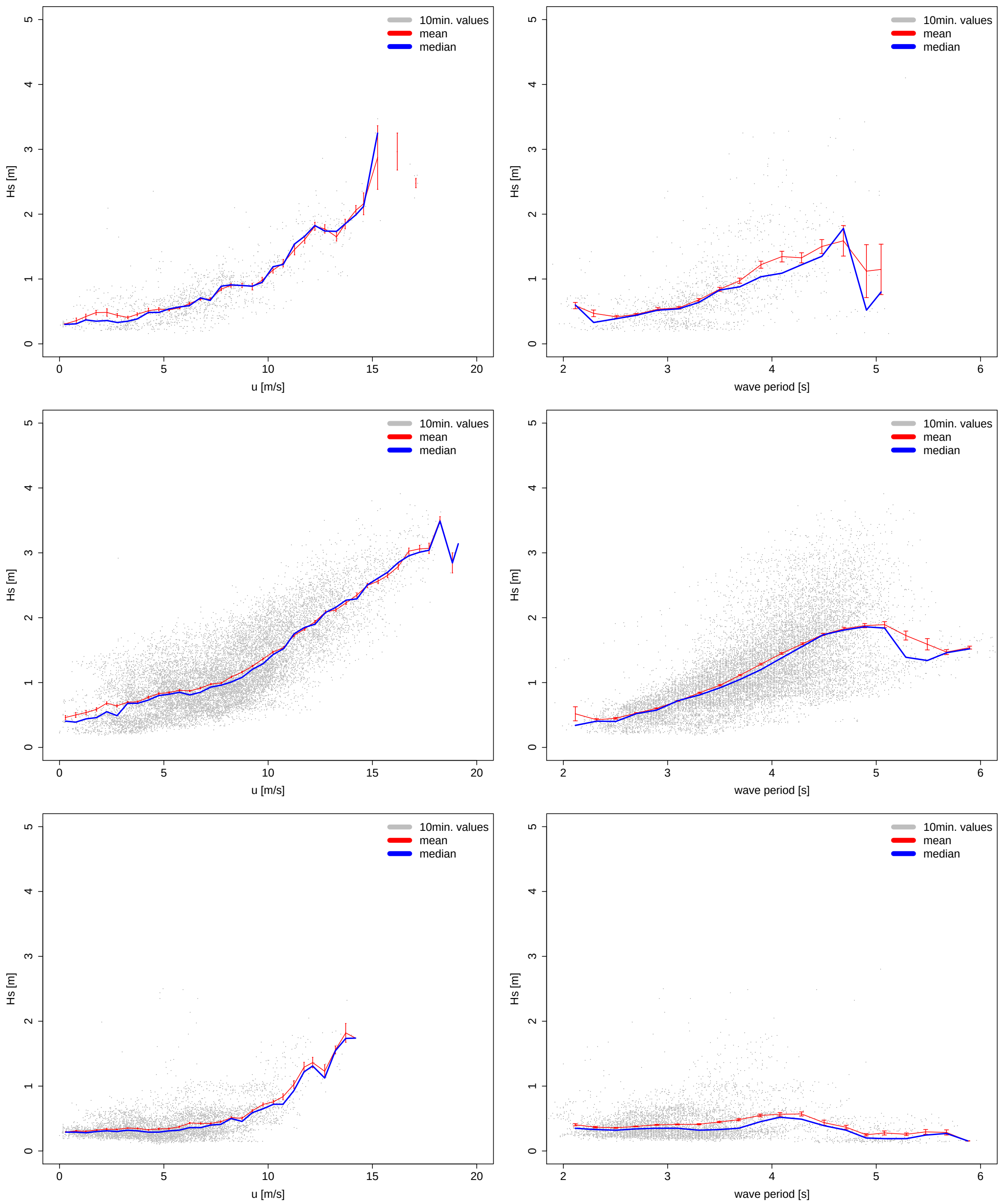


Figure 12: Significant wave height as function of wind speed (left) and wave period (right) for conditionally unstable, unstable and stable atmospheric conditions (top to bottom).

It can be seen that during periods of stable conditions of the marine atmospheric boundary layer the frictional coupling over the sea decreases. This means that during stable atmospheric conditions the wind has a minimal impact on the water surface and therefore the probability of large wave heights is very low.

Nevertheless, is must be mentioned that due to the limited amount of available data points, the significance of Figures 1112 is rather limited.

5 Time series

In this section the time series of the ADCP channels are shown for the period from 1 May 2006 until 30 October 2006. During this period the ADCP has recorded data successfully. The time series of the remaining channels can be found in the half year reports 'Meteorological Measurements OWEZ' [8][9][10][11].

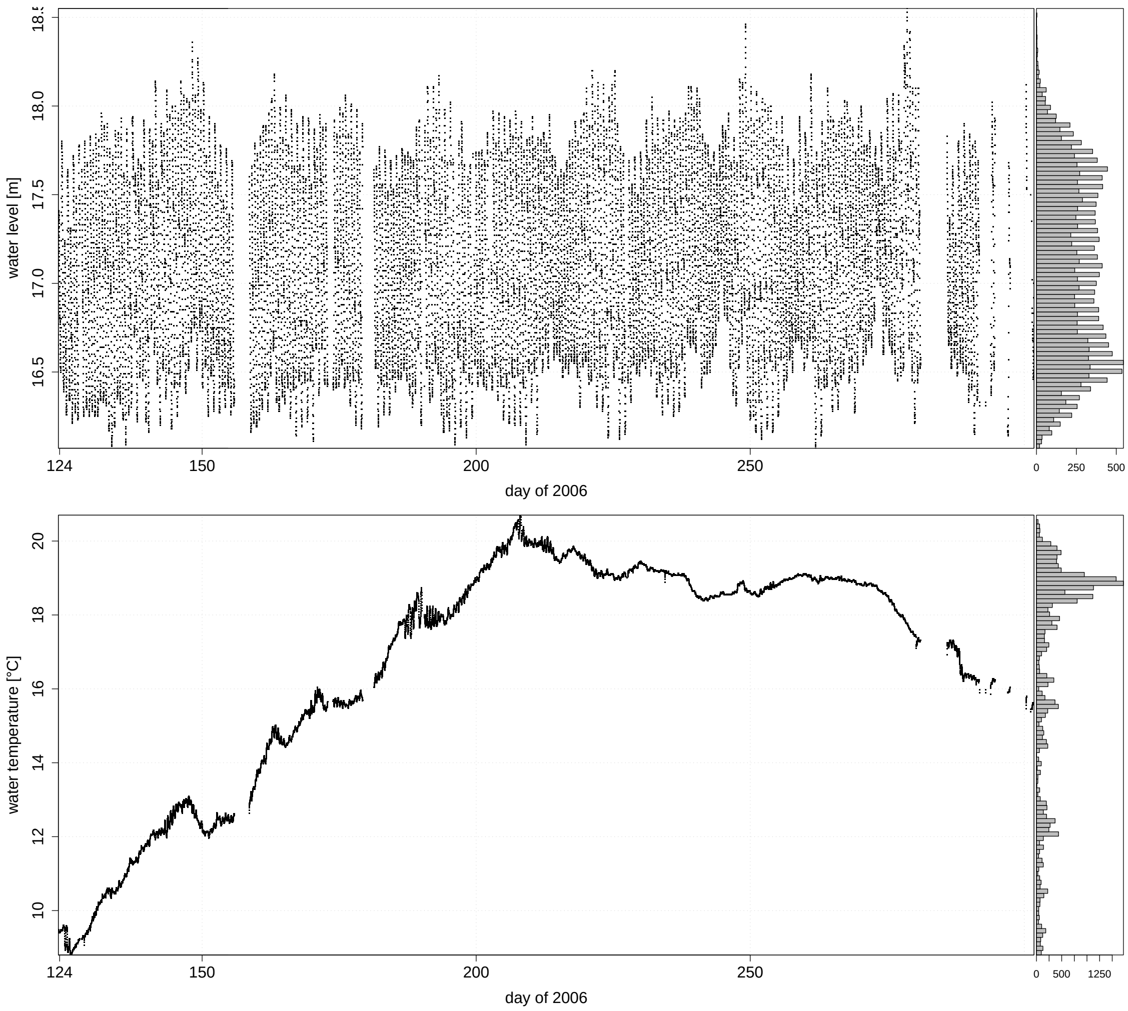


Figure 13: Time serie of 10 minutes averages of water level (top) and water temperature (bottom). Also shown are the histograms of the time series (barplots at the right side, units are numbers of observations).

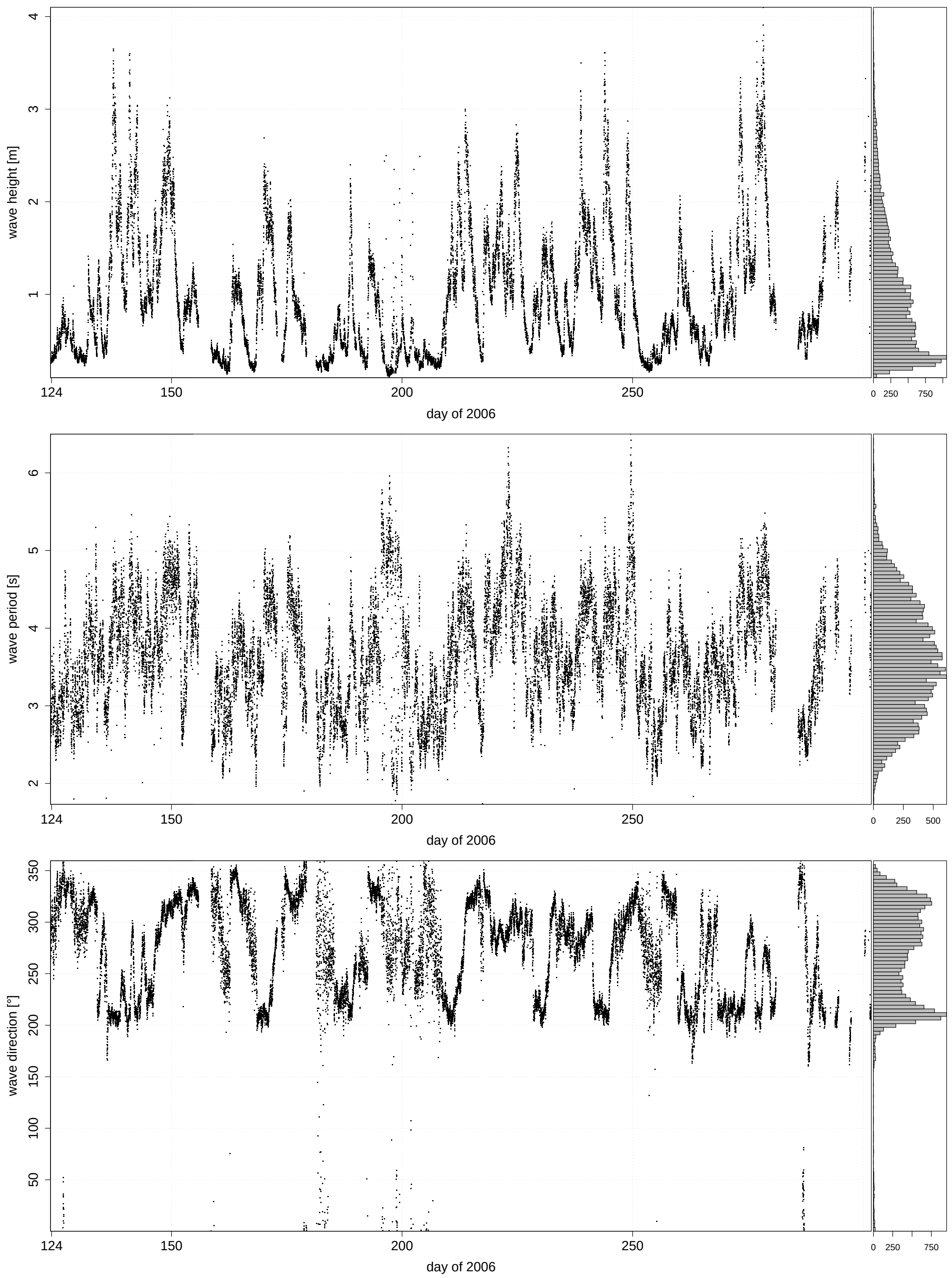


Figure 14: Time serie of 10 minutes averages of wave height (top), wave period (middle) and wave direction (bottom). Also shown are the histograms of the time series (barplots at the right side, units are numbers of observations).

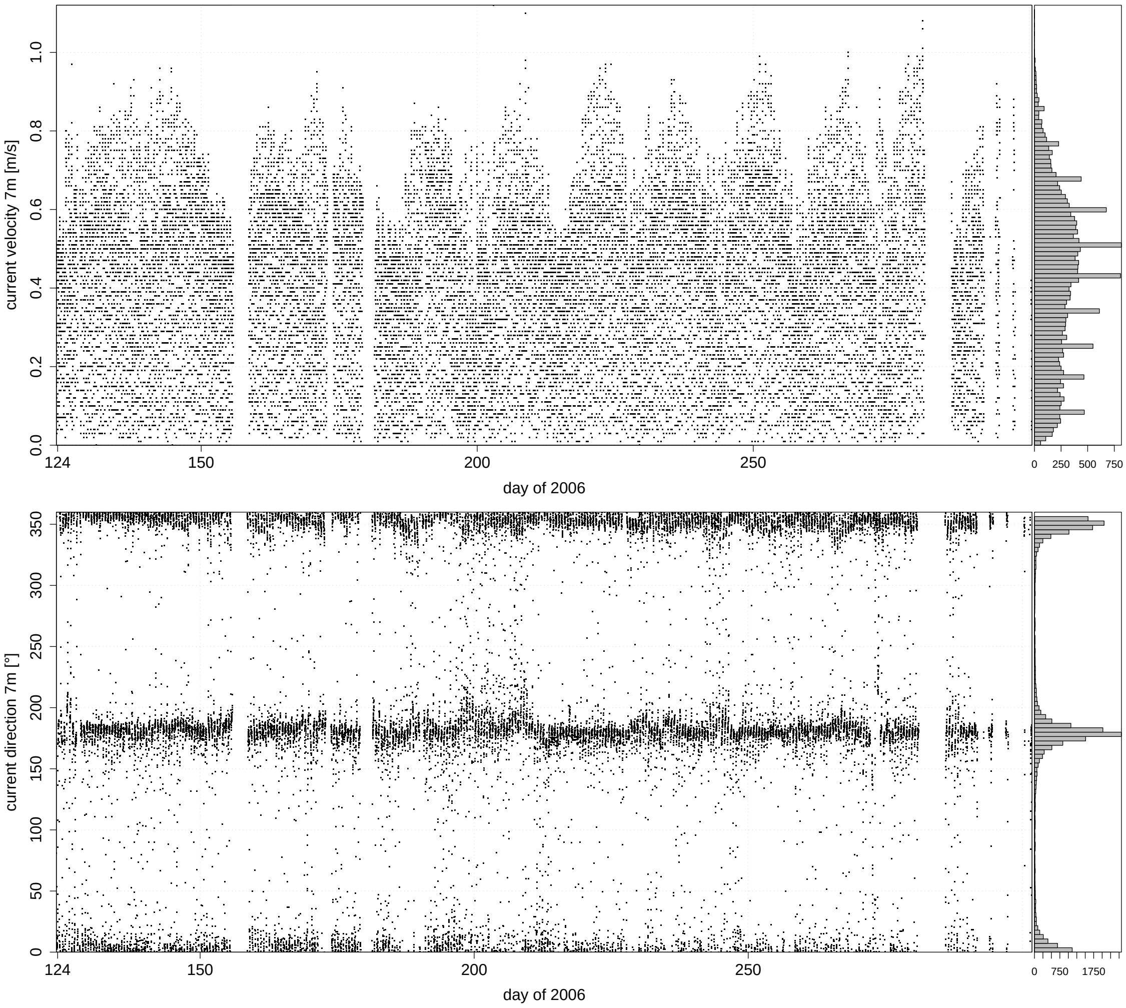


Figure 15: Time serie of 10 minutes averages of current velocity at the depth of $7m$ (top) and current direction at the depth of $7m$ (bottom). Also shown are the histograms of the time series (barplots at the right side, units are numbers of observations).

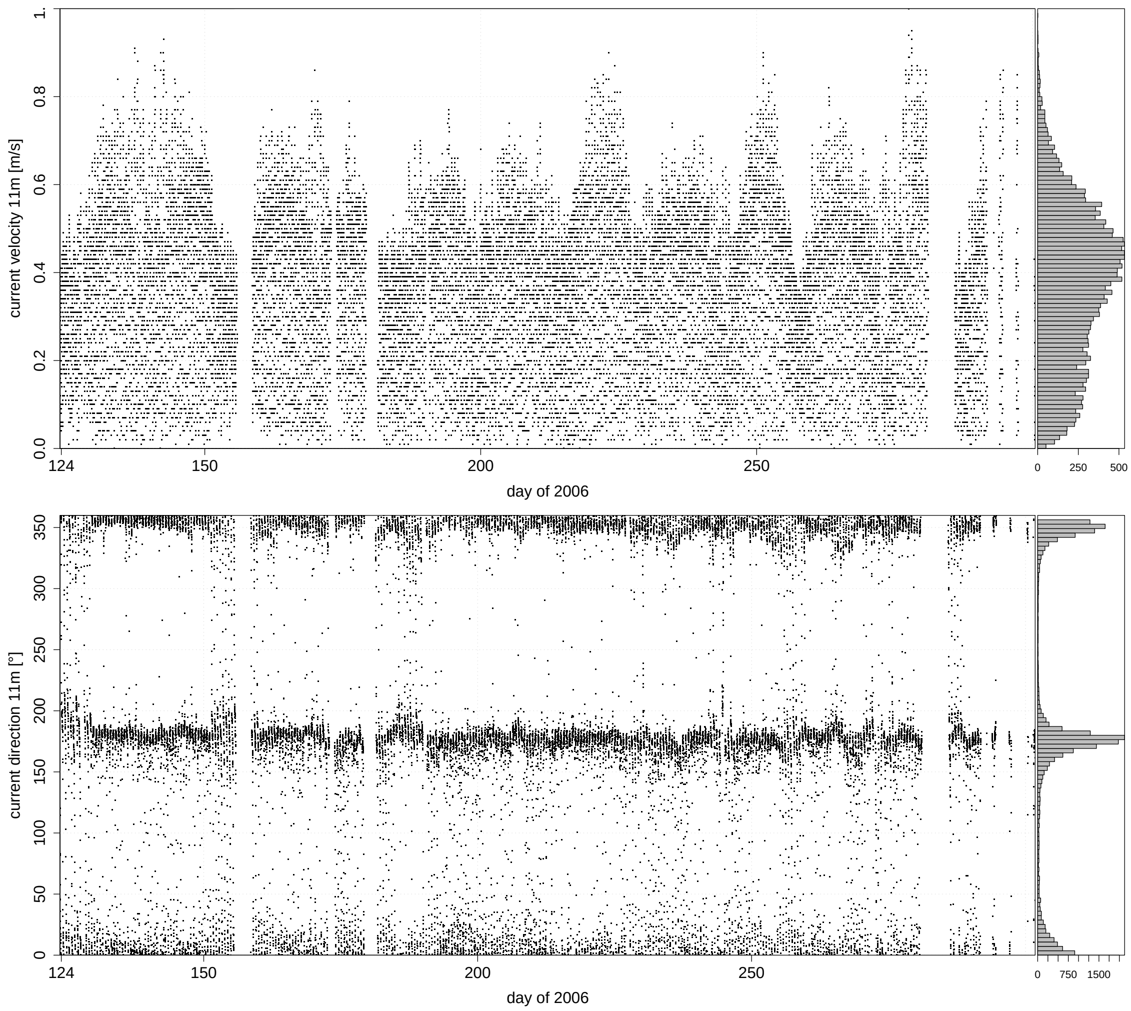


Figure 16: Time serie of 10 minutes averages of current velocity at the depth of $11m$ (top) and current direction at the depth of $11m$ (bottom). Also shown are the histograms of the time series (barplots at the right side, units are numbers of observations).

6 Conclusions

Based on the limited number of data points the following conclusions can be drawn for the OWEZ location:

- According to the wind speed Weibull distributions and the fitting parameters of which, the scale parameter increases (exponentially) with height, while the shape parameter decreases with height.
- The orientation of the prevailing wind direction changes to the West with increasing height (Ekman spiral). Furthermore, the variation in wind directions increases with height, meaning that a prevailing wind direction is less pronounced for high altitudes.
- Simultaneous wave measurements at IJmuiden and OWEZ are highly correlated, giving good confidence in the quality of the OWEZ wave measurements.
- Wave directions are strongly influenced by the orientation of the coast and occur almost only in north-west or south-west directions.
- Wind and wave misalignment is strongly influenced by atmospheric stability. For unstable situations wave directions and wind directions are strongly coupled, while for unstable situations wave and wind directions are independent.
- Water currents are bi-directional in north-south direction.

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