



Reference Site Technical Report D: Reference site 4 preliminary metocean site conditions assessment (Ulsan)

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Executive Summary

This report presents a preliminary Front-End Engineering Design (FEED) Metocean Study for the Integrated Design of Floating Wind Arrays - Ireland’s (IDEA-IRL) reference site 4. The results presented herein can only be considered as a pre-FEED study and are aimed to serve as input for preliminary design. This report will primarily serve as an appendix to the Summary Report for Work Package 1 (WP1) Deliverable (D1), which collates the various site conditions defined as part of WP1 D1. These conditions will be provided to WP2 of the IDEA-IRL project, to inform reference floating offshore wind farm designs.

Reference site 4 was chosen as a global site for consideration and development of the global offshore wind research. It utilises the location of the proposed Ulsan Floating Offshore Wind Farm, which is approximately 60 km east of the Ulsan Port in South Korea. The site is in development by a consortium of companies under a joint venture of offshore wind company Corio Generation, TotalEnergies, and SK ecoplant. It is expected to reach a capacity of 1.5 GW at full capacity.

To conduct a preliminary site characterisation study in the proximity of this site, a 45-year timeseries was utilised from the ERA5 reanalysis dataset for both wind and wave conditions, whereas a 20-year modelled timeseries was extracted for water levels and currents from the three-dimensional HYCOM global reanalysis model.

Normal, extreme and severe metocean statistics and parameters were generated from these datasets. Operability statistics such as wind-wave persistence was also generated. A summary of parameters most relevant to design are presented in Table 1-1.

Table 1-1 Summary of metocean conditions at Ulsan Floating

Variable	Value
High Still Water Level (50-year) (mMSL)	1.25
High Still Water Level (1-year) (mMSL)	0.28
Highest Astronomical Tide (HAT) (mMSL)	0.13
Lowest Astronomical Tide (LAT) (mMSL)	-0.17
Low Still Water Level (1-year) (mMSL)	-0.32
Low Still Water Level (50-year) (mMSL)	0.60
Bottom current speed (m/s) (Normal Conditions)	Mean: 0.12 Max: 0.32 P25: 0.08 P50: 0.12 P75: 0.15
Bottom current speed (m/s) (1-year)	0.24
Bottom current speed (m/s) (50-year)	0.35

Mid current speed (m/s) (Normal Conditions)	Mean: 0.12 Max: 0.56 P25: 0.06 P50: 0.11 P75: 0.17
Mid current speed (m/s) (1-year)	0.27
Mid current speed (m/s) (50-year)	0.56
Surface current speed (m/s) (Normal Conditions)	Mean: 0.24 Max: 1.71 P25: 0.13 P50: 0.21 P75: 0.32
Surface current speed (m/s) (1-year)	0.74
Surface current speed (m/s) (50-year)	1.66
Wind speed (150 m above sea level) (m/s) mean	9.2
Wind speed (150 m above sea level) (m/s) max	39.3
Wind speed (150 m above sea level) (m/s) P95	16.7
Wind direction (150 m above sea level) (°) mean	313.3
Wind speed (10 m above sea level) – Weibull parameters	A = 8.60; k = 2.20
Wind speed (150 m above sea level) – Weibull parameters	A = 11.06; k = 2.38
Extreme 10-min wind speed (150 m above sea level) (m/s) (1-year)	19.82
Extreme 10-min wind speed (150 m above sea level) (m/s) (50-year)	41.73
Extreme 10-min wind speed (150 m above sea level) (m/s) (100-year)	45.50
Normal Sea State (NSS)	See relevant report section
Extreme Sea State (ESS) – Significant wave height (1-year) (m)	2.5
ESS – Peak wave period (1-year) (s)	$6.2 \leq 8.0$

ESS – Individual maximum wave height (1-year) (m)	4.7
ESS – Period of maximum wave height (1-year) (s)	$5.6 \leq 7.2$
ESS – Significant wave height (50-year) (m)	9.4
ESS – Peak wave period (50-year) (s)	$12.1 \leq 15.6$
ESS – Individual maximum wave height (50-year) (m)	17.4
ESS – Period of maximum wave height (50-year) (s)	$10.9 \leq 14.0$
Severe Sea State	See relevant report section

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Distribution parameters: location = 0.324224; scale = 0.032306; shape = 0.176208 44

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1 Introduction

This report appendix has been prepared by the IDEA-IRL project as one of the deliverables for WP1 of the project. It primarily serves as an Appendix to the WP1 D1 Summary report [1]. Specifically, this technical appendix delivers a preliminary met ocean site characterisation study of reference site 4, selected based on a review of the global pipeline of floating offshore wind projects.

1.1 Scope of the report

The scope of this report is to conduct a preliminary FEED Metocean Study for IDEA-IRL reference site 4. The results presented herein can only be considered as a pre-FEED study and are aimed to serve as input for preliminary design. Section 2 gives an overview of the data sources utilised; Section 3 provides the results of a preliminary metocean site characterisation. This includes the production of normal and extreme conditions of water levels, currents, wind and wave conditions, alongside operability statistics. Section 4 provides conclusions and recommendations.

Reference site 4 was chosen in consultation with IEA Wind Task 49 as a global site for consideration and development of the global offshore wind research. It utilises the location of the proposed Ulsan Floating Offshore Wind Farm, which is approximately 60 km east of the Ulsan Port in South Korea(Figure 1-1). The site is in development by a consortium of companies under a joint venture of offshore wind company Corio Generation, TotalEnergies, and SK ecoplant. It is expected to reach a capacity of 1.5 GW at full capacity.

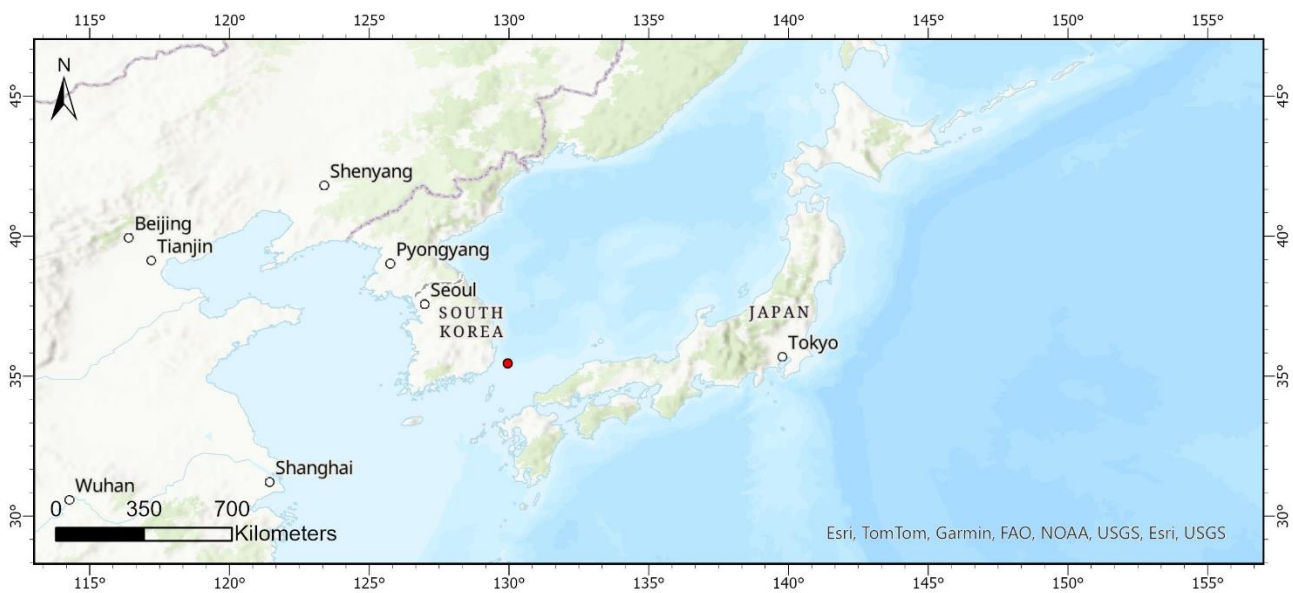


Figure 1-1 – Ulsan data collation point, chosen as IDEA-IRL reference site 4

2 Data Sources

The coordinates of the Ulsan Floating Offshore wind farm available on the 4C Offshore Database is used as a reference point for metocean data compilation (35.449°, 129.949°). The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 climate reanalysis model was identified as the best model to provide numerical datasets for wind and wave variables for this study. ERA5 is the fifth-generation atmospheric reanalysis model produced by the Copernicus Climate Change Service (C3S) at the ECMWF and is based on the 2016 version of the integrated forecasting system (C3S, 2017). It produces data from 1950 to the present. Its outputs include atmospheric, ocean wave and land surface data. The reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. The horizontal resolution of the model is 0.25° x 0.25° (atmosphere variables) and 0.5° x 0.5° (ocean waves variables). Parameters of interest for this study are displayed in Table 2-1. Data from the closest grid point to the site were downloaded and analysed. A detailed description of the model and each parameter can be found on the ECMWF website [2].

Table 2-1 Wind and wave variables obtained from the ERA5 model

ERA5 code	Parameter	Metocean discipline	Units	Time frame	Temporal resolution (hours)	Data point
hmax	Maximum individual wave height	Wave	m	1979 – 2024	1	130°, 35.5°
pp1d	Peak wave period	Wave	s	1979 – 2024	1	130°, 35.5°
swh	Significant wave height of combined wind waves and swell	Wave	m	1979 – 2024	1	130°, 35.5°
mwd	Mean wave direction	Wave	degrees	1979 – 2024	1	130°, 35.5°
u10	10 m u-component of wind	Wind	m/s	1979 – 2024	1	130°, 35.5°
v10	10 m v-component of wind	Wind	m/s	1979 – 2024	1	130°, 35.5°
u100	100 m u-component of wind	Wind	m/s	1979 – 2024	1	130°, 35.5°
v100	100 m v-component of wind	Wind	m/s	1979 – 2024	1	130°, 35.5°

In addition, data and analysis conducted as a part of the IEA Wind Task 49 [3] on the Ulsan site has been gleaned from the report on that research project. The following table presents the datasets used in that analysis:

Table 2-2 – IEA Wind Task 49 – Ulsan Metrocean Analysis Data Sources [3]

Source	Parameter	Metocean discipline	Units	Time frame	Temporal resolution (hours)	Location
Ulsan Buoy	Wind speed @5m	Wind	m/s	2016 – 2022	1	N/A
Ulsan Buoy	Wind direction	Wind	deg	2016 – 2024	1	N/A
ERA5	100 m u-component of wind	Wind	m/s	1980 – 2022	1	130.25°, 35.25°
ERA5	100 m v-component of wind	Wind	m/s	1980 - 2022	1	130.25°, 35.25
MERRA-2	Wind Speed @50m	Wind	m/s	2010-2022	1	130°, 35.5°
MERRA-2	Wind Direction	Wind	deg	2010-2022	1	130°, 35.5°

In the IEA Wind Task 49 report [3] details about the wave data used is not specified, however it was observed that from the Ulsan Buoy time series that there is also data provided for significant wave height, maximum wave height, wave period and mean wave direction. It is stated that the Ulsan Buoy dataset was obtained from the Korea Meteorological Administration, the location of the buoy is N35.345, E129.841.

A gap analysis was conducted to study the extent of missing values and suitability of the dataset for gap filling. In Figure 2-1 to Figure 2-6 the timeseries plots of the Ulsan Buoy measurements are shown. There are significant gaps in the years 2021, 2022 and 2023 and only a small portion of 2015 is documented. Table 2-3 shows the gaps for each variable in each year provided as a percentage of the total time in the year. Due to the limited duration and significant gaps in the Ulsan Buoy dataset, it is considered unsuitable for extreme value analysis.

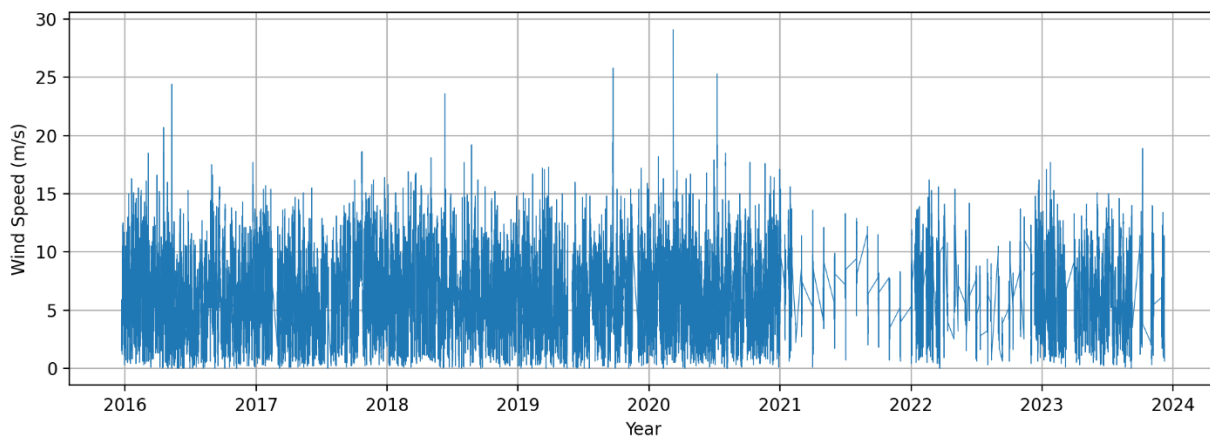


Figure 2-1 – Ulsan Buoy wind speed timeseries

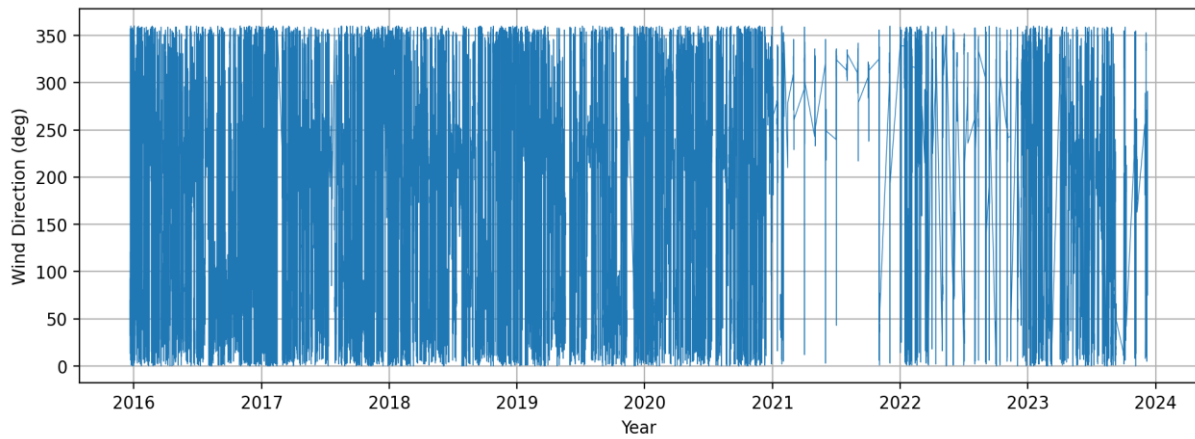


Figure 2-2 – Ulsan Buoy wind direction timeseries

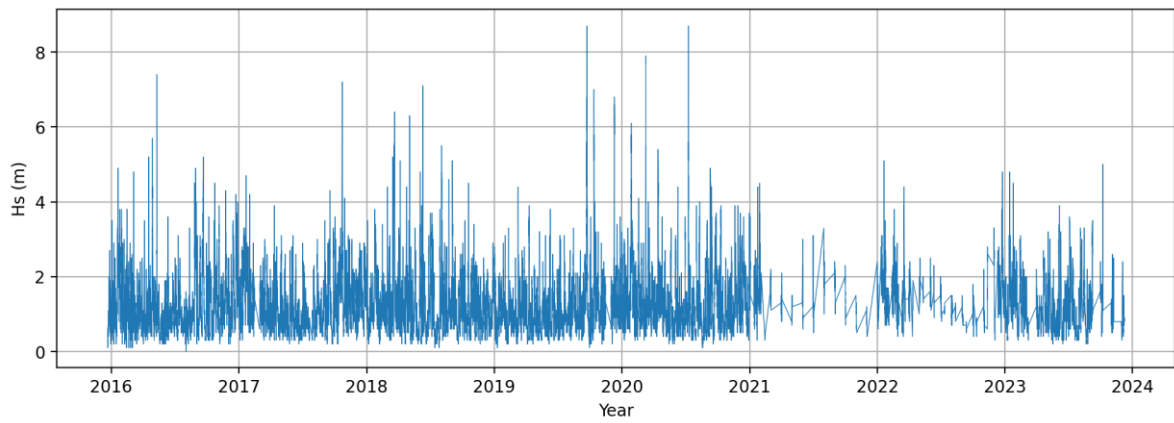


Figure 2-3 - Ulsan Buoy significant wave height timeseries

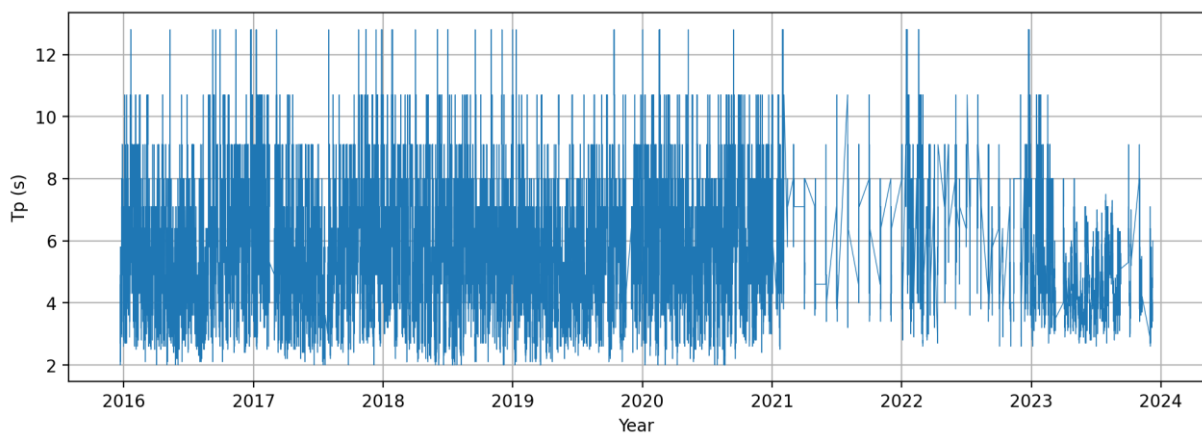


Figure 2-4 - Ulsan Buoy peak wave period timeseries

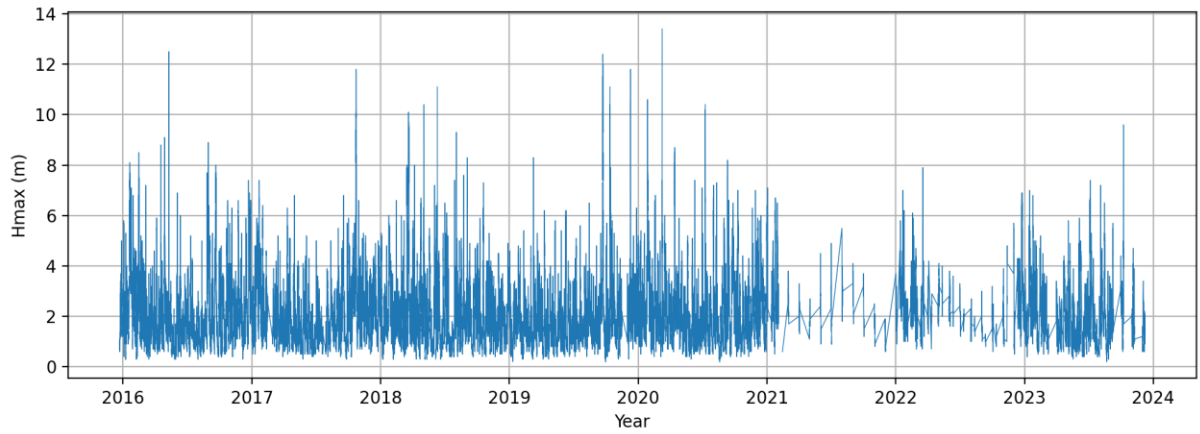


Figure 2-5 - Ulsan Buoy maximum individual wave height timeseries

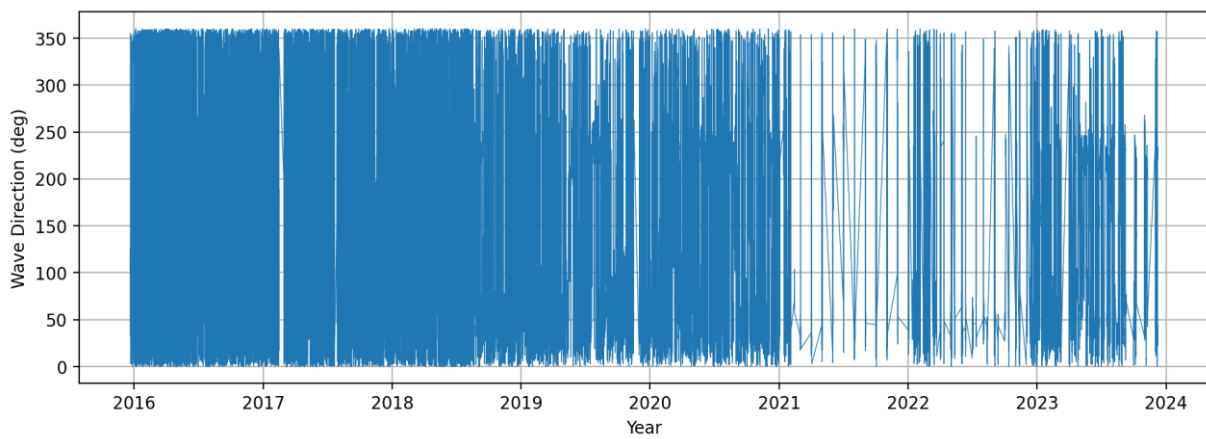


Figure 2-6 - Ulsan Buoy wave direction timeseries

Table 2-3 - Ulsan Buoy gaps and missing data as percentage of the total hours in each year

Year	Wind speed	Wind direction	Hs	Tp	Hmax	Wave direction
2015	97.3	97.3	97.5	97.4	97.5	97.4
2016	0.2	0.2	1.6	1.2	1.7	1.2
2017	6.3	6.3	6.4	6.4	6.4	6.3
2018	2.4	2.4	2.6	2.5	2.6	2.5
2019	11.3	11.3	6.8	6.8	6.8	6.8
2020	0.8	4.0	1.2	1.1	0.7	1.1
2021	89.9	89.9	88.1	88.1	88.3	88.1
2022	69.5	69.5	69.5	69.5	69.6	69.5
2023	38.8	38.8	38.9	38.8	38.8	38.8

The Ulsan buoy wind measurements were taken at 4.3 m above sea level. To observational and numerical wind and wave datasets the Ulsan Buoy wind speed data was first scaled to 10, 100 and 150 m using the power scaling law with an exponent of 0.14, while the 100m ERA5 dataset was scaled to 150 m. Quantile-Quantile (QQ) plots were then prepared, and in an ideal scenario the two datasets would have a ratio of slope equal to 1. For the wind datasets, the 10 m above sea level dataset had a slope of 1.14, and the 100 and 150m datasets had an equal slope of 1.31. It can be seen from Figure 2-7 and Figure 2-8 that the ERA5 dataset overpredicts the wind speed at both altitudes. The difference becomes wider at higher speeds. With these findings, the ERA5 data for wind speed was then corrected to remove any biases. The method used is discussed in the proceeding text.

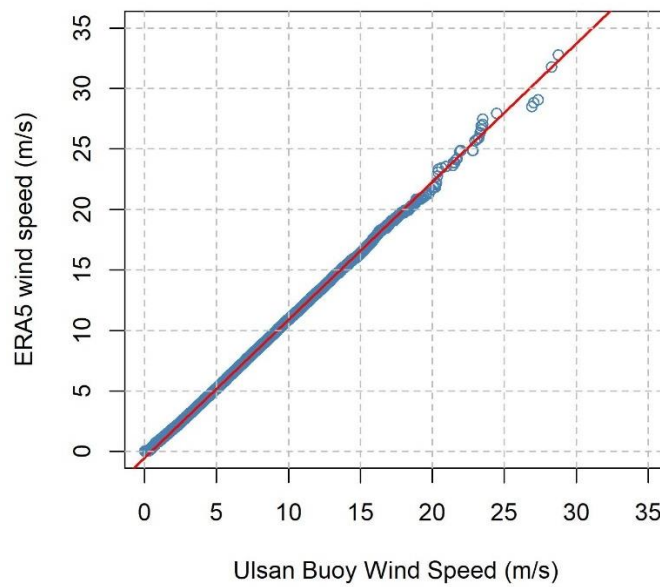


Figure 2-7 – QQ plot for wind speed comparing the ERA5 and Ulsan Buoy datasets (10m above sea level)

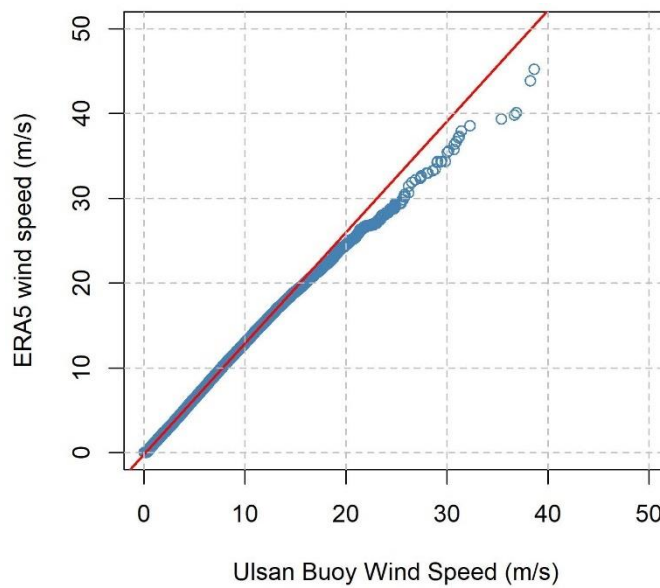


Figure 2-8 – QQ plot for wind speed comparing the ERA5 and Ulsan Buoy datasets (100m above sea level)

The QQ plots for significant wave height and peak wave period are illustrated in Figure 2-9 and Figure 2-10 respectively. The significant wave height plot shows good correlation between the measured and modelled datasets, with a slope value equalling 0.99, whereas the peak wave period plot shows some possible erroneous values in the measured dataset. These plots suggest that the ERA5 Hs is directly suitable for gap filling the measured dataset, while the peak wave period is unsuitable, given that there appears to be unrealistic measurements taken.

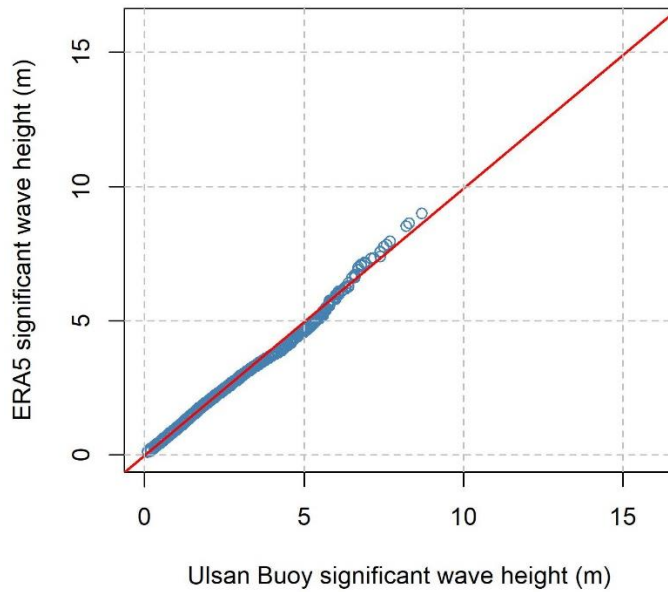


Figure 2-9 - QQ plot for significant wave height comparing the ERA5 and Ulsan Buoy datasets

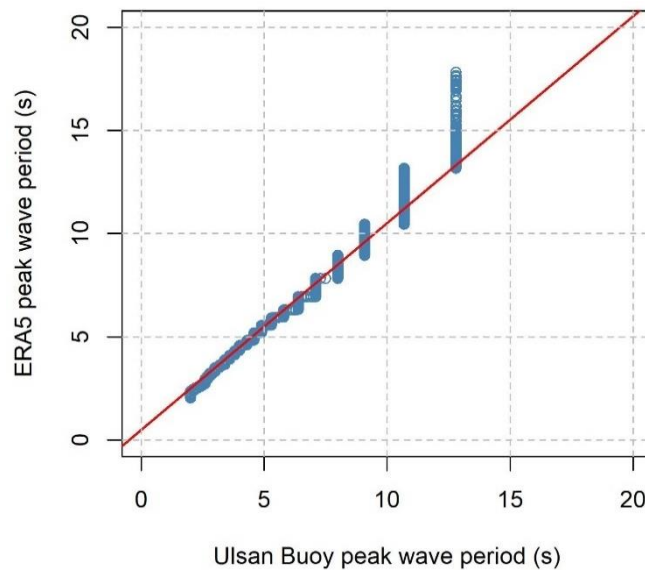


Figure 2-10 - QQ plot for peak wave period comparing the ERA5 and Ulsan Buoy datasets

In summary, the ERA5 wind speeds have been corrected using a mean bias correction, while the measured significant wave height dataset appears suitable for gap filling using the modelled ERA5 data due to the good agreement between the two datasets, the resultant set of wave conditions (Hs and Tp) showed unrealistic Hs and Tp combinations, therefore for analysis the ERA5 wave conditions were assumed. Further, the measured peak wave period dataset shows a level of uncertainty in the accuracy of the measurements, therefore the modelled peak wave period dataset is better used in place of the measured dataset.

Due to the lack of availability of measured water level and tidal current data for the site of interest, modelled data from the HYCOM Global Ocean Forecasting System (GOFS) 3.1 model was acquired and analysed. This model is a global-scale forecasting system that uses HYCOM as its core model. It is a reanalysis and forecast 3D physics model with a cartesian grid. Grid spatial resolution is 1/12 degrees in both longitude and latitude. It should be noted that it is not currently known whether the GOFS model has been specifically validated at or near the location of the OWF using in situ datasets, therefore currents and water levels should be interpreted with caution until in situ measured data is collected. Data from the model grid point closest to the centre of the site was downloaded and utilised (Longitude: 129.92°, Latitude: 35.44°) (Figure 2-11).

Table 2-4 Parameters utilised from the GOFS 3.1 model

Parameter	Units	Time frame	Temporal resolution (hours)
Surface elevation	m	1994 – 2015	3
Bottom-water u component	m/s	1994 – 2015	3
Bottom-water v component	m/s	1994 – 2015	3
Mid-water u component	m/s	1994 – 2015	3
Mid-water v component	m/s	1994 – 2015	3
Surface-water u component	m/s	1994 – 2015	3
Surface-water v component	m/s	1994 – 2015	3

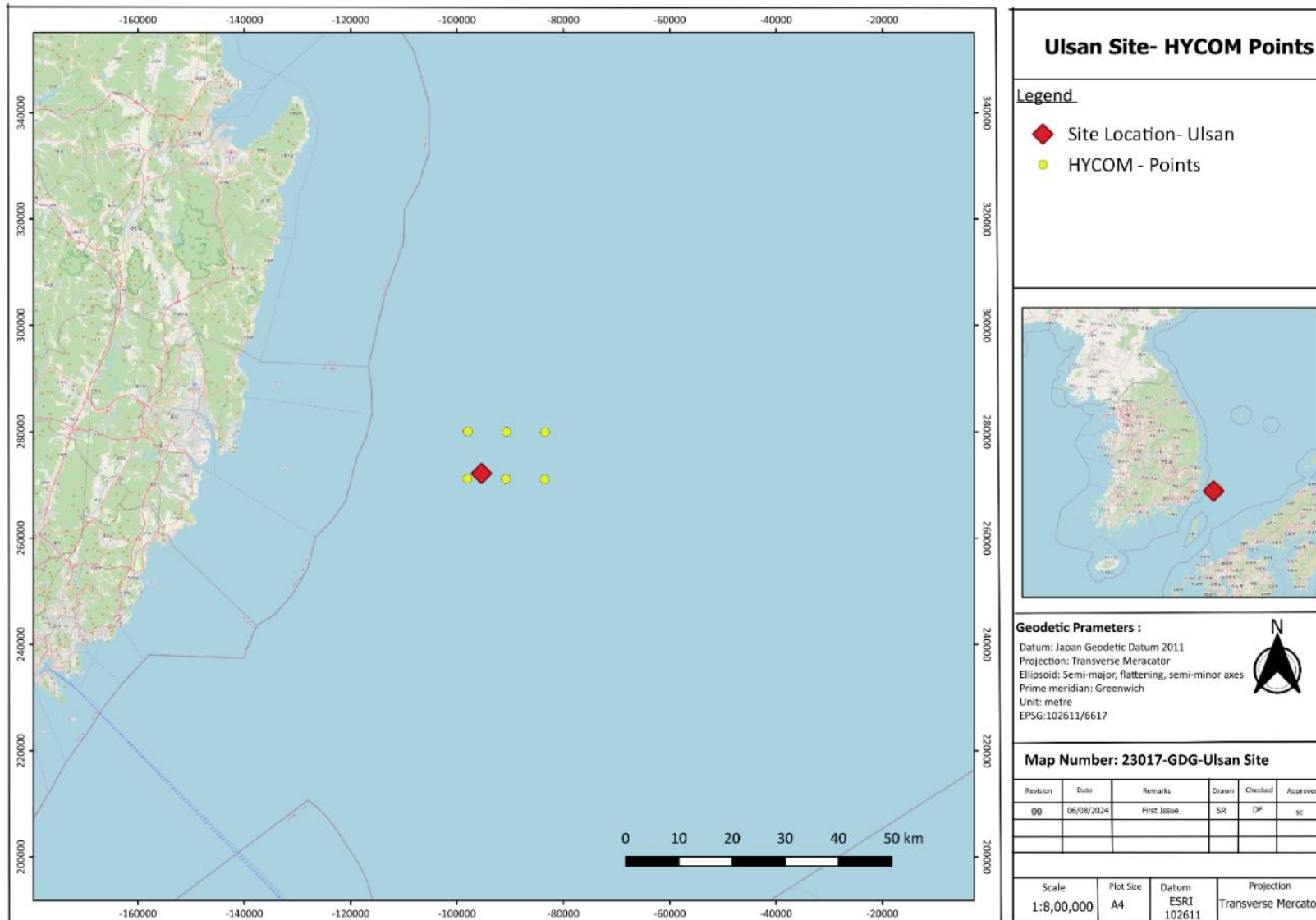


Figure 2-11: HYCOM'S GOFS (3.1) data points for currents and water level analysis of the site.

3 Preliminary Metocean Site Conditions Assessment

3.1 Water Levels

The Ulsan site, located in the Sea of Japan, is characterized by small diurnal and semi-diurnal variations that is a result of its semi-enclosed geography. The interaction of seasonal atmospheric pressure changes, monsoon seasons, temperature fluctuations, and the Tsushima Current results in pronounced annual shifts in sea level and tidal behaviour. This situation contrasts with Irish waters and other reference wind farm sites, where tidal forces from large water bodies such as the Atlantic Ocean result in larger diurnal and semi-diurnal tides and less pronounced annual fluctuations.

A 22-year time series of water levels was extracted from the three-dimensional HYCOM re-analysis model, which is part of the Global Ocean Forecasting System (GOFS 3.1). The data obtained has a 3-hour temporal resolution and was interpolated to a 1-hour to allow for a more detailed analysis. It is understood that 3-hour resolution is not ideal for studying the semi-diurnal and diurnal tides as it can result in a lower accuracy of the tidal constituents of those with short periods. The temporal range of the data is between 1994 and 2015. The sea surface height datum level for the HYCOM model is understood to measured relative to a global mean sea surface height which is close to zero.

A number of gaps were identified in the HYCOM dataset, consisting of approximately 1 to 4 % of the dataset on an annual basis. The majority of the gaps had a duration of 5 hours. Gaps in the data present a challenge for performing a constituent analysis due to the reduced accuracy in decomposing the timeseries and results. However, upon studying the entire timeseries (Figure 3-1) of the sea surface height, an annular trend was identified and found to have a much more significant amplitude than the diurnal and semi-diurnal variations. For this reason, the HYCOM dataset was interpolated for gaps up to 5 hours, which slightly reduces the accuracy of the diurnal and semi-diurnal constituents at this site but allowed us to gather a 1-year (2004) uninterrupted sea surface height data set and study the larger amplitude annular constituents observed at this location.

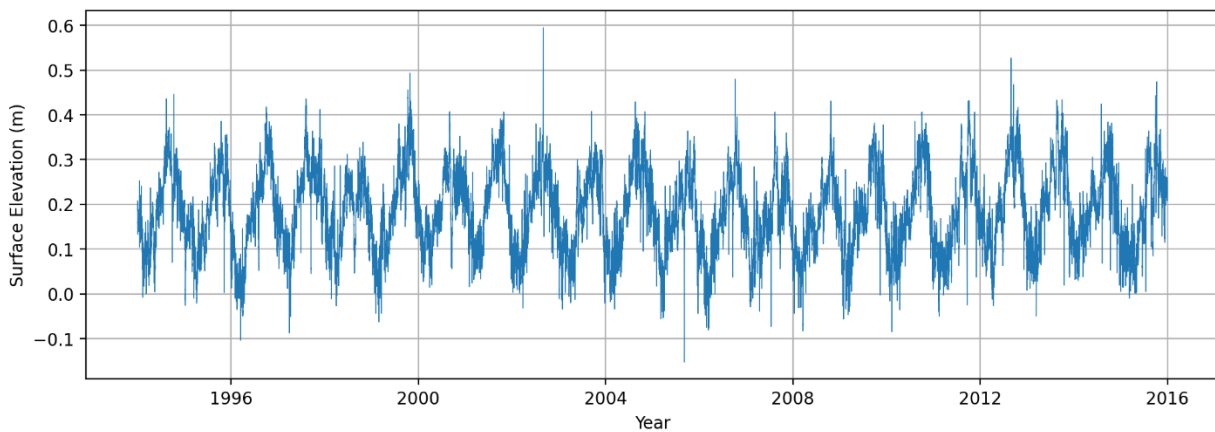


Figure 3-1 – HYCOM GOFS 3.1 model sea surface height timeseries

A tidal harmonic analysis was performed on the uninterrupted data to separate tidal components into astronomical and meteorological components using the MIKE 21 software suite. Figure 3-2 illustrates one spring-neap cycle decomposed into astronomical and meteorological (residual) components. The figure demonstrates the small diurnal and semi-diurnal changes in sea surface height at the location.

Figure 3-3 illustrates an annular decomposition for the year of 1994, and further demonstrates that the tidal patterns at this location are predominantly influenced by annual astronomical cycles rather than daily diurnal or semi-diurnal tides.

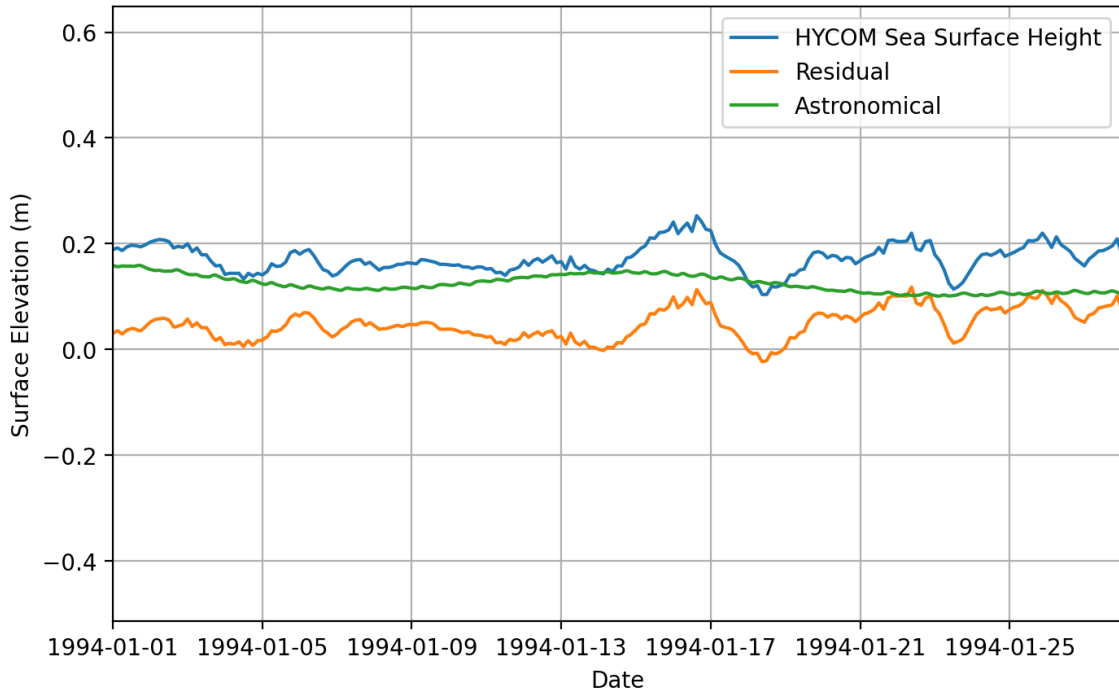


Figure 3-2 – Decomposition of sea surface height for one spring-neap cycle.

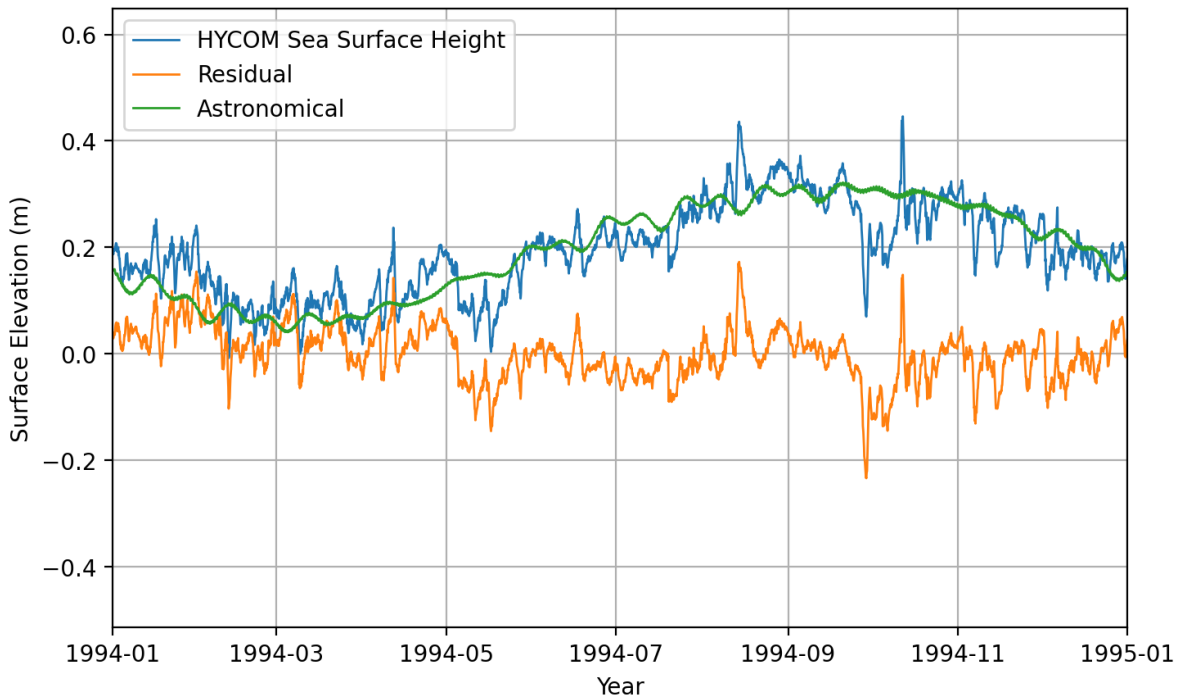


Figure 3-3 – Decomposition of sea surface height for one full year between 1994 to 1995

Insights from the MIKE 21 model indicated that the highest tidal constituent amplitudes at Ulsan were associated with the SA and SSA (solar annular and semi-annular). These results emphasize the significance of the longer-period astronomical cycles in influencing the site’s tidal behaviour.

A 22-year dataset was predicted using the tidal harmonic results, from which long-term water level parameters ranging from Highest Astronomical Tide (HAT) to Lowest Astronomical Tide (LAT) were produced. Design water level parameters, ranging from High Still Water Level (HSWL) to Low Still Water Level (LSWL) are presented in Table 3-1.

Extreme positive and negative surge values were calculated from this 22-year modelled dataset. A generalised extreme value (GEV) methodology was chosen as the best-fitting analysis to calculate the extreme surge values for this location. A peaks-over-threshold approach was chosen to extract discrete extreme events over the 22-year time period as input into the general extreme value analysis. Long-term global sea level rise is given by the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report 2014 [4].

Table 3-1 Statistics of water levels based on 22-year dataset

Component	Statistic	Water Level (mMSL)
Total	max	0.60
	min	-0.15
	mean	0.18
	standard deviation	0.09
Tide	max	0.33
	min	0.03
	mean	0.20
	standard deviation	0.09
Residual	max	0.30
	min	-0.46
	mean	-0.01
	standard deviation	0.06

Table 3-2 Design Water Level

Parameter	Water Levels (mMSL)
High Still Water Level (50-year)	1.25
High Still Water Level (1-year)	0.28
Long-term Sea Level Rise	0.63
Positive storm surge (50-year)	0.49
Positive storm surge (1-year)	0.15
Highest Astronomical Tide (HAT)	0.13
Mean High Water Spring (MHWS)	0.00
Mean High Water Neap (MHWN)	0.00
Mean Sea Level (MSL)	0.00
Mean Low Water Neap (MLWN)	-0.00
Mean Low Water Spring (MLWS)	-0.00
Lowest Astronomical Tide (LAT)	-0.17
Negative storm surge (1-year)	-0.16
Negative storm surge (50-year)	-0.44
Low Still Water Level (1-year)	-0.32
Low Still Water Level (50-year)	-0.60

3.2 Normal Wind Conditions

The ERA5 provides wind speed and direction values at heights of 10 m and 100 m above sea level. The spatial resolution is 0.25° x 0.25° and temporal resolution is 1 hour. 10 m and 100 m timeseries was downloaded at 130°, 35.5° for a 45-year period (1979 to 2024). As discussed previously, the ERA5 dataset was corrected using the Ulsan buoy measurements and mean bias correction method. Both the 10 m and 100 m datasets were corrected, while the Ulsan measurements were extrapolated to the required heights above sea level prior to bias correction. The extrapolation method used prior to correction is discussed in the following paragraph.

A 15 MW reference turbine is assumed. Based on the technical report produced by IEA Wind TCP Task 39 [5], hub height is therefore assumed to be 150 m. The corrected ERA5 1-hour wind speeds at 100 m above sea level were extrapolated to hub height (150 m) using the power law with the shear exponent value 0.14 as recommended by IEC 61400-3-1: 2019 [6] for normal wind conditions:

$$V_{power\ law} = V_{ref} * \left(\frac{z}{z_{ref}}\right)^\alpha$$

Where $V_{power\ law}$ and V_{ref} are the wind speeds at z and z_{ref} respectively, and α is the shear exponent.

150 m and 10 m wind rose are displayed in Figure 3-7 and Figure 3-8 respectively. Monthly, annual and overall statistics of 10 m and 150 m wind speeds are presented in Table 3-3 to Table 3-6.

In Figure 3-4 to Figure 3-6 the wind roses prepared in the IEA wind task 49 report for the Ulsan site are presented.

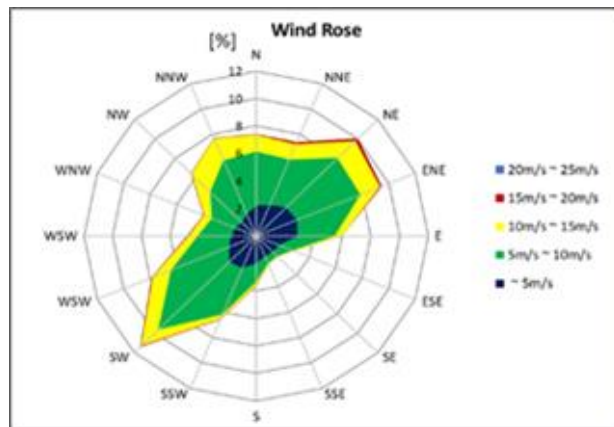


Figure 3-4 – Wind rose at 4.3 m above sea level (Ulsan Buoy Dataset) [3]

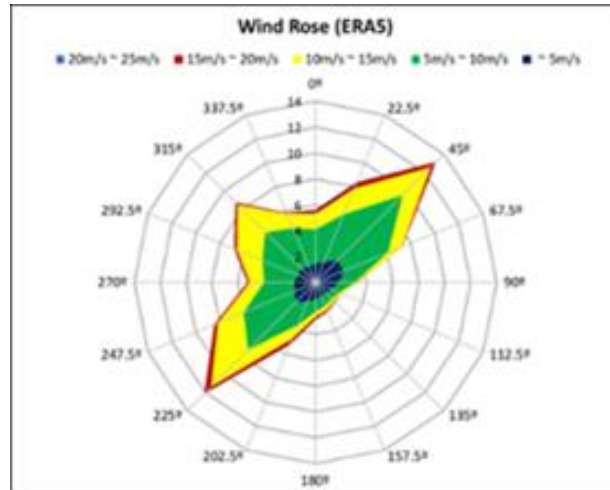


Figure 3-5 - ERA5 Wind Rose at 50m above sea level [3]

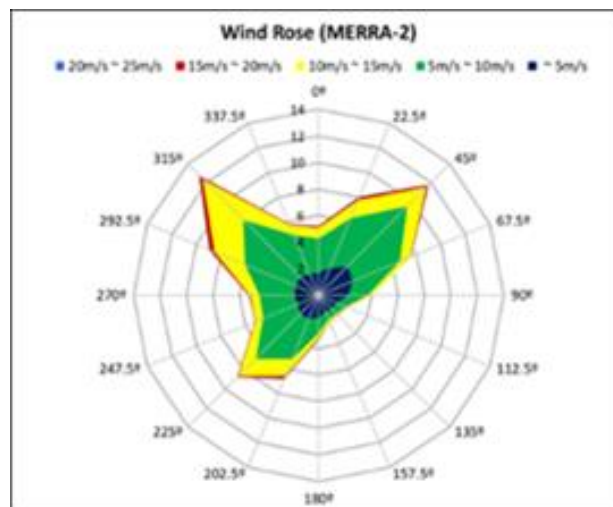


Figure 3-6 MERRA-2 Wind Rose at 100m above sea level [3]

Wind rose based on 1979 to 2024 dataset

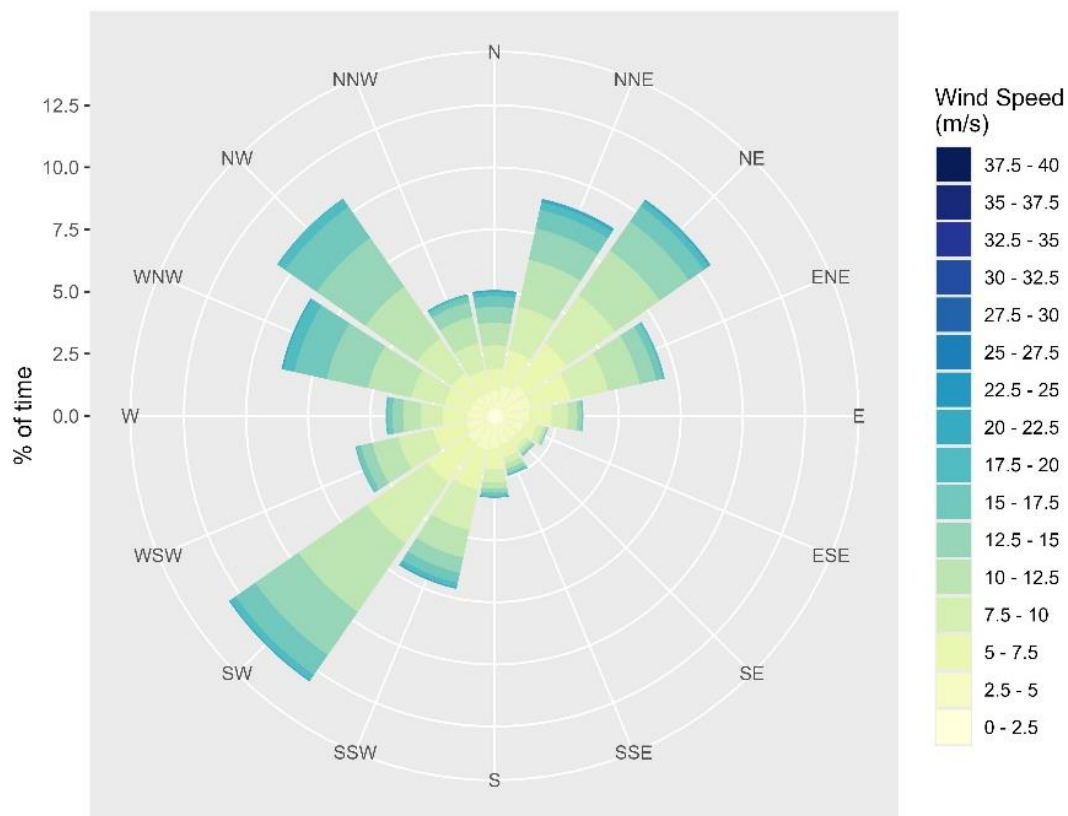


Figure 3-7 Rose plot of 1-hour averaged wind speed and direction at hub height (150 m) from 1979 to 2024 corrected dataset

Table 3-3 Monthly wind statistics from the corrected ERA5 at 150 m hub height (1979 – 2024)

Data type	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
wind speed at hub height (m/s)	mean	10.9	10.1	9.6	9.2	8.2	7.6	8.4	8.3	8.8	8.8	9.4	10.7
	median	11.2	10.3	9.6	9.0	8.0	7.2	8.1	8.1	8.5	8.5	9.3	10.8
	standard deviation	4.4	4.5	4.4	4.3	4.0	3.9	4.1	4.2	4.6	4.4	4.4	4.3
	max	24.9	29.5	24.8	27.1	22.3	22.3	29.5	39.3	35.4	29.3	26.3	23.2
	min	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0
	P25	7.8	6.7	6.2	6.0	5.1	4.5	5.3	5.1	5.3	5.5	6.1	7.6
	P50	11.2	10.3	9.6	9.0	8.0	7.2	8.1	8.1	8.5	8.5	9.3	10.8
	P75	14.1	13.4	12.9	12.2	11.0	10.3	11.2	11.1	11.8	11.9	12.6	13.9
	P90	16.5	15.9	15.5	15.1	13.7	13.0	14.0	13.8	14.8	14.8	15.3	16.3
	P95	17.6	17.2	16.9	16.7	15.4	14.7	15.6	15.5	16.9	16.4	16.6	17.4
wind direction (°)	mean	313.0	319.2	324.2	253.2	225.5	193.8	212.7	155.2	38.1	6.3	316.6	306.6

Table 3-4 Annual and overall wind statistics from corrected ERA5 at 150 m hub height (1979 – 2024)

Year	wind speed at hub height (m/s)										wind direction (°)
	mean	median	standard deviation	max	min	P25	P50	P75	P90	P95	mean
1979	9.1	9.0	4.5	27.9	0.1	5.7	9.0	12.1	15.2	16.9	301.7
1980	9.4	9.2	4.7	26.6	0.0	5.7	9.2	12.9	15.8	17.7	309.3
1981	9.0	8.8	4.3	22.7	0.1	5.8	8.8	11.9	15.1	16.6	295.1
1982	8.6	8.3	4.3	26.2	0.1	5.3	8.3	11.6	14.6	16.0	304.2
1983	9.4	9.3	4.5	24.5	0.1	5.8	9.3	12.7	15.3	16.9	310.7
1984	8.9	8.6	4.3	21.9	0.1	5.5	8.6	11.9	14.9	16.4	321.4
1985	9.1	8.9	4.5	28.8	0.0	5.7	8.9	12.3	15.2	16.8	306.1
1986	8.6	8.2	4.2	28.0	0.1	5.3	8.2	11.5	14.4	15.8	308.4
1987	9.1	8.7	4.5	39.3	0.1	5.7	8.7	12.2	15.3	16.9	291.1
1988	9.5	9.5	4.2	21.9	0.1	6.4	9.5	12.5	14.9	16.4	328.6
1989	9.0	8.7	4.2	21.9	0.1	6.0	8.7	12.0	14.9	16.6	347.1
1990	9.3	9.2	4.5	22.3	0.1	5.8	9.2	12.5	15.3	17.0	299.2
1991	9.3	8.9	4.7	29.5	0.1	5.7	8.9	12.9	16.1	17.2	330.5
1992	9.3	9.2	4.4	24.9	0.1	6.1	9.2	12.5	15.1	16.7	321.5
1993	9.0	8.6	4.5	24.8	0.1	5.5	8.6	12.2	15.2	16.8	319.0
1994	9.1	9.0	4.3	25.4	0.1	5.8	9.0	12.2	14.8	16.4	307.8
1995	9.5	9.6	4.1	26.3	0.1	6.4	9.6	12.3	14.8	15.9	286.9
1996	8.9	8.7	4.2	21.1	0.0	5.5	8.7	11.9	14.7	16.3	308.3
1997	9.3	9.0	4.5	23.2	0.1	5.7	9.0	12.5	15.5	17.0	300.2
1998	9.2	9.3	4.4	24.8	0.1	6.0	9.3	12.3	15.1	16.8	336.6
1999	9.2	9.0	4.4	23.3	0.1	5.8	9.0	12.5	15.3	16.9	317.2
2000	9.0	8.6	4.5	24.8	0.1	5.5	8.6	12.3	15.2	16.7	308.5
2001	9.5	9.6	4.3	22.5	0.1	6.4	9.6	12.6	15.2	16.8	326.8
2002	9.5	9.3	4.5	24.8	0.1	6.0	9.3	13.0	15.7	17.0	309.7
2003	9.0	8.8	4.4	32.3	0.1	5.5	8.8	12.2	15.1	16.3	350.5
2004	9.1	8.8	4.4	28.9	0.1	5.7	8.8	12.2	15.2	16.6	308.5
2005	9.6	9.5	4.4	29.5	0.1	6.2	9.5	12.7	15.3	17.0	299.4
2006	9.2	9.2	4.5	28.6	0.1	5.6	9.2	12.5	14.9	16.5	332.8
2007	9.0	8.9	4.2	22.9	0.1	5.8	8.9	11.9	14.4	15.8	320.5
2008	9.0	9.0	4.0	21.7	0.1	5.8	9.0	11.9	14.3	15.5	325.7
2009	9.3	9.2	4.5	23.2	0.1	5.8	9.2	12.5	15.5	16.9	317.6
2010	9.4	9.2	4.6	26.4	0.1	5.7	9.2	12.9	15.7	17.0	299.1
2011	9.7	9.7	4.4	22.5	0.1	6.5	9.7	12.8	15.6	17.2	319.1
2012	9.5	9.4	4.3	26.3	0.1	6.4	9.4	12.5	15.2	16.6	323.4
2013	9.5	9.3	4.4	24.0	0.1	6.1	9.3	12.8	15.5	16.8	297.3
2014	9.1	8.9	4.4	25.5	0.1	5.7	8.9	12.2	15.5	17.0	334.3
2015	8.9	8.5	4.5	30.5	0.1	5.5	8.5	12.1	15.0	16.7	332.1
2016	8.8	8.6	4.4	27.1	0.1	5.4	8.6	11.6	14.7	16.6	326.1
2017	9.2	9.0	4.3	24.8	0.1	5.8	9.0	12.3	15.1	16.3	301.8
2018	9.2	8.9	4.6	29.3	0.1	5.8	8.9	12.5	15.2	16.8	315.9
2019	8.7	8.6	4.3	29.5	0.1	5.4	8.6	11.7	14.3	15.9	317.2
2020	9.3	9.2	4.5	35.4	0.1	5.8	9.2	12.5	15.2	17.0	304.6
2021	9.3	9.0	4.5	24.6	0.1	5.8	9.0	12.5	15.6	17.0	316.0
2022	9.4	9.3	4.3	31.7	0.1	6.0	9.3	12.3	14.9	16.6	310.1
2023	9.1	8.8	4.3	24.7	0.0	5.8	8.8	12.1	14.9	16.4	283.5
Overall	9.2	9.0	4.4	39.3	0.0	5.8	9.0	12.3	15.2	16.7	313.3

Wind rose based on 1979 to 2024 dataset

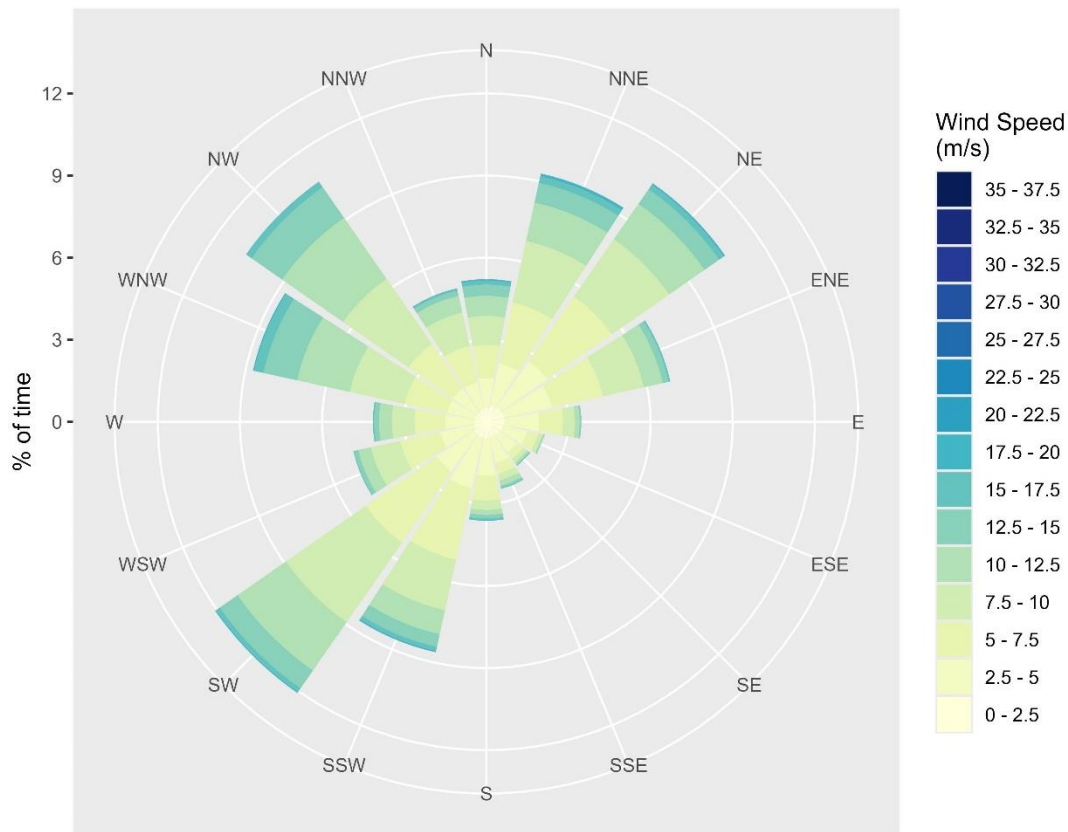


Figure 3-8 Rose plot of 1-hour averaged wind speed and direction at hub height (10 m) from corrected 1979 to 2024 dataset

Table 3-5 Monthly wind statistics from ERA5 at 10 m above sea level (1979 – 2024)

Data type	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
wind speed at 10 m above sea level (m/s)	mean	8.8	8.1	7.7	7.3	6.5	6.0	6.7	6.6	7.0	7.0	7.5	8.6
	median	8.9	8.1	7.6	7.1	6.2	5.6	6.3	6.3	6.6	6.6	7.3	8.6
	standard deviation	3.7	3.7	3.7	3.6	3.3	3.2	3.4	3.5	3.9	3.7	3.6	3.6
	max	22.1	26.6	22.0	24.3	19.6	19.6	26.6	36.4	32.6	26.2	23.6	20.2
	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	P25	6.1	5.2	4.9	4.6	4.0	3.5	4.1	4.0	4.1	4.3	4.7	6.0
	P50	8.9	8.1	7.6	7.1	6.2	5.6	6.3	6.3	6.6	6.6	7.3	8.6
	P75	11.4	10.8	10.3	9.7	8.7	8.1	8.9	8.8	9.4	9.5	10.1	11.2
	P90	13.5	13.0	12.5	12.2	11.0	10.4	11.2	11.1	11.9	11.9	12.4	13.3
P95	14.6	14.2	13.9	13.7	12.4	11.8	12.6	12.5	13.9	13.4	13.6	14.4	
wind direction (°)	mean	312.8	319.0	324.5	248.7	217.5	185.0	207.2	149.9	37.5	5.9	316.4	306.3

Table 3-6 Annual and overall wind statistics from ERA5 at 10 m above sea level (1979 – 2024)

Year	wind speed at 10 m above sea level (m/s)										wind direction (°)
	mean	median	standard deviation	max	min	P25	P50	P75	P90	P95	mean
1979	7.3	7.0	3.7	25.0	0.0	4.3	7.0	9.6	12.3	13.9	302.0
1980	7.5	7.2	3.9	23.9	0.0	4.4	7.2	10.3	12.9	14.6	309.3
1981	7.2	6.9	3.6	20.0	0.0	4.5	6.9	9.5	12.2	13.6	294.7
1982	6.8	6.5	3.5	23.3	0.0	4.1	6.5	9.3	11.7	13.1	304.3
1983	7.5	7.3	3.7	22.0	0.0	4.5	7.3	10.1	12.4	13.8	310.9
1984	7.1	6.8	3.6	18.8	0.0	4.3	6.8	9.5	12.0	13.4	321.9
1985	7.3	7.0	3.7	26.0	0.0	4.4	7.0	9.9	12.3	13.7	306.8
1986	6.8	6.4	3.5	25.2	0.0	4.1	6.4	9.2	11.6	12.9	308.5
1987	7.3	6.9	3.8	36.4	0.0	4.4	6.9	9.7	12.4	13.9	290.9
1988	7.6	7.4	3.5	18.9	0.0	5.0	7.4	10.0	12.0	13.4	328.7
1989	7.2	6.9	3.5	19.1	0.0	4.6	6.9	9.6	12.0	13.5	347.9
1990	7.4	7.2	3.7	19.4	0.0	4.5	7.2	10.0	12.4	14.0	299.2
1991	7.5	7.0	3.9	26.6	0.0	4.4	7.0	10.3	13.1	14.2	331.4
1992	7.4	7.2	3.6	22.2	0.0	4.7	7.2	10.0	12.2	13.7	322.1
1993	7.2	6.8	3.7	22.0	0.0	4.3	6.8	9.7	12.3	13.7	319.2
1994	7.3	7.1	3.6	23.0	0.0	4.5	7.1	9.7	11.9	13.4	308.4
1995	7.5	7.6	3.4	23.6	0.0	5.0	7.6	9.9	11.9	13.0	286.1
1996	7.1	6.9	3.5	18.1	0.0	4.3	6.9	9.5	11.8	13.3	308.5
1997	7.4	7.1	3.8	20.3	0.0	4.4	7.1	10.0	12.5	14.0	299.8
1998	7.4	7.3	3.7	21.9	0.0	4.6	7.3	9.9	12.2	13.7	337.8
1999	7.4	7.1	3.7	20.4	0.0	4.5	7.1	10.0	12.4	13.9	317.6
2000	7.2	6.8	3.7	21.9	0.0	4.3	6.8	9.9	12.3	13.7	308.2
2001	7.6	7.6	3.6	20.0	0.0	5.0	7.6	10.1	12.3	13.8	327.1
2002	7.6	7.3	3.8	22.0	0.0	4.6	7.3	10.4	12.7	14.0	309.5
2003	7.1	6.9	3.7	29.9	0.0	4.3	6.9	9.7	12.2	13.3	351.0
2004	7.3	6.9	3.7	26.0	0.0	4.4	6.9	9.7	12.3	13.6	308.5
2005	7.7	7.4	3.7	26.5	0.0	4.9	7.4	10.2	12.4	14.0	299.0
2006	7.3	7.2	3.7	25.9	0.0	4.3	7.2	10.0	12.0	13.5	333.8
2007	7.2	7.0	3.4	20.3	0.0	4.5	7.0	9.5	11.6	12.9	320.8
2008	7.1	7.1	3.3	19.1	0.0	4.5	7.1	9.5	11.5	12.5	326.1
2009	7.4	7.2	3.8	20.4	0.0	4.5	7.2	10.0	12.5	13.9	317.4
2010	7.5	7.2	3.8	23.4	0.0	4.4	7.2	10.3	12.7	13.9	299.1
2011	7.8	7.7	3.7	19.9	0.0	5.1	7.7	10.2	12.6	14.2	319.3
2012	7.6	7.4	3.6	23.3	0.0	5.0	7.4	10.0	12.3	13.6	323.1
2013	7.5	7.3	3.6	21.1	0.0	4.7	7.3	10.2	12.5	13.7	296.6
2014	7.3	7.0	3.7	23.1	0.0	4.4	7.0	9.7	12.5	14.0	336.1
2015	7.1	6.6	3.7	28.3	0.0	4.3	6.6	9.6	12.0	13.7	332.7
2016	7.0	6.8	3.6	24.3	0.0	4.2	6.8	9.3	11.8	13.5	326.3
2017	7.3	7.1	3.6	22.1	0.0	4.5	7.1	9.9	12.2	13.3	301.5
2018	7.3	7.0	3.8	26.2	0.0	4.5	7.0	10.0	12.3	13.7	316.5
2019	6.9	6.8	3.6	26.4	0.0	4.2	6.8	9.3	11.5	13.0	318.0
2020	7.4	7.2	3.8	32.6	0.0	4.5	7.2	10.0	12.3	14.0	304.2
2021	7.4	7.1	3.7	22.0	0.0	4.5	7.1	10.0	12.6	14.0	316.0
2022	7.5	7.3	3.6	29.4	0.0	4.6	7.3	9.9	12.0	13.5	310.0
2023	7.2	6.9	3.5	22.0	0.0	4.5	6.9	9.6	12.0	13.4	283.1
Overall	7.3	7.1	3.7	36.4	0.0	4.5	7.1	9.9	12.2	13.7	313.6

3.3 Weibull Parameters

Weibull parameters for normal wind speeds have been calculated for the omni-directional conditions for both wind speeds at 10 m and 150 m above sea level. The Weibull scale (A) and shape (k) parameters fitted to the omni-directional wind data are given in Table 3-7, Figure 3-9 and Figure 3-10.

Table 3-7 Weibull fit parameters for wind speed 10mMSL and 150mMSL

Wind speed height above sea level (m)	Weibull parameters	
	Scale (A)	Shape (k)
10	8.60	2.20
150	11.06	2.38

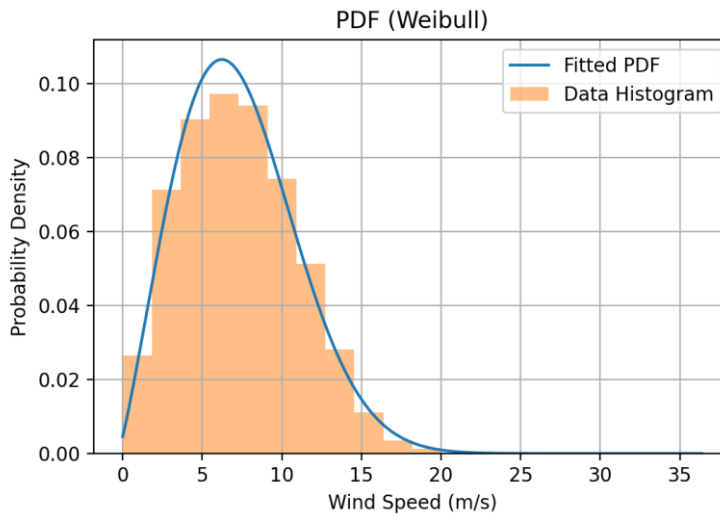


Figure 3-9 Histogram and Weibull fit parameters for wind speed 10 mMSL

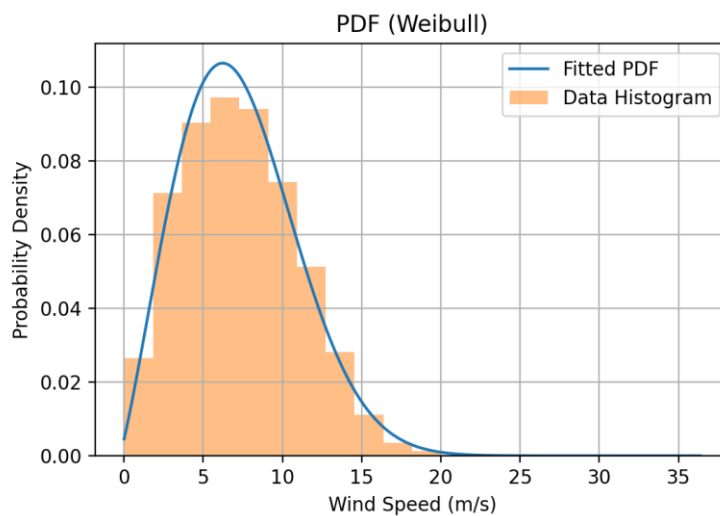


Figure 3-10 Histogram and Weibull fit parameters for wind speed 150 mMSL

3.4 Extreme Wind Conditions

The corrected ERA5 dataset was used to calculate 10-minute extreme wind speeds at hub height. A GEV methodology was chosen as the best-fitting analysis to calculate the extreme values for wind speed at this location. Due to the adequate length of the wave dataset, the block maxima (annual maxima) approach was chosen to extract extreme events over the 45-year time period as input into the general extreme value analysis. The corrected 1-hour averaged wind speed dataset at 100 m above sea level was used as an input to predict 1-, 50- and 100-year return values.

The predicted 1-hour extreme wind speeds at 100 m above sea level were converted to 10-minute extreme wind speeds using the Frøya wind speed profile which is documented in DNVGL-RP-C205: 2021 [7]:

$$U(T, z) = U_0 \cdot \left\{ 1 + C \cdot \ln \frac{z}{H} \right\} \cdot \left\{ 1 - 0.41 \cdot I_U(z) \cdot \ln \frac{T}{T_0} \right\}$$

Where U_0 represents the 1-hr mean wind speed at height H above the sea level (100 m) to the mean wind speed U with averaging period T at height z above the sea level. T_0 is fixed at 3600 s. The expression for C is given as:

$$C = 5.73 \times 10^{-2} \sqrt{1 + 0.148 U_0}$$

and

$$I_U = 0.06 \cdot (1 + 0.043 U_0) \cdot \left(\frac{z}{H} \right)^{-0.22}$$

These 10-minute extreme wind speeds at 100 m above sea level were extrapolated to hub height (150 m) using the power law (IEC 61400-3-1: 2019) with the shear exponent value 0.11 as recommended by IEC 61400-3-1: 2019 [6] for extreme conditions:

$$V_{power\ law} = V_{ref} * \left(\frac{z}{z_{ref}} \right)^\alpha$$

Where $V_{power\ law}$ and V_{ref} are the wind speeds at z and z_{ref} respectively, and α is the shear exponent.

The final 1-year, 50-year, and 100-year return values are presented in Table 3-8.

Table 3-8 Extreme wind speeds

Height above sea level (m)	Averaging period	Extreme wind speed (m/s)		
		1-Year	50-Year	100-Year
100	1-hour	18.15	37.00	40.12
100	10-min	19.58	41.20	44.90
150	10-min	19.82	41.73	45.50



Figure 3-11 Return values of wind speed (m/s) at 100 m above sea level in the GEV model. Red curve represents the best fit with the data and aligns with the input data. Dashed lines represent the 95 % confidence intervals. Distribution parameters: location = 24.0669; scale = 2.6934; shape = 0.0819.

3.5 Normal Sea States

For normal sea states, the metocean database is analysed in order to establish the long-term joint probability distribution of the following parameters:

- Mean wind speed at hub height, V_{hub}
- Significant wave height, H_s
- Peak wave period, T_p

According to IEC 61400-3-1: 2019 [6], a 1-hour averaging period is required for the establishment of the long-term joint probability distribution of V_{hub} , H_s and T_p under NSS. The wind and wave data are subsequently gathered in bins. The V_{hub} bins cover 2 m/s, the H_s bins cover 0.5 m and the T_p bins span 0.5 s (IEC 61400-3-1: 2019). The binning of the V_{hub} data is done in such a way that the wind speed bin corresponding to for example $V_{hub} = 2 \text{ m/s}$ contains all wind speed observations ranging from $\geq 1 \text{ m/s}$ to $< 3 \text{ m/s}$. The bin $H_s = 2 \text{ m}$ contains all wave height observations between $\geq 1.75 \text{ m}$ and $< 2.25 \text{ m}$, while the bin $T_p = 2 \text{ s}$ includes all wave period observations from $\geq 1.75 \text{ s}$ to $< 2.25 \text{ s}$. Subsequently, the occurrence of all combinations of V_{hub} , H_s and T_p is counted. The data is gathered per wind speed bin and entered in a scatter diagram giving the frequency of occurrences of each combination of H_s and T_p for that wind speed bin as a percentage value. The full set of scatter diagrams make up the 3-D scatter diagram. The H_s/T_p scatter diagram for all wind speeds (Figure 0-1) and the full set of 3D scatter diagrams are available in the Appendix.

The data is gathered per wind speed bin and entered in a scatter diagram giving the frequency of occurrences of each combination of H_s and T_p for that wind speed bin as a percentage value. The full set of scatter diagrams make up the 3-D scatter diagram. From each scatter plot, the most probable H_s/T_p bin was identified. The average H_s and T_p bin was then calculated and assigned to each V_{hub} . The reduced (lumped) scatter is shown in Table 3-9.

Table 3-9 Lumped scatter diagram of the given offshore site

Vhub (m/s)	Hs (m)	Tp (s)	Wave direction (°)	Wind direction (°)	Frequency of Occurrence (%)
2	0.48	6.05	33.75	90.00	0.75
4	0.49	6.05	33.75	45.00	1.17
6	0.56	4.49	33.75	45.00	1.19
8	0.54	3.49	45.00	225.00	1.20
10	0.91	4.50	213.75	225.00	1.93
12	1.02	4.50	213.75	225.00	1.75
14	1.53	5.50	213.75	303.75	1.60
16	1.99	5.99	315.00	303.75	0.94
18	2.47	6.45	315.00	303.75	0.43
20	3.45	7.59	33.75	303.75	0.11
22	4.05	8.44	22.50	22.50	0.03
24	5.93	9.98	33.75	33.75	0.00
26	5.51	9.08	56.25	0.00	0.00
28	6.53	9.53	45.00	337.50	0.00
30	7.00	10.46	168.75	168.75	0.00
32	8.02	10.48	180.00	146.25	0.00
34	6.61	9.04	112.50	112.50	0.00
36	7.69	10.71	146.25	146.25	0.00
40	7.95	9.36	135.00	135.00	0.00

A rose plot displaying wave direction and significant wave height is presented in Figure 3-12, whereby monthly, annual and overall wave summary statistics are given in Table 3-10 to Table 3-13. Kernel density and contour plots of significant wave height and peak wave period are presented in Figure 3-13 and Figure 3-14.

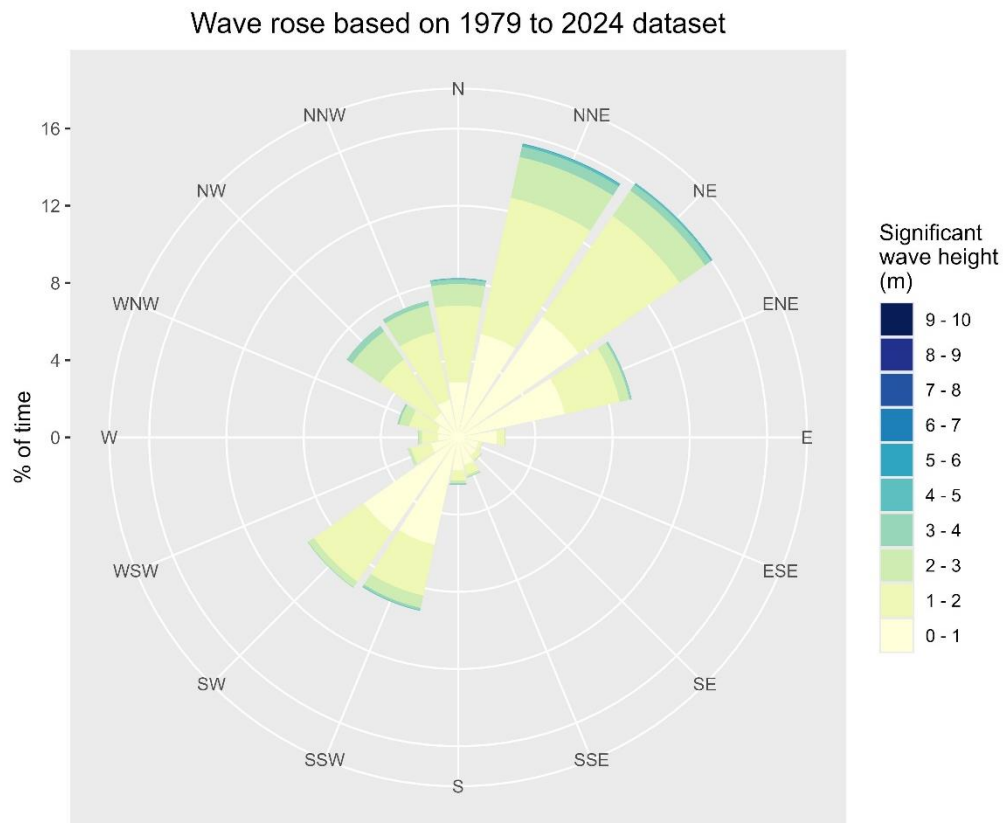


Figure 3-12 Rose plot of significant wave height and wave direction from 1979 to 2024 dataset

Table 3-10 Monthly wave statistics from ERA5 dataset (1979 – 2024)

Variable	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hs (m)	mean	1.7	1.5	1.3	1.1	0.9	0.8	0.9	1.0	1.2	1.2	1.3	1.6
	median	1.5	1.4	1.2	1.0	0.8	0.7	0.8	0.8	1.0	1.0	1.2	1.5
	standard deviation	0.8	0.7	0.7	0.7	0.5	0.5	0.5	0.6	0.8	0.8	0.7	0.7
	max	6.5	8.2	5.7	5.4	4.4	4.8	7.9	8.6	9.0	7.4	6.1	5.4
	min	0.3	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2
	P25	1.1	1.0	0.8	0.6	0.5	0.5	0.5	0.5	0.6	0.7	0.8	1.0
	P50	1.5	1.4	1.2	1.0	0.8	0.7	0.8	0.8	1.0	1.0	1.2	1.5
	P75	2.1	1.9	1.7	1.4	1.1	1.0	1.1	1.2	1.5	1.5	1.7	2.0
	P95	3.1	2.9	2.7	2.4	2.0	1.8	1.9	2.1	2.8	2.6	2.6	3.0
Hmax (m)	mean	3.2	2.9	2.5	2.2	1.7	1.6	1.7	1.8	2.3	2.3	2.5	3.0
	median	3.0	2.7	2.3	1.8	1.5	1.3	1.4	1.5	1.8	2.0	2.2	2.8
	standard deviation	1.5	1.4	1.4	1.3	1.1	1.0	1.1	1.2	1.6	1.4	1.4	1.4
	max	12.5	15.6	11.0	10.7	8.7	9.3	15.3	16.6	17.6	14.3	11.8	10.1
	min	0.5	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.3
	P25	2.1	1.8	1.5	1.2	0.9	0.9	1.0	1.0	1.2	1.3	1.5	1.9
	P50	3.0	2.7	2.3	1.8	1.5	1.3	1.4	1.5	1.8	2.0	2.2	2.8
	P75	4.1	3.7	3.2	2.8	2.2	2.0	2.1	2.3	2.9	2.9	3.3	3.9
	P95	5.2	4.8	4.3	3.9	3.1	2.8	3.0	3.3	4.1	4.1	4.4	5.0
Tp (s)	mean	7.2	7.0	6.4	5.8	5.4	5.5	5.7	5.9	6.3	6.4	6.6	7.1
	median	7.0	6.8	6.1	5.6	5.1	5.4	5.6	5.6	6.1	6.2	6.4	6.9
	standard deviation	1.9	1.9	1.9	1.8	1.7	1.7	1.8	2.1	1.9	1.9	2.0	2.0
	max	13.6	13.3	14.4	13.2	16.6	14.8	18.6	18.5	17.8	17.5	15.2	14.6
	min	2.4	2.2	2.2	2.2	2.0	2.2	2.2	2.1	2.1	2.1	2.2	2.4
	P25	5.7	5.6	5.0	4.5	4.2	4.3	4.5	4.5	4.9	4.9	5.1	5.5
	P50	7.0	6.8	6.1	5.6	5.1	5.4	5.6	5.6	6.1	6.2	6.4	6.9
	P75	8.5	8.3	7.6	6.8	6.3	6.3	6.4	6.7	7.3	7.6	8.0	8.4
	P95	9.9	9.5	8.8	8.2	7.7	7.7	7.8	8.4	8.9	9.0	9.2	9.9
Wave direction (°)	mean	205.0	175.3	149.4	147.9	145.7	125.7	149.9	124.9	88.9	117.3	173.5	213.8

Table 3-11 Annual and overall significant wave height (Hs) from ERA5 dataset (1979 – 2024)

Year	Hs (m)									
	mean	median	standard deviation	max	min	P25	P50	P75	P90	P95
1979	1.2	1.0	0.8	5.8	0.2	0.6	1.0	1.5	2.2	2.7
1980	1.2	1.0	0.8	6.0	0.2	0.6	1.0	1.7	2.3	2.9
1981	1.1	1.0	0.7	4.8	0.1	0.6	1.0	1.5	2.1	2.6
1982	1.1	0.9	0.7	6.2	0.2	0.6	0.9	1.4	2.0	2.4
1983	1.2	1.1	0.7	5.6	0.1	0.7	1.1	1.6	2.2	2.5
1984	1.1	1.0	0.7	4.9	0.1	0.6	1.0	1.5	2.1	2.5
1985	1.2	1.0	0.8	6.8	0.2	0.6	1.0	1.6	2.2	2.7
1986	1.1	0.9	0.7	6.3	0.2	0.6	0.9	1.4	2.0	2.3
1987	1.2	1.0	0.8	8.6	0.1	0.6	1.0	1.5	2.3	2.7
1988	1.2	1.0	0.7	4.6	0.2	0.7	1.0	1.6	2.1	2.5
1989	1.2	1.0	0.7	4.3	0.2	0.7	1.0	1.5	2.1	2.5
1990	1.2	1.0	0.8	5.4	0.2	0.6	1.0	1.6	2.2	2.7
1991	1.3	1.0	0.8	6.3	0.2	0.6	1.0	1.6	2.4	2.8
1992	1.2	1.1	0.7	6.0	0.2	0.7	1.1	1.6	2.2	2.7
1993	1.2	1.1	0.7	4.9	0.2	0.7	1.1	1.6	2.2	2.6
1994	1.2	1.0	0.7	6.1	0.1	0.7	1.0	1.5	2.1	2.5
1995	1.2	1.1	0.6	5.0	0.2	0.8	1.1	1.5	2.1	2.4
1996	1.2	1.0	0.7	4.0	0.2	0.7	1.0	1.5	2.1	2.5
1997	1.3	1.1	0.8	5.3	0.2	0.7	1.1	1.6	2.3	2.7
1998	1.2	1.1	0.8	6.5	0.1	0.7	1.1	1.6	2.2	2.7
1999	1.2	1.0	0.8	5.7	0.2	0.7	1.0	1.6	2.3	2.7
2000	1.2	1.0	0.7	5.2	0.2	0.7	1.0	1.6	2.1	2.6
2001	1.3	1.1	0.7	4.3	0.2	0.8	1.1	1.6	2.2	2.6
2002	1.3	1.1	0.8	5.5	0.2	0.7	1.1	1.7	2.3	2.7
2003	1.2	1.1	0.7	9.0	0.2	0.7	1.1	1.6	2.3	2.6
2004	1.2	1.0	0.7	5.0	0.2	0.6	1.0	1.6	2.2	2.6
2005	1.3	1.1	0.8	8.2	0.1	0.7	1.1	1.7	2.3	2.7
2006	1.2	1.1	0.8	6.7	0.1	0.7	1.1	1.6	2.2	2.6
2007	1.2	1.0	0.6	4.5	0.2	0.7	1.0	1.5	1.9	2.3
2008	1.1	1.0	0.7	4.3	0.1	0.6	1.0	1.5	2.0	2.3
2009	1.2	1.0	0.8	6.1	0.2	0.7	1.0	1.6	2.3	2.7
2010	1.2	1.0	0.8	4.7	0.2	0.6	1.0	1.7	2.4	2.8
2011	1.3	1.1	0.8	5.4	0.2	0.7	1.1	1.6	2.4	2.9
2012	1.3	1.1	0.7	6.0	0.2	0.7	1.1	1.7	2.2	2.6
2013	1.2	1.1	0.7	6.0	0.2	0.7	1.1	1.6	2.2	2.6
2014	1.2	1.0	0.8	6.1	0.2	0.7	1.0	1.6	2.3	2.8
2015	1.2	1.0	0.8	7.2	0.2	0.6	1.0	1.7	2.3	2.7
2016	1.2	1.0	0.8	5.4	0.1	0.6	1.0	1.5	2.3	2.8
2017	1.2	1.1	0.7	6.1	0.2	0.7	1.1	1.6	2.2	2.5
2018	1.2	1.0	0.8	7.4	0.2	0.7	1.0	1.6	2.3	2.8
2019	1.2	1.0	0.7	8.0	0.1	0.7	1.0	1.5	2.0	2.4
2020	1.2	1.1	0.8	9.0	0.2	0.7	1.1	1.6	2.2	2.7
2021	1.2	1.1	0.7	4.7	0.2	0.7	1.1	1.6	2.3	2.7
2022	1.2	1.0	0.7	7.7	0.2	0.7	1.0	1.5	2.2	2.7
2023	1.1	0.9	0.7	4.7	0.2	0.6	0.9	1.5	2.0	2.5
Overall	1.2	1.0	0.7	9.0	0.1	0.7	1.0	1.6	2.2	2.6

Table 3-12 Annual and overall individual maximum wave height (Hmax) from ERA5 dataset (1979 – 2023)

Year	Hmax (m)									
	mean	median	standard deviation	max	min	P25	P50	P75	P90	P95
1979	2.3	1.8	1.5	11.3	0.3	1.2	1.8	2.9	4.3	5.3
1980	2.4	2.0	1.6	11.7	0.3	1.2	2.0	3.2	4.5	5.5
1981	2.2	1.9	1.4	9.3	0.3	1.1	1.9	2.8	4.0	4.9
1982	2.1	1.7	1.3	11.9	0.3	1.1	1.7	2.8	3.9	4.6
1983	2.3	2.0	1.4	10.9	0.2	1.3	2.0	3.0	4.3	4.9
1984	2.1	1.8	1.4	9.5	0.3	1.1	1.8	2.9	4.1	4.9
1985	2.3	1.9	1.5	13.4	0.3	1.1	1.9	3.0	4.2	5.1
1986	2.1	1.7	1.3	12.3	0.4	1.1	1.7	2.7	3.8	4.5
1987	2.3	1.8	1.6	16.6	0.2	1.1	1.8	2.9	4.4	5.2
1988	2.3	2.0	1.3	8.8	0.4	1.3	2.0	3.0	4.1	4.9
1989	2.2	1.9	1.3	8.4	0.4	1.3	1.9	2.8	4.1	4.8
1990	2.3	1.9	1.5	10.1	0.3	1.2	1.9	3.0	4.3	5.3
1991	2.4	2.0	1.6	12.2	0.3	1.2	2.0	3.1	4.7	5.4
1992	2.4	2.1	1.4	11.6	0.3	1.4	2.1	3.0	4.2	5.1
1993	2.3	2.0	1.4	9.7	0.3	1.2	2.0	3.1	4.3	5.0
1994	2.2	1.9	1.4	11.9	0.2	1.2	1.9	2.9	4.1	4.8
1995	2.3	2.1	1.2	9.7	0.3	1.5	2.1	3.0	4.0	4.6
1996	2.2	1.9	1.3	7.8	0.4	1.2	1.9	2.9	4.0	4.8
1997	2.4	2.1	1.5	10.3	0.3	1.3	2.1	3.1	4.4	5.2
1998	2.4	2.0	1.5	12.5	0.3	1.4	2.0	3.0	4.2	5.2
1999	2.4	2.0	1.5	11.0	0.3	1.3	2.0	3.1	4.4	5.3
2000	2.3	2.0	1.4	10.2	0.3	1.2	2.0	3.0	4.0	5.0
2001	2.4	2.1	1.3	8.3	0.3	1.4	2.1	3.1	4.3	5.0
2002	2.4	2.1	1.5	10.5	0.3	1.3	2.1	3.3	4.5	5.1
2003	2.4	2.0	1.4	17.6	0.4	1.3	2.0	3.1	4.4	5.0
2004	2.3	2.0	1.4	9.7	0.3	1.2	2.0	3.1	4.3	5.0
2005	2.5	2.1	1.6	15.8	0.2	1.3	2.1	3.3	4.4	5.3
2006	2.3	2.0	1.5	13.1	0.2	1.3	2.0	3.1	4.2	5.0
2007	2.2	2.0	1.2	8.9	0.4	1.3	2.0	2.9	3.7	4.5
2008	2.2	1.9	1.3	8.4	0.2	1.2	1.9	2.9	3.9	4.5
2009	2.4	2.0	1.5	11.8	0.3	1.3	2.0	3.1	4.4	5.2
2010	2.4	2.0	1.5	9.2	0.3	1.2	2.0	3.3	4.6	5.3
2011	2.5	2.2	1.5	10.3	0.3	1.4	2.2	3.1	4.5	5.6
2012	2.4	2.2	1.4	11.6	0.3	1.3	2.2	3.2	4.2	4.9
2013	2.4	2.1	1.4	11.6	0.3	1.3	2.1	3.1	4.3	5.0
2014	2.4	2.0	1.5	11.9	0.3	1.3	2.0	3.0	4.4	5.4
2015	2.4	2.0	1.5	13.9	0.3	1.2	2.0	3.2	4.3	5.1
2016	2.2	1.9	1.5	10.6	0.2	1.2	1.9	2.9	4.3	5.3
2017	2.4	2.0	1.4	11.8	0.4	1.3	2.0	3.1	4.2	4.9
2018	2.4	2.0	1.5	14.3	0.3	1.3	2.0	3.1	4.4	5.3
2019	2.2	2.0	1.4	15.5	0.2	1.3	2.0	2.8	3.8	4.6
2020	2.4	2.0	1.5	17.5	0.3	1.3	2.0	3.1	4.3	5.2
2021	2.3	2.0	1.4	9.0	0.3	1.2	2.0	3.0	4.4	5.2
2022	2.3	2.0	1.4	14.9	0.4	1.3	2.0	3.0	4.2	5.1
2023	2.1	1.8	1.3	9.2	0.4	1.2	1.8	2.8	4.0	4.7
Overall	2.3	1.8	1.5	11.3	0.3	1.2	1.8	2.9	4.3	5.3

Table 3-13 Annual and overall peak wave period (Tp) and wave direction from ERA5 dataset (1979 – 2023)

Year	Tp (s)										Wave direction (°)
	mean	median	standard deviation	max	min	P25	P50	P75	P90	P95	mean
1979	6.2	6.0	1.9	13.3	2.2	4.7	6.0	7.5	8.6	9.3	160.2
1980	6.2	6.0	1.9	12.7	2.1	4.8	6.0	7.4	8.7	9.9	159.2
1981	6.1	5.7	2.1	15.7	2.2	4.5	5.7	7.5	8.7	10.0	173.4
1982	6.0	5.8	1.9	12.6	2.2	4.6	5.8	7.1	8.5	9.4	153.4
1983	6.1	6.0	1.7	13.4	2.2	4.9	6.0	7.2	8.5	9.2	151.0
1984	5.9	5.8	1.8	11.5	2.3	4.6	5.8	7.0	8.3	9.1	156.7
1985	6.1	5.9	1.9	17.5	2.2	4.8	5.9	7.0	8.6	9.7	160.4
1986	6.0	5.7	1.8	15.5	2.4	4.7	5.7	7.3	8.4	9.0	160.6
1987	6.0	5.8	1.9	17.7	2.2	4.6	5.8	7.2	8.6	9.4	161.2
1988	6.0	5.8	1.6	11.7	2.4	4.8	5.8	7.0	8.2	8.9	152.7
1989	6.1	6.1	1.8	12.7	2.4	4.8	6.1	7.2	8.4	9.3	132.5
1990	6.0	5.8	1.9	14.7	2.2	4.7	5.8	7.1	8.6	9.5	152.0
1991	6.2	6.1	1.9	14.9	2.4	4.8	6.1	7.5	8.6	9.4	143.1
1992	6.4	6.1	1.9	14.4	2.4	4.9	6.1	7.7	9.0	9.6	148.2
1993	6.5	6.2	2.1	14.2	2.3	5.0	6.2	7.8	9.6	10.2	147.8
1994	6.2	5.8	2.2	18.1	2.2	4.7	5.8	7.6	9.1	10.1	155.0
1995	6.3	5.9	1.9	13.7	2.4	4.9	5.9	7.6	9.0	10.2	169.7
1996	6.3	5.8	2.1	14.9	2.2	4.7	5.8	7.5	9.1	10.3	153.5
1997	6.4	6.1	2.1	17.7	2.3	4.9	6.1	7.8	9.1	10.2	149.8
1998	6.3	6.1	1.7	14.7	2.4	5.1	6.1	7.5	8.6	9.2	144.3
1999	6.3	6.1	1.9	13.4	2.3	4.9	6.1	7.5	9.0	9.8	157.1
2000	6.3	6.1	1.9	13.9	2.2	4.9	6.1	7.6	9.0	9.8	152.8
2001	6.3	6.1	1.8	13.8	2.2	5.0	6.1	7.6	8.5	9.4	144.7
2002	6.4	6.2	1.9	18.2	2.2	5.1	6.2	7.6	8.9	9.9	150.2
2003	6.4	6.2	1.9	14.9	2.5	5.0	6.2	7.6	9.0	9.9	126.4
2004	6.4	6.1	2.1	15.8	2.2	4.9	6.1	7.7	9.3	10.4	145.2
2005	6.6	6.3	2.3	17.7	2.2	5.0	6.3	8.1	9.7	10.6	170.5
2006	6.3	6.1	2.1	16.6	2.2	4.9	6.1	7.3	9.1	10.5	140.3
2007	6.2	5.9	1.9	15.7	2.4	4.8	5.9	7.2	8.6	10.0	149.4
2008	6.1	5.8	2.0	14.9	2.1	4.7	5.8	7.4	8.7	10.1	150.0
2009	6.4	6.1	2.0	13.3	2.2	4.8	6.1	7.6	9.4	10.3	144.9
2010	6.2	6.0	1.9	12.7	2.2	4.7	6.0	7.5	8.6	9.7	157.8
2011	6.3	6.0	2.0	15.3	2.5	4.9	6.0	7.7	9.2	9.9	150.8
2012	6.4	6.1	2.0	16.0	2.2	5.0	6.1	7.7	9.1	10.0	148.1
2013	6.3	5.9	2.0	13.2	2.5	4.8	5.9	7.6	9.1	10.4	155.7
2014	6.5	6.2	2.1	18.6	2.3	4.8	6.2	8.0	9.1	10.1	133.9
2015	6.6	6.2	2.3	18.5	2.3	4.8	6.2	8.2	9.8	10.9	137.9
2016	6.3	6.1	2.1	17.8	2.2	4.8	6.1	7.5	9.0	10.1	140.0
2017	6.4	6.1	2.1	15.2	2.2	4.8	6.1	7.9	9.5	10.3	157.3
2018	6.5	6.3	2.1	17.3	2.2	4.9	6.3	7.7	9.3	10.4	148.4
2019	6.3	6.2	1.9	15.6	2.0	4.8	6.2	7.5	8.7	9.7	145.7
2020	6.3	6.1	1.9	15.2	2.3	4.9	6.1	7.4	9.0	10.0	155.7
2021	6.2	6.0	1.9	13.6	2.2	4.8	6.0	7.1	8.6	10.1	153.2
2022	6.2	5.9	1.9	12.5	2.4	4.8	5.9	7.4	8.6	10.0	154.4
2023	6.1	5.8	2.0	16.0	2.5	4.6	5.8	7.4	8.7	9.8	160.8
Overall	6.3	6.0	2.0	18.6	2.0	4.8	6.0	7.5	8.9	9.9	151.5

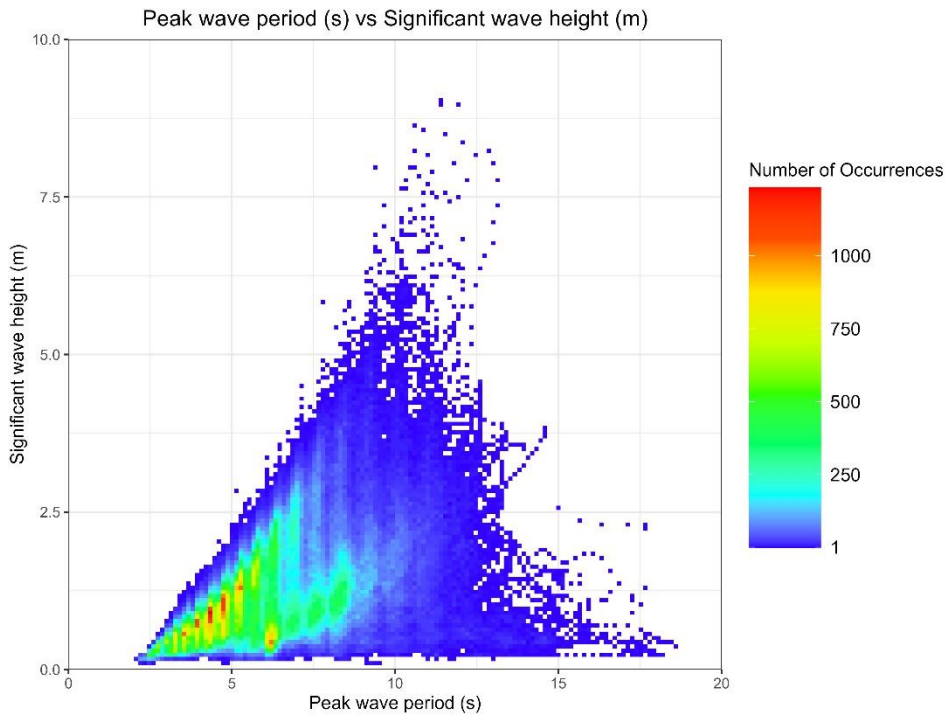


Figure 3-13 Kernel density plot of significant wave height and peak wave period

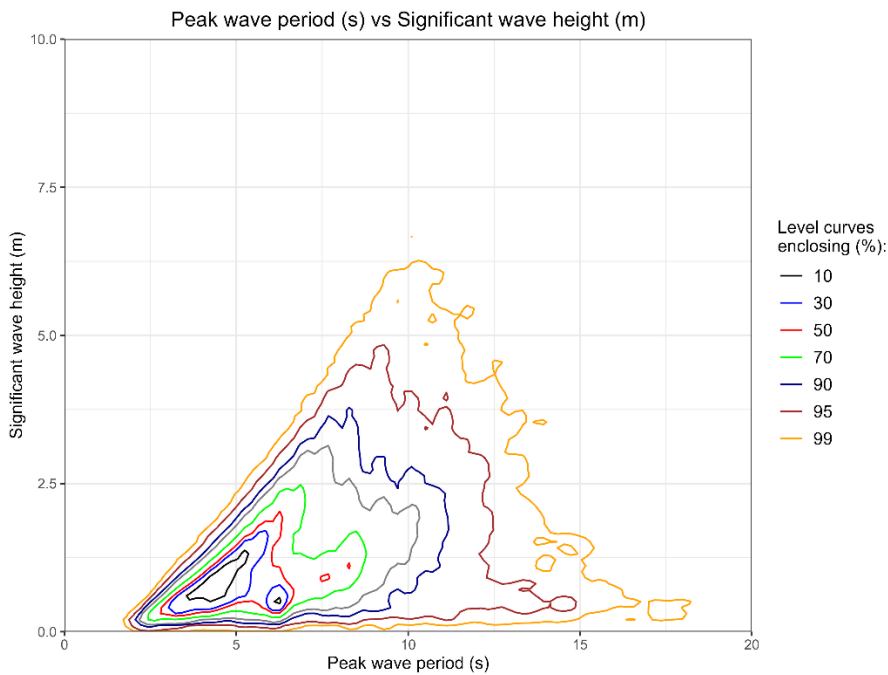


Figure 3-14 Contour plot of significant wave height and peak wave period

A weather window analysis was carried out using various limits of significant wave height and wind speed at 10 m above sea level. Table 3-14 shows the percentage of time for each month, for which weather window limits with specific H_s and wind speed specifications, along with durations ranging from 3 hours and 72 hours, occur.

Table 3-14 Wind-wave persistence – Weather Windows (10 m wind speeds)

	Time duration threshold (hours)	Month												Overall dataset
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Hs < 1.5 m, Uw < 5m/s	3	15.2	21.4	25.4	28.8	36.2	43.0	35.5	36.1	33.3	32.5	26.3	15.8	29.2
	6	13.8	19.7	22.7	25.3	33.2	40.6	33.1	33.8	31.4	30.6	24.8	14.4	27.0
	12	10.4	15.3	15.7	18.1	25.6	35.6	28.9	29.3	27.5	25.6	20.7	11.2	22.2
	24	4.9	8.7	6.3	8.3	16.2	25.4	20.4	21.9	19.4	16.6	12.3	5.8	14.1
	48	1.0	2.3	0.6	1.7	5.6	11.6	7.8	12.8	9.2	4.3	3.7	1.2	5.4
	72	NA	0.6	0.2	NA	1.5	4.0	3.2	4.6	3.9	1.4	1.2	NA	1.9
Hs < 2.0 m, Uw < 5m/s	3	17.3	23.3	27.1	29.6	36.7	43.3	35.8	36.6	34.3	33.6	27.7	17.6	30.3
	6	15.9	21.6	24.3	25.9	33.6	40.9	33.4	34.3	32.4	31.7	26.2	16.1	28.1
	12	12.2	16.8	16.6	18.7	26.0	35.9	29.1	29.6	28.3	26.7	21.7	12.6	23.0
	24	5.6	9.5	6.8	8.4	16.5	25.5	20.7	22.0	20.3	17.2	12.9	6.3	14.6
	48	1.0	2.4	0.6	1.7	5.8	11.7	7.8	12.8	9.3	4.7	3.7	1.2	5.5
	72	NA	0.9	0.2	NA	1.5	4.0	3.2	4.6	3.9	1.4	1.2	NA	1.9
Hs < 2.5 m, Uw < 5m/s	3	17.9	23.8	27.3	29.8	36.8	43.4	35.9	36.7	34.6	33.9	28.0	18.0	30.5
	6	16.5	22.0	24.5	26.1	33.7	41.0	33.5	34.4	32.7	32.0	26.5	16.4	28.3
	12	12.8	17.1	16.7	18.7	26.0	36.0	29.2	29.6	28.7	26.9	21.8	12.8	23.2
	24	5.7	9.5	6.8	8.4	16.5	25.6	20.8	22.1	20.4	17.2	12.9	6.4	14.6
	48	1.0	2.4	0.6	1.7	5.8	11.8	7.8	12.8	9.3	4.7	3.7	1.3	5.5
	72	NA	0.9	0.2	NA	1.5	4.0	3.2	4.6	3.9	1.4	1.2	NA	2.0
Hs < 3.5 m, Uw < 5m/s	3	17.9	23.9	27.4	29.8	36.8	43.4	35.9	36.8	34.6	34.0	28.1	18.1	30.6
	6	16.5	22.2	24.5	26.1	33.7	41.0	33.5	34.4	32.7	32.1	26.5	16.6	28.4
	12	12.8	17.3	16.7	18.7	26.0	36.0	29.2	29.7	28.7	27.0	21.9	12.9	23.2
	24	5.7	9.6	6.8	8.4	16.5	25.6	20.8	22.1	20.5	17.3	12.9	6.4	14.7
	48	1.0	2.4	0.6	1.7	5.8	11.8	7.8	12.8	9.3	4.7	3.7	1.3	5.5
	72	NA	0.9	0.2	NA	1.5	4.0	3.2	4.6	3.9	1.4	1.2	NA	2.0
Hs < 1.5 m, Uw < 7.5 m/s	3	32.4	40.9	48.9	55.8	66.2	72.5	65.8	65.5	59.1	57.9	50.1	36.2	54.3
	6	30.8	39.3	47.2	53.9	64.7	71.3	64.4	64.0	57.8	57.0	48.8	34.9	53.0
	12	27.5	35.3	42.1	48.3	60.4	67.9	61.4	60.7	55.7	54.4	46.2	31.4	49.5
	24	20.2	27.3	31.8	38.0	51.5	62.3	56.0	56.3	50.6	47.3	39.5	23.0	42.6
	48	7.3	13.7	14.1	23.1	34.8	50.4	44.7	47.0	39.7	32.7	24.0	10.8	29.6
	72	1.9	5.5	5.9	12.8	23.9	38.0	32.7	37.9	26.6	19.3	11.9	4.5	19.8
Hs < 2.0 m, Uw < 7.5 m/s	3	38.6	46.7	53.2	58.1	67.7	73.3	66.6	67.1	61.5	61.1	54.4	41.9	57.6
	6	36.9	44.9	51.4	56.2	66.1	72.1	65.0	65.5	60.2	60.1	53.0	40.3	56.1
	12	33.1	40.4	45.9	50.2	61.7	68.5	62.0	62.0	58.0	57.3	50.1	36.5	52.4
	24	24.8	31.5	34.7	39.5	52.4	62.8	56.7	57.6	52.8	50.2	42.4	27.8	45.1
	48	9.2	15.8	15.6	23.9	35.8	51.0	45.0	48.2	41.2	35.0	26.8	13.1	31.2
	72	3.1	6.8	6.6	13.1	25.1	38.8	32.8	39.2	28.8	21.5	12.9	4.5	20.9
Hs < 2.5 m, Uw < 7.5 m/s	3	40.5	48.1	54.1	58.5	67.9	73.6	66.7	67.3	62.2	62.0	55.5	43.5	58.4
	6	38.6	46.4	52.3	56.6	66.3	72.3	65.2	65.8	60.8	61.0	53.9	41.9	56.9
	12	34.8	41.7	46.7	50.4	61.9	68.8	62.1	62.2	58.6	58.3	51.1	38.1	53.2
	24	26.4	32.6	35.1	39.7	52.7	63.0	56.8	57.8	53.5	51.0	43.3	29.1	45.7

	48	10.0	16.1	15.8	24.1	35.9	51.3	45.1	48.7	42.2	35.4	27.6	13.3	31.7
	72	3.6	6.8	6.6	13.1	25.1	39.0	32.8	39.2	29.1	21.8	13.0	5.4	21.1
Hs < 3.5 m, Uw < 7.5 m/s	3	40.9	48.6	54.2	58.6	67.9	73.6	66.7	67.5	62.3	62.4	55.7	44.0	58.6
	6	39.1	46.8	52.4	56.7	66.3	72.4	65.2	65.9	61.0	61.4	54.1	42.4	57.1
	12	35.2	42.2	46.8	50.6	61.9	68.9	62.1	62.3	58.8	58.7	51.3	38.6	53.4
	24	26.8	33.2	35.3	39.7	52.7	63.1	56.8	58.0	53.6	51.2	43.4	29.2	45.9
	48	10.0	16.1	16.0	24.1	35.9	51.4	45.1	48.7	42.2	35.6	27.6	13.7	31.7
	72	3.6	6.8	6.8	13.1	25.1	39.0	32.8	39.2	29.2	22.0	13.0	5.6	21.2
Hs < 1.5 m, Uw < 10 m/s	3	45.9	54.3	65.0	73.9	84.3	88.3	84.9	83.1	73.8	71.7	64.6	50.2	70.1
	6	45.2	53.7	64.2	73.4	83.9	87.9	84.5	82.5	73.4	71.3	63.9	49.5	69.5
	12	42.6	51.7	62.1	71.6	82.5	86.9	83.4	81.8	72.6	70.1	62.4	47.8	68.2
	24	37.9	46.6	56.5	66.3	79.3	85.4	80.7	80.1	71.1	67.4	58.7	43.3	65.0
	48	24.1	34.2	42.4	55.8	72.4	82.1	75.3	75.3	64.3	58.7	50.4	32.1	57.1
	72	12.6	23.1	27.4	45.1	62.8	75.8	67.3	69.0	55.6	49.2	38.4	20.4	47.9
Hs < 2.0 m, Uw < 10 m/s	3	61.4	69.2	75.8	80.8	88.1	91.0	87.2	87.4	81.7	81.1	76.0	64.9	78.7
	6	60.1	68.2	74.8	80.2	87.4	90.3	86.7	86.7	81.2	80.6	75.2	64.0	78.0
	12	57.5	66.2	72.4	78.2	86.1	89.3	85.4	85.6	80.4	79.4	72.7	62.1	76.5
	24	51.5	60.4	66.8	72.4	82.3	87.5	82.6	83.6	78.6	76.6	69.2	56.3	72.9
	48	37.0	48.4	52.0	62.9	76.6	84.4	77.5	79.5	72.1	68.7	60.8	43.5	65.1
	72	21.9	33.8	35.9	50.0	66.7	79.7	69.4	75.0	64.4	59.7	47.8	30.7	55.4
Hs < 2.5 m, Uw < 10 m/s	3	67.1	73.6	78.7	82.1	88.7	91.6	87.5	88.0	83.4	83.4	79.2	69.7	81.1
	6	66.0	72.5	77.7	81.4	88.0	90.9	86.9	87.4	82.7	82.9	78.5	68.4	80.3
	12	62.8	70.2	75.3	79.3	86.6	89.9	85.6	86.3	82.0	81.6	76.0	66.2	78.7
	24	56.1	64.6	69.4	73.7	83.1	88.1	82.9	84.1	80.0	78.6	71.9	60.9	75.1
	48	40.5	52.5	54.9	63.8	77.1	84.8	77.7	80.3	73.9	70.2	63.9	47.1	67.1
	72	24.3	36.4	38.4	51.2	67.4	80.5	70.2	75.7	65.8	61.8	50.4	33.6	57.1

3.6 Wind-wave misalignment

The wind-wave misalignment was defined as the wind direction minus the mean wave direction for each model time step and was analysed with respect to the wind speed at hub height (150 mMSL). Scatter diagram of the misalignment of the full datasets against wind speed at hub height is presented in Figure 3-15. Wind speed was binned into 2 m/s bins and the mean misalignment for that bin was calculated. A scatter plot displaying the results of this analysis for omni-directional and 22.5 ° sectors is given in Figure 3-16.

The location of the Ulsan offshore wind farm exhibits unique wind-wave misalignment conditions not observed in other reference sites. While there is generally a wider spread of misalignment values in the lower wind speeds and decreasing trend at higher wind speeds, which is generally expected, there is some directional bins which exhibit greater misalignment around 25 to 30 m/s wind speeds. This can be seen for the 0-, 315- and 337.5-degree directional sectors shown in Figure 3-16. These high wind speed misalignment observations could be attributed several factors including: typhoons or cyclones where the wind speed and direction can vary significantly over time, swell waves being dominant over wind generated waves, or possible fetch limitations where the wind does not have enough time and distance to transfer kinetic energy to the sea surface.

From the density plot shown in Figure 3-15 it can be seen that there is a wider spread at the low wind speeds and a generally decreasing misalignment as the wind speed increases, which generally agrees with the observations from Figure 3-16.

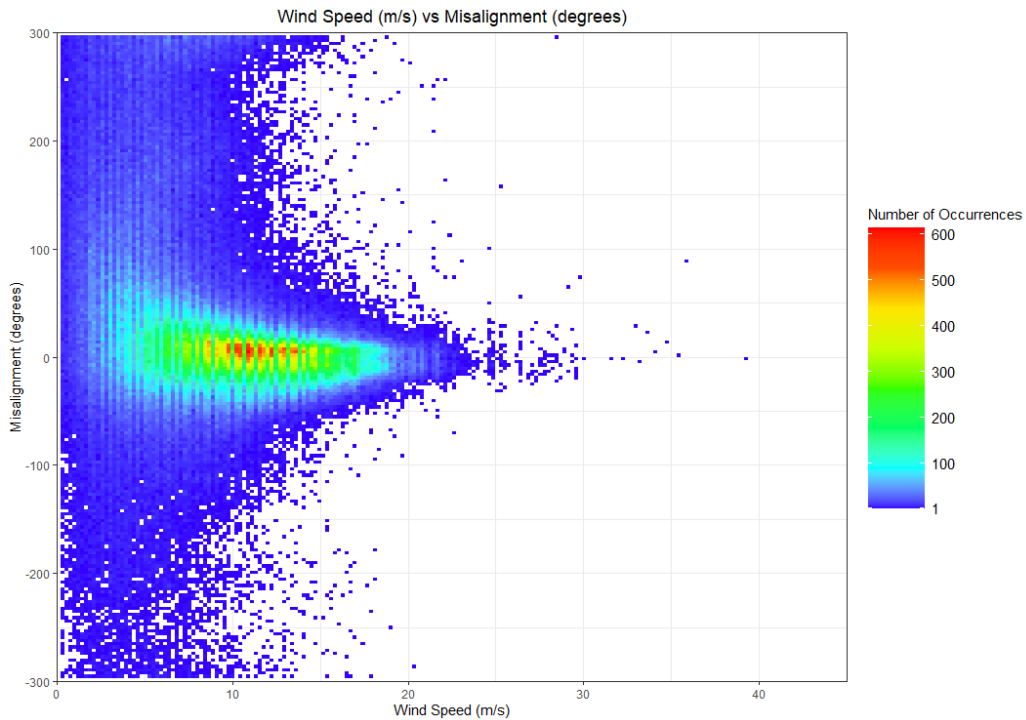


Figure 3-15 Wind-wave misalignment – full dataset (wind speed at hub height)

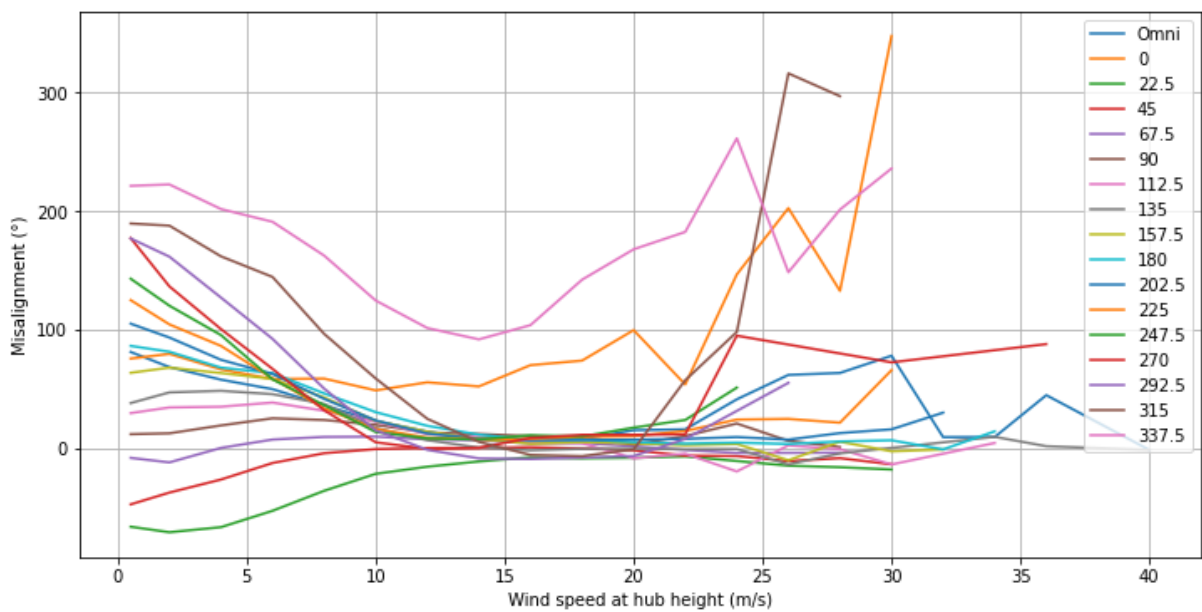


Figure 3-16 Wind-wave misalignment. Mean misalignment per 2 m/s wind speed bins are given for each wind speed directional sector

Kernel density and contour plots for significant wave height and wind speed at hub height (150 m) are presented in Figure 3-17 and Figure 3-18.

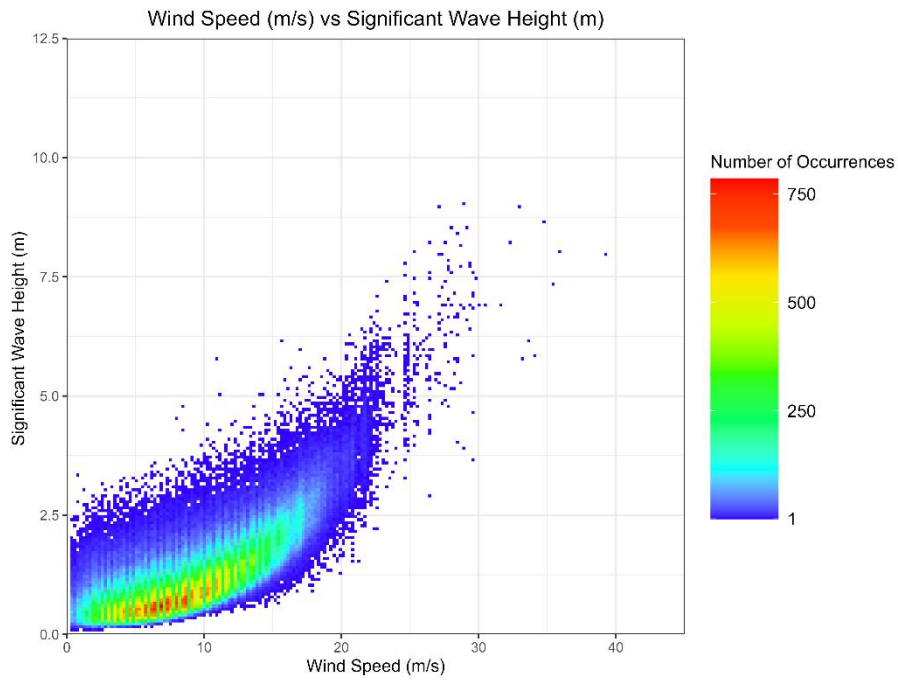


Figure 3-17 Kernel density plot of significant wave height and wind speed at 150 m above sea level

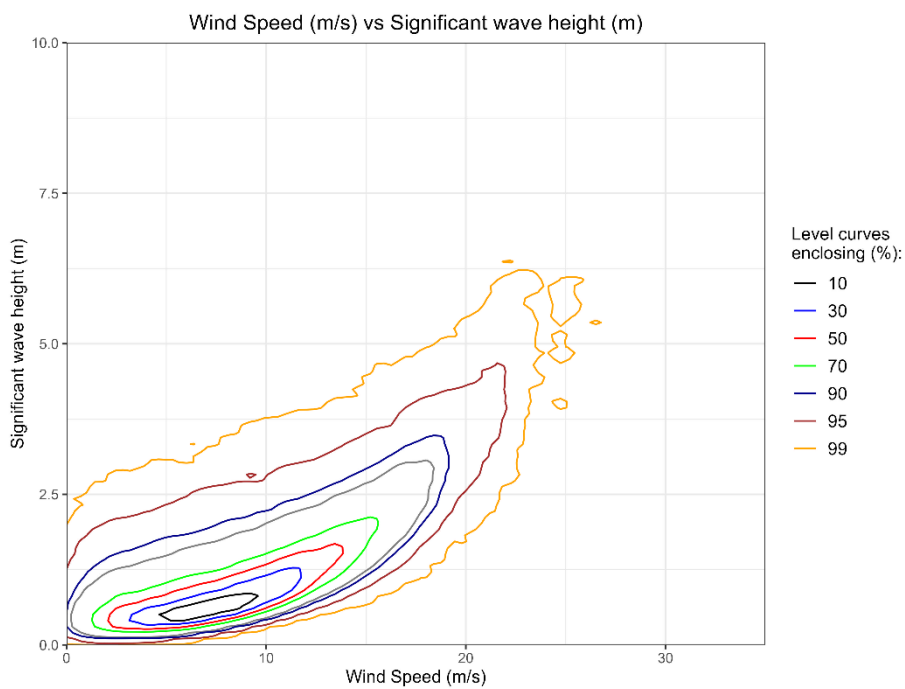


Figure 3-18 Contour plot of significant wave height and wind speed at 150 m above sea level

Wind-wave coincidence and exceedance tables for wind speeds at 10 m above sea level are provided in Figure 0-2.

3.7 Extreme Sea States

The ERA5 dataset [2] was used to calculate extreme wave variables. For this study, a generalised extreme value (GEV) methodology was chosen as the best-fitting analysis to calculate the extreme values for wave height at this location. Due to the adequate length of the wave dataset, the block maxima (annual maxima) approach was chosen to extract extreme events over the 45-year time period as input into the general extreme value analysis.

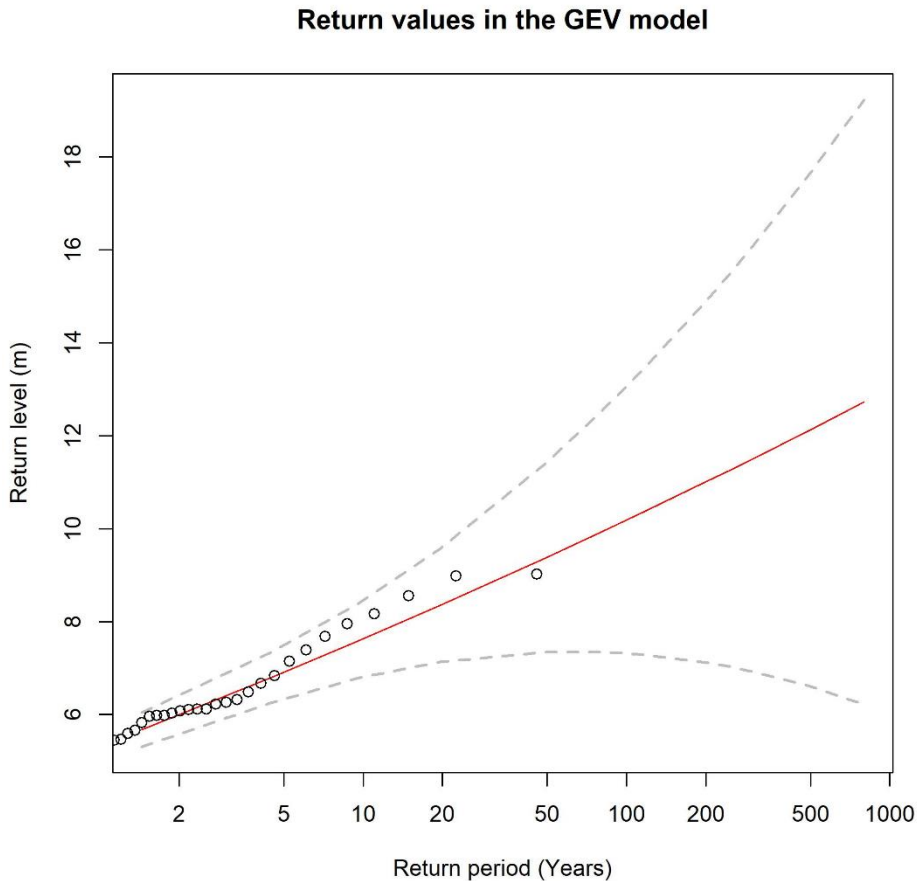


Figure 3-19 Return values of significant wave height (H_s) in the GEV model. Red curve represents the best fit with the data and aligns with the input data. Dashed lines represent the 95 % confidence intervals. Distribution parameters: location = 5.318; scale = 1.002; shape = 0.019.

The predicted 1-, 50- and 100-year return values of significant wave height H_s is presented in Table 3-5. The maximum wave height is determined according to the equation provided in IEC 61400-3-1: 2019 [6].

$$H_{max} = 1.86H_s$$

The wave period associated with maximum wave height, T_{Hmax} or T_{ass} , is calculated based on the relationship between H_s and T_{ass} (IEC 61400-3-1: 2019)

$$11.1 \sqrt{\frac{H_s}{g}} \leq T_{ass} \leq 14.3 \sqrt{\frac{H_s}{g}}$$

Where g is the acceleration due to gravity. The following equation provided in DNV-RP-C205: 2021 [7] is used to estimate the upper and lower limits of peak wave period T_p .

$$T_{ass} = 0.9T_p$$

It is noted that, IEC 61400-3-1: 2019 [6] recommend a 3-hour sea state as input into extreme value analysis. In this study, a 1-hour sea state is utilised and therefore the calculated extreme values are considered conservative.

Table 3-15 Omni-directional Extreme Wave Data

Return Period (Years)	Significant Wave Height, H_s (m)	Peak Period, T_p (s) (Lower Limit)	Peak Period, T_p (s) (Upper Limit)	Maximum Wave Height, H_{max} (m)	Period of Max Wave, T_{Hmax} (s) (Lower Limit)	Period of Max Wave, T_{Hmax} (s) (Upper Limit)
1	2.5	6.2	8.0	4.7	5.6	7.2
2	5.7	9.3	12.1	10.5	8.4	10.9
50	9.4	12.1	15.6	17.4	10.9	14.0
100	10.2	12.6	16.2	18.9	11.3	14.6

3.8 Severe Sea States

The severe sea states (SSS) conditions are found using Inverse First-Order Reliability Method (IFORM) as recommended by IEC 61400-3-1; 2019 [6]. The methodology described in Papi et al [8] was followed. The 50-year and 1-year environmental contours of $V_{hub}-H_s$ are shown as solid lines in Figure 3-20. The SSS values, defined by the points along the 50-year contours between the cut-in and cut-out wind speeds are provided in Table 3-16.

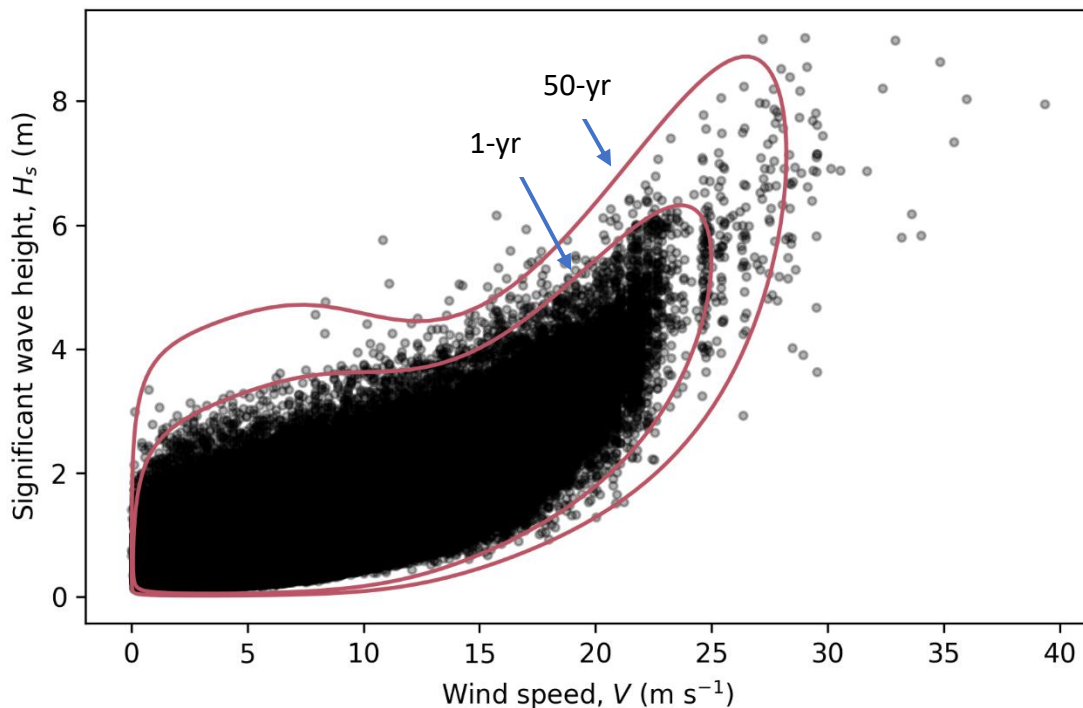


Figure 3-20 Wind speed (150 m) – significant wave height environmental contours compute with IFORM method

Table 3-16 Severe sea states within cut-in and cut-out wind speeds, computed from IFORM Method

ID	Vhub (150 m)	Hs	Tp	Tp min	Tp max
0	1	3.78	8.90	6.82	11.42
1	2	4.13	9.15	7.17	11.52
2	3	4.33	9.29	7.37	11.58
3	4	4.47	9.40	7.51	11.62
4	5	4.59	9.48	7.62	11.66
5	6	4.67	9.53	7.70	11.68
6	7	4.71	9.56	7.73	11.69
7	8	4.70	9.56	7.73	11.69
8	9	4.65	9.52	7.68	11.68
9	10	4.57	9.47	7.61	11.65
10	11	4.50	9.42	7.53	11.63
11	12	4.45	9.38	7.49	11.62
12	13	4.47	9.39	7.50	11.62
13	14	4.54	9.45	7.58	11.64
14	15	4.69	9.55	7.71	11.69
15	16	4.91	9.70	7.92	11.76
16	17	5.20	9.88	8.17	11.85
17	18	5.54	10.10	8.47	11.97
18	19	5.93	10.35	8.79	12.11
19	20	6.36	10.60	9.12	12.26
20	21	6.81	10.87	9.45	12.43
21	22	7.27	11.12	9.78	12.61
22	23	7.72	11.37	10.08	12.78
23	24	8.13	11.59	10.34	12.95
24	25	8.47	11.77	10.55	13.09
25	26	8.69	11.88	10.68	13.18
26	27	8.67	11.87	10.67	13.17
27	28	8.00	11.52	10.26	12.90
28	29	7.14	11.05	9.69	12.56
29	30	7.14	11.05	9.69	12.56

3.9 Currents – Normal Conditions

A 22-year 3-hour averaged modelled dataset was obtained from the HYCOM GOFS 3.1 numerical model for various depths (surface, mid and bottom). It contained U and V velocity components which was converted to speed and direction and then interpolated to an hourly format. The data was obtained for a location nearby the Ulsan Offshore Wind Farm (35.44°, 129.92°).

The current roses of this dataset are presented in Figure 3-21 to Figure 3-23. Monthly, annual and overall statistics are presented in Table 3-17 to Table 3-20.

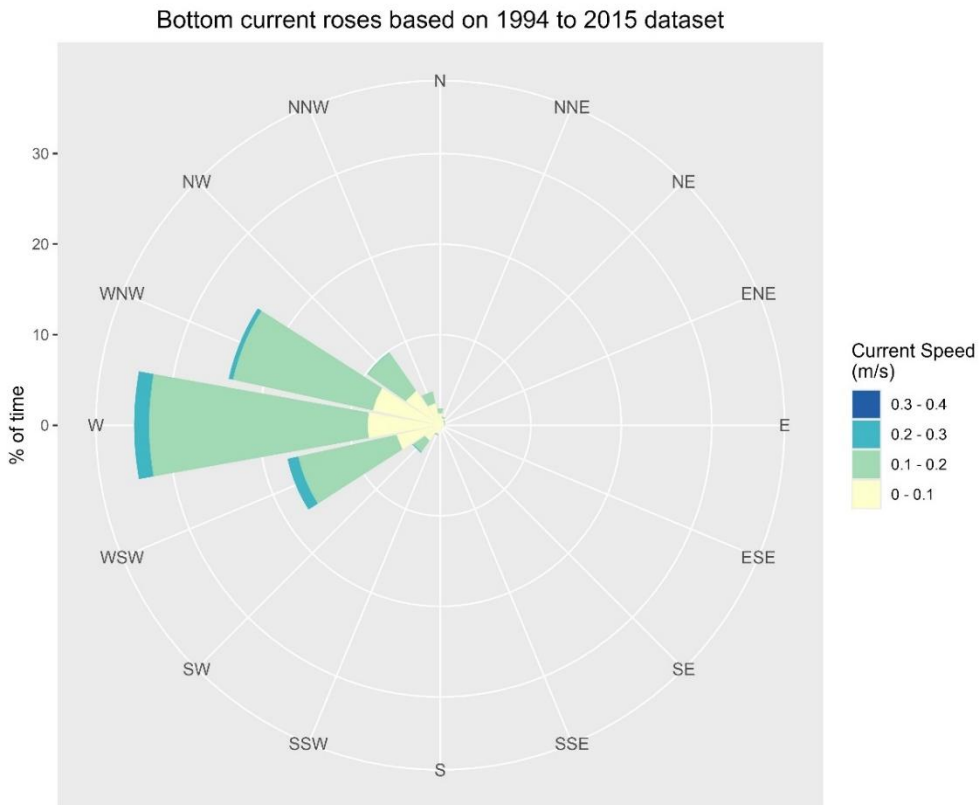


Figure 3-21 Current rose (22-year modelled bottom current)

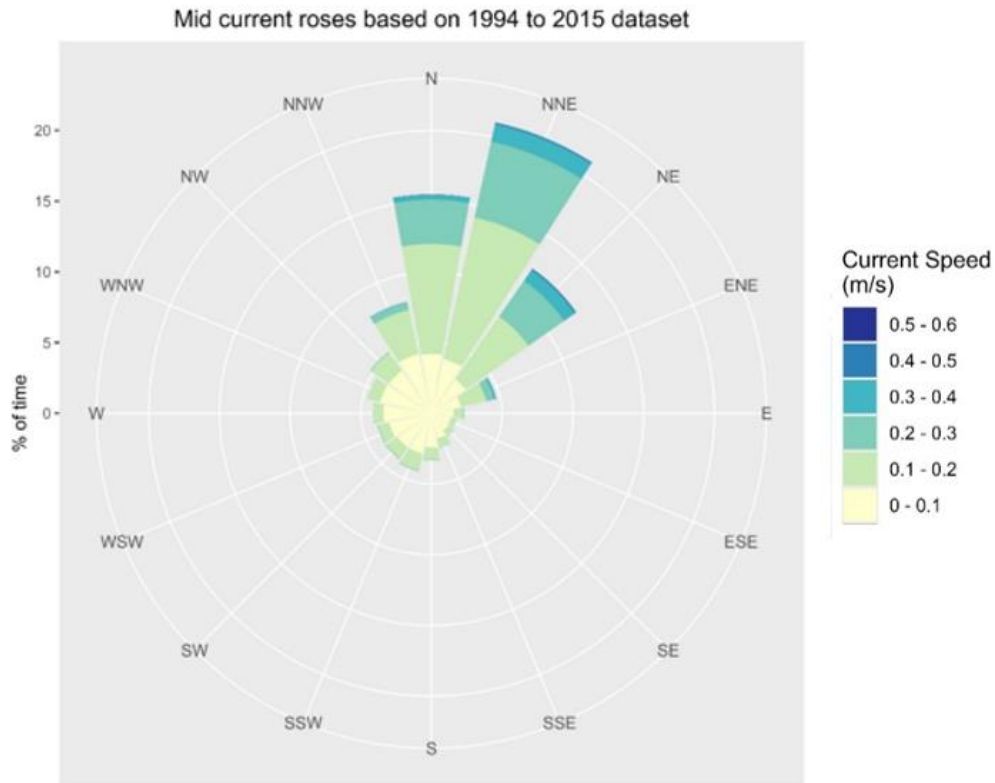


Figure 3-22 Current rose (22-year modelled mid current)

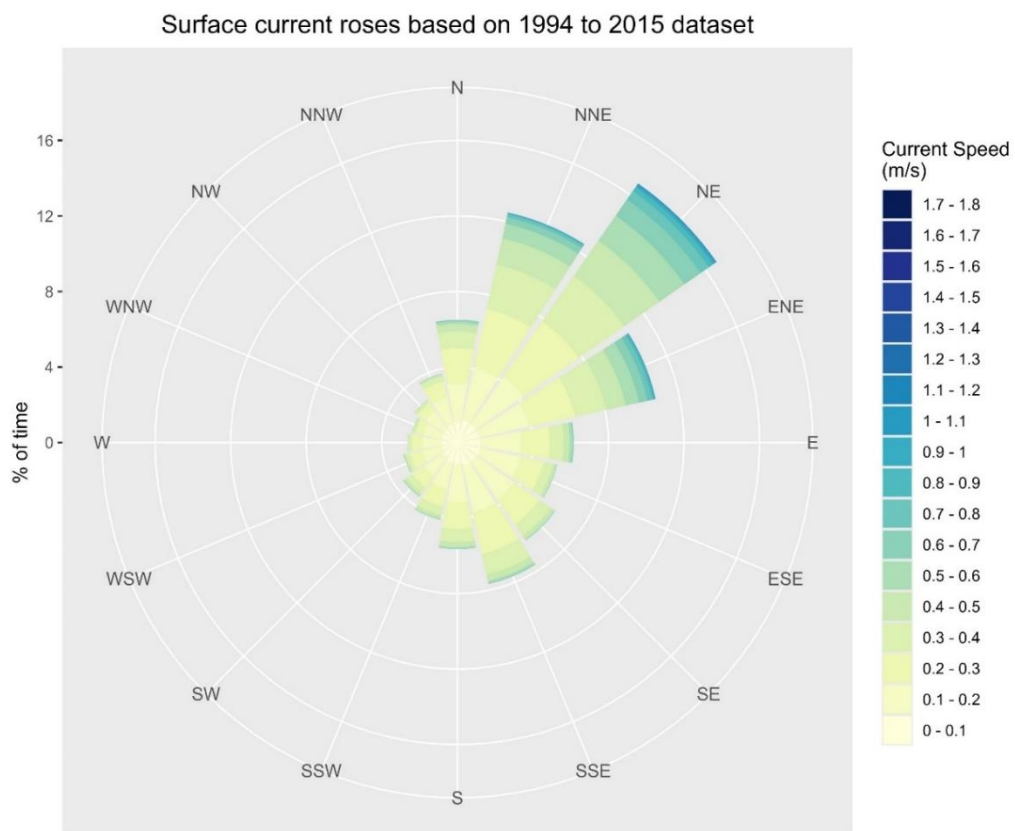


Figure 3-23 Current rose (22-year modelled surface current)

Table 3-17 Percent exceedance of bottom, mid and surface current speeds (derived from 22-year modelled dataset)

Exceedance threshold (m/s)	Bottom current speed exceedance (%)	Mid current speed exceedance (%)	Surface current speed (%)
0.1	64.08	53.78	82.60
0.2	3.55	16.32	52.18
0.3	0.00	3.07	28.33
0.4		0.28	14.89
0.5		0.01	7.84
0.6			3.94
0.7			1.88
0.8			0.86
0.9			0.40
1.0			0.18
1.1			0.08
1.2			0.04
1.3			0.02
1.4			0.01
1.5			0.00

Table 3-18 Monthly bottom, mid and surface current statistics (derived from a 22-year modelled dataset)

	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
bottom current speed (m/s)	mean	0.07	0.08	0.07	0.08	0.09	0.10	0.10	0.09	0.08	0.09	0.09	0.08
	max	0.25	42.99	0.26	0.30	0.32	0.29	0.30	0.29	0.32	0.28	0.30	0.27
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03
	P50	0.07	0.06	0.06	0.08	0.09	0.10	0.10	0.08	0.07	0.08	0.09	0.08
	P75	0.11	0.10	0.10	0.12	0.14	0.15	0.15	0.15	0.13	0.14	0.15	0.13
	P90	0.15	0.13	0.13	0.16	0.17	0.18	0.18	0.18	0.17	0.18	0.18	0.17
	P95	0.16	0.15	0.15	0.17	0.18	0.20	0.20	0.20	0.19	0.19	0.20	0.19
mid current speed (m/s)	mean	0.08	0.07	0.07	0.07	0.09	0.11	0.15	0.18	0.18	0.18	0.18	0.13
	max	0.29	17.18	0.33	0.31	0.32	0.34	0.40	0.56	0.54	0.49	0.51	0.42
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.05	0.04	0.04	0.04	0.06	0.07	0.10	0.13	0.11	0.12	0.12	0.07
	P50	0.07	0.06	0.06	0.07	0.08	0.10	0.15	0.18	0.17	0.17	0.17	0.11
	P75	0.11	0.09	0.09	0.09	0.12	0.14	0.19	0.24	0.24	0.22	0.22	0.17
	P90	0.14	0.12	0.12	0.12	0.15	0.18	0.23	0.29	0.31	0.28	0.27	0.23
	P95	0.16	0.14	0.14	0.15	0.18	0.20	0.25	0.33	0.34	0.31	0.31	0.28
surface current speed(m/s)	mean	0.16	0.16	0.18	0.20	0.20	0.22	0.34	0.38	0.27	0.21	0.19	0.17
	max	0.75	28.67	0.96	0.93	0.86	0.95	1.71	1.55	1.59	1.50	1.10	0.80
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.08	0.08	0.10	0.11	0.11	0.12	0.19	0.22	0.15	0.12	0.11	0.09
	P50	0.14	0.13	0.16	0.18	0.18	0.20	0.32	0.35	0.24	0.19	0.18	0.15
	P75	0.22	0.20	0.24	0.27	0.27	0.29	0.46	0.51	0.36	0.28	0.25	0.23
	P90	0.30	0.29	0.34	0.38	0.36	0.40	0.60	0.67	0.50	0.37	0.33	0.32
	P95	0.35	0.36	0.40	0.46	0.42	0.48	0.68	0.78	0.58	0.42	0.39	0.38
bottom current direction (°)	mean	216.3	219.6	215.4	215.8	217.1	222.7	225.3	222.8	221.1	221.8	218.9	216.5
	mean	262.8	270.6	265.2	278.6	280.0	281.9	276.0	270.8	263.8	268.8	271.4	266.7
mid current direction (°)	mean	212.0	207.0	209.0	206.1	203.4	200.2	198.5	202.3	210.7	206.3	207.1	206.5
	mean	229.0	233.2	222.4	210.0	173.4	133.5	109.2	91.0	100.5	89.9	73.2	131.7
surface current direction (°)	mean	195.7	196.7	199.0	199.5	199.2	199.5	200.1	205.1	206.2	202.3	193.0	192.6
	mean	160.0	174.6	174.7	166.3	141.5	127.8	91.7	90.1	116.9	107.2	113.4	133.8

Table 3-19 Annual bottom, mid and surface current statistics (derived from 22-year modelled dataset)

	Statistic	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
bottom current speed (m/s)	mean	0.11	0.11	0.10	0.12	0.11	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.12
	max	0.27	0.25	0.27	0.30	0.25	0.26	0.26	0.25	0.29	0.30	0.25	0.28	0.27
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.08	0.08	0.07	0.09	0.07	0.09	0.08	0.10	0.08	0.09	0.09	0.07	0.09
	P50	0.12	0.11	0.10	0.12	0.11	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.12
	P75	0.15	0.15	0.13	0.15	0.14	0.15	0.14	0.15	0.16	0.15	0.15	0.15	0.16
	P90	0.17	0.17	0.16	0.18	0.17	0.17	0.17	0.17	0.18	0.17	0.18	0.18	0.19
	P95	0.18	0.18	0.18	0.20	0.19	0.19	0.18	0.18	0.20	0.18	0.19	0.20	0.20
mid current speed (m/s)	mean	0.13	0.10	0.10	0.15	0.13	0.13	0.12	0.11	0.12	0.11	0.14	0.14	0.13
	max	0.49	0.40	0.36	0.45	0.41	0.40	0.42	0.42	0.56	0.39	0.51	0.44	0.42
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.07	0.05	0.06	0.07	0.07	0.07	0.06	0.07	0.07	0.06	0.06	0.09	0.06
	P50	0.11	0.09	0.09	0.13	0.11	0.12	0.10	0.11	0.10	0.09	0.11	0.14	0.11
	P75	0.18	0.15	0.13	0.21	0.19	0.18	0.17	0.15	0.17	0.14	0.20	0.19	0.17
	P90	0.24	0.21	0.19	0.29	0.24	0.23	0.24	0.19	0.24	0.20	0.28	0.24	0.26
	P95	0.26	0.24	0.22	0.33	0.27	0.27	0.28	0.22	0.28	0.24	0.32	0.27	0.31
surface current speed(m/s)	mean	0.24	0.22	0.21	0.25	0.26	0.23	0.25	0.21	0.24	0.22	0.25	0.28	0.23
	max	1.44	1.71	0.89	1.28	0.97	1.22	1.20	0.73	1.42	1.21	1.31	1.02	1.38
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.12	0.11	0.11	0.13	0.12	0.12	0.12	0.12	0.13	0.12	0.14	0.15	0.12
	P50	0.20	0.19	0.18	0.22	0.21	0.20	0.20	0.18	0.21	0.20	0.21	0.24	0.21
	P75	0.32	0.28	0.28	0.34	0.35	0.32	0.33	0.27	0.31	0.29	0.33	0.36	0.32
	P90	0.48	0.45	0.38	0.47	0.55	0.44	0.47	0.37	0.42	0.40	0.50	0.52	0.42
	P95	0.57	0.55	0.47	0.56	0.65	0.55	0.59	0.43	0.50	0.48	0.59	0.61	0.49
bottom current direction (°)	mean	266.1	268.5	272.2	262.8	263.5	272.6	267.2	274.9	274.7	280.7	275.2	268.0	268.0
	mean	207.2	235.5	220.6	208.8	204.6	295.7	257.3	261.3	225.0	276.5	235.2	236.7	219.6
mid current direction (°)	mean	261.3	247.6	239.2	244.0	244.4	241.7	242.5	244.3	225.0	240.1	230.0	220.8	240.0
	mean	121.6	137.1	145.3	108.7	107.1	115.6	119.4	121.1	111.2	119.1	95.3	94.8	98.9
surface current direction (°)	mean	208.2	206.7	202.9	203.6	214.0	211.0	197.0	215.8	201.6	219.7	195.1	200.7	206.4
	mean	87.4	90.2	98.7	87.3	93.7	91.5	88.0	98.4	92.7	100.3	84.9	85.7	91.9

	Statistic	2007	2008	2009	2010	2011	2012	2013	2014	2015
bottom current speed (m/s)	mean	0.12	0.12	0.13	0.12	0.11	0.11	0.12	0.11	0.12
	max	0.26	0.25	0.30	0.26	0.24	0.28	0.26	0.27	0.32
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.08	0.08	0.10	0.10	0.08	0.08	0.08	0.08	0.08
	P50	0.12	0.12	0.13	0.13	0.11	0.11	0.12	0.11	0.12
	P75	0.15	0.15	0.17	0.16	0.14	0.15	0.16	0.14	0.15
	P90	0.18	0.18	0.19	0.18	0.17	0.18	0.19	0.17	0.18
	P95	0.19	0.19	0.21	0.20	0.18	0.19	0.20	0.19	0.20
mid current speed (m/s)	mean	0.13	0.11	0.12	0.10	0.11	0.13	0.14	0.13	0.12
	max	0.39	0.37	0.37	0.47	0.38	0.54	0.45	0.39	0.42
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.07	0.05	0.06	0.05	0.06	0.07	0.07	0.07	0.07
	P50	0.12	0.09	0.11	0.09	0.10	0.11	0.12	0.11	0.10
	P75	0.18	0.15	0.17	0.14	0.16	0.17	0.20	0.18	0.16
	P90	0.23	0.21	0.22	0.19	0.21	0.22	0.28	0.24	0.22
	P95	0.27	0.24	0.25	0.24	0.25	0.26	0.35	0.29	0.27
surface current speed(m/s)	mean	0.26	0.23	0.23	0.25	0.25	0.26	0.31	0.24	0.23
	max	1.16	1.10	0.95	1.18	1.13	1.54	1.18	1.13	1.25
	min	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	P25	0.14	0.12	0.13	0.12	0.13	0.14	0.15	0.13	0.12
	P50	0.23	0.20	0.20	0.21	0.21	0.22	0.26	0.21	0.20
	P75	0.34	0.29	0.30	0.33	0.32	0.34	0.41	0.32	0.31
	P90	0.48	0.42	0.41	0.51	0.49	0.48	0.63	0.44	0.42
	P95	0.58	0.54	0.52	0.60	0.59	0.60	0.76	0.55	0.52
bottom current direction (°)	mean	269.5	274.1	273.6	277.9	272.3	269.5	265.9	267.3	268.5
	mean	234.1	275.6	268.8	258.7	250.9	215.8	234.6	220.2	224.9
mid current direction (°)	mean	205.7	227.5	237.9	231.5	227.2	226.8	229.3	237.6	233.1
	mean	88.8	91.2	108.5	93.0	133.8	105.8	105.7	115.4	135.0
surface current direction (°)	mean	195.5	205.6	197.3	196.8	196.9	207.0	193.6	211.9	208.6
	mean	86.4	81.0	94.6	82.6	90.4	93.2	84.0	90.6	98.7

Table 3-20 Overall bottom, mid and surface current statistics (derived from 22-year modelled dataset)

Current variable	Statistic	Value
bottom current speed (m/s)	mean	0.12
	max	0.32
	min	0.00
	P25	0.08
	P50	0.12
	P75	0.15
	P90	0.18
	P95	0.19
mid current speed (m/s)	mean	0.12
	max	0.56
	min	0.00
	P25	0.06
	P50	0.11
	P75	0.17
	P90	0.23
	P95	0.27
surface current speed(m/s)	mean	0.24
	max	1.71
	min	0.00
	P25	0.13
	P50	0.21
	P75	0.32
	P90	0.46
	P95	0.57
bottom current direction (°)	mean	270.5
	mean	239.4
mid current direction (°)	mean	234.6
	mean	112.5
surface current direction (°)	mean	204.4
	mean	90.52

3.10 Currents – Extreme Conditions

The 1- and 50-year extreme omni directional bottom, mid and surface current speeds, calculated from the 22-year hourly HYCOM's timeseries are presented in Table 3-21 and Figure 3-24 to Figure 3-26. The GEV methodology was chosen to calculate the extreme values for current speeds and the peaks-over-threshold method was chosen to extract discrete extreme events over the 21-year time period as input into the general extreme value analysis.

Table 3-21 Omni-directional bottom, mid and surface current extreme return values statistics (derived from a 21-year modelled dataset)

	1-Year	50-Year
Bottom current speed (m/s)	0.24	0.35
Mid current speed (m/s)	0.27	0.56
Surface current speed (m/s)	0.74	1.66

Return values in the GEV model

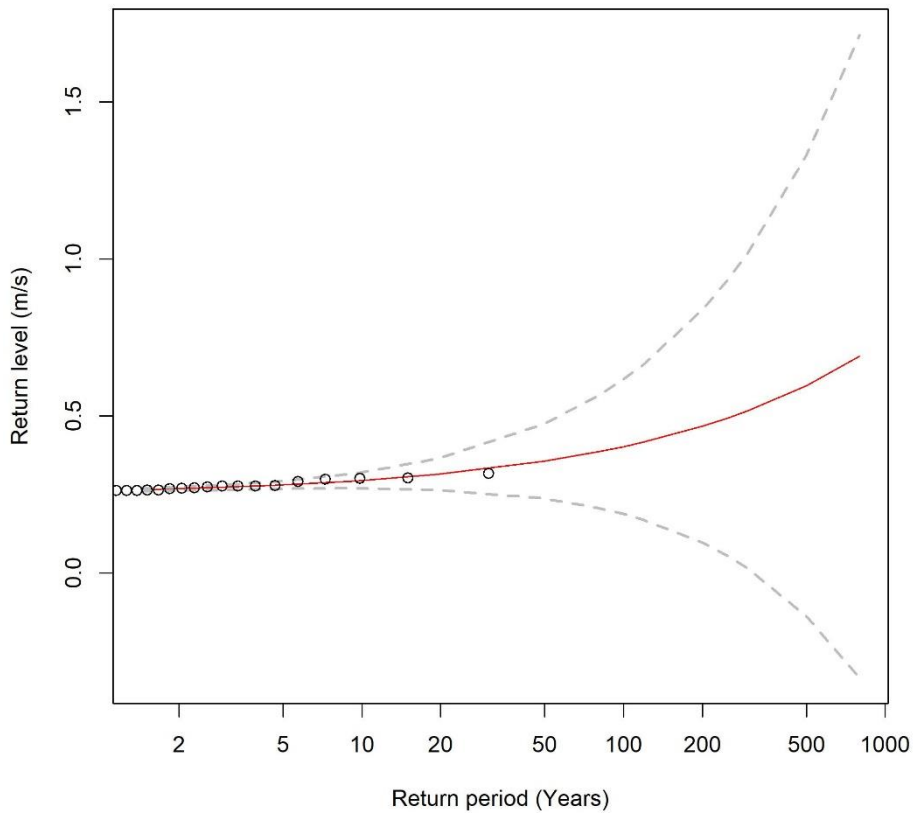


Figure 3-24 Return values of bottom current speed (m/s) in the GEV model. Red curve represents the best fit with the data and aligns with the input data. Dashed lines represent the 95 % confidence intervals. Distribution parameters: location = 0.26115; scale = 0.009524; shape = 0.249104

Return values in the GEV model

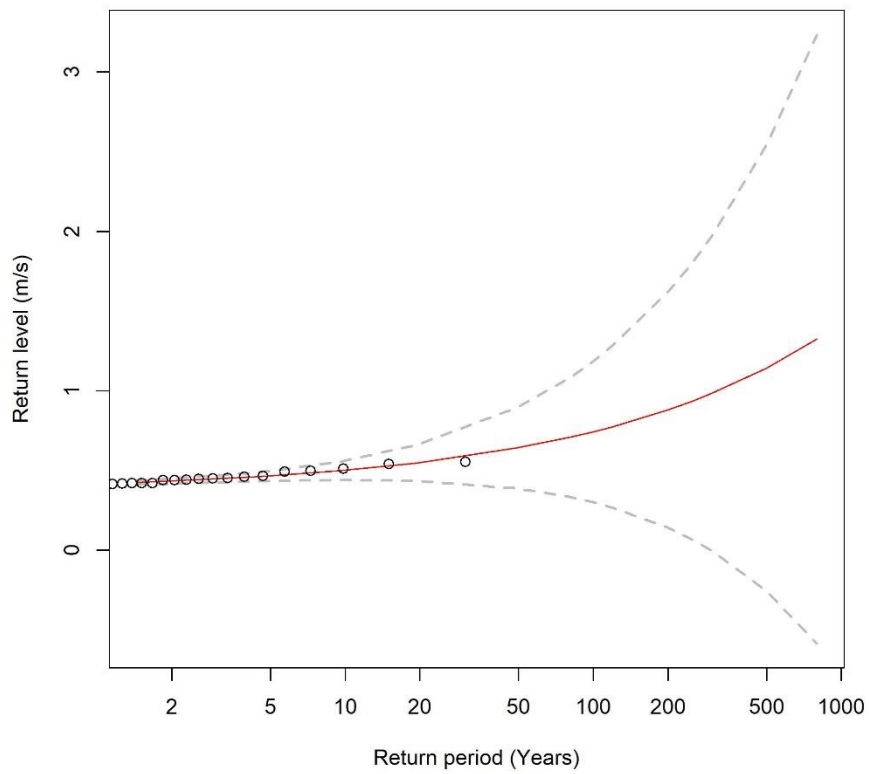


Figure 3-25 Return values of mid current speed (m/s) in the GEV model. Red curve represents the best fit with the data and aligns with the input data. Dashed lines represent the 95 % confidence intervals. Distribution parameters: location = 0.324224; scale = 0.032306; shape = 0.176208

Return values in the GEV model

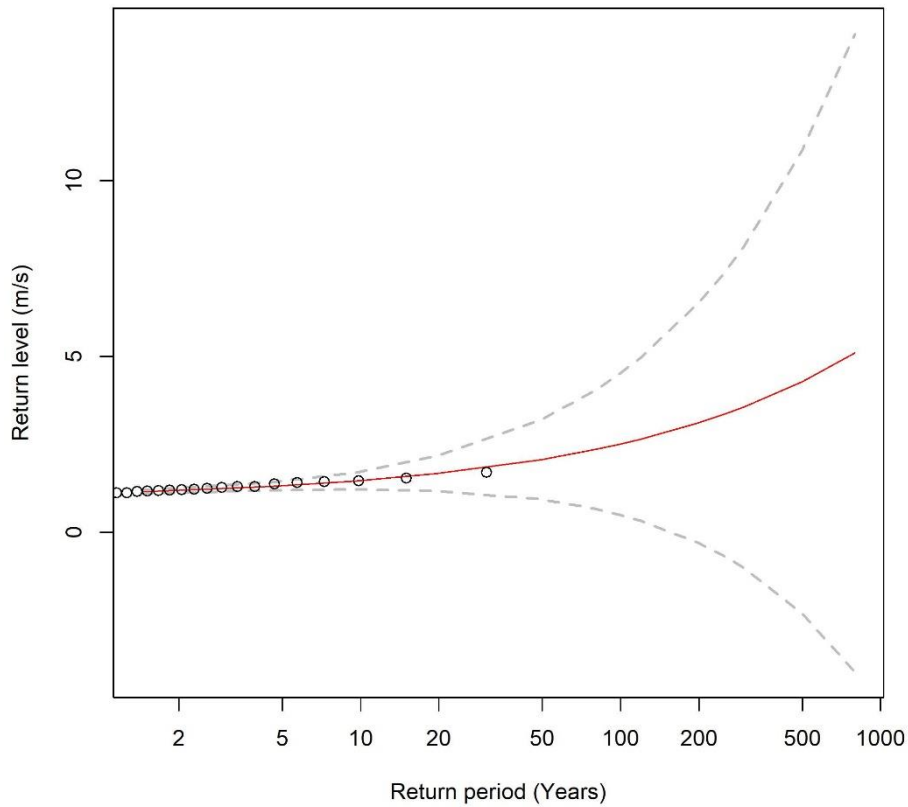


Figure 3-26 Return values of surface current speed (m/s) in the GEV model. Red curve represents the best fit with the data and aligns with the input data. Dashed lines represent the 95 % confidence intervals. Distribution parameters: location = 0.836714; scale = 0.073335; shape = 0.313603.

3.11 Marine Growth

As no confirmed measurements have been carried out, marine growth thicknesses for design for both cases are based on recommended values for UK waters in DNVGL-ST-0437 [9]. These are summarised in Table 3-22. The dry density of marine growth will be taken as 1325 kg/m³ (DNVGL-ST-0437 [9]).

Table 3-22 Marine growth thickness

Depth below MWL (m)	Marine Growth Thickness (mm)
-2 to 40	100
> 40	50

3.12 Other parameters

Other environmental parameters are defined as follows (DNVGL-ST-0437 [9]):

- Sea water density: 1025 kg/m³ (assumed in lieu of site-specific measurement)
- Sea water salinity: 3.5 %

4 Conclusion

A preliminary FEED Metocean Study has been produced for IDEA-IRL's reference site 4. This reference site represents the Ulsan Offshore Wind Farm located approximately 30 km off the east coast of Korea in the Sea of Japan (East Sea). A robust set of metocean parameters was produced that will be used to inform the design of the reference floating wind arrays in WP2. The results presented herein can only be considered as a pre-FEED study and are aimed to serve as input for preliminary design.

This report serves as an appendix to the summary report for WP1.

5 References

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