REPORT

Scottish Salmon - Wave Climate Assessment

Client: The Scottish Salmon Company

Reference: PC2241-RHD-ZZ-XX-RP-Z-0002

Status: S3/P03

Date: 11/11/2021

Royal HaskoningDHV
Enhancing Society Together

HASKONINGDHV NEDERLAND B.V.

Burns House
Harlands Road
Haywards Heath
West Sussex
RH16 1PG
Water & Maritime
Trade register number: 56515154

+44 1444 458551 **T**
info.haywards.heath@uk.rhdhv.com **E**
royalhaskoningdhv.com **W**

Document title:	Scottish Salmon - Wave Climate Assessment
Document short title:	Wave Climate Assessment
Reference:	PC2241-RHD-ZZ-XX-RP-Z-0002
Status:	P03/S3
Date:	11/11/2021
Project name:	Scottish Salmon Wave Modelling
Project number:	PC2241

Classification
Project related

Revision history

Revision	Date	Description	Prepared	Checked	Approved
S0-P01	29.09.2021	First Draft	Katarzyna Bozek	Keming Hu	Nick Cooper
S3-P02	04.11.2021	Second Draft	Katarzyna Bozek	Keming Hu	Nick Cooper
S3-P03	11.11.2021	Final	Katarzyna Bozek	Keming Hu	Nick Cooper

1	**Introduction**	**1**
2	**Methodology**	**3**
2.1	Steps	3
2.2	Wave modelling	3
2.3	Water level	4
2.4	Extreme Value Analysis	5
2.5	Diffraction adjustment	5
3	**Data Collection**	**7**
3.1	Offshore wave and wind data	7
3.2	Measured wave data	8
3.3	Bathymetry data	10
4	**Wave Model Set-up**	**12**
4.1	Model domains	12
4.2	Model mesh	13
4.3	Model parameters	14
4.4	Boundary conditions	15
5	**Model Calibration**	**16**
5.1	Storm events	16
5.2	Wave height	16
5.3	Wave period	17
5.3.1	Calibration results	17
5.3.2	Wave period adjustments	18
5.4	Wave direction	20
5.4.1	Calibration results	20
5.4.2	Wave direction adjustment	20
6	**Extreme Value Analysis**	**23**
6.1	Overview	23
6.2	Wave direction adjustment	23
6.3	Extreme wave height	25
6.4	Extreme wind speed	26
6.5	Extreme wind speed checks	27
6.5.1	Overview	27
6.5.2	Sensitivity test	29
6.5.3	Comparison wind measured wind speed	29

7 Model Results 32

7.1 Sensitivity tests 32

7.2 Production runs 40

8 Conclusions and Recommendations 50

Appendix A – Extreme Value Analysis: Wave Distributions Fitting 51

Appendix B – Extreme Value Analysis: Wind Distributions Fitting 63

Appendix C – Comparison with measured wind conditions 75

Appendix D – Contour plots of the wave model results 80

Table of Tables

Table 2-1: MHWS levels at selected locations (Admiralty Tide Tables, 2020) 4

Table 4-1: Adopted MIKE21-SW model settings 14

Table 5-1: Selected storm events for the regional wave model calibration and validation 16

Table 5-2: Comparison of modelled and measured significant wave height during the selected storm events 17

Table 6-1: Comparison of derived wave height with and without the wave direction adjustment – ERA5 Point 1 24

Table 6-2: Comparison of derived wave height with and without the wave direction adjustment – ERA5 Point 2 24

Table 6-3: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 1 25

Table 6-4: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 2 25

Table 6-5: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 3 25

Table 6-6: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 4 26

Table 6-7: Derived Extreme Wind Speed (m/s) for ERA5 – Point 1 26

Table 6-8: Derived Extreme Wind Speed (m/s) for ERA5 – Point 2 26

Table 6-9: Derived Extreme Wind Speed (m/s) for ERA5 – Point 3 27

Table 6-10: Derived Extreme Wind Speed (m/s) for ERA5 – Point 4 27

Table 6-11: Wind Speed sensitivity test results 29

Table 7-1: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 1 32

Royal HaskoningDHV

Table 7-2: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 2 35
Table 7-3: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 3 36
Table 7-4: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 4 39
Table 7-5: Results of the wave modelling for all sites for the 1 in 1-year return period event 40
Table 7-6: Results of the wave modelling for all sites for the 1 in 10-year return period event 42
Table 7-7: Results of the wave modelling for all sites for the 1 in 50-year return period event 43
Table 7-8: Results of the wave modelling for all sites for the 1 in 100-year return period event 44
Table 7-9: Results of the wave modelling for all sites for the 1 in 500-year return period event 46

Table of Figures

Figure 1-1: Approximate assessment area 1
Figure 2-1: Wave diffraction by a headland (extract from Figure 3.19 in section 3.2.4, Y. Goda, 2000**)** 6
Figure 2-2: Wave diffraction by an island (extract from Figure 3.20 in section 3.2.4, Y. Goda, 2000) 6
Figure 3-1: Location of the ERA5 hindcast data (green squares) and the wave buoys (red diamonds) 7
Figure 3-2: Wave rose (significant wave height) at West Hebrides 8
Figure 3-3: Wave rose (peak wave period) at West Hebrides 9
Figure 3-4: Wave rose (significant wave height) at Blackstones 9
Figure 3-5: Wave rose (peak wave period) at Blackstones 10
Figure 3-6: Extent of the available bathymetry data from C-Map and the Admiralty Data Service 11
Figure 4-1: Illustration of the adopted regional and local wave model domains 12
Figure 4-2: Computational mesh of the regional model with the locations of the open boundaries 13
Figure 4-3: Regional wave model domain and interpolated bathymetry 14
Figure 5-1: Comparison of modelled (red line) and measured (blue line) significant wave height at West Hebrides 16
Figure 5-2: Comparison of modelled (red line) and measured (blue line) significant wave height at Blackstones 17
Figure 5-3: Comparison of modelled (red line) and measured (blue line) peak wave period at West Hebrides 18
Figure 5-4: Comparison of modelled (red line) and measured (blue line) peak wave period at Blackstones 18

Figure 5-5: Measure vs Modelled peak wave period at West Hebrides 19
Figure 5-6: Measure vs Modelled peak wave period at Blackstones 19
Figure 5-7: Comparison of modelled (red line) and measured (blue line) peak wave direction at West Hebrides 20
Figure 5-8: Comparison of modelled (red line) and measured (blue line) peak wave direction at Blackstones 20
Figure 5-9: Measure vs Modelled peak wave period at West Hebrides 22
Figure 5-10: Measure vs Modelled peak wave period at Blackstones 23
Figure 6-1: Extract form the HSE (2002) report – Contours of 1 in 50-year extreme wind speeds 28
Figure 6-2: Comparison of wind speed from the ERA5 data Point2, Benbecula and Stronoway Airports 30
Figure 6-3: Comparison of wind direction from the ERA5 data Point2, Benbecula and Stronoway Airports 31
Figure 7-1: Contour plots of significant wave height within model Domain 1 – 1 in 50-year return period event 47
Figure 7-2: Contour plots of significant wave height within model Domain 2 – 1 in 50-year return period event 48
Figure 7-3: Contour plots of significant wave height within model Domain 3 – 1 in 50-year return period event 48
Figure 7-4: Contour plots of significant wave height within model Domain 4 – 1 in 50-year return period event 49

1 Introduction

The Scottish Salmon Company (SSC) are reviewing extreme conditions at several locations across the west coast of Scotland. Royal HaskoningDHV have been commissioned to undertake the Wave Climate Assessment (WCA) at a number of sites.

The sites included within the WCA are located across the western coast of mainland Scotland and around Outer Hebrides. All sites are sited in water depths exceeding 10m above Chart Datum (CD) and distances greater than 150m from the shoreline. The study area is presented in **Figure 1-1**.

This report provides a description of the comprehensive assessment of the extreme wave conditions undertaken at the considered sites. This includes derivation of the extreme offshore waves and wave transformation modelling to determine the wave conditions at each of the sites, considering directional vulnerability of each site to the extreme waves.

Figure 1-1: Approximate assessment area

This report comprises the following sections:

- **Section 2** – outlining the methodology adopted in data analysis and wave modelling;
- **Section 1** – describing the data collated for the analysis;
- **Section 1** – outlining the wave model set-up;
- **Section 1** – describing the model calibration and its results;
- **Section 6** – outlining the extreme value analysis of offshore wind and wave conditions;
- **Section 1** – describing the simulated scenarios and obtained results of the wave modelling;
- **Section 1** – presenting the conclusions and recommendations.

Attached to this report there are three appendices, which present additional plots in support of the extreme value analysis described in **section 6**.

In addition, a series of Annexes has been prepared for each evaluated site separately. Each Annex describes each site's specific conditions and presents the wave modelling results for the particular site.

This report describes the methodology applied in the wave climate assessment and modelling, whereas details and modelled outputs for each site can be found in the relevant annexes.

2 Methodology

2.1 Steps

The assessment has been undertaken in accordance with a number of steps in the following sequence:

1) data collection, processing, and analysis;
2) regional wave model set-up and calibration;
3) derivation of extreme wave and wind at offshore conditions;
4) local wave models set-up and simulations to identify the worst wave direction for each site;
5) local wave models' simulations for all return period events for the worst direction;
6) results processing to determine wave conditions at each site.

2.2 Wave modelling

The wave modelling in this study has considered offshore to nearshore transformed waves as well as locally wind generated waves for all sites. Where appropriate based on individual site location, for partially sheltered sites both offshore wave propagation and locally generated waves were assessed and for fully sheltered sites where the offshore wave propagation is highly unlikely, only the locally wind generated waves were assessed. Where a local model for the wind generated waves was developed for a specific site, further details are discussed in the respective Annex.

For the purpose of this study, the offshore wave transformation and local wind waves generation was undertaken using the phase averaging MIKE21 Spectral Wave (SW) Model developed by the Danish Hydraulic Institute (DHI). The MIKE21 SW is a new generation spectral wind-wave model based on unstructured mesh. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas and can simulate the following physical phenomena:

- wave growth by action of wind;
- non-linear wave-wave interaction;
- dissipation due to white capping;
- dissipation due to bottom friction;
- dissipation due to depth-induced wave breaking;
- refraction and shoaling due to depth variations;
- diffraction;
- wave-current interaction; and

- effect of time-varying water depth and flooding and drying.

Considering that the assessment sites extend across a large area, the wave modelling has been based on a two-step approach. Firstly, a larger regional wave model has been developed, calibrated and validated with the obtained local wave data. Secondly, the regional model has been used to derive boundary conditions for the smaller local models, which were defined based on the site locations, where one local model covers multiple sites. This approach allows development of multiple small, local models for specific areas with required refinement of the mesh but without compromising computational time required for the simulations. In addition, the regional model can be used in the future to derive boundary conditions for other locations within its extent, that were not considered in this study.

Measured wave data was only available for calibrating the regional model and, therefore, the calibrated regional model settings were used in all local models. Further details on the model set-up and calibration are provided in **section 1** and **section 1**, respectively.

The wave conditions were derived for the required return periods, i.e. 1 in 1-year 1 in 10-year, 1 in 50-year, 1 in 100-year and 1 in 500-year, that is 100% Annual Exceedance Probability (AEP), 10%AEP, 2%AEP, 1%AEP and 0.2%AEP, respectively. As agreed with the client, no climate change allowances for sea level rise or increase in wave heights were considered in this study.

2.3 Water level

The mean high water spring (MHWS) tide level was used in the wave modelling for all considered cases return period events. The levels were obtained from the Admiralty Tide Tables published by the UK Hydrographic Office[1] for a number of locations, in close proximity to the sites, and are presented in **Table 2-1**.

The highest MHWS was adopted for the regional model, i.e. +5.6mCD (at Shieldaig), as discrepancies in deep water is of less importance than for shallower areas. For the local wave models, the MHWS levels were defined by the closest available location, and where multiple locations are available the highest value was adopted. The selected water levels for each model domain are presented in **section 4.4**.

Table 2-1: MHWS levels at selected locations (Admiralty Tide Tables, 2020)

Area	Port Location	MHWS (mCD)	MHWS (mOD)
Loch Torridon	Shieldaig	+5.6	+2.8
Outer Hebrides	Little Bernera	+4.3	+2.1
Isle of Lewis	Stornoway	+4.8	+2.1
The Little Minch	Lochmaddy	+4.8	+2.3
Loch Tuath	Sound of Ulva	+4.4	+2.5
Loch na Lathaich	Bunessan	+4.3	+2.4
Loch Fyne	East Lock Tarbert	+3.6	+2.0
Loch Fyne	Inveraray	+3.3	+1.7
Firth of Clyde	Rothesay Bay	+3.6	+2.0

[1] *the UK Hydrographic Office (UKHO), NP20IB, Volume IB, 2020*

2.4 Extreme Value Analysis

The Extreme Value Analysis (EVA) of the offshore waves and wind was undertaken using an in-house developed tool run in MATLAB, a programming language and numeric computing environment developed by MathWorks. The tool is based on the Wave Analysis for Fatigue and Oceanography (WAFO) toolbox, a third-generation package of MATLAB routines for handling statistical modelling, calculation and analysis of random waves and wave characteristics and their statistical distributions, developed by Lund University and generally accepted as best practise approach (http://www.maths.lth.se/matstat/wafo/).

The tool extracts extreme events from the defined dataset (described in **section 3.1**) using a Peak over Threshold (POT) approach. This approach means that any values below the set threshold are ignored in the analysis. This is to avoid skewing the results by frequent low values associated with normal (not extreme) conditions. The filtered peaks were then fitted to a typical distribution curve including Weibull, Generalised Pareto Distribution (GPD) and Generalized Extreme Value (GEV). The distribution with the best fit to the input data is chosen to derive the extreme values.

The obtained wave data was also used to determine relationship between offshore wave height and wave period (square root of wave height versus wave period). Based on that correlation, a simple formula was derived and then used to calculate wave period corresponding to the derived extreme offshore wave height for each return period event.

The EVA considered a total of 12 directional sectors (in 30° intervals), starting from 0° sector that includes directions from 345° to 15°. The number of directions tested for each site was determined based on the site location, i.e. if the site is completely sheltered from a particular directional sector, this directional sector was not considered (e.g. west and north-west directions were modelled for sites located on the eastern coast of Outer Hebrides).

2.5 Diffraction adjustment

It is important to note that wave diffraction is approximately represented in the MIKE21-SW phase-averaged model, particularly in areas close behind an obstruction (such as breakwater or headland). Therefore, manual calculations were carried out, to quantify the effect of wave diffraction and derive a correction factor for the most sheltered sites where diffraction could be of importance.

The manual calculations were carried out using the well-known Goda method described in his book: Random Seas and Design of Maritime Structures[2]. The method is described in Section 3.2.4 of the Goda's book, i.e. "Approximate Estimation of Diffracted Height by the Angular Spreading Method". **Figure 2-1** and **Figure 2-2** below were extracted from this section of the book for demonstrating the diffraction calculation method for points sheltered by a headland and an island, respectively.

Past experience shows that the Goda method produces reasonably conservative estimation of wave height. Results obtained from the MIKE21-SW model (direct reading at sheltered locations) were therefore compared to the Goda method (transforming MIKE21-SW model results from outside a headland or an island) and more conservative wave heights adopted for further assessment.

Details of the diffraction calculations for the specific sites are described in the respective Annexes for the sites where diffraction was of concern.

[2] Random Seas and Design of Maritime Structures, Advanced Series on Ocean Engineering – Volume 15 (Y. Goda, 2000, published by World Scientific)

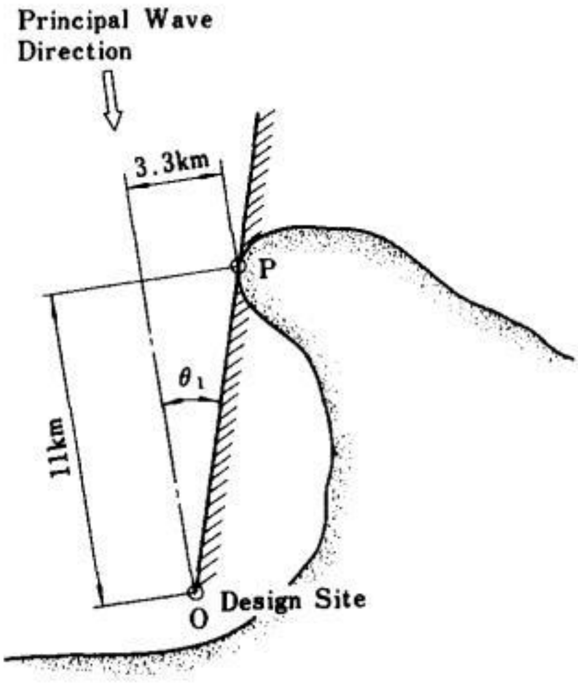


Fig. 3.19. Wave diffraction by a headland.

Figure 2-1: Wave diffraction by a headland (extract from Figure 3.19 in section 3.2.4, Y. Goda, 2000)

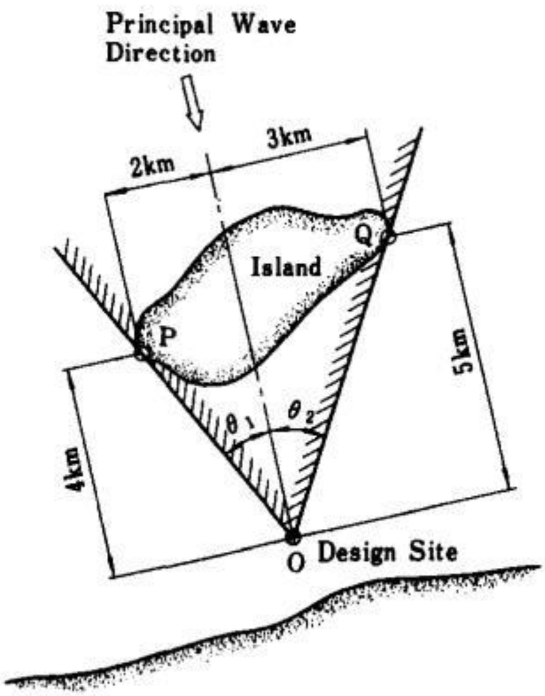


Fig. 3.20. Wave diffraction by an island.

Figure 2-2: Wave diffraction by an island (extract from Figure 3.20 in section 3.2.4, Y. Goda, 2000)

3 Data Collection

3.1 Offshore wave and wind data

There are various specialist institutes and companies that develop operational wave models to provide information on offshore wave and wind. For this study, offshore hindcast data was downloaded from ERA5[3] to provide offshore wind and wave conditions. ERA5 is an open data source available from the European Centre for Medium-Range Weather Forecasts (ECMWF). Four grid points were selected to represent wave and wind conditions approaching from different directions.

The wind and wave data from ERA5 was available from their hindcast model covering over a 40-year period at one hourly intervals from January 1979 to September 2020. Locations of the selected ERA5 points are shown in **Figure 3-1**. The data comprises significant wave height, peak wave period, mean wave direction, wind speed and wind direction for each point. This offshore wind and wave data were used to define boundary conditions of the regional wave model and local wind generated wave models. The wind data was available at a grid resolution of around 31km, whereas the wave data was available at a reduced latitude/longitude grid with a resolution of approximately 40km. The regional model boundaries were defined along these locations.

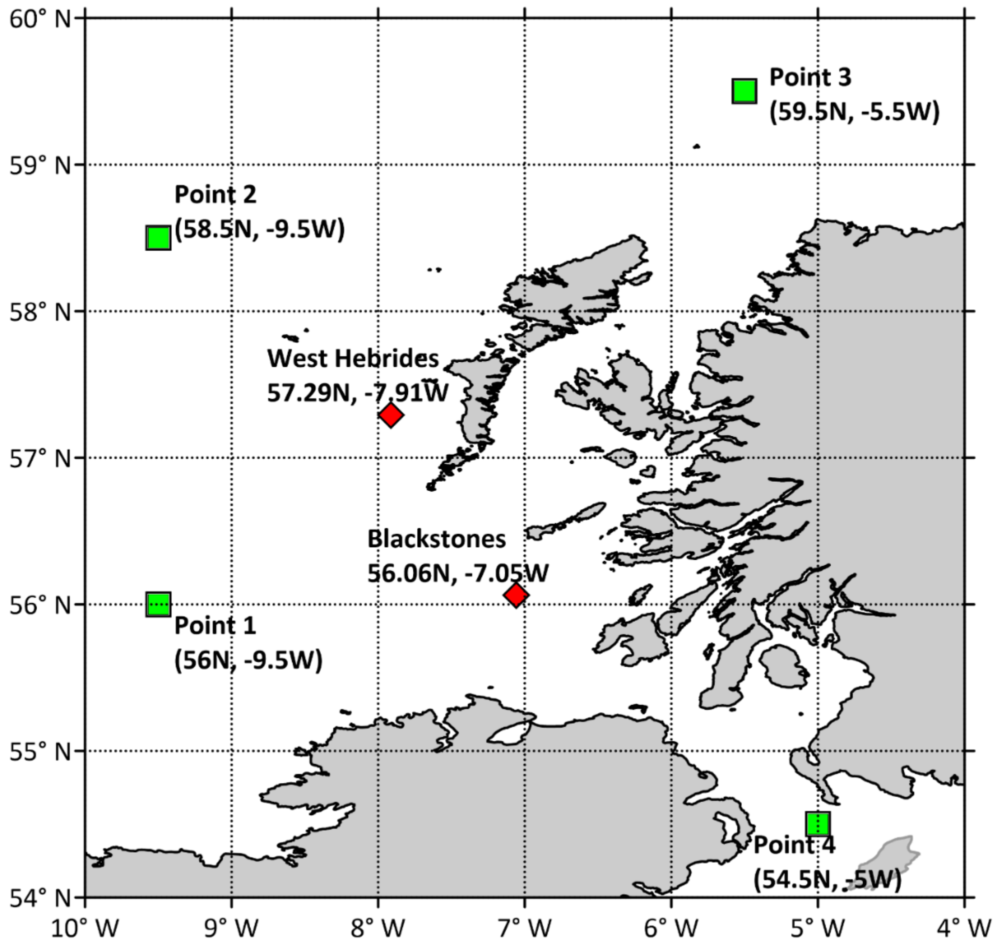


Figure 3-1: Location of the ERA5 hindcast data (green squares) and the wave buoys (red diamonds)

[3] *https://cds.climate.copernicus.eu/cdsapp#!/home*

3.2 Measured wave data

To calibrate and validate the regional wave model, wave data from two local wave buoys were used, namely Blackstones and West Hebrides wave buoys (illustrated by the red diamonds in **Figure 3-1**). For that purpose, two years of wave data was obtained from Cefas, for year 2019 and year 2020, which include a number of storms that impacted the areas of interest, such as Storm Ciara which occurred in early February 2020 and Storm Gareth which occurred in March 2019. In total five suitable storm events were identified for the model calibration and validation. These are summarized in **Table 5-1** in **section 1**, with indicated maximum gust speed at Hebrides.

The two stations West Hebrides (57°17'.53N, 007°54'.85W) and Blackstones (56°03'.72N, 007°03'.41W) are located at a water depth of 100m LAT and 90m LAT, respectively. The wave data provides the information of significant wave height, peak wave period and peak wave direction.

Figure 3-2 to **Figure 3-5** present the derived wave roses for significant wave height and peak wave period at the West Hebrides and Blackstones wave buoys, respectively. The figures show that at both locations the dominant wave direction is from the westerly and north-westerly sectors.

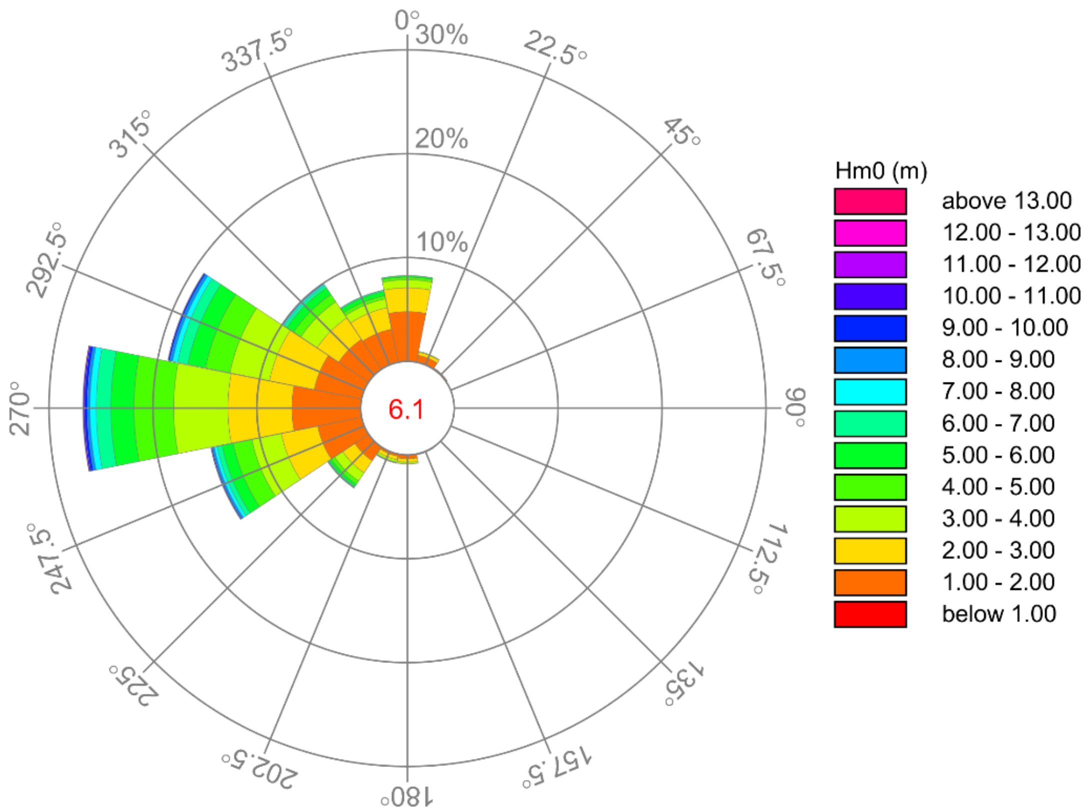


Figure 3-2: Wave rose (significant wave height) at West Hebrides

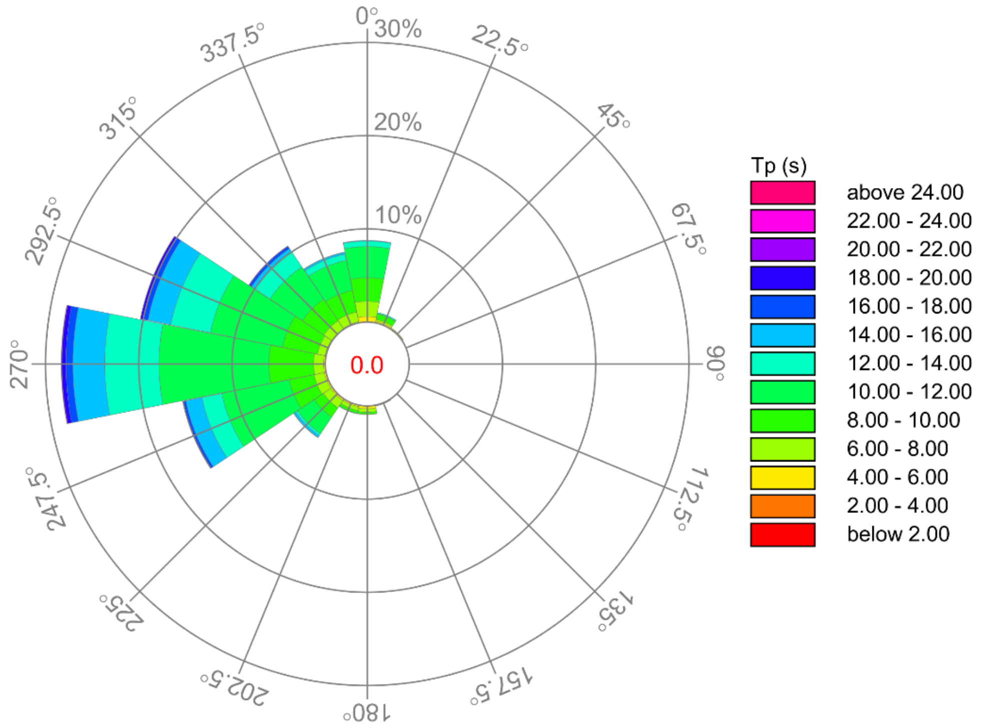


Figure 3-3: Wave rose (peak wave period) at West Hebrides

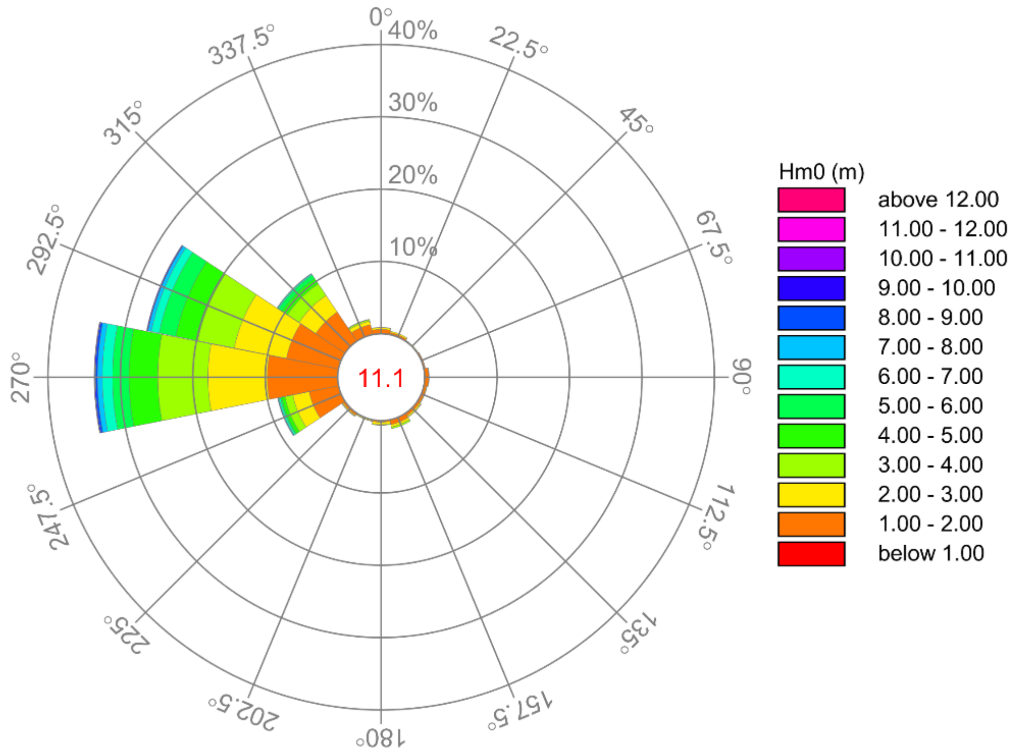


Figure 3-4: Wave rose (significant wave height) at Blackstones

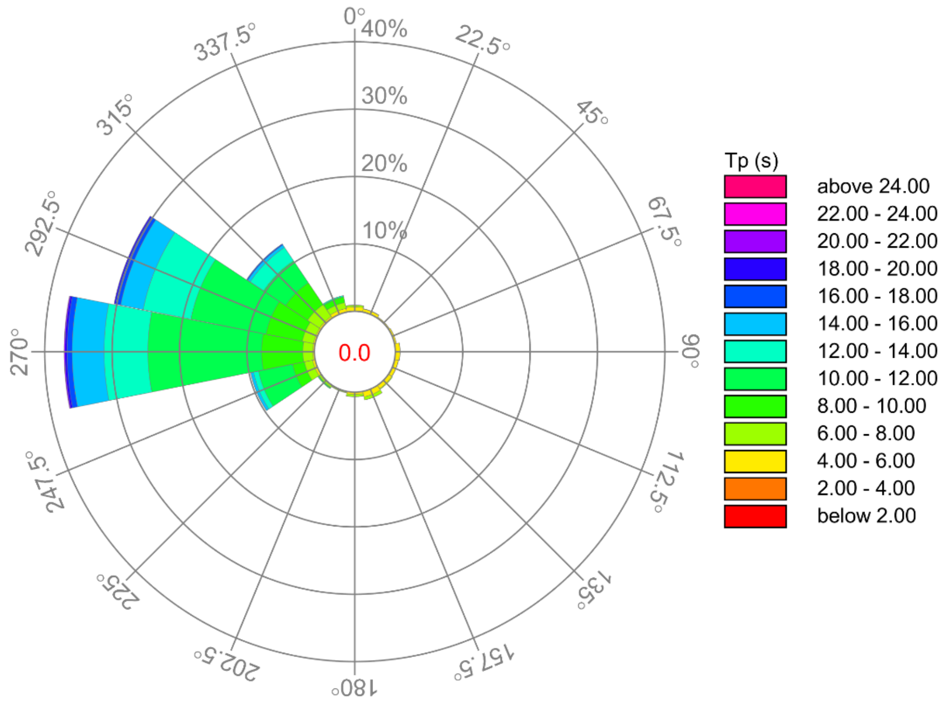


Figure 3-5: Wave rose (peak wave period) at Blackstones

3.3 Bathymetry data

The bathymetry data for the regional and local wave models was taken from three sources, as follows:

- Local survey data provided by the Client;
- Bathymetric data from the UK Hydrographic Office's Admiralty Maritime Data Solutions; and
- C-Map, a digital global navigation charts provided by Jeppesen

The local survey data was provided for 17 locations, approximately 2km^2 for each site, focussed on the nearshore zone. The survey was undertaken with a single beam transducer, in ~100m rows or columns depending on weather conditions. Where the survey data was used in the local wave model for a particular site, details are provided in the respective Annex for that site.

The bathymetric data from the UK Hydrographic Office's Admiralty Maritime Data Solutions covers different locations to a variable extent. Depending on the location, the data was available for different period and at different resolution. All latest (from 2015 onwards) data was collated and used in the model. The extent of available Admiralty data is presented in **Figure 3-6** (orange points).

The C-map data is much coarser than the local survey or the Admiralty data and is distributed mostly at the offshore area, with its extent shown in **Figure 3-6** (green points).

The bathymetry data from all sources was converted to Chart Datum (CD) vertical reference levels.

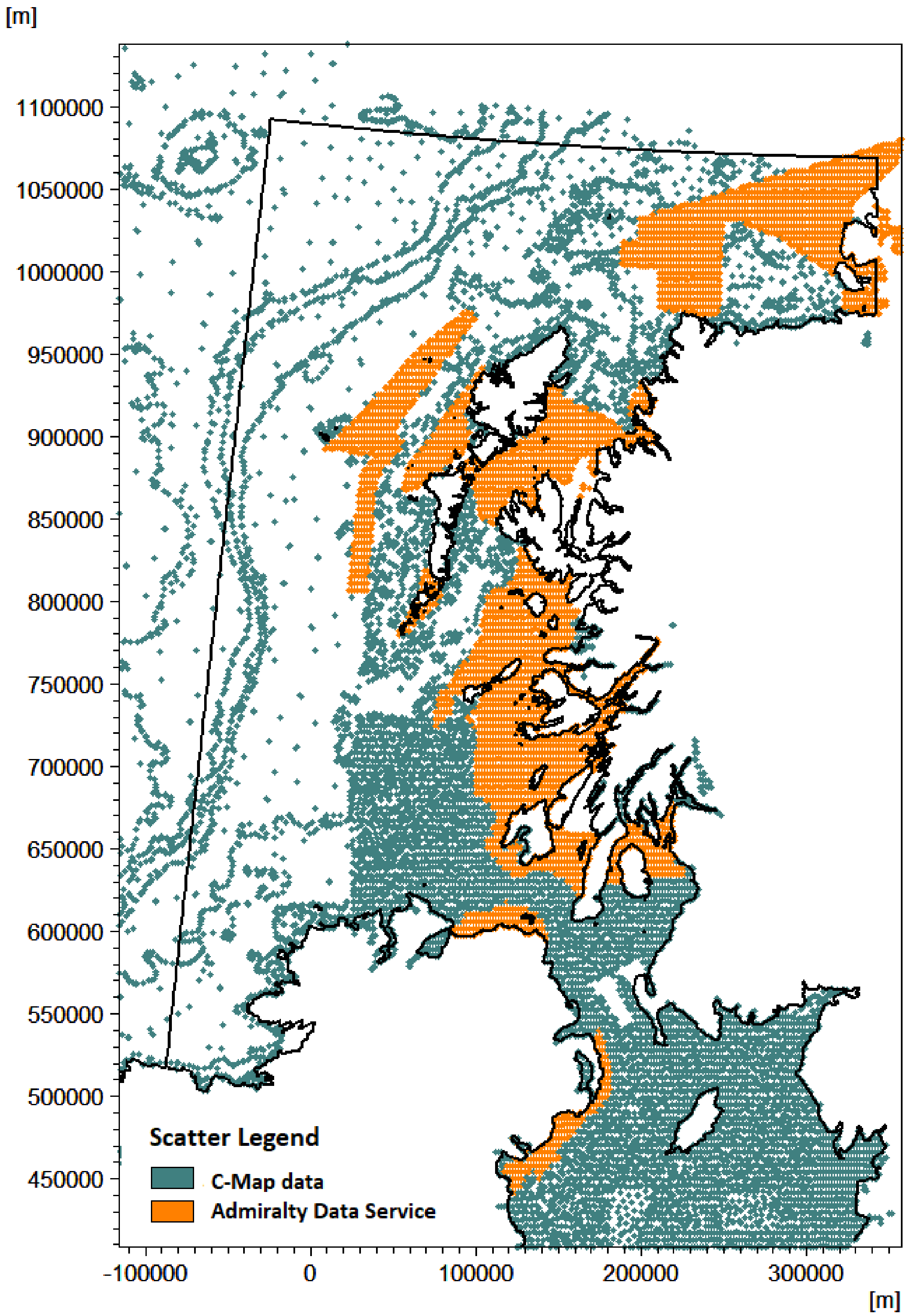


Figure 3-6: Extent of the available bathymetry data from C-Map and the Admiralty Data Service

4 Wave Model Set-up

4.1 Model domains

As discussed in **section 2.2**, for the wave transformation modelling, firstly a regional model was developed, and then local models were nested within the regional model, developed to cover multiple sites based on their location. Figure 3-4 presents the offshore boundaries of the regional model (red lines) and the approximate domains of the main 4 local models. Additional small local models were also developed for particular sites for locally wind generated waves modelling and are presented in respective Annexes for the considered sites.

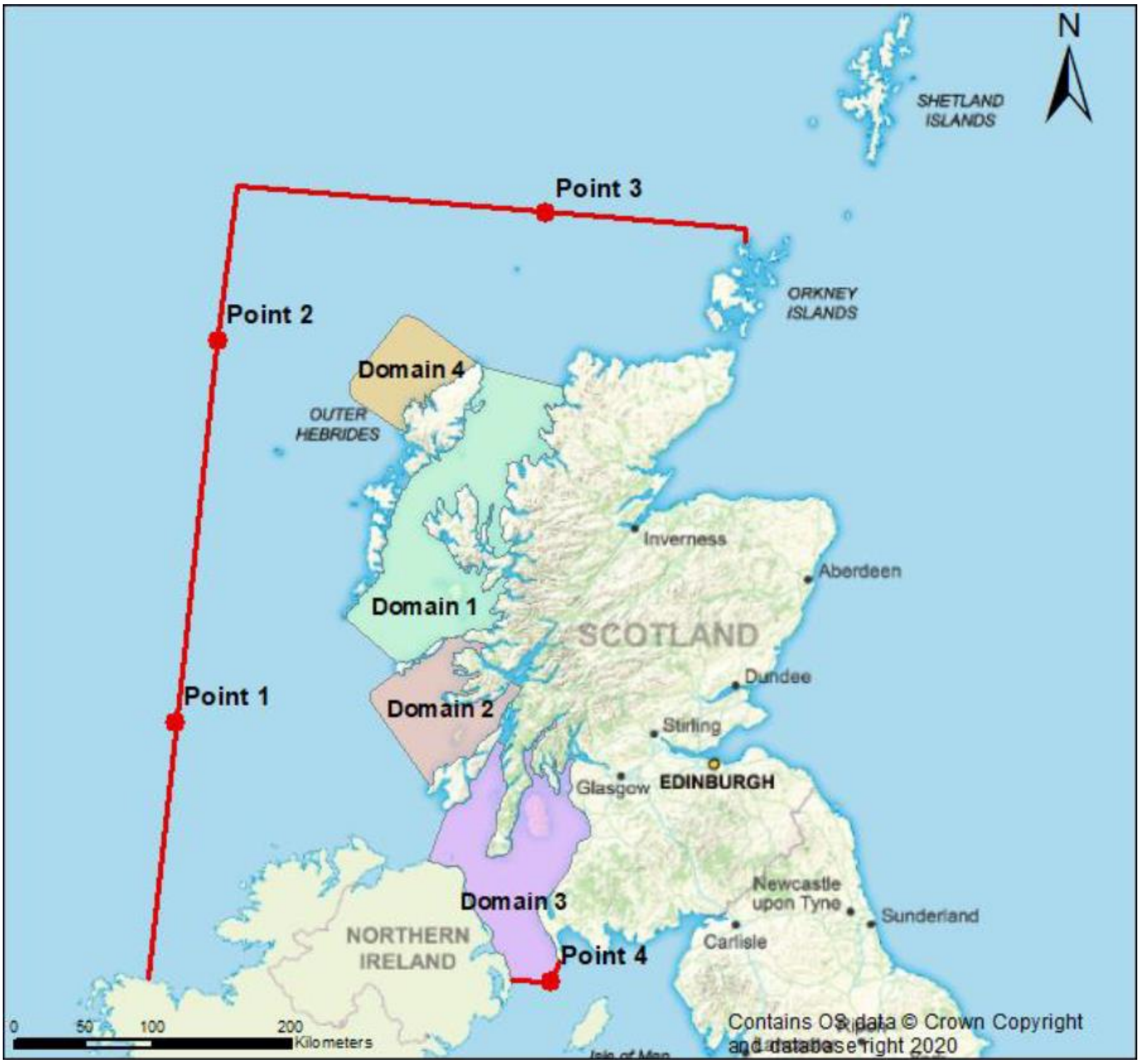


Figure 4-1: Illustration of the adopted regional and local wave model domains

4.2 Model mesh

The derived regional model mesh (grid resolution) is presented in **Figure 4-2**, whereas the regional model bathymetry interpolated based on the available data is presented in **Figure 4-3**.

The mesh resolution in each of the local models was refined around the site locations, whereas in other areas (i.e. areas not important for this study), to limit overall mesh size and subsequently the computational time required for model simulations, a coarser mesh was applied.

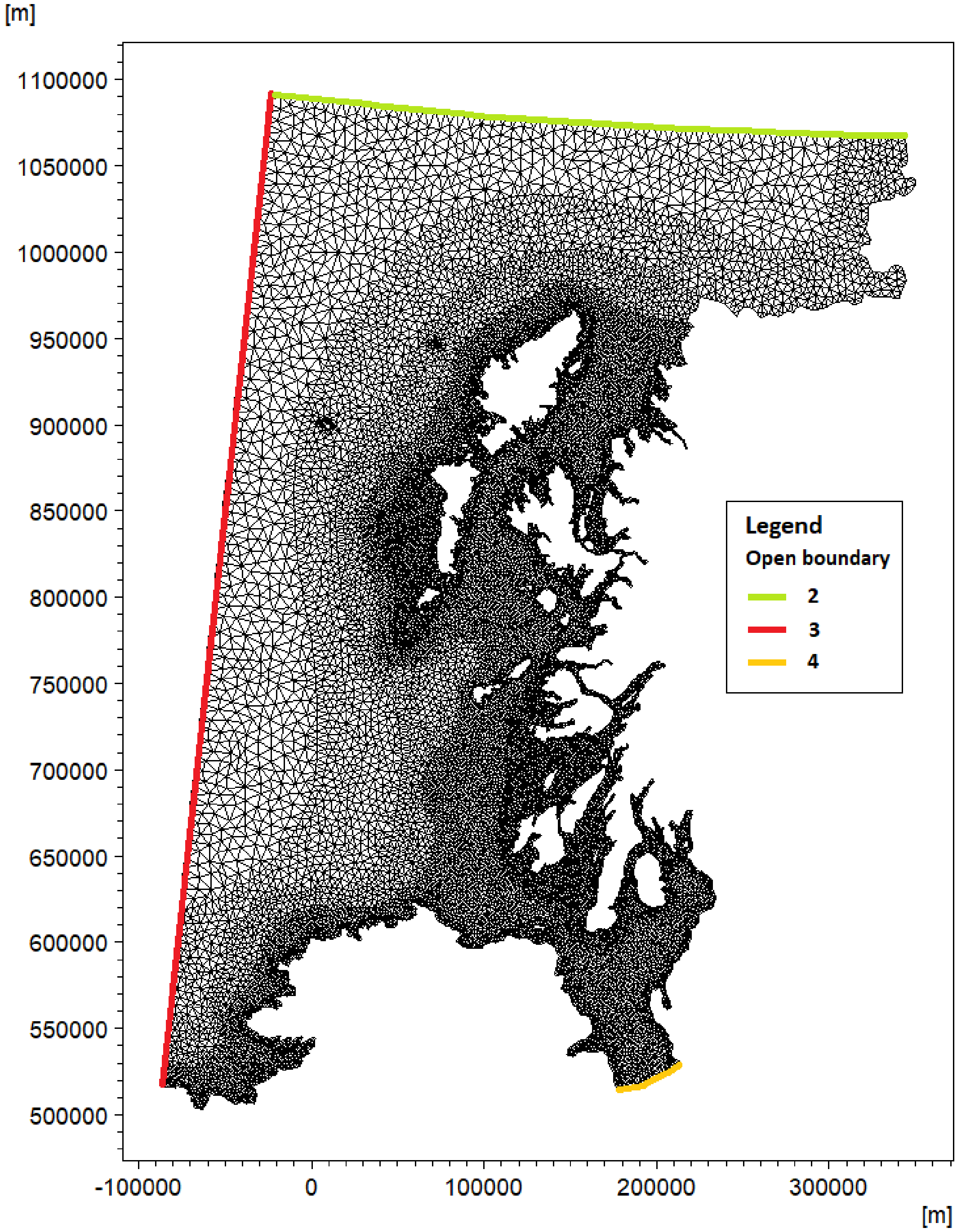


Figure 4-2: Computational mesh of the regional model with the locations of the open boundaries

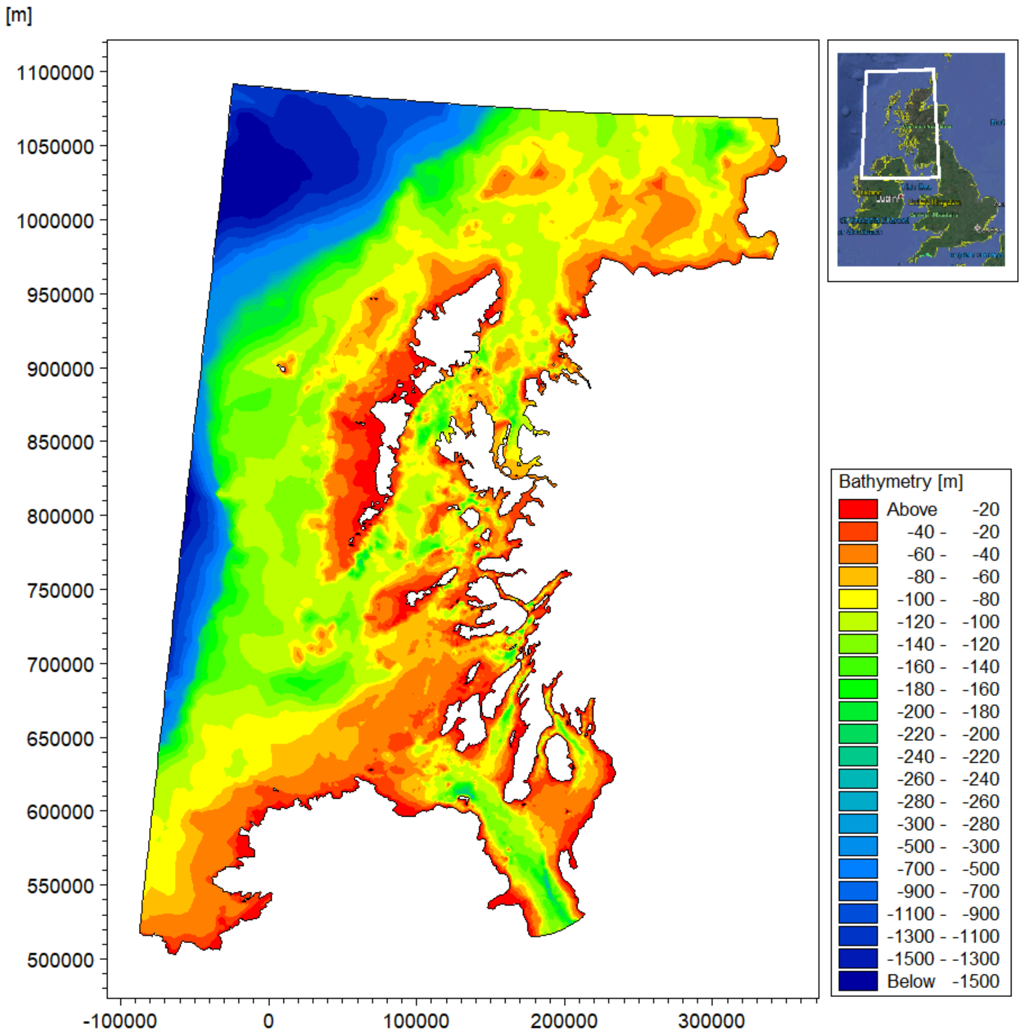


Figure 4-3: Regional wave model domain and interpolated bathymetry

4.3 Model parameters

For the purpose of this analysis, the Fully Spectral Formulation was chosen together with the Uncoupled Wind setting, which is an optimised setting determined during model calibration (discussed in **section 5**). Adopted model settings are listed in **Table 4-1** below.

Table 4-1: Adopted MIKE21-SW model settings

Description	Adopted Settings
Basic Equations	Spectral formulation: Fully Spectral formulation Time formulation: Quasi stationary formulation
Spectral Discretization	Discretization type: 360 degree rose Number of directions: 72
Wind Forcing	Type of air-sea: Uncoupled, Version 1 Charmock parameter: 0.01
Bottom Friction	Model: Nikuradse roughness, kn Constant value: 0.017m

4.4 Boundary conditions

The boundary conditions for the regional model were adopted from the ERA5 data points, taking the closest point to the respective model boundary and depending on the wave/wind direction modelled. For example, for model Domain 3, for directions from southerly sectors, ERA5 point 4 was used, whereas for westerly directions, ERA5 point 1 was used instead.

For the local models, the boundary conditions were derived from the regional wave model results. For the locally wind generated waves the extreme wind conditions were adopted directly from the ERA5 data point, as appropriate for the particular site locations and wind direction.

For both, the regional and local models, the wave and wind boundary conditions were applied to the respective open boundaries, e.g. open boundaries for the regional model are shown in **Figure 4-2. T**he eastern boundaries were specified as land and therefore had no wave or wind forcing's applied.

The wave modelling considered transformation of the resultant wave heights (i.e. combined wave height of swell and wind waves) from offshore to nearshore. In the simulation, the derived extreme offshore wave height and wind condition were applied with the same return period. The use of same return period for both offshore waves and wind data may lead to conservative estimation of nearshore waves along the Atlantic coast. However, based on past experience, the overestimation is likely to be small considering the dominance of offshore waves from the Atlantic Ocean. Therefore, this approach ensures that the locally generated waves by wind are properly predicted where it is dominant.

For locally wind generated waves, the wave models were driven by a constant and uniform extreme wind conditions, derived in the extreme value analysis for the relevant ERA5 data point.

As discussed in **section 2.3**, The MHWS water levels presented in **Table 2-1**, were applied in each model domain based on the highest level from the closest location for each model domain, as follows:

- Regional model - +5.6mCD (highest MHWS);
- Domain 1: +4.8mCD (Stornoway and Lochmaddy);
- Domain 2: +4.4mCD (Sound of Ulva);
- Domain 3: +3.6mCD (East Lock Tarbert and Rothesay Bay);
- Domain 4: +4.3mCD (Little Bernera).

For the additional local models (for local wind generated waves) specific to a particular site, the same approach of adopting the water level from the closest location was adopted. This is discussed in the respective Annexes for the considered sites.

Royal HaskoningDHV

5 Model Calibration

5.1 Storm events

As discussed in **section 3.2**, for the regional model calibration and validation, local wave buoy data was used to compare the modelled and measured wave conditions. The focus of the comparison was on storm events to ensure the model is reliable for predicting extreme wave conditions that are of concern in this study. For the purpose, 5 storm events were selected within the period of the measured data availability. There are listed in **Table 5-1**, providing the maximum gust speed for each event. Since the ERA5 data was only available up to end of September 2020, comparison for Storm Aiden was not possible.

The regional model was simulated for the period of the measured data availability and results for wave height, wave period and direction compared. These are discussed in the following **section 5.2**, **section 5.3** and **section 5.4**, respectively.

Table 5-1: Selected storm events for the regional wave model calibration and validation

Storm Name	Dates	Max Gust Speed (Kt)
Storm Gareth	12 - 13 March 2019	56
Storm Brendan	13 January 2020	76
Storm Aiden	31 October – 2 November 2020	66
Storm Ciara	8 – 9 February 2020	54
Storm Ellen	19 – 21 August 2020	54

5.2 Wave height

Comparison of the modelled and measured significant wave height at the two wave buoy locations shows overall good calibration, as presented in **Figure 5-1** and **Figure 5-2** for the West Hebrides and Blackstones, respectively. In addition, the significant wave height during the 5 storm events was compared, as presented in **Table 5-2**.

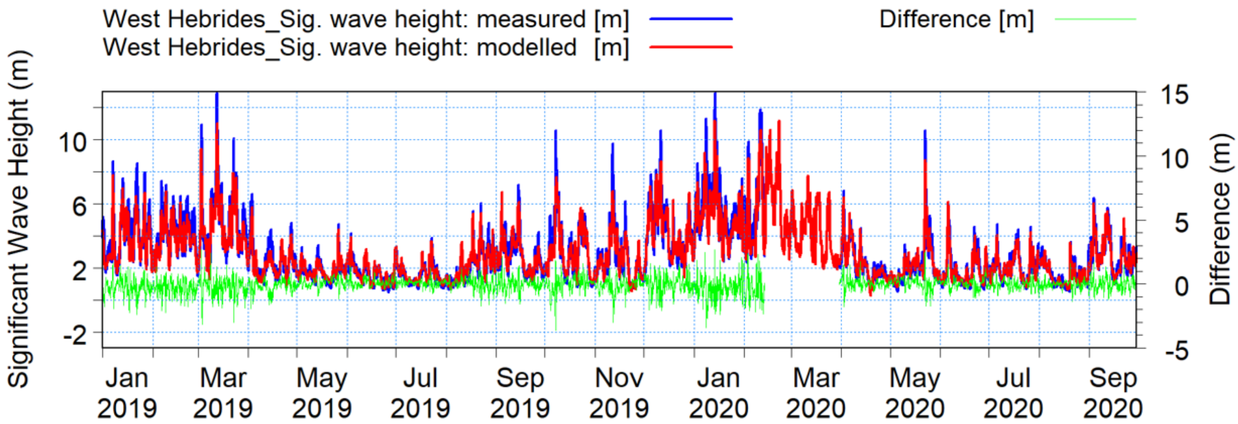


Figure 5-1: Comparison of modelled (red line) and measured (blue line) significant wave height at West Hebrides

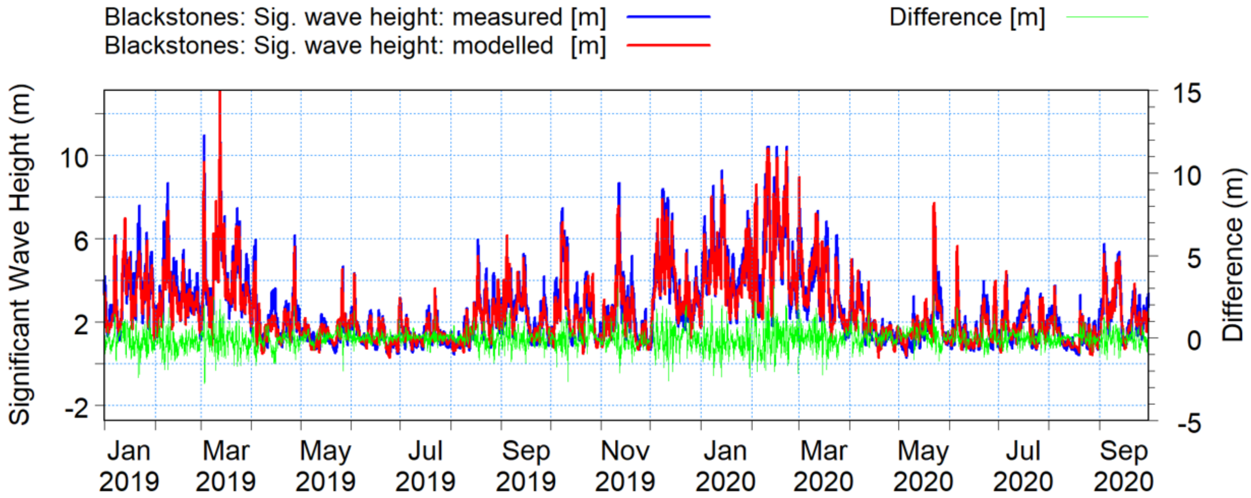


Figure 5-2: Comparison of modelled (red line) and measured (blue line) significant wave height at Blackstones

Table 5-2: Comparison of modelled and measured significant wave height during the selected storm events

Storm Name	Measured Significant Wave Height (m)		Modelled Significant Wave Height (m)	
	West Hebrides	Blackstones	West Hebrides	Blackstones
Gareth	12.9	12.1	12.0	13.1
Brendan	12.9	9.0	11.2	8.8
Ciara	7.6	9.1	7.7	8.4
Storm Ellen	3.6	3.3	3.6	2.5

Comparison presented in **Table 5-2** shows that the modelled wave heights are overall very close to the measured wave heights and therefore, it was concluded that the model is reliable to predict extreme wave conditions. As such, no further calibration for wave heights was undertaken.

5.3 Wave period

5.3.1 Calibration results

Similarly to the wave height comparison, the predicted peak wave periods were also compared with measured data, as presented in **Figure 5-3** and **Figure 5-4** for the West Hebrides and the Blackstone wave buoy locations, respectively.

Figure 5-3 and **Figure 5-4** show that the modelled peak wave period does not perfectly match measured peak wave period, where for longer wave periods it is observed to be consistently lower. Therefore, further investigation was undertaken to determine whether an adjustment factor should be applied. This is discussed in the following **section 5.3.2**.

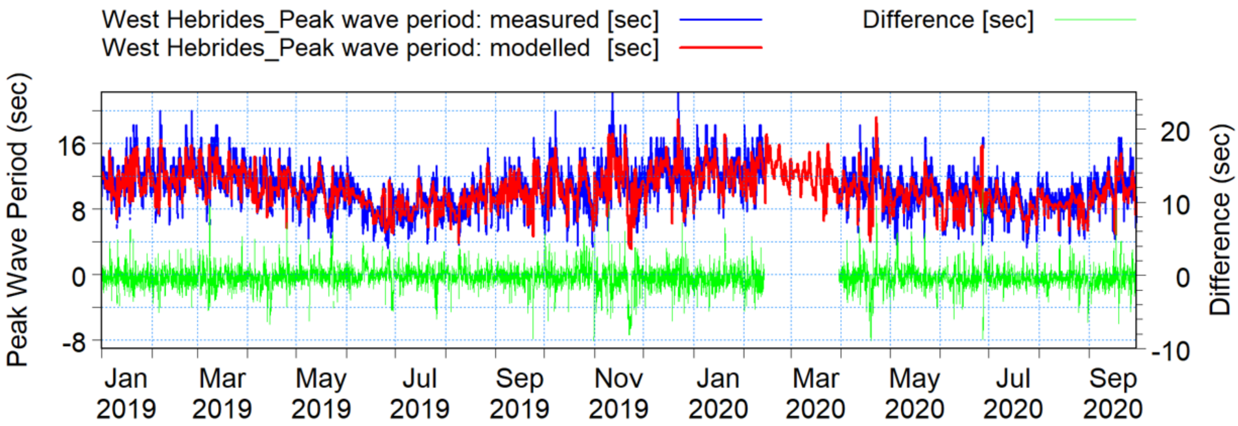


Figure 5-3: Comparison of modelled (red line) and measured (blue line) peak wave period at West Hebrides

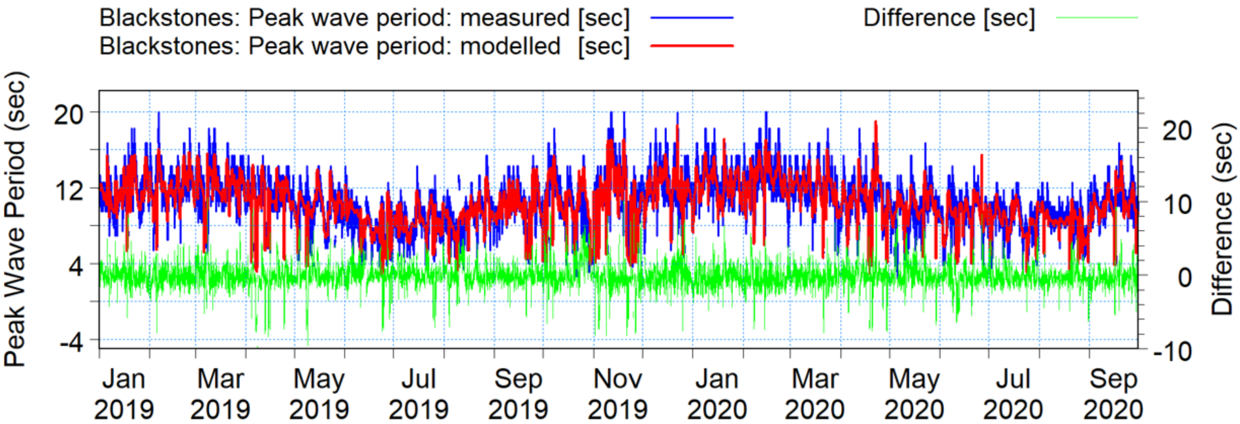


Figure 5-4: Comparison of modelled (red line) and measured (blue line) peak wave period at Blackstones

5.3.2 Wave period adjustments

Following model calibration, further data analysis was undertaken to investigate relationship between the modelled and measured wave period at the two local wave buoy locations. The aim was to investigate whether an adjustment factor could be determined to improve match between the measured and modelled wave period.

Initially, measured vs modelled wave period was plotted. It was noticed that good corelation was present for shorter wave periods, such as below 12 seconds. For higher return periods, the modelled wave period was lower than the measured. This is shown in the left images in **Figure 5-5** and **Figure 5-6** below for the West Hebrides and the Blackstones locations, respectively. The blue line indicates linear relationship between the two datasets, and the blue points are the measured vs modelled wave periods without any adjustment, showing that the blue points are below the blue line for higher wave periods. Subsequently, an adjustment to the wave period was determined and applied to the wave period conditions specified at the offshore model boundaries, as follows:

- Tp < 12 seconds – no adjustment;
- 12 seconds < Tp < 17 seconds = Tp + 2 seconds;
- Tp > 17 seconds = Tp + 2.5 seconds.

Such adjustment results in best fit of the measured vs modelled wave periods along the linear relationship line, as indicated by the orange points centred along the line in the right images in **Figure 5-5** and **Figure 5-6**, for the West Hebrides and Blackstones locations, respectively.

The determined wave period adjustments were agreed with the client and applied to the derived wave period conditions at the offshore model boundaries, as appropriate for all relevant return period events.

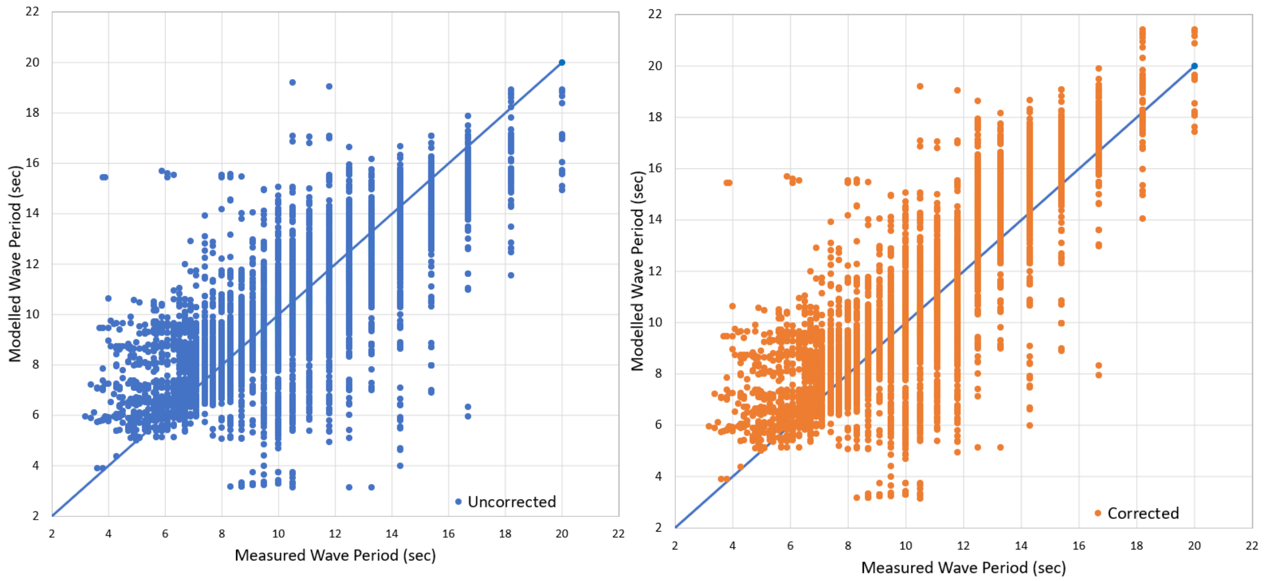


Figure 5-5: Measure vs Modelled peak wave period at West Hebrides

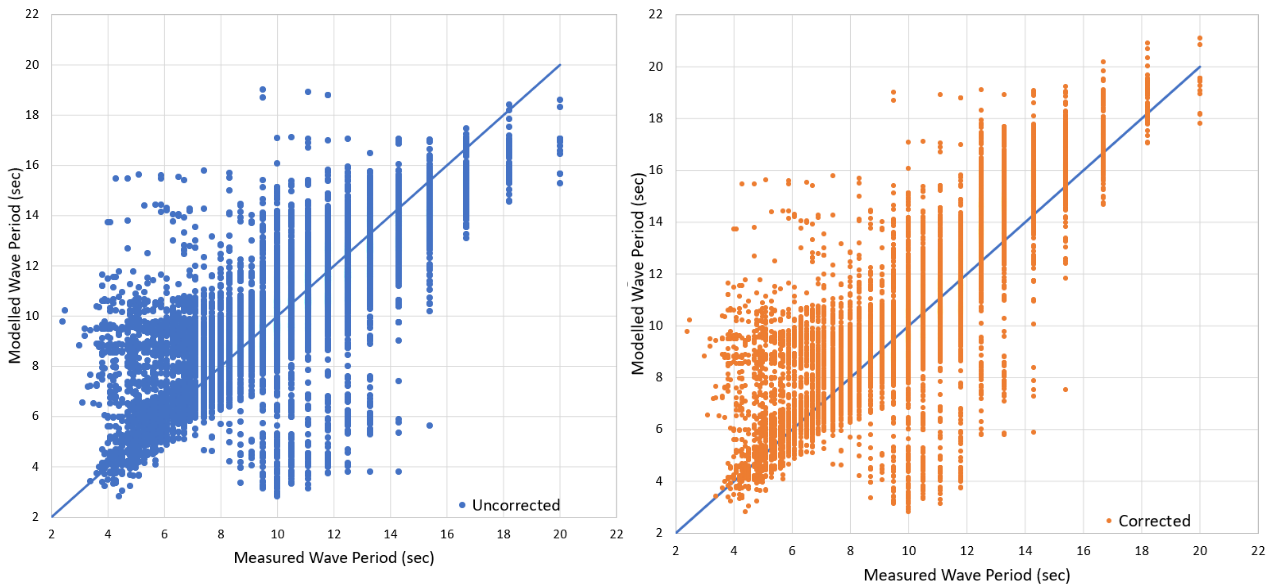


Figure 5-6: Measure vs Modelled peak wave period at Blackstones

5.4 Wave direction

5.4.1 Calibration results

Following comparison of significant wave height and peak wave period, modelled peak wave direction was also compared, as presented in **Figure 5-7** and **Figure 5-8** for the West Hebrides and the Blackstones locations, respectively. It was found that the modelled wave directions were slightly more west orientated, whereas measurements suggest more northerly direction. Therefore, similarly to the wave period, further investigation was undertaken to determine whether an adjustment factor should be applied. This is discussed in the following **section 5.4.2**.

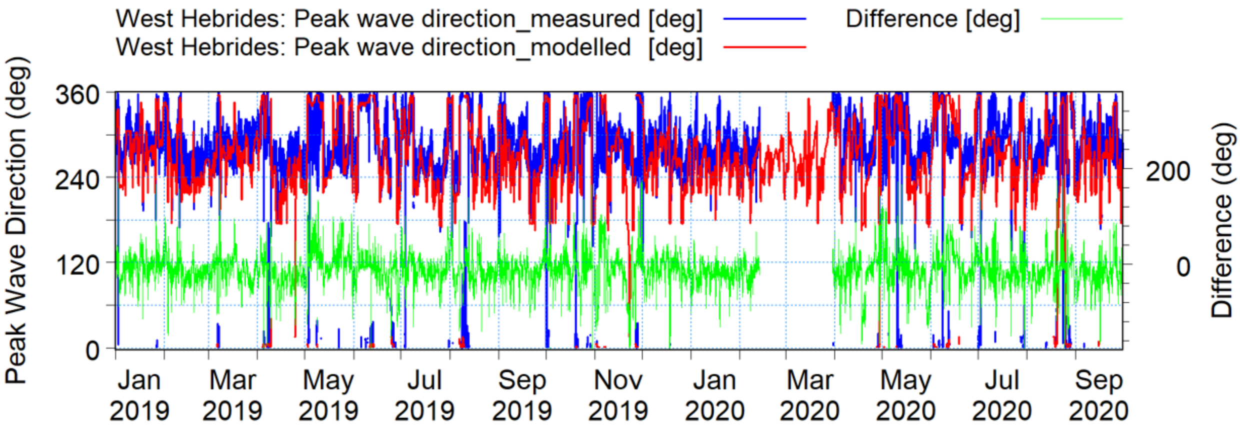


Figure 5-7: Comparison of modelled (red line) and measured (blue line) peak wave direction at West Hebrides

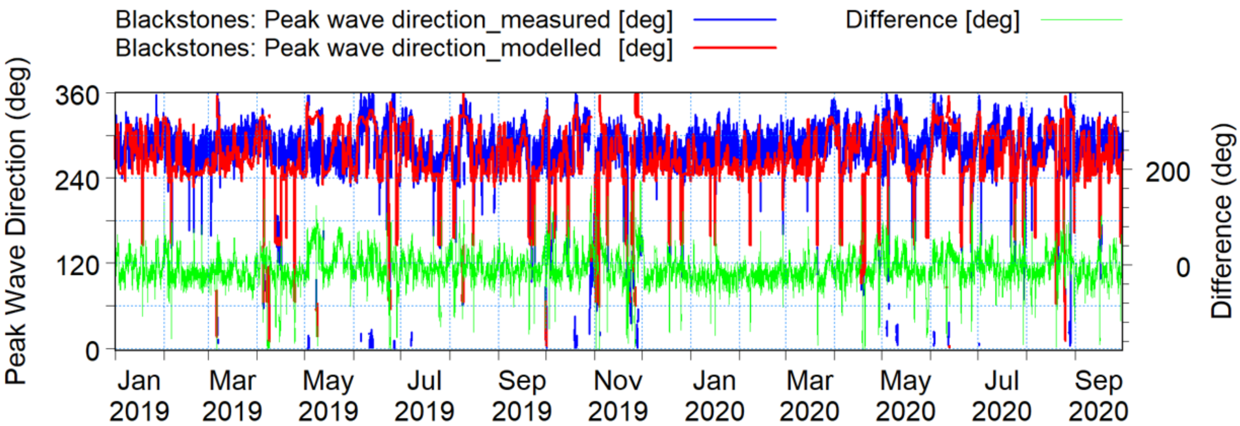


Figure 5-8: Comparison of modelled (red line) and measured (blue line) peak wave direction at Blackstones

5.4.2 Wave direction adjustment

Similarly to the wave period, as part of model calibration further data analysis was undertaken to investigate relationship between the modelled and measured peak wave direction at the two local wave buoy locations. The aim was to investigate whether an adjustment factor could be determined to improve match between the measured and modelled wave direction.

The measured vs modelled wave direction (blue points) was plotted in

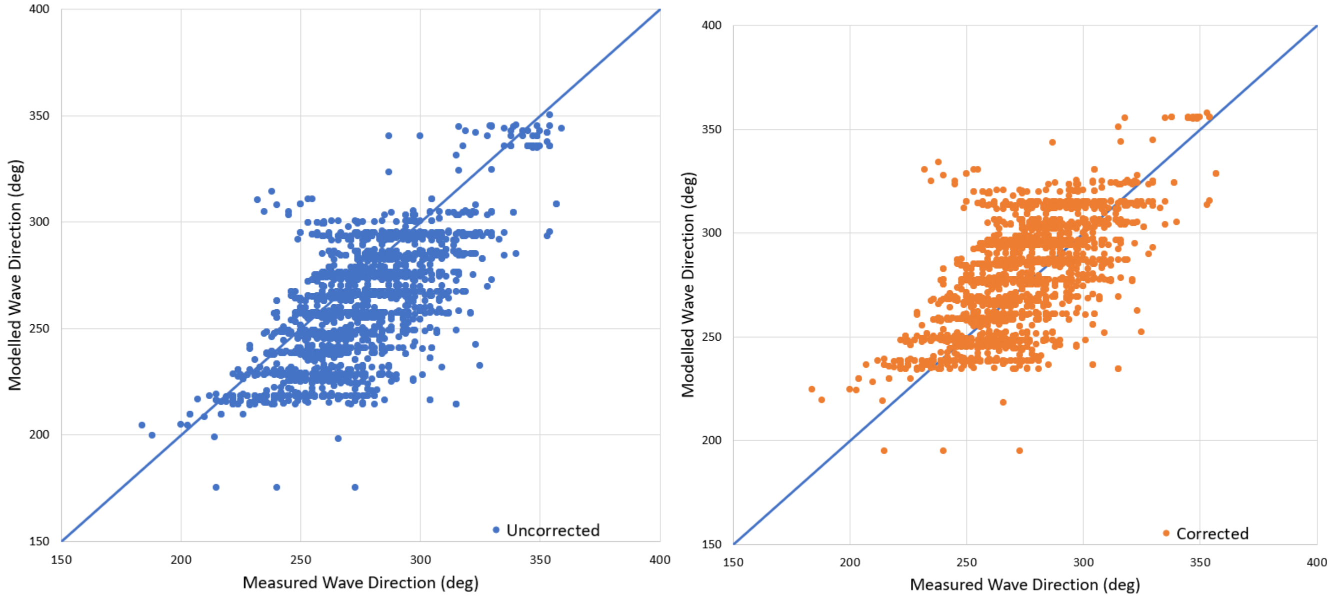


Figure 5-9 (left image) together with a line indicating a linear relationship, showing that majority of the blue points are below the line and therefore the modelled wave direction is lower than measured. To improve the alignment of the points with the line and therefore the match between the modelled and measured wave direction, the modelled wave direction was adjusted by approximately 20 degrees towards north as illustrated in the right image in

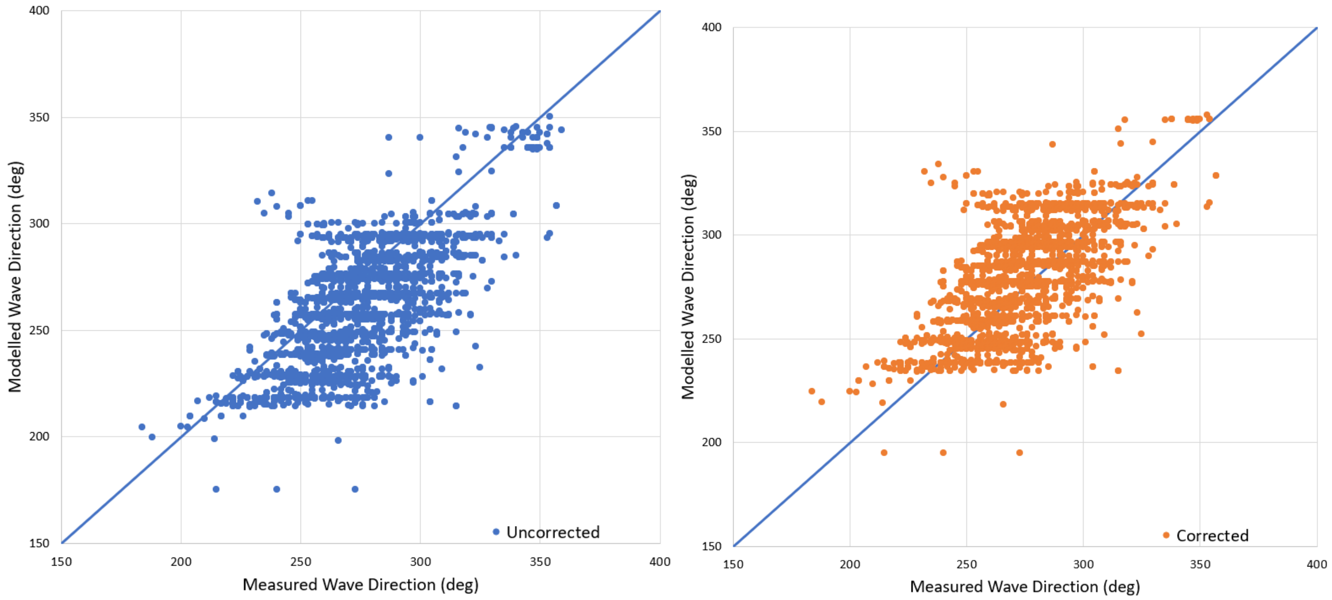


Figure 5-9 (orange points). The comparison between the uncorrected and corrected modelled wave direction in

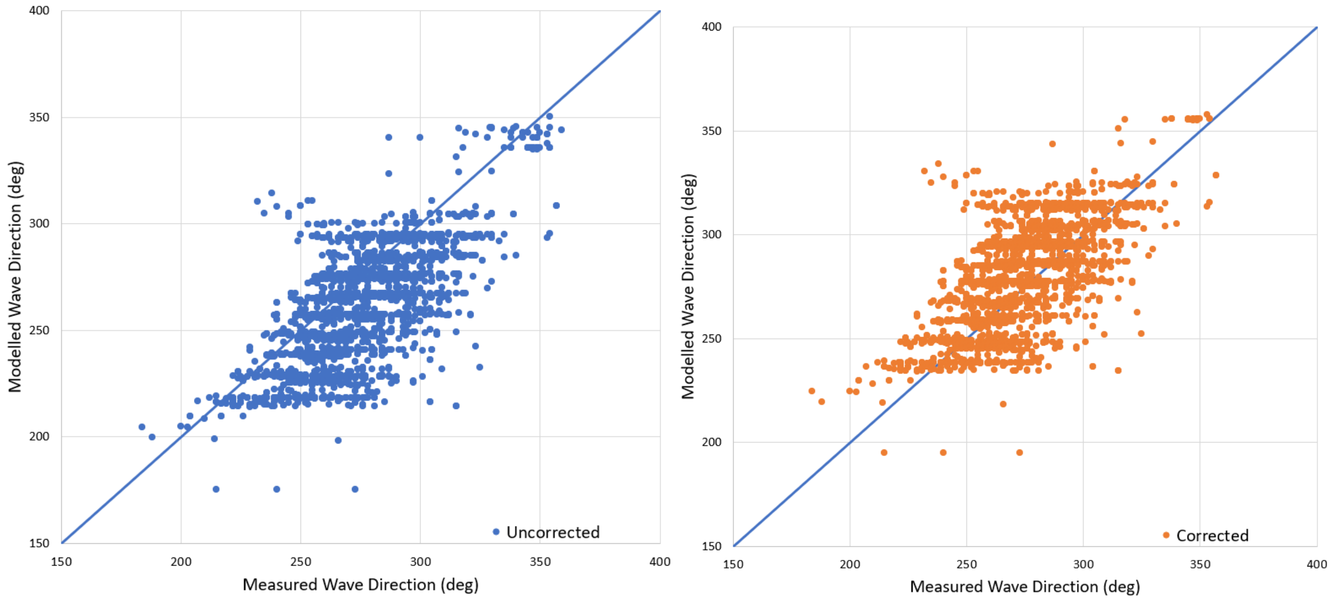


Figure 5-9 showed that the adjusted wave direction follows closer the linear relationship line (i.e., the points are centred along the line) indicating better match between modelled and measured wave direction.

On that basis, it was agreed to consider wave direction adjustment in the Extreme Value Analysis to determine impact on the offshore wave conditions for the various return period events and wave directions. This is discussed in **section 6.2**.

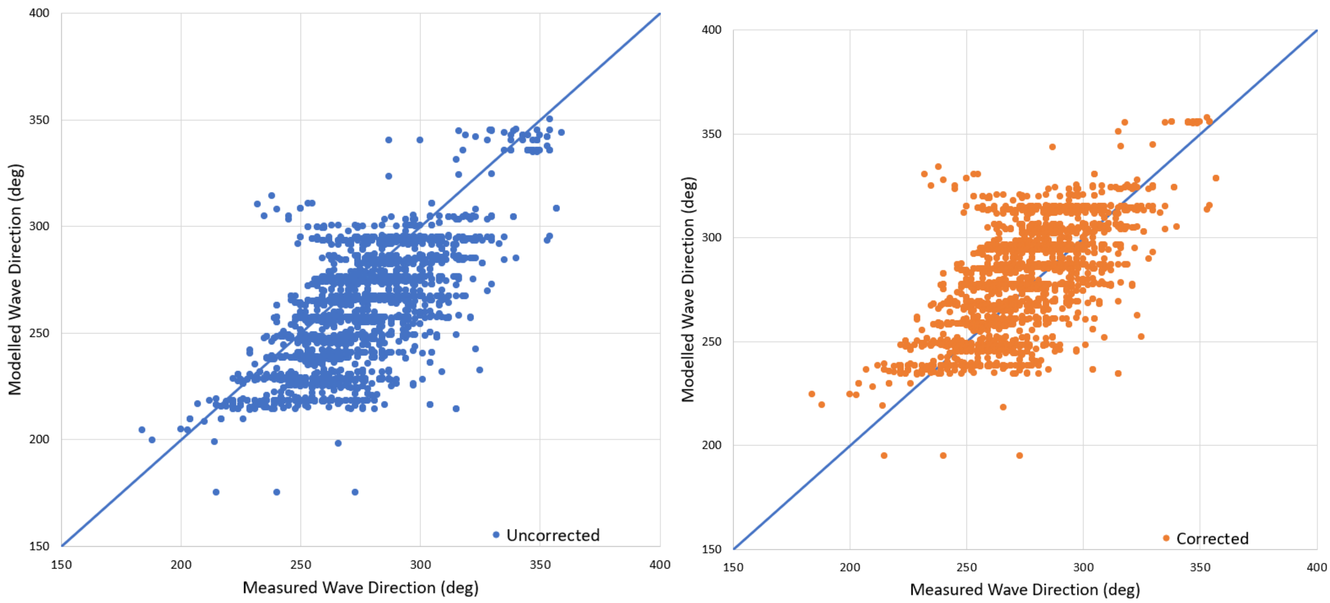


Figure 5-9: Measure vs Modelled peak wave period at West Hebrides

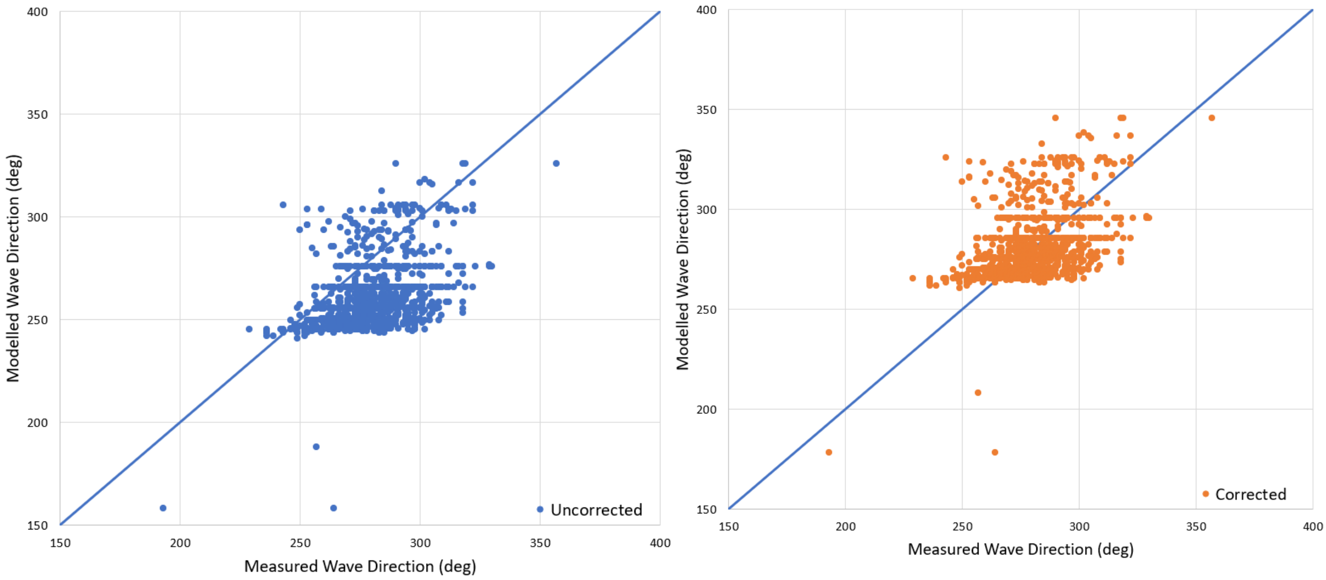


Figure 5-10: Measure vs Modelled peak wave period at Blackstones

6 Extreme Value Analysis

6.1 Overview

The Extreme Value Analysis of the offshore waves and wind was undertaken for the four selected ERA5 data points (shown in **Figure 3-1**). As discussed in **section 2.4**, the assessment was carried out using a MATLAB tool developed based on the WAFO toolbox. The tool was used to obtain extreme values of wind speed and wave height for the required return periods (1 in 1-year, 1 in 10-year, 1 in 50-year, 1 in 100-year and 1 in 500-year). Three distribution methods including Weibull, GPD and GEV were considered. Distribution with the best fit to the input data was chosen to derive the extreme values for each variable.

The obtained extreme wave data was then used to determine a relationship between offshore wave height and wave period (square root of wave height versus wave period). Based on that correlation, a simple formula was derived and then used to calculate wave period corresponding to the derived extreme offshore wave height for each return period event.

The analysis was undertaken for the key directional sectors (30º sectors) specific to each ERA5 data point. For example, for Point 1 and Point 2 easterly direction were not considered as not relevant. As discussed in **section 2.1**, the worst wave and wind direction for each site was determined based on results of sensitivity tests.

6.2 Wave direction adjustment

As discussed in the section 5.4.2, sensitivity of the derived extreme wave conditions was examined by undertaking the extreme value analysis of wave height with and without a 20 degrees adjustment of the wave direction towards north. For this purpose, the direction in the hindcast ERA5 data was manually adjusted, and the EVA analysis repeated to derive and compare the extreme wave heights. The same distribution was used for this comparison.

This was undertaken for the offshore ERA5 Point 1 and Point 2, as the westerly directions are of most significance for those two points. Results are presented in **Table 6-1** and **Table 6-2** for the ERA5 data Point 1 and Point 2, respectively.

Table 6-1: Comparison of derived wave height with and without the wave direction adjustment – ERA5 Point 1

	Return Period (years)	Extreme Wave Height (m) for direction		
		240º	270º	300º
No Adjustment	1	9.84	10.45	8.91
	10	12.85	13.65	11.82
	50	14.83	15.80	13.78
	100	15.67	16.71	14.62
	500	17.56	18. 80	16.55
Adjusted by 20deg	1	9.72	10.35	9.31
	10	12.98	13.41	12.17
	50	15.17	15.43	14.03
	100	16.10	16.28	14.80
	500	18.23	18.21	16.56

Table 6-2: Comparison of derived wave height with and without the wave direction adjustment – ERA5 Point 2

	Return Period (years)	Extreme Wave Height (m) for direction		
		240º	270º	300º
No Adjustment	1	10.44	10.63	8.20
	10	12. 97	13.82	11.54
	50	14.52	15.97	14.04
	100	15.16	16.88	15.14
	500	16.58	18. 80	17.76
Adjusted by 20deg	1	10.26	10. 62	8.76
	10	12.80	13.91	12.55
	50	14.38	16.13	15.37
	100	15.03	17.08	16.61
	500	16.49	10. 62	19.56

Based on the results above, and as agreed with the client, the more conservative values, whether with or without the wind adjustment, were used in the wave transformation modelling. These are outlined in red in **Table 6-1** and **Table 6-2**.

6.3 Extreme wave height

Following the wave direction adjustment test, the extreme wave heights were derived using both, the Weibull and GPD distributions. For each ERA5 offshore point and each wave direction, the best fitting distribution was chosen. As such for different directions and different offshore points, the chosen distributions vary.

For each of the ERA5 points only the relevant directions were considered, e.g., for Point 1 only the westerly (180deg – 330deg) directions are relevant based on the location of the point and locations of the sites of interest. Plots for each point and each relevant direction comparing the two assessed distributions are presented in **Appendix A** – Extreme Value Analysis: Wave Distributions Fitting, with the selected distribution outlined in red.

Based on selected distribution the derived extreme wave heights for the required return period events and the calculated corresponding peak wave period are presented in **Table 6-3** to **Table 6-6** for the ERA5 data Point 1 to Point 4, respectively.

Table 6-3: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 1

Return Period (years)	180º		210º		240º		270º		300º		330º	
	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)
1	5.95	10.85	7.88	12.01	9.84	12.98	10.45	14.19	8.91	14.59	6.65	11.66
10	7.75	12.39	10.75	14.03	12.85	14.84	13.65	16.22	11.82	16.8	9.47	13.92
50	9.1	13.42	12.94	15.39	14.83	15.94	15.8	17.45	13.78	18.14	11.42	15.29
100	9.71	13.86	13.94	15.97	15.67	16.38	16.71	17.95	14.62	18.69	12.26	15.84
500	11.17	14.87	16.37	17.31	17.56	17.35	18.8	19.04	16.55	19.88	14.21	17.05

Table 6-4: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 2

Return Period (years)	210º		240º		270º		300º		330º	
	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)
1	8.79	12.64	10.44	14.48	10.63	14.77	8.20	13.09	7.07	11.60
10	11.93	14.72	12.97	16.14	13.82	16.84	11.54	15.53	10.10	13.87
50	14.09	16.00	14.52	17.08	15.97	18.10	14.04	17.13	12.19	15.24
100	15.01	16.51	15.16	17.45	16.88	18.61	15.14	17.79	13.09	15.79
500	17.15	17.65	16.58	18.25	18.98	19.73	17.76	19.26	15.17	17.00

Table 6-5: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 3

Return Period (years)	0º		30º		60º		90º		270º		300º		330º	
	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)
1	6.81	10.93	5.27	9.91	4.32	8.43	4.55	8.49	9.98	13.80	7.65	12.85	7.09	11.55
10	9.38	12.83	7.79	12.04	6.46	10.31	6.30	9.99	12.34	15.34	10.44	15.01	9.61	13.45

50	11.10	13.95	9.64	13.39	7.97	11.45	7.42	10.84	13.43	16.00	12.30	16.29	11.26	14.55
100	11.82	14.40	10.44	13.95	8.62	11.90	7.89	11.17	13.79	16.22	13.08	16.81	11.95	14.99
500	13.48	15.38	12.35	15.16	10.13	12.91	8.95	11.90	14.45	16.60	14.88	17.92	13.52	15.95

Table 6-6: Derived Significant Wave Height (Hs, m) and Peak Wave Period (Tp, seconds) for ERA5 – Point 4

Return Period (years)	150°		180°		210°		240°	
	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)
1	3.29	7.16	4.61	8.62	4.34	8.34	3.54	7.79
10	4.24	8.12	5.64	9.54	5.64	9.50	4.82	9.09
50	4.64	8.50	6.29	10.08	6.46	10.18	5.65	9.85
100	4.77	8.62	6.57	10.30	6.81	10.44	6.01	10.15
500	5.00	8.82	7.18	10.77	7.59	11.03	6.81	10.81

6.4 Extreme wind speed

For the extreme value analysis of wind, the Weibull, GPD and GEV distributions were considered. For each ERA5 offshore point and each wind direction, the best fitting distribution was chosen. As such for different directions and different offshore points, the chosen distributions vary.

For each of the points only the relevant directions were considered, e.g., for Point 1 only the westerly (180deg – 330deg) directions are relevant based on the location of the point and locations of the sites of interest. Plots for each point and each relevant direction comparing the three assessed distributions are presented in **Appendix B** – Extreme Value Analysis: Wind Distributions Fitting, with the selected distribution outlined in red. Based on selected distribution the derived extreme wind speeds for the required return period events are presented in **Table 6-7** to **Table 6-10** for the ERA5 data Point 1 to Point 4, respectively.

Table 6-7: Derived Extreme Wind Speed (m/s) for ERA5 – Point 1

Return Period (years)	180°	210°	240°	270°	300°	330°
1	20.59	21.18	21.90	22.30	20.85	18.45
10	23.69	24.36	25.91	25.83	24.42	21.33
50	25.89	27.27	29.67	28.78	27.25	23.59
100	26.85	28.76	31.62	30.24	28.59	24.68
500	29.07	32.91	37.13	34.11	32.04	27.50

Table 6-8: Derived Extreme Wind Speed (m/s) for ERA5 – Point 2

Return Period (years)	210°	240°	270°	300°	330°
1	22.23	22.98	22.94	20.93	18.86
10	25.35	25.86	26.88	24.96	23.74
50	27.24	27.55	30.37	28.62	28.73

100	28.02	28.23	32.17	30.53	31.47
500	29.75	29.77	37.17	35.96	39.64

Table 6-9: Derived Extreme Wind Speed (m/s) for ERA5 – Point 3

Return Period (years)	0º	30º	60º	90º	270º	300º	330º
1	18.62	17.35	16.02	16.33	22.04	20.50	18.77
10	22.20	21.20	20.53	19.63	25.12	24.37	23.91
50	25.32	23.65	23.50	21.85	27.40	27.32	29.26
100	26.92	24.67	24.75	22.80	28.49	28.74	32.21
500	31.35	26.99	27.61	24.96	31.33	32.43	41.06

Table 6-10: Derived Extreme Wind Speed (m/s) for ERA5 – Point 4

Return Period (years)	150º	180º	210º	240º
1	17.33	18.66	18.29	17.88
10	19.53	21.78	21.28	21.29
50	20.79	23.82	24.05	23.90
100	21.29	24.66	25.50	25.17
500	22.41	26.53	29.65	28.57

6.5 Extreme wind speed checks

6.5.1 Overview

The derived extreme speeds for the 1 in 50-year return period event presented in **section 6.4** were compared with those presented in the Offshore Technology Report[4] published by the Health & Safety Executive (HSE) in 2002. Extract from the HSE Report is presented in **Figure 6-1**.

[4] *Offshore Technology Report: Environmental Considerations - the Health & Safety Executive (HSE), 2002*

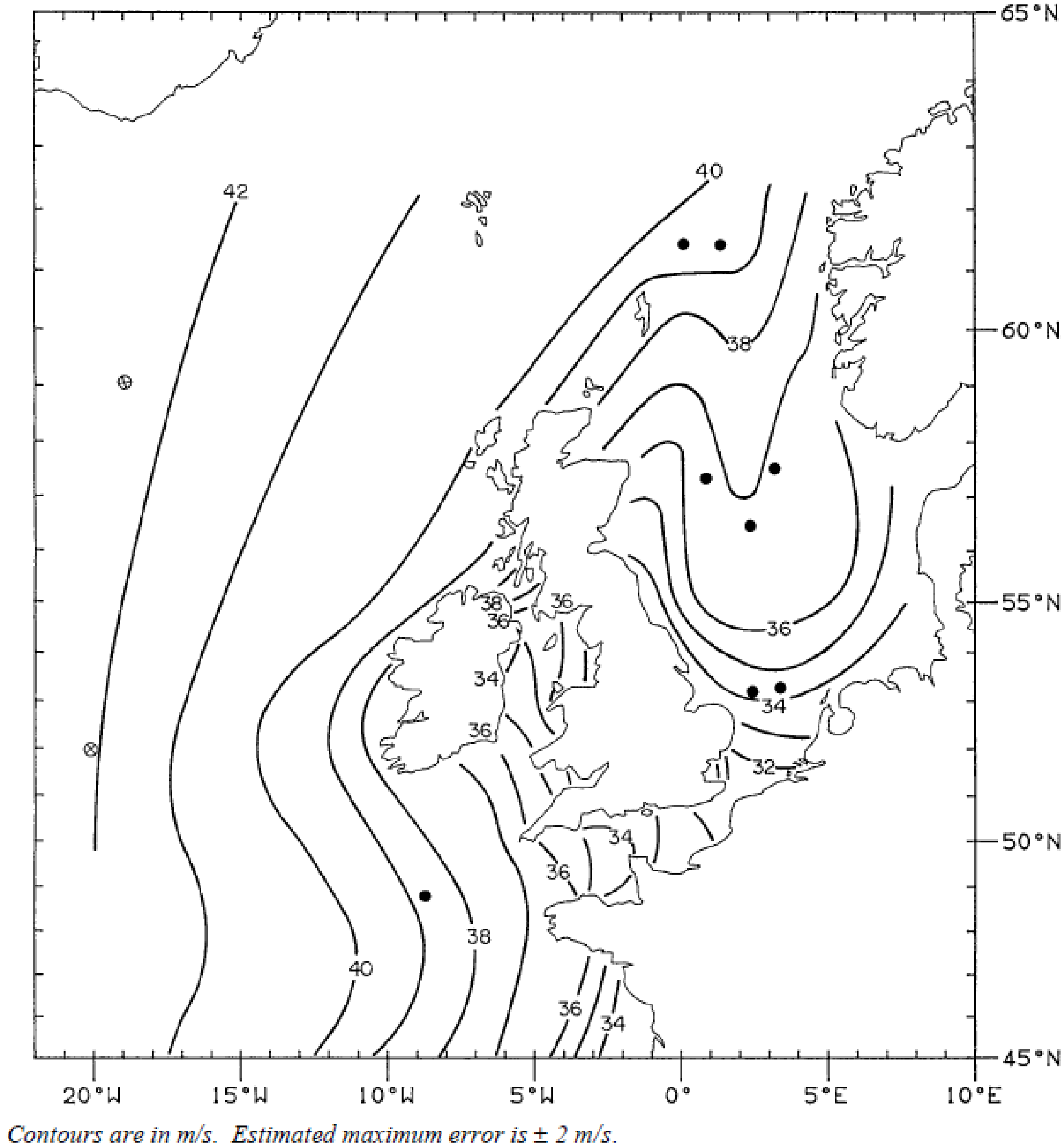


Figure 6-1: Extract form the HSE (2002) report – Contours of 1 in 50-year extreme wind speeds

The HSE report suggests wind speeds in order of 40-39m/s for the 1 in 50-year return period on the western coast of the Outer Hebrides, which is approximately 30% higher than the derived extreme values presented in **section 6.4** up to 30m/s from the westerly direction.

The HSE report considers all directions. As such, as a sensitivity test, the EVA was also performed considering all wind directions, however the derived extreme wind speed was similar to that for the dominant westerly direction, i.e., no more than 31m/s. Therefore, further investigation was undertaken to determine whether the derived extreme wind speed conditions are likely to be underestimated and subsequently impact nearshore wave conditions. This is discussed in the following **section 6.5.2** and **section 6.5.3**.

6.5.2 Sensitivity test

To investigate the impact of potentially increased wind speed on nearshore wave conditions, sensitivity tests were performed in the wave transformation model for the 1 in 50-year return period event with the derived extreme wind conditions and also with adjusted (increased) wind speed.

The test was undertaken considering westerly directions, as a dominant wind direction. For this test, the extreme wind speeds from the ERA5 Point 2 were used at the offshore boundary of the regional model. Then two local models (Domain 1 and Domain 4) were simulated with the boundary conditions extracted from the two runs of the regional model. In all of the models, constant wind speed was applied to the whole model domain.

Results from the sensitivity test comparing the significant wave height at selected sites within these model domains are presented in **Table 6-11**, where **Run 1** is with the derived extreme wind speeds presented in **section 6.4**, and **Run 2** is with wind speed increased by 31% (based on difference in derived wind speed and the HSE report for the dominant direction).

Table 6-11: Wind Speed sensitivity test results

Site ID	Significant Wave Height (m)		
	Run 1	Run 2	Difference (Run 2 – Run 1)
34	5.02	5.36	0.34
33	4.03	4.52	0.50
32	2.82	3.47	0.64
29	0.97	1.45	0.48
28	8.82	10.23	1.41
23	1.89	2.86	0.98
22	1.20	1.93	0.73
20	2.25	3.27	1.02
21	2.27	3.27	1.00

Table 6-11 shows that the increased wind speed would have rather significant impact on the nearshore wave conditions at the assessed sites, i.e. between 0.3 and 1.4m of increase in significant wave height. Considering such increase would be of importance, further checks were carried out to determine whether the wind conditions derived in the EVA analysis or the HSE Report would be more accurate when compared with the locally measure wind speeds. For that purpose, a comparison with some freely available wind data was undertaken, as discussed in the following **section 6.5.3**.

6.5.3 Comparison wind measured wind speed

To determine whether the wind conditions derived in the extreme value analysis are more representative of the local wind conditions than the HSE Report, a comparison with locally measured wind speeds was carried out. Due to project time constraints and lack of freely available long-term records of wind speed (in a digital format usable in the EVA or the modelling), this assessment was based on a visual comparison of plots of wind speeds from the ERA5 dataset used in the EVA analysis and winds speeds recorded at the Benbecula and Stornoway Airports accessed from WeatherSpark.com. The wind speed on the WeatherSpark.com website is presented in kph, therefore the ERA5 data was also converted to kph to allow direct comparison.

The comparison was undertaken for few years when the highest winds speeds in the ERA5 dataset were determined. These plots are presented in **Appendix C** – Comparison with measured wind conditions. Furthermore, individual events of high winds speed were selected and compared, as presented in **Figure 6-2** for wind speed and **Figure 6-3** for wind direction.

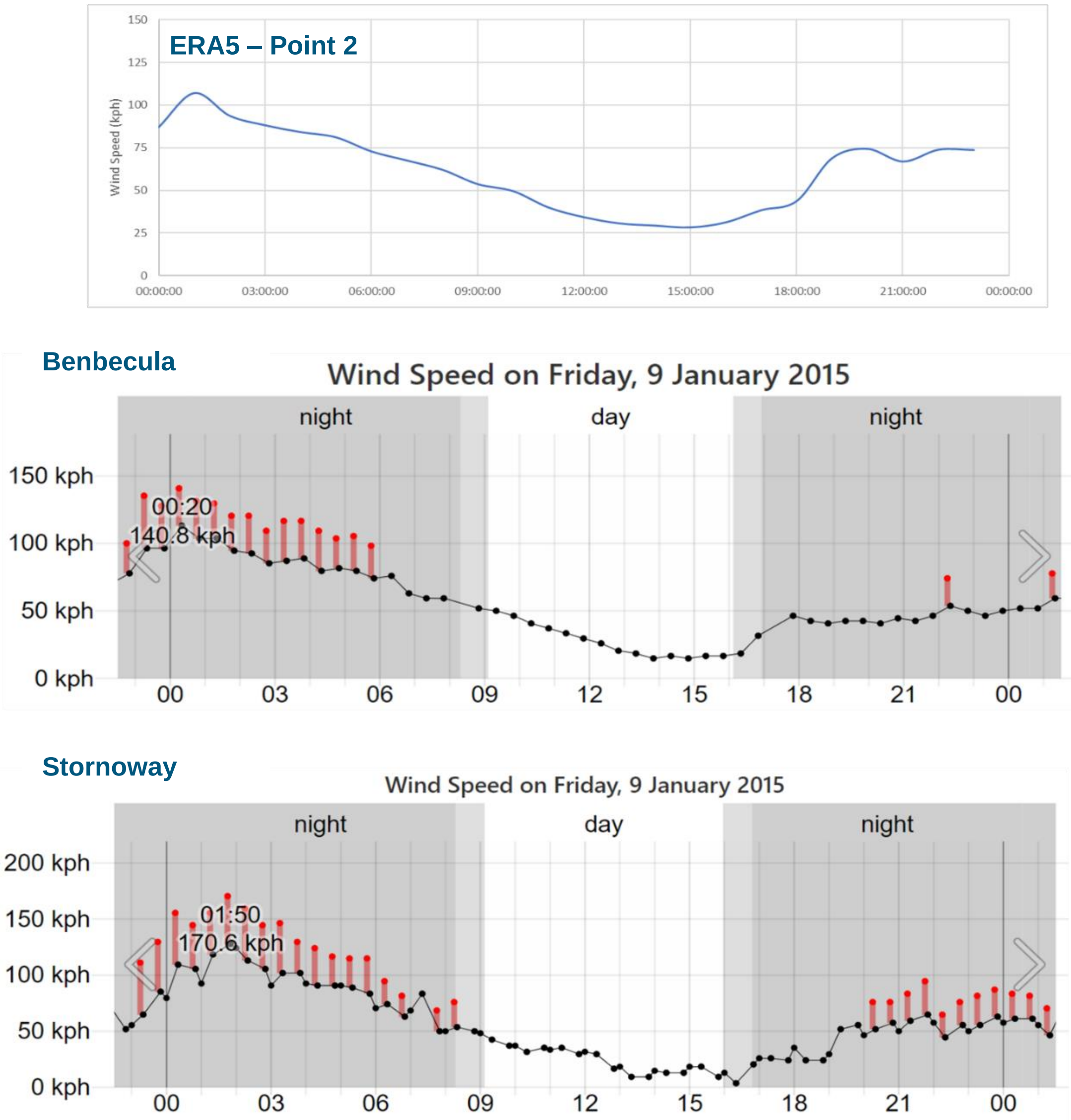


Figure 6-2: Comparison of wind speed from the ERA5 data Point2, Benbecula and Stronoway Airports

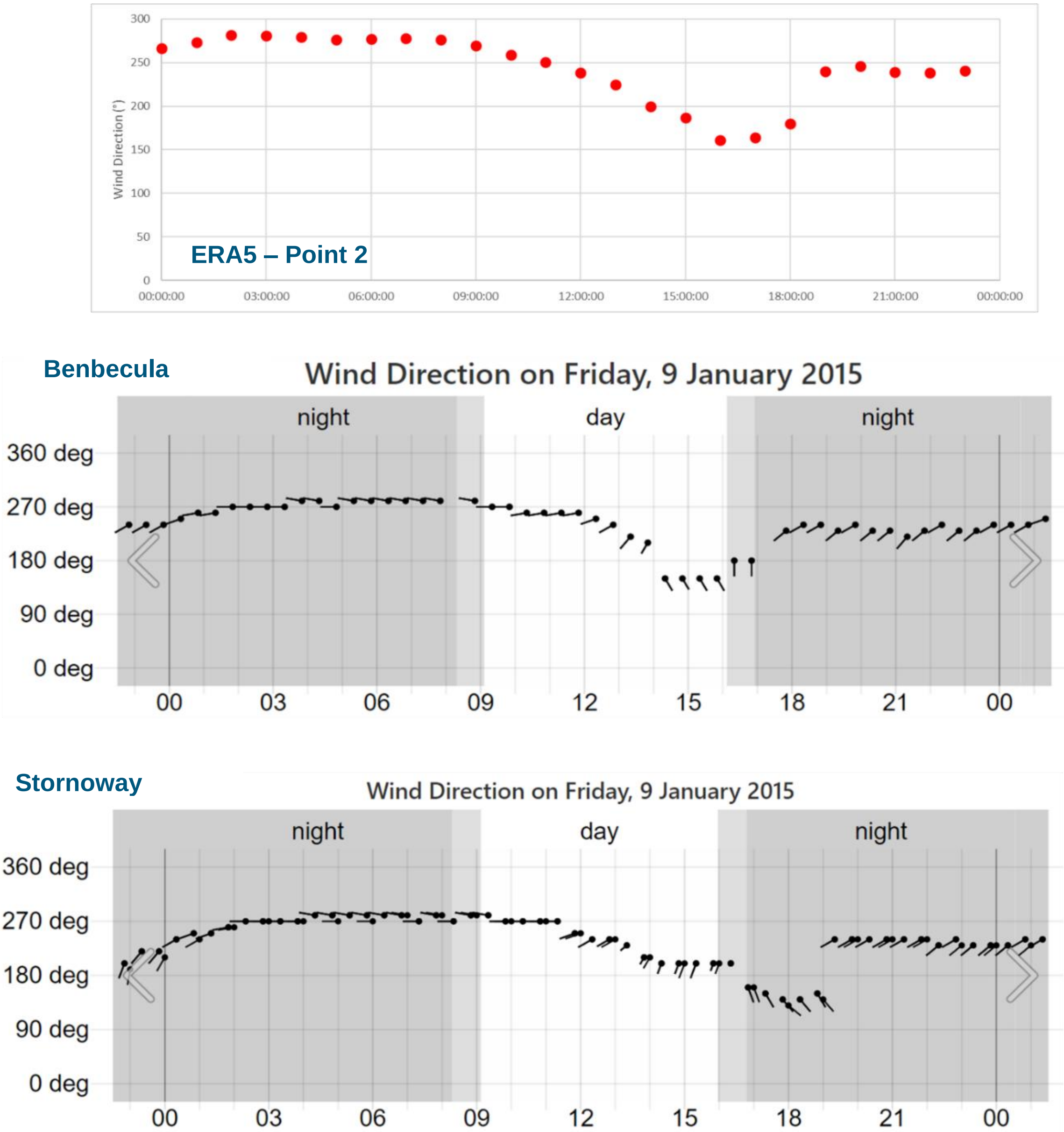


Figure 6-3: Comparison of wind direction from the ERA5 data Point2, Benbecula and Stronoway Airports

The comparison between the measured wind speed and the ERA5 dataset presented in **Figure 6-2** and **Figure 6-3** shows relatively good match, with the ERA5 wind often slightly higher than the measured wind speed. This suggests that the hindcast ERA5 data is more representative of the local wind conditions than the HSE Report, which seems very conservative. Although the ERA5 data also overestimates the wind conditions, the bias for the peak wind speed is estimated to be less than 10%.

Based on the above comparisons, and as agreed with the client, the derived extreme winds speed from the EVA for the ERA5 data points were adopted in the modelling without any adjustment.

7 Model Results

7.1 Sensitivity tests

As discussed in **section 2.1**, following derivation of the extreme wave and wind conditions, a series of sensitivity tests were carried out to determine the worst wave direction for each considered site location. These tests were undertaken for the 1 in 50-year return period only. The derived worst direction was then adopted in modelling for the remaining return period events discussed in the next **section 7.2**.

For these tests both the resultant waves and locally wind generated waves were considered, depending on the respective site locations. For the sensitivity test, diffraction was not enabled in the SW model to reduce computation time required for the simulations. However, for the production runs (**section 7.2**) the diffraction was included for all return period events.

Results of the sensitivity test for all sites are presented in **Table 7-1** to **Table 7-4** for the four local domains shown in **Figure 4-1**, with the determined worst wave direction outlined in red. The results show that for sites within Domain 1, the worst direction varies between north-westerly and north-easterly with couple sites with worst direction from the south. For sites within Domain 2 and Domain 3, for majority of the sites the worst wave direction is from westerly direction and for site within Domain 4 the worst direction is from the north-westerly direction.

There is one site (site ID 25) that was not included in the main four local model domains due its location, but rather had its own small local model for locally wind generated waves only. The worst wave direction derived for this site was from the west.

Table 7-1: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 1

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
20	330	Point 3	29.26	14.98	14.96	2.29	14.94	25
	0	Point 3	25.32	13.12	14.06	3.16	13.86	51
	30	Point 3	23.65	11.02	13.62	3.78	12.79	57
	60	Point 3	23.50	8.42	12.09	3.68	11.35	62
	90	Point 3	21.85	WIND ONLY		2.56	6.69	85
	120	Point 3	23.99	WIND ONLY		2.72	7.47	111
	150	Point 3	24.88	WIND ONLY		2.44	7.91	120
	180	Point 1	25.89	8.80	12.66	2.21	12.66	132
	210	Point 1	27.27	13.18	15.34	2.17	15.44	129
	240	Point 1	29.67	16.06	16.29	1.89	16.59	143
26	330	Point 3	29.26	14.98	14.96	2.62	14.99	45
	0	Point 3	25.32	13.12	14.06	4.22	13.97	57
	30	Point 3	23.65	11.02	13.62	5.12	13.60	59

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
26	60	Point 3	23.50	8.42	12.09	4.74	11.75	60
	90	Point 3	21.85	WIND ONLY		2.78	6.73	75
	120	Point 3	23.99			2.43	6.75	93
	150	Point 3	24.88			1.61	6.75	105
27	330	Point 3	29.26	14.98	14.96	3.25	14.82	29
	0	Point 3	25.32	13.12	14.06	5.00	13.89	44
	30	Point 3	23.65	11.02	13.62	6.01	13.48	49
	60	Point 3	23.50	8.42	12.09	5.58	11.70	52
	90	Point 3	21.85	WIND ONLY		3.08	6.73	81
	120	Point 3	23.99			3.32	6.75	117
	150	Point 3	24.88			3.31	7.25	144
1	90	Point 4	20.19	WIND ONLY		0.91	4.97	112
	120	Point 4	20.47	WIND ONLY		0.97	4.97	118
	150	Point 4	20.79	4.64	8.50	0.86	4.86	120
	180	Point 4	23.82	6.29	10.08	0.74	4.79	123
	210	Point 4	24.05	6.46	10.18	0.44	5.29	140
	240	Point 4	23.90	5.65	9.85	0.58	2.66	293
28	30	Point 3	23.65	11.02	13.62	4.73	13.66	352
	0	Point 3	25.32	13.12	14.06	7.18	14.00	347
	330	Point 3	29.26	14.98	14.96	8.76	15.03	346
	300	Point 3	27.32	14.17	16.29	7.06	15.95	344
	270	Point 3	27.40	12.42	16.38	3.88	16.27	337
23	30	Point 3	23.65	11.02	13.62	1.28	3.85	8
	0	Point 3	25.32	13.12	14.06	1.58	4.61	352
	330	Point 3	29.26	14.98	14.96	1.93	5.08	342
	300	Point 3	27.32	14.17	16.29	1.53	4.83	329
	270	Point 3	27.40	12.42	16.38	1.15	2.88	303
22	30	Point 3	23.65	11.02	13.62	0.97	3.13	35
	0	Point 3	25.32	13.12	14.06	1.04	3.26	6
	330	Point 3	29.26	14.98	14.96	1.24	3.54	352

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
22	300	Point 3	27.32	14.17	16.29	0.89	5.48	347
	270	Point 3	27.40	12.42	16.38	0.83	3.52	290
	60	Point 3	23.50	WIND ONLY		0.96	3.22	67
	90	Point 3	21.85			0.91	3.15	97
	120	Point 3	23.99			1.01	3.36	117
	150	Point 3	24.88			1.01	3.41	132
21	330	Point 3	29.26	14.98	14.96	2.30	15.07	36
	0	Point 3	25.32	13.12	14.06	3.19	13.94	61
	30	Point 3	23.65	11.02	13.62	3.86	13.01	65
	60	Point 3	23.50	8.42	12.09	3.71	11.37	68
	90	Point 3	21.85	WIND ONLY		2.63	6.79	89
	120	Point 3	23.99			2.92	7.69	117
	150	Point 3	24.88			2.75	8.03	127
	180	Point 1	25.89	8.80	12.66	2.66	12.66	132
	210	Point 1	27.27	13.18	15.34	2.80	15.39	129
	240	Point 1	29.67	16.06	16.29	2.21	16.44	128
24	330	Point 3	29.26	14.98	14.96	2.51	14.92	43
	0	Point 3	25.32	13.12	14.06	3.71	13.85	55
	30	Point 3	23.65	11.02	13.62	4.63	12.61	57
	60	Point 3	23.50	8.42	12.09	4.58	11.21	58
	90	Point 3	21.85	WIND ONLY		3.14	7.18	78
	120	Point 3	23.99			3.61	7.94	135
	150	Point 3	24.88			4.15	8.42	156
	180	Point 1	25.89	8.80	12.66	4.91	12.12	164
	210	Point 1	27.27	13.18	15.34	4.87	15.17	164
	240	Point 1	29.67	16.06	16.29	3.59	16.18	167

Table 7-2: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 2

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
15	180	Point 1	25.89	7.99	12.60	1.58	12.56	267
	210	Point 1	27.27	12.72	15.36	2.50	15.25	293
	240	Point 1	29.67	16.46	16.28	3.26	16.02	296
	270	Point 1	28.78	17.75	17.09	3.41	16.86	299
	300	Point 1	27.25	WIND ONLY		2.73	6.40	306
	330	Point 1	23.59			2.37	5.59	324
16	180	Point 1	25.89	7.99	12.60	2.81	12.36	213
	210	Point 1	27.27	12.72	15.36	3.77	15.22	229
	240	Point 1	29.67	16.46	16.28	4.21	16.00	235
	270	Point 1	28.78	17.75	17.09	3.73	16.87	240
	300	Point 1	27.25	WIND ONLY		1.97	6.76	267
	330	Point 1	23.59			0.98	3.21	322
17	180	Point 1	25.89	7.99	12.60	1.93	12.44	214
	210	Point 1	27.27	12.72	15.36	2.91	15.18	224
	240	Point 1	29.67	16.46	16.28	3.44	15.86	227
	270	Point 1	28.78	17.75	17.09	3.08	16.82	231
	300	Point 1	27.25	WIND ONLY		1.66	7.01	253
	330	Point 1	23.59			0.58	2.94	267
18	180	Point 1	25.89	7.99	12.60	0.78	12.51	142
	210	Point 1	27.27	12.72	15.36	0.96	15.18	243
	240	Point 1	29.67	16.46	16.28	1.31	15.85	300
	270	Point 1	28.78	17.75	17.09	1.53	12.84	308
	300	Point 1	27.25	WIND ONLY		1.47	4.33	310
	330	Point 1	23.59			1.12	3.86	317
19	180	Point 1	25.89	7.99	12.60	1.33	12.53	285
	210	Point 1	27.27	12.72	15.36	2.27	15.23	289
	240	Point 1	29.67	16.46	16.28	2.88	15.98	289
	270	Point 1	28.78	17.75	17.09	2.77	16.88	291
	300	Point 1	27.25	WIND ONLY		2.11	5.42	298

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
	330	Point 1	23.59			1.59	4.82	311

Table 7-3: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 3

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
4	330	Point 3	29.26	WIND ONLY		2.11	5.37	349
	0	Point 3	25.32	WIND ONLY		1.79	4.98	353
	30	Point 3	23.65			1.54	4.47	11
	120	Point 4	20.47			1.65	5.85	121
	150	Point 4	20.79	4.64	8.50	1.48	5.96	129
	180	Point 4	23.82	6.29	10.08	0.73	5.38	134
	210	Point 4	24.05	6.46	10.18	0.73	5.38	134
	240	Point 4	23.90	5.65	9.85	0.17	3.29	107
3	330	Point 3	29.26	WIND ONLY		1.87	4.75	314
	0	Point 3	25.32	WIND ONLY		1.28	4.29	320
	30	Point 3	23.65			0.80	3.26	336
	120	Point 4	20.47			0.44	6.33	184
	150	Point 4	20.79	4.64	8.50	0.67	6.29	188
	180	Point 4	23.82	6.29	10.08	1.00	3.66	195
	210	Point 4	24.05	6.46	10.18	1.12	3.53	214
	240	Point 4	23.90	5.65	9.85	1.19	3.49	248
6	330	Point 3	29.26	WIND ONLY		1.57	4.35	310
	0	Point 3	25.32	WIND ONLY		1.03	3.50	318
	30	Point 3	23.65			0.72	2.45	355
	120	Point 4	20.47			0.88	5.79	168
	150	Point 4	20.79	4.64	8.50	1.12	5.08	173
	180	Point 4	23.82	6.29	10.08	1.44	4.40	178
	210	Point 4	24.05	6.46	10.18	1.38	4.04	197
	240	Point 4	23.90	5.65	9.85	1.24	3.55	240

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
8	330	Point 3	29.26	WIND ONLY		1.74	4.82	6
	0	Point 3	25.32			1.65	4.63	16
	30	Point 3	23.65			1.57	4.57	24
	120	Point 4	20.47			1.71	5.87	138
8	150	Point 4	20.79	4.64	8.50	1.79	5.88	142
	180	Point 4	23.82	6.29	10.08	1.88	5.91	144
	210	Point 4	24.05	6.46	10.18	1.13	4.51	150
	240	Point 4	23.90	5.65	9.85	0.45	2.95	168
9	330	Point 3	29.26	WIND ONLY		2.07	4.91	331
	0	Point 3	25.32	WIND ONLY		1.60	4.47	346
	30	Point 3	23.65			1.29	4.18	357
	120	Point 4	20.47			0.65	3.74	185
	150	Point 4	20.79	4.64	8.50	0.99	3.84	187
	180	Point 4	23.82	6.29	10.08	1.36	4.14	192
	210	Point 4	24.05	6.46	10.18	1.32	4.02	203
	240	Point 4	23.90	5.65	9.85	1.27	3.74	227
10	330	Point 3	29.26	WIND ONLY		1.51	4.17	0
	0	Point 3	25.32			1.44	4.13	20
	30	Point 3	23.65			1.46	4.36	40
	120	Point 4	20.47			1.49	4.78	138
	150	Point 4	20.79	4.64	8.50	1.56	5.06	146
	180	Point 4	23.82	6.29	10.08	1.66	5.15	148
	210	Point 4	24.05	6.46	10.18	1.11	4.57	151
	240	Point 4	23.90	5.65	9.85	0.81	2.31	226
11	330	Point 3	29.26	WIND ONLY		1.72	4.15	325
	0	Point 3	25.32	WIND ONLY		1.32	3.91	352
	30	Point 3	23.65			1.11	3.92	4
	120	Point 4	20.47			0.70	3.56	183
	150	Point 4	20.79	4.64	8.50	1.14	4.18	191
	180	Point 4	23.82	6.29	10.08	1.56	4.61	195

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
	210	Point 4	24.05	6.46	10.18	1.49	4.41	204
	240	Point 4	23.90	5.65	9.85	1.40	4.00	228
12	0	Point 3	25.32	WIND ONLY		0.97	3.74	48
12	22	Point 3	23.65	WIND ONLY		1.07	3.79	52
12	30	Point 3	23.65	WIND ONLY		1.11	3.83	53
12	120	Point 4	20.47	WIND ONLY		0.76	2.77	113
12	150	Point 4	20.79	4.64	8.50	0.78	3.14	175
12	180	Point 4	23.82	6.29	10.08	1.18	4.02	188
12	210	Point 4	24.05	6.46	10.18	1.21	4.22	192
12	210	Point 1	27.27	6.06	15.28	1.46	4.44	192
12	240	Point 1	29.67	9.70	15.88	1.39	4.51	196
12	270	Point 1	28.78	11.52	17.01	0.92	3.01	230
13	0	Point 3	25.32	WIND ONLY		0.87	3.59	55
13	30	Point 3	23.65	WIND ONLY		1.13	3.95	62
13	60	Point 3	23.50	WIND ONLY		1.22	4.01	65
13	120	Point 4	20.47	WIND ONLY		0.74	3.19	103
13	150	Point 4	20.79	4.64	8.50	0.77	3.30	190
13	180	Point 4	23.82	6.29	10.08	1.25	4.03	196
13	210	Point 4	24.05	6.46	10.18	1.34	4.20	200
13	210	Point 1	27.27	6.06	15.28	1.61	4.48	200
13	240	Point 1	29.67	9.70	15.88	1.60	4.52	206
13	270	Point 1	28.78	11.52	17.01	1.09	3.90	219
14	0	Point 3	25.32	WIND ONLY		0.52	3.79	65
14	30	Point 3	23.65	WIND ONLY		0.81	3.62	72
14	120	Point 4	20.47	WIND ONLY		0.67	2.95	93
14	150	Point 4	20.79	4.64	8.50	0.74	2.75	142
14	180	Point 4	23.82	6.29	10.08	1.06	3.61	204
14	210	Point 4	24.05	6.46	10.18	1.20	4.06	223
14	210	Point 1	27.27	6.06	15.28	1.45	4.35	221
14	240	Point 1	29.67	9.70	15.88	1.58	4.44	225

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
	270	Point 1	28.78	11.52	17.01	1.21	4.02	230
	120	Point 4	20.47	WIND ONLY		0.82	3.44	161
7	150	Point 4	20.79	4.64	8.50	1.02	3.74	165
	180	Point 4	23.82	6.29	10.08	1.26	4.04	168
7	330	Point 3	29.26	WIND ONLY		1.44	4.13	357
	300	Point 3	27.32	WIND ONLY		0.99	3.74	353
	120	Point 4	20.47	WIND ONLY		0.47	3.50	169
	150	Point 4	20.79	4.64	8.50	0.67	3.06	173
5	180	Point 4	23.82	6.29	10.08	1.00	3.61	185
	330	Point 3	29.26	WIND ONLY		1.70	4.29	327
	300	Point 3	27.32	WIND ONLY		1.48	4.03	307
	180	Point 4	23.82	6.29	10.08	2.21	6.61	213
	210	Point 4	24.05	6.46	10.18	2.59	6.72	221
2	210	Point 1	27.27	6.06	15.28	3.98	8.62	232
	240	Point 1	29.67	9.70	15.88	5.18	13.60	240
	270	Point 1	28.78	11.52	17.01	4.77	16.79	250

Table 7-4: Results of the sensitivity tests to derive the worst wave direction – Local Model Domain 4

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
29	270	Point 2	30.37	19.97	18.19	0.76	3.79	292
	300	Point 2	28.62	18.50	18.01	0.71	18.08	311
	330	Point 2	28.73	16.36	15.52	0.86	15.59	339
	0	Point 3	25.32	13.63	14.17	0.75	14.31	40
30	270	Point 2	30.37	19.97	18.19	1.50	3.52	279
	300	Point 2	28.62	18.50	18.01	1.53	13.31	315
	330	Point 2	28.73	16.36	15.52	1.65	15.51	330
	0	Point 3	25.32	13.63	14.17	1.38	14.20	333

Site ID	Boundary Conditions					Results		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
31	270	Point 2	30.37	19.97	18.19	2.12	18.24	297
	300	Point 2	28.62	18.50	18.01	2.78	18.05	297
	330	Point 2	28.73	16.36	15.52	3.13	15.57	297
	0	Point 3	25.32	13.63	14.17	2.67	14.29	297
32	270	Point 2	30.37	19.97	18.19	2.15	18.30	332
	300	Point 2	28.62	18.50	18.01	2.37	18.17	335
	330	Point 2	28.73	16.36	15.52	2.47	15.62	335
	0	Point 3	25.32	13.63	14.17	2.05	14.24	335
33	270	Point 2	30.37	19.97	18.19	3.79	18.34	332
	300	Point 2	28.62	18.50	18.01	4.37	18.21	332
	330	Point 2	28.73	16.36	15.52	4.33	15.65	333
	0	Point 3	25.32	13.63	14.17	3.65	14.27	333
34	270	Point 2	30.37	19.97	18.19	3.91	18.37	350
	300	Point 2	28.62	18.50	18.01	5.02	18.24	352
	330	Point 2	28.73	16.36	15.52	5.33	15.66	353
	0	Point 3	25.32	13.63	14.17	4.87	14.28	353

7.2 Production runs

The derived worst wave direction was adopted for each site and used in the model simulations for all the required return period events. **Table 7-5** to **Table 7-9** present the derived wave conditions at all sites for the 1 in 1-year, 1 in 10-year, 1 in 50-year, 1 in 100-year and 1 in 500-year return period event, respectively.

In addition, contour plots of the wave model results for the 1 in 50-year return period event for the four local model domains are presented in **Figure 7-1** to **Figure 7-4**, respectively. Contour plots for the remaining return period events are provided in **Appendix D** – Contour plots of the wave model results.

Table 7-5: Results of the wave modelling for all sites for the 1 in 1-year return period event

Site ID	Boundary Conditions					Results 1 in 1-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
1	120	Point 4	16.27	WIND ONLY		0.74	4.47	118
2	240	Point 1	21.90	6.41	13.01	3.73	12.59	238

Site ID	Boundary Conditions					Results 1 in 1-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
3	330	Point 3	18.77	WIND ONLY		0.93	3.76	315
4	330	Point 3	18.77	WIND ONLY		1.10	4.16	349
5	330	Point 3	18.77	WIND ONLY		0.85	3.27	326
6	330	Point 3	18.77	WIND ONLY		0.76	3.45	310
7	330	Point 3	18.77	WIND ONLY		0.69	3.23	356
8	180	Point 4	18.66	4.61	8.62	1.39	5.36	144
9	330	Point 3	18.77	WIND ONLY		1.07	3.76	333
10	180	Point 4	18.66	4.61	8.62	1.22	4.62	149
11	330	Point 3	18.77	WIND ONLY		0.93	3.34	328
12	210	Point 1	21.18	4.00	11.80	1.01	4.00	192
13	210	Point 1	21.18	4.00	11.80	1.12	3.98	200
14	240	Point 1	21.90	6.41	13.01	1.00	3.77	226
15	270	Point 1	22.30	11.87	14.14	2.63	13.91	298
16	240	Point 1	21.90	10.34	13.56	3.21	13.19	236
17	240	Point 1	21.90	10.34	13.56	2.49	13.13	230
18	270	Point 1	22.30	11.87	14.14	1.04	13.07	307
19	240	Point 1	21.90	10.34	13.56	1.92	13.46	287
20	30	Point 3	17.35	6.14	10.58	2.45	10.32	54
21	30	Point 3	17.35	6.14	10.58	2.45	10.34	61
22	330	Point 3	18.77	7.98	11.79	0.59	2.89	350
23	330	Point 3	18.77	7.98	11.79	0.95	4.73	343
24	180	Point 1	20.59	6.23	11.28	3.60	9.87	167
25	270	Point 1	22.30	WIND ONLY		0.73	3.05	263
26	30	Point 3	17.35	6.14	10.58	3.17	10.49	54
27	30	Point 3	17.35	6.14	10.58	3.74	10.48	47
28	330	Point 3	18.77	7.98	11.79	4.87	11.62	340
29	330	Point 2	28.73	16.36	15.52	0.33	11.77	45
30	330	Point 2	18.86	8.36	11.89	0.98	11.66	335
31	330	Point 2	18.86	8.36	11.89	1.96	11.84	302
32	330	Point 2	18.86	8.36	11.89	1.49	11.73	329
33	300	Point 2	20.93	10.45	13.76	2.21	13.79	336

Site ID	Boundary Conditions					Results 1 in 1-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
34	330	Point 2	18.86	8.36	11.89	3.43	11.83	350

Table 7-6: Results of the wave modelling for all sites for the 1 in 10-year return period event

Site ID	Boundary Conditions					Results 1 in 10-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
1	120	Point 4	18.89	WIND ONLY		0.89	4.85	118
2	240	Point 1	25.91	8.25	15.10	4.45	12.45	239
3	330	Point 3	23.91	WIND ONLY		1.37	4.24	314
4	330	Point 3	23.91	WIND ONLY		1.56	4.85	349
5	330	Point 3	23.91	WIND ONLY		1.24	3.77	327
6	330	Point 3	23.91	WIND ONLY		1.13	3.90	309
7	330	Point 3	23.91	WIND ONLY		1.03	3.68	358
8	180	Point 4	21.78	5.64	9.54	1.68	5.80	144
9	330	Point 3	23.91	WIND ONLY		1.52	4.37	333
10	180	Point 4	21.78	5.64	9.54	1.48	4.95	148
11	330	Point 3	23.91	WIND ONLY		1.29	3.75	326
12	210	Point 1	24.36	5.05	13.86	1.24	4.28	192
13	210	Point 1	24.36	5.05	13.86	1.37	4.24	200
14	240	Point 1	25.91	8.25	15.10	1.29	4.11	225
15	270	Point 1	25.83	15.29	16.11	3.05	15.66	299
16	240	Point 1	25.91	13.65	15.25	3.76	15.16	235
17	240	Point 1	25.91	13.65	15.25	2.97	15.09	228
18	270	Point 1	25.83	15.29	16.11	1.29	11.98	308
19	240	Point 1	25.91	13.65	15.25	2.44	15.18	289
20	30	Point 3	21.20	9.02	12.51	3.26	12.16	56
21	30	Point 3	21.20	9.02	12.51	3.30	12.26	63
22	330	Point 3	23.91	11.60	13.87	0.85	3.03	350
23	330	Point 3	23.91	11.60	13.87	1.38	4.83	345

Site ID	Boundary Conditions					Results 1 in 10-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
24	180	Point 1	23.69	8.18	12.48	4.36	11.77	165
25	270	Point 1	25.83	WIND ONLY		0.91	3.30	263
26	30	Point 3	21.20	9.02	12.51	4.33	12.52	57
27	30	Point 3	21.20	9.02	12.51	5.11	12.45	48
28	330	Point 3	23.91	11.60	13.87	6.87	13.85	344
29	330	Point 2	23.74	12.45	14.06	0.63	14.07	21
30	330	Point 2	23.74	12.45	14.06	1.34	14.01	333
31	330	Point 2	23.74	12.45	14.06	2.90	14.10	300
32	330	Point 2	23.74	12.45	14.06	1.97	14.06	330
33	300	Point 2	24.96	14.87	16.21	2.86	16.05	337
34	330	Point 2	23.74	12.45	14.06	4.99	14.12	350

Table 7-7: Results of the wave modelling for all sites for the 1 in 50-year return period event

Site ID	Boundary Conditions					Results 1 in 50-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
1	120	Point 4	20.47	WIND ONLY		0.98	4.97	118.22
2	240	Point 1	29.67	9.70	15.88	5.19	14.20	240.12
3	330	Point 3	29.26	WIND ONLY		1.86	4.73	314.53
4	330	Point 3	29.26	WIND ONLY		2.11	5.37	348.69
5	330	Point 3	29.26	WIND ONLY		1.70	4.28	327.27
6	330	Point 3	29.26	WIND ONLY		1.58	4.33	309.76
7	330	Point 3	29.26	WIND ONLY		1.44	4.12	357.30
8	180	Point 4	23.82	6.29	10.08	1.88	5.91	143.86
9	330	Point 3	29.26	WIND ONLY		2.07	4.92	331.57
10	180	Point 4	23.82	6.29	10.08	1.66	5.16	148.27
11	330	Point 3	29.26	WIND ONLY		1.74	4.17	325.35
12	210	Point 1	27.27	6.06	15.28	1.47	4.46	191.77
13	210	Point 1	27.27	6.06	15.28	1.61	4.49	200.16
14	240	Point 1	29.67	9.70	15.88	1.58	4.44	225.30

Site ID	Boundary Conditions					Results 1 in 50-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
15	270	Point 1	28.78	17.75	17.09	3.41	16.86	299.31
16	240	Point 1	29.67	16.46	16.28	4.23	16.01	234.49
17	240	Point 1	29.67	16.46	16.28	3.39	15.83	227.34
18	270	Point 1	28.78	17.75	17.09	1.52	8.68	307.43
19	240	Point 1	29.67	16.46	16.28	2.88	15.98	289.12
20	30	Point 3	23.65	11.02	13.62	3.79	12.80	57.04
21	30	Point 3	23.65	11.02	13.62	3.85	13.01	65.25
22	330	Point 3	29.26	14.98	14.96	1.24	3.54	351.64
23	330	Point 3	29.26	14.98	14.96	1.93	5.08	341.77
24	180	Point 1	25.89	8.80	12.66	4.91	12.12	163.90
25	270	Point 1	28.78	WIND ONLY		1.11	3.48	263.06
26	30	Point 3	23.65	11.02	13.62	5.12	13.60	59.05
27	30	Point 3	23.65	11.02	13.62	6.00	13.47	48.64
28	330	Point 3	29.26	14.98	14.96	8.73	15.02	345.96
29	330	Point 2	28.73	16.36	15.52	1.10	15.57	335.36
30	330	Point 2	28.73	16.36	15.52	1.66	15.52	330.99
31	330	Point 2	28.73	16.36	15.52	3.61	15.59	299.36
32	330	Point 2	28.73	16.36	15.52	2.37	15.59	330.05
33	300	Point 2	28.62	18.50	18.01	3.23	18.11	337.15
34	330	Point 2	28.73	16.36	15.52	6.05	15.65	351.24

Table 7-8: Results of the wave modelling for all sites for the 1 in 100-year return period event

Site ID	Boundary Conditions					Results 1 in 100-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
1	120	Point 4	21.12	WIND ONLY		1.03	5.01	118.19
2	240	Point 1	31.62	10.36	16.59	5.54	10.73	240.54
3	330	Point 3	32.21	WIND ONLY		2.16	4.98	314.56
4	330	Point 3	32.21	WIND ONLY		2.44	5.74	348.63
5	330	Point 3	32.21	WIND ONLY		1.97	4.52	327.31
6	330	Point 3	32.21	WIND ONLY		1.85	4.54	310.21

Site ID	Boundary Conditions					Results 1 in 100-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
7	330	Point 3	32.21	WIND ONLY		1.68	4.41	356.75
8	180	Point 4	24.66	6.57	10.30	1.96	6.02	143.94
9	330	Point 3	32.21	WIND ONLY		2.41	5.15	331.08
10	180	Point 4	24.66	6.57	10.30	1.74	5.25	148.25
11	330	Point 3	32.21	WIND ONLY		2.02	4.46	324.75
12	210	Point 1	28.76	6.59	15.60	1.59	4.58	191.78
13	210	Point 1	28.76	6.59	15.60	1.74	4.60	200.07
14	240	Point 1	31.62	10.36	16.59	1.74	4.57	225.25
15	270	Point 1	30.24	18.83	17.81	3.57	17.37	299.44
16	240	Point 1	31.62	17.57	16.71	4.46	16.68	234.11
17	240	Point 1	31.62	17.57	16.71	3.60	16.59	227.27
18	270	Point 1	30.24	18.83	17.81	1.64	8.64	307.22
19	240	Point 1	31.62	17.57	16.71	3.09	16.66	288.98
20	30	Point 3	24.67	11.88	13.98	4.01	13.55	57.40
21	30	Point 3	24.67	11.88	13.98	4.10	13.66	65.72
22	330	Point 3	32.21	16.74	15.42	1.47	3.75	351.51
23	330	Point 3	32.21	16.74	15.42	2.24	5.36	341.87
24	180	Point 1	26.85	10.21	13.73	5.22	12.77	162.82
25	270	Point 1	30.24	WIND ONLY		1.23	3.65	263.50
26	30	Point 3	24.67	11.88	13.98	5.47	13.89	59.67
27	30	Point 3	24.67	11.88	13.98	6.39	13.82	48.95
28	330	Point 3	32.21	16.74	15.42	9.69	15.36	346.49
29	330	Point 2	31.47	17.90	15.88	1.04	16.05	349.97
30	330	Point 2	31.47	17.90	15.88	1.83	15.95	330.75
31	330	Point 2	31.47	17.90	15.88	3.81	16.10	299.42
32	330	Point 2	31.47	17.90	15.88	2.56	16.22	329.78
33	300	Point 2	30.53	20.25	18.57	3.38	18.59	336.49
34	330	Point 2	31.47	17.90	15.88	6.28	16.37	351.48

Table 7-9: Results of the wave modelling for all sites for the 1 in 500-year return period event

Site ID	Boundary Conditions					Results 1 in 500-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
1	120	Point 4	22.59	WIND ONLY		1.12	5.34	118.22
2	240	Point 1	37.13	12.10	17.16	6.67	11.33	241.62
3	330	Point 3	41.06	WIND ONLY		3.16	5.73	314.25
4	330	Point 3	41.06	WIND ONLY		3.54	6.51	348.76
5	330	Point 3	41.06	WIND ONLY		2.88	5.21	327.42
6	330	Point 3	41.06	WIND ONLY		2.73	5.25	309.42
7	330	Point 3	41.06	WIND ONLY		2.48	5.05	355.64
8	180	Point 4	26.53	7.18	10.77	2.14	6.24	144.13
9	330	Point 3	41.06	WIND ONLY		3.55	6.00	329.74
10	180	Point 4	26.53	7.18	10.77	1.91	5.40	148.22
11	330	Point 3	41.06	WIND ONLY		2.98	5.12	322.90
12	210	Point 1	32.91	8.15	16.93	1.95	4.85	191.87
13	210	Point 1	32.91	8.15	16.93	2.12	4.93	199.83
14	240	Point 1	37.13	12.10	17.16	2.23	4.98	225.15
15	270	Point 1	34.11	21.30	18.66	4.05	18.51	299.93
16	240	Point 1	37.13	20.86	17.30	5.19	17.02	233.16
17	240	Point 1	37.13	20.86	17.30	4.26	16.94	227.05
18	270	Point 1	34.11	21.30	18.66	1.98	6.93	306.59
19	240	Point 1	37.13	20.86	17.30	3.75	17.00	288.38
20	30	Point 3	26.99	13.82	15.21	4.51	14.69	58.09
21	30	Point 3	26.99	13.82	15.21	4.64	14.93	67.19
22	330	Point 3	41.06	21.35	16.89	2.22	4.42	349.35
23	330	Point 3	41.06	21.35	16.89	3.32	5.96	341.74
24	180	Point 1	29.07	11.37	14.65	5.84	13.75	161.38
25	270	Point 1	34.11	WIND ONLY		1.54	3.94	264.15
26	30	Point 3	26.99	13.82	15.21	6.23	15.15	61.05
27	30	Point 3	26.99	13.82	15.21	7.21	15.05	49.78
28	330	Point 3	41.06	21.35	16.89	12.50	16.84	347.71
29	330	Point 2	39.64	23.45	17.15	1.50	4.15	342.50
30	330	Point 2	39.64	23.45	17.15	2.38	6.80	330.15

Site ID	Boundary Conditions					Results 1 in 500-year		
	Offshore Direction (deg)	ERA5 Point	Wind speed (m/s)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Wave Height, Hs (m)	Wave Period, Tp (sec)	Mean Wave Direction (deg)
31	330	Point 2	39.64	23.45	17.15	4.26	17.51	300.20
32	330	Point 2	39.64	23.45	17.15	3.20	17.64	328.65
33	300	Point 2	35.96	24.93	20.07	3.67	20.05	337.52
34	330	Point 2	39.64	23.45	17.15	6.67	17.78	351.41

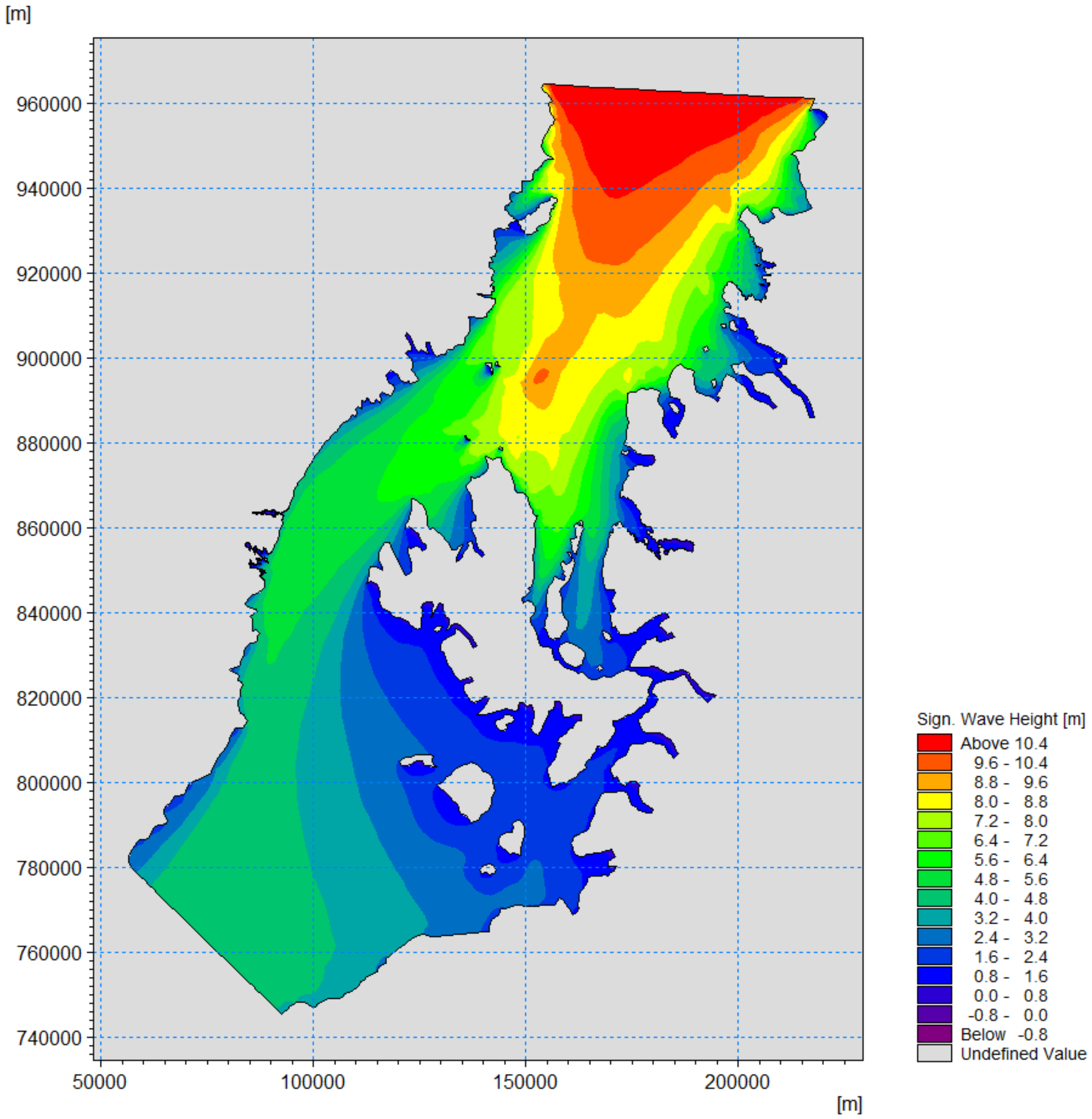


Figure 7-1: Contour plot of significant wave height within model Domain 1 – 1 in 50-year return period event

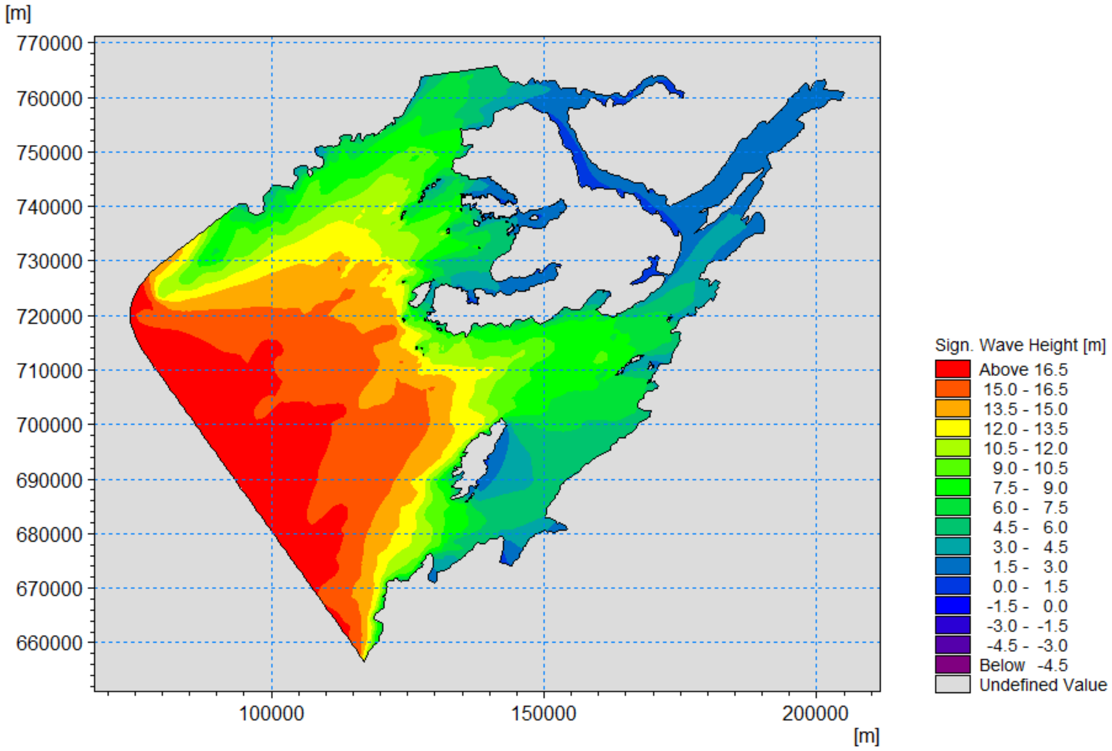


Figure 7-2: Contour plot of significant wave height within model Domain 2 – 1 in 50-year return period event

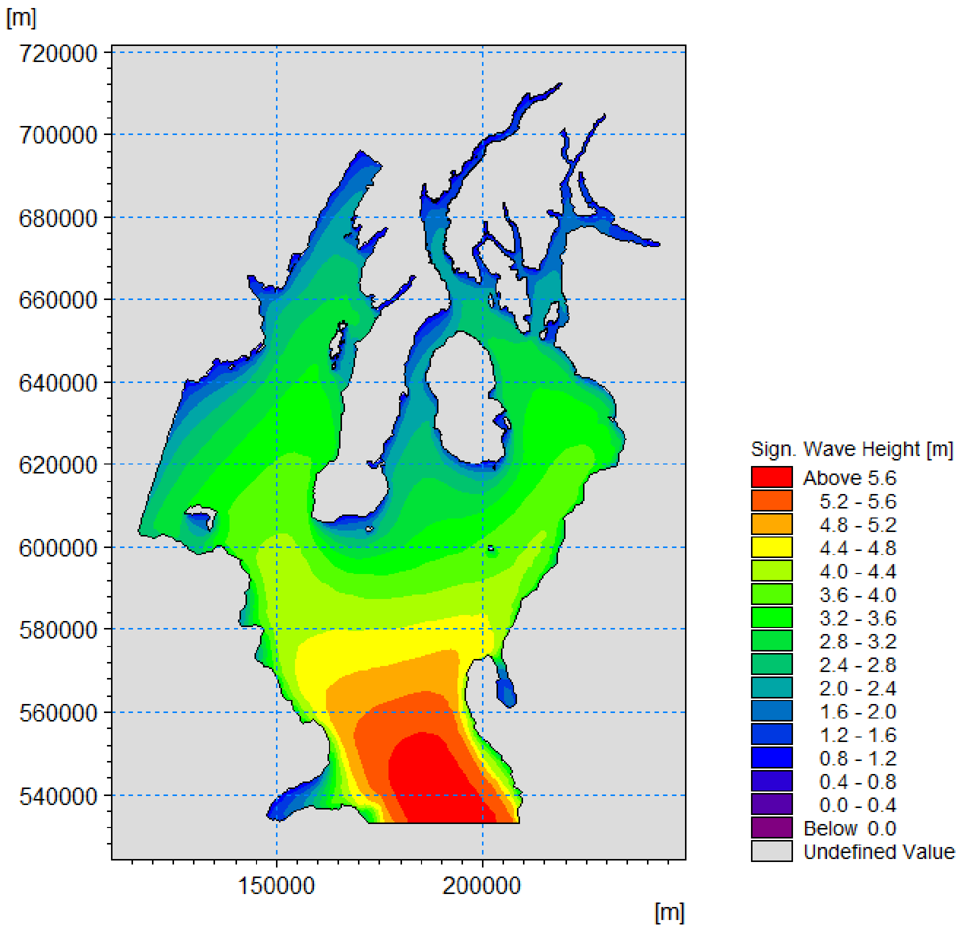


Figure 7-3: Contour plot of significant wave height within model Domain 3 – 1 in 50-year return period event

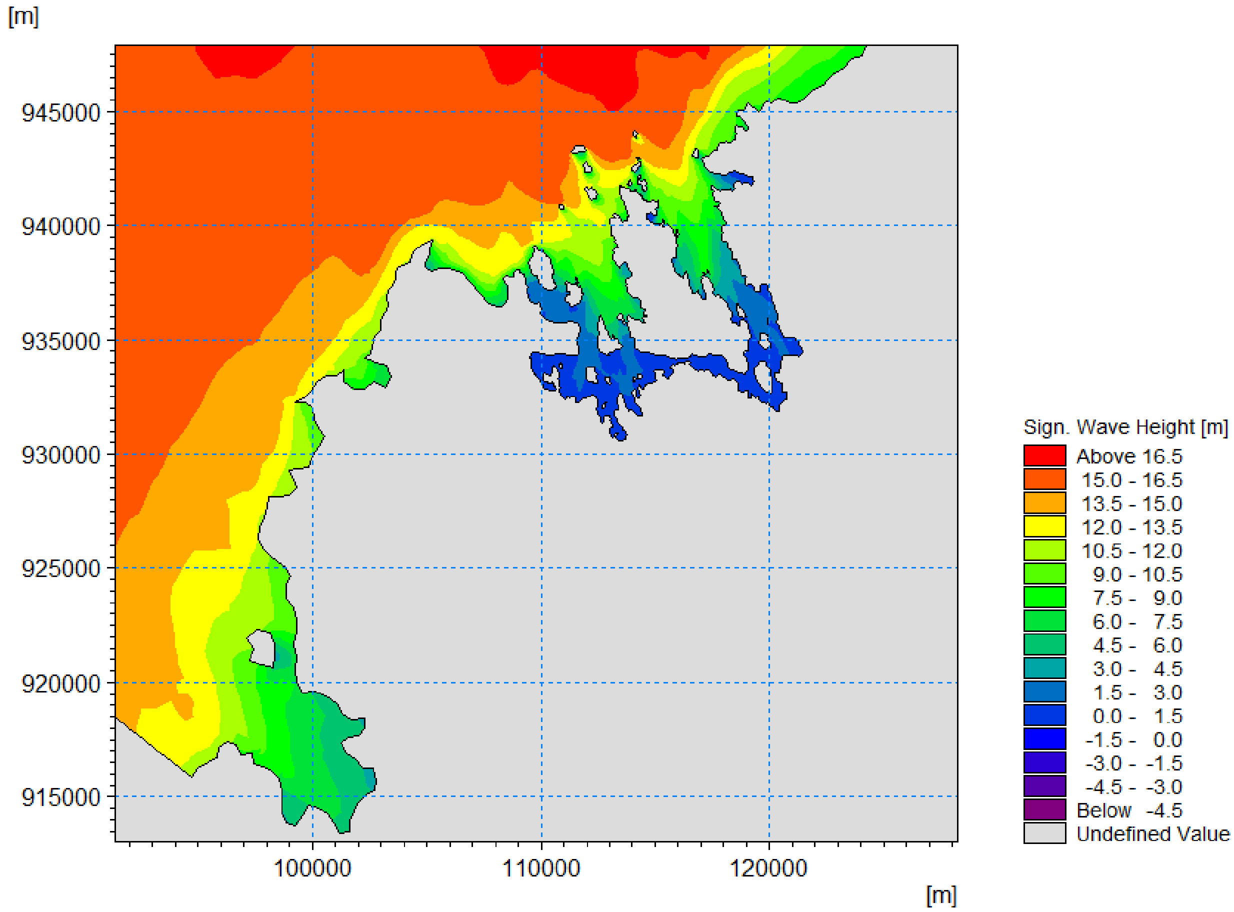


Figure 7-4: Contour plot of significant wave height within model Domain 4 – 1 in 50-year return period event

8 Conclusions and Recommendations

Wave climate assessment has been undertaken for 34 areas of interest. The sites are located across the western coast of mainland Scotland and around Outer Hebrides. Understanding of the extreme wave conditions is important for safe design and operation of the sites. Therefore, extreme value analysis was carried out to derive extreme wave conditions, that were then used in wave transformation modelling to determine derived wave conditions at each site.

Based on the regional model calibration with local wave buoy data, it was found that the model predicts the wave height well. For wave period, an adjustment factor was applied as the model was slightly underpredicting the longer wave periods. Similarly, for the wave direction from the north-westerly sector, a bias was observed with the observed conditions originating from a north westerly direction, whilst the modelled wave conditions show a more westerly direction. To offset the potential impact on nearshore wave conditions, the extreme value analysis was repeated, incorporating the most conservative wave height estimation from the standard directional bin and the directional bin rotated 20 degree clockwise, mitigating this bias.

A series of sensitivity runs was carried out to determine worst wave direction for each site, i.e. the direction of offshore waves that result in the highest wave conditions at the site location. For the majority of sites, the north-westerly or the north-easterly direction present the worst (greatest) wave conditions, with a few sites with the south direction as worst.

The model runs for all required return period events was carried out for the worst wave direction for each site. Results vary across the sites as some are more sheltered than others. The significant wave height ranges from 1.0m to 8.7m for the 1 in 50-year return period event. Results for each individual site are presented in a series of standalone Annexes.

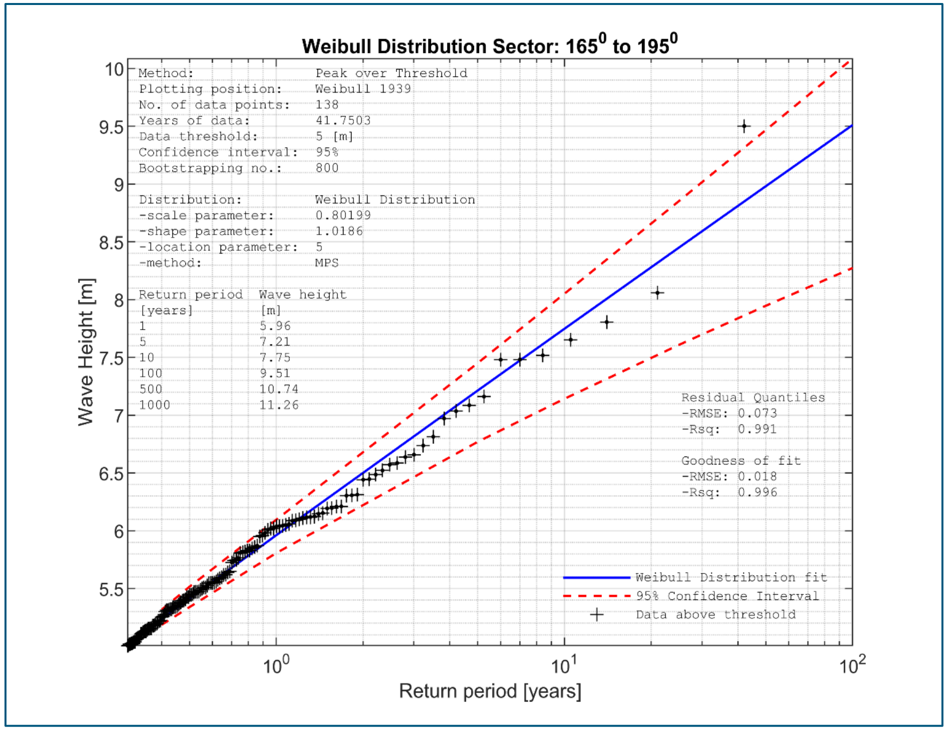
The regional model has been calibrated, but to further improve the model calibration against other local wave measurements (for different locations) could be carried out. Similarly, if local wind measurements would be available in appropriate format, it could be used in model calibration and validation.

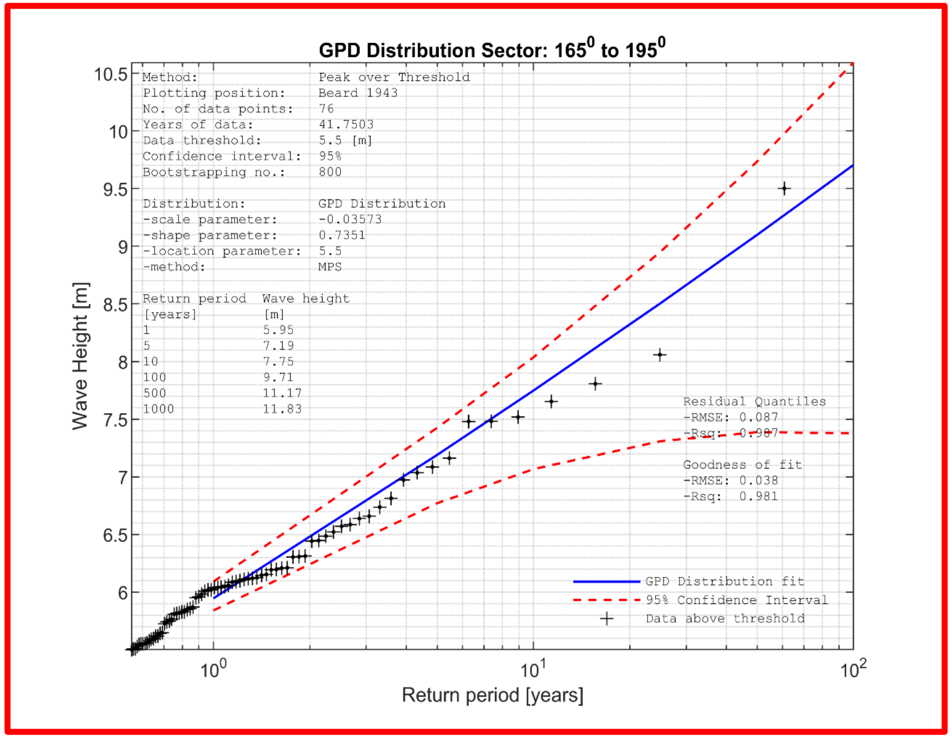
Appendix A – Extreme Value Analysis: Wave Distributions Fitting

Plots in this Appendix present the distributions fitting for the four ERA5 data points resulting from the extreme value analysis of offshore significant wave heights. Plots for each point are presented in a clockwise order of the directional sectors relevant for each point, with the selected distribution outlined in red.

Extreme Wave Height fitting – ERA5 Point 1

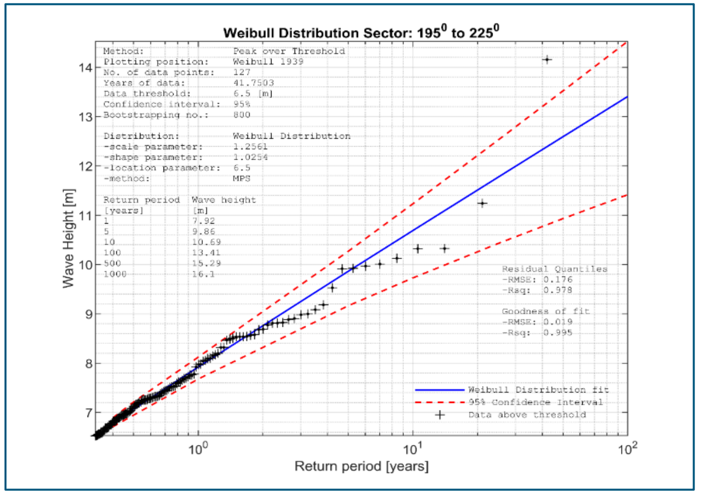
180deg:

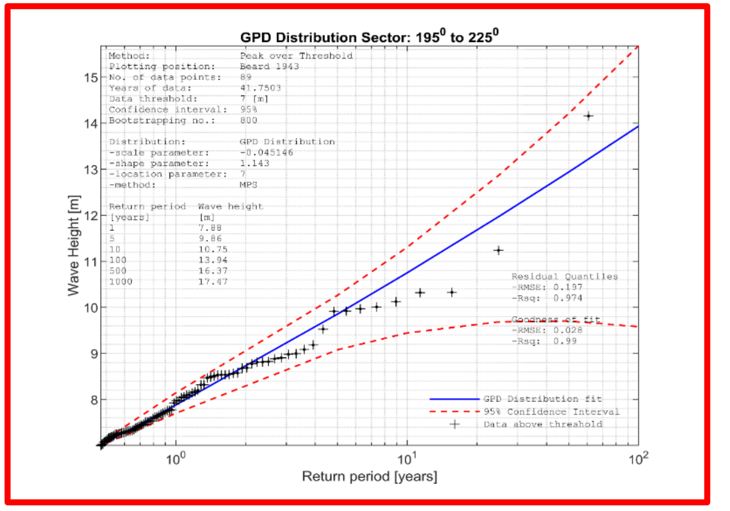




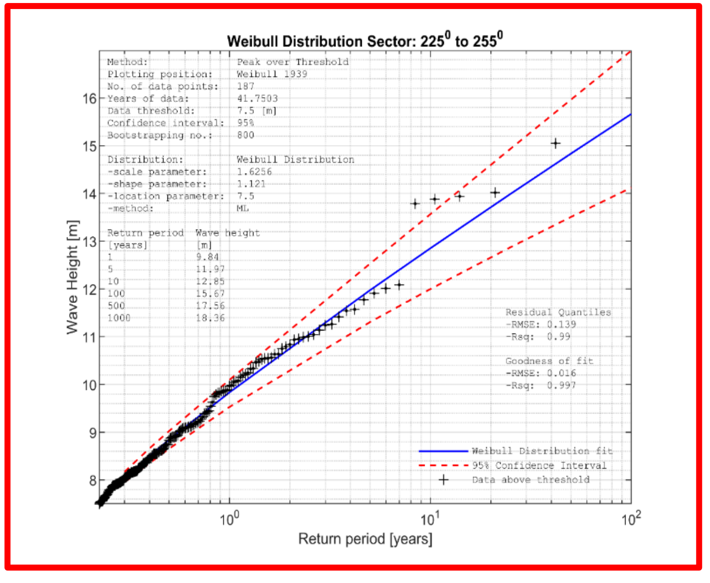
Royal HaskoningDHV

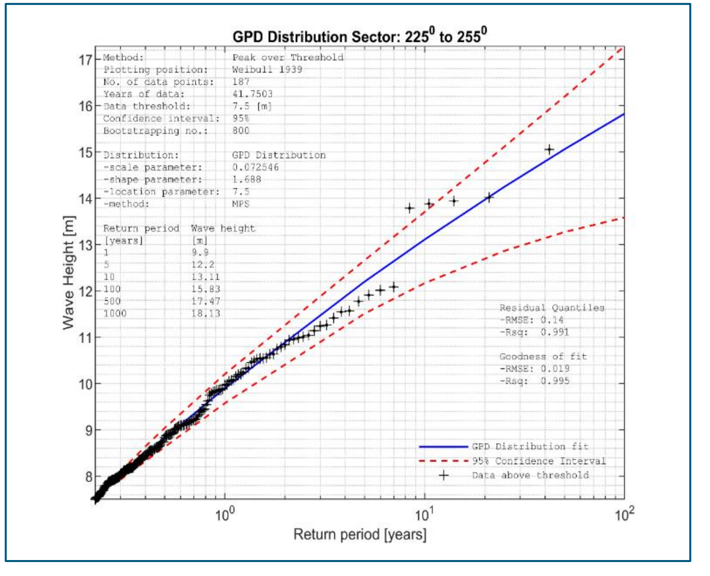
210deg:



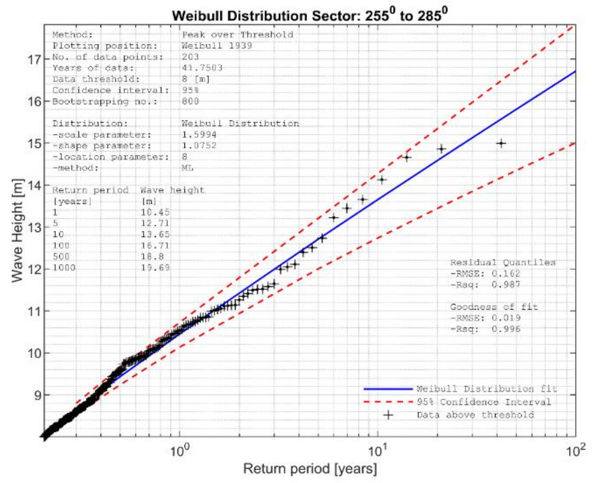


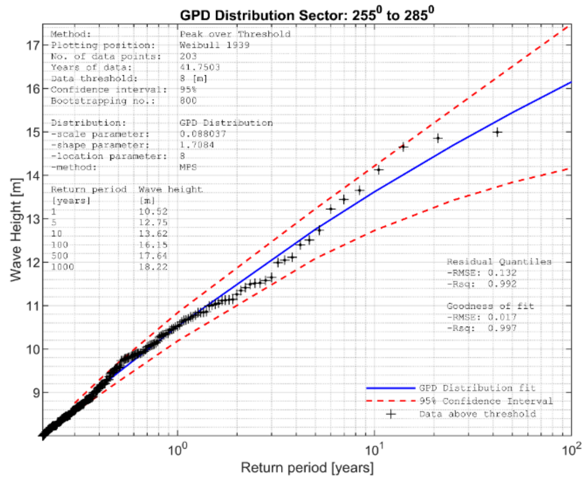
240deg:



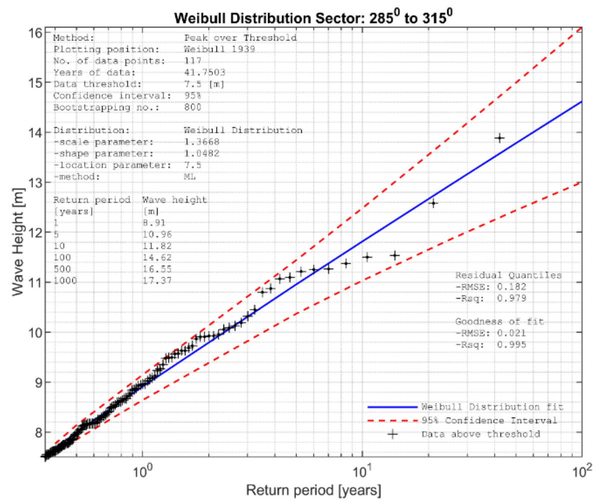


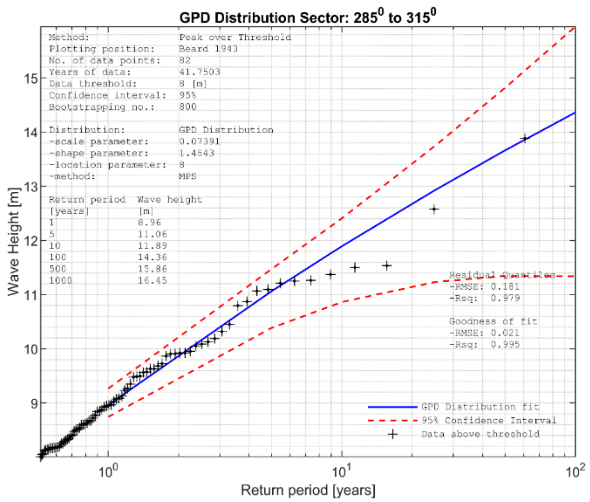
270deg:



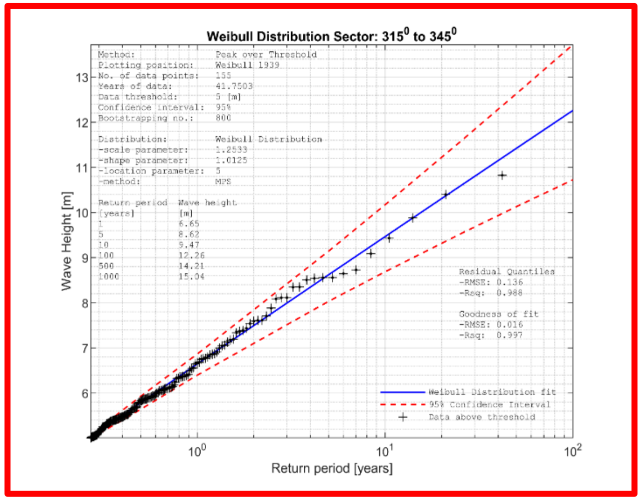


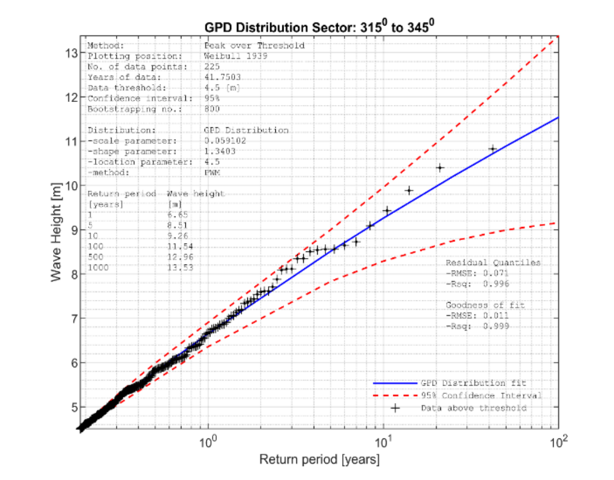
300deg:





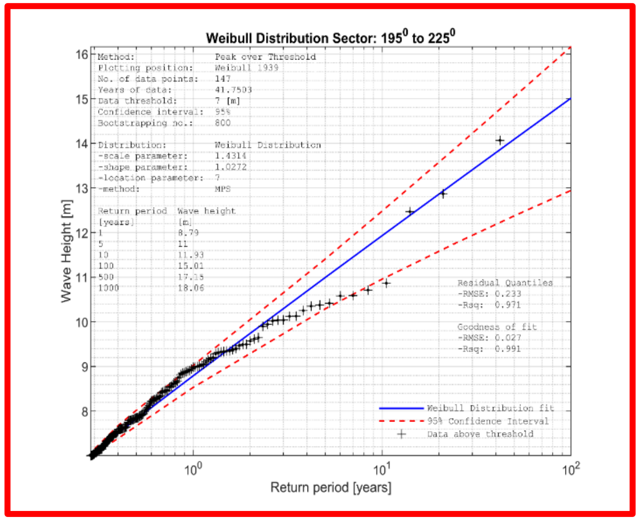
330deg:

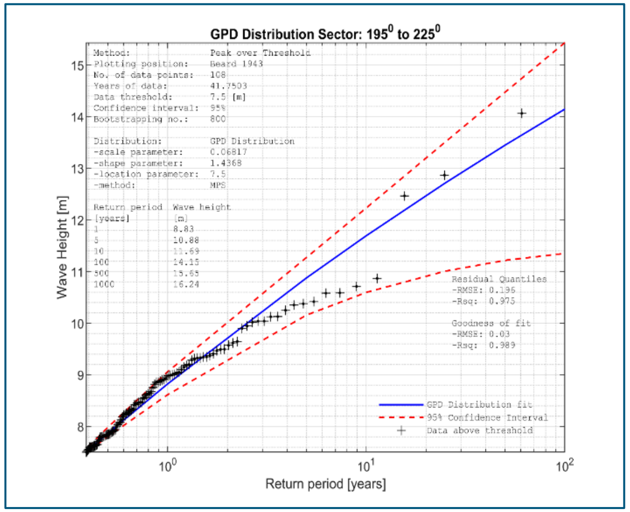




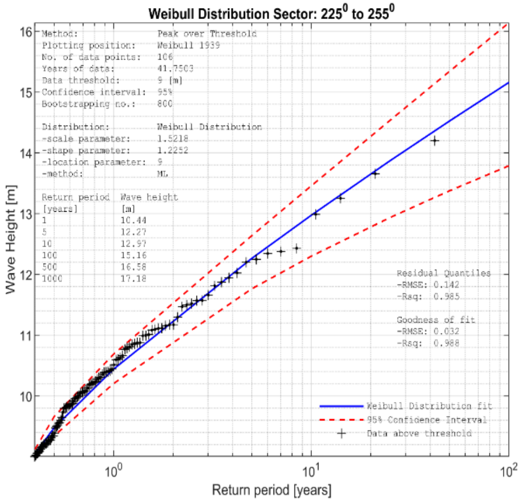
Extreme Wave Height fitting – ERA5 Point 2

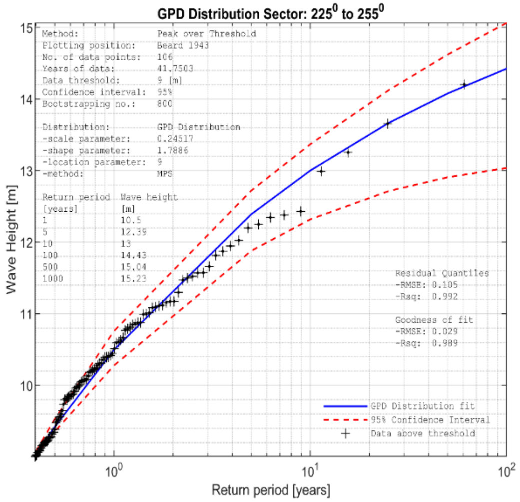
210deg:



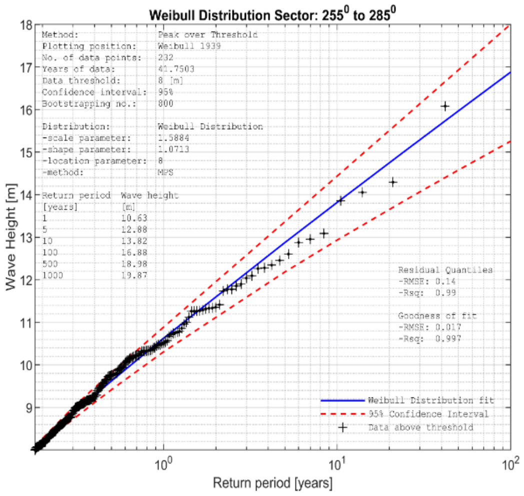


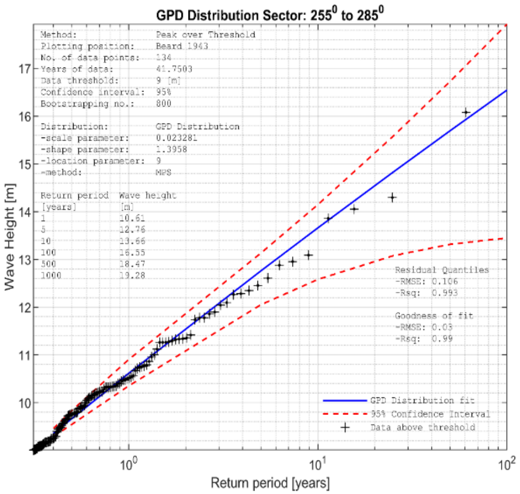
240deg:



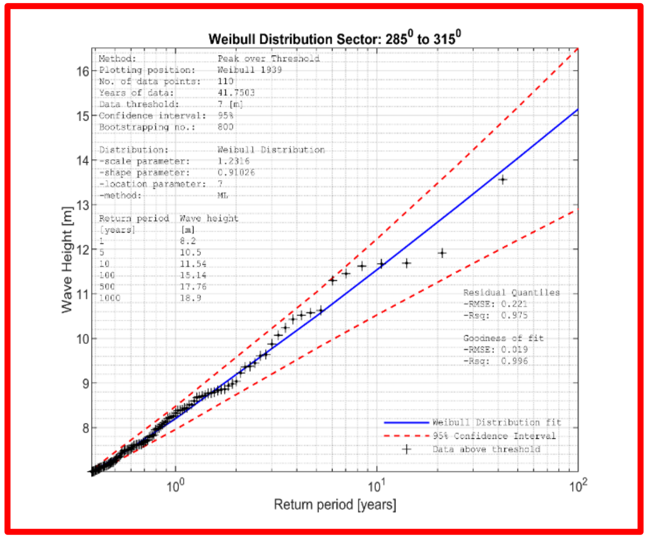


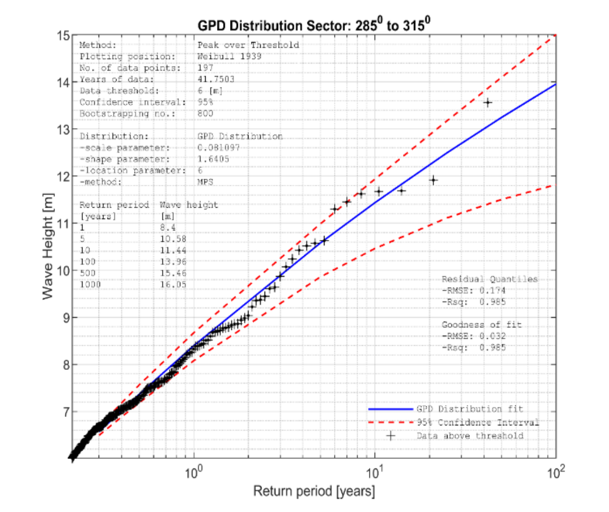
270deg:



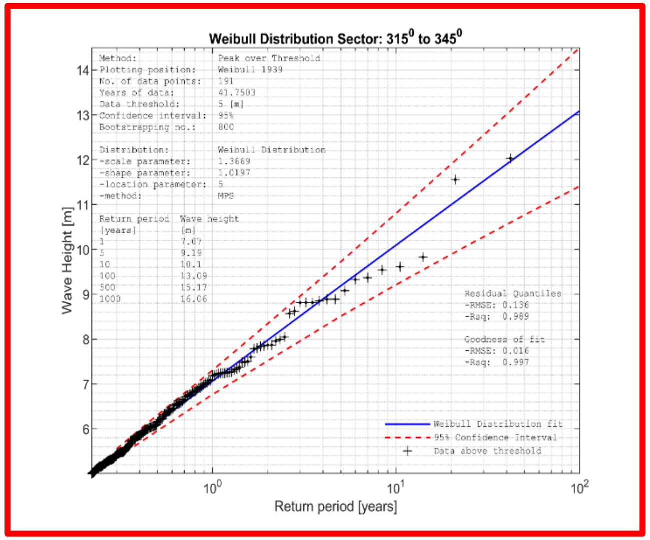


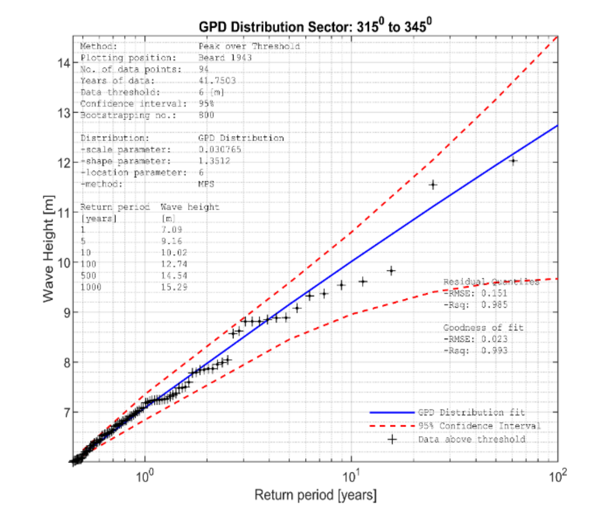
300deg:





330deg:

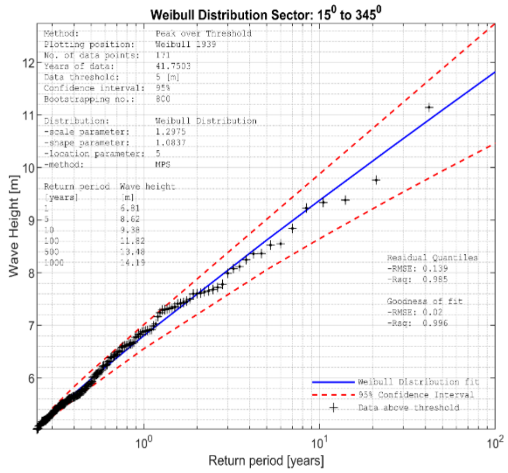


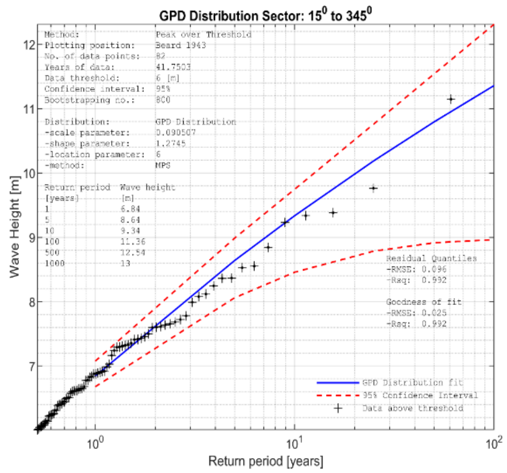


Royal HaskoningDHV

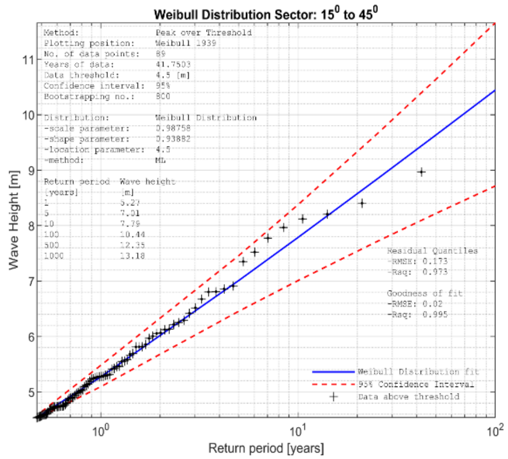
Extreme Wave Height fitting – ERA5 Point 3

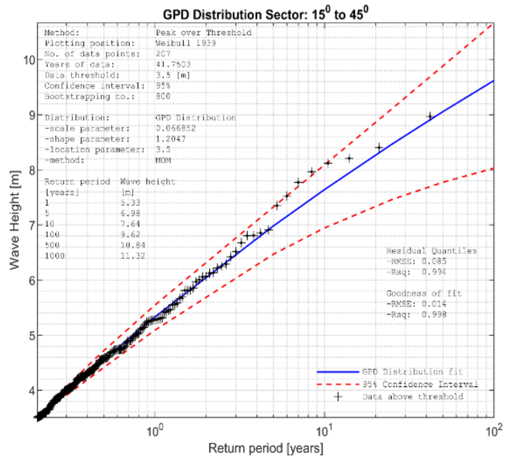
0deg:



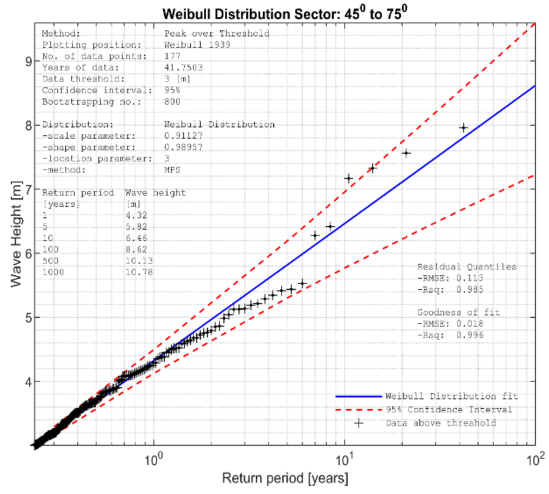


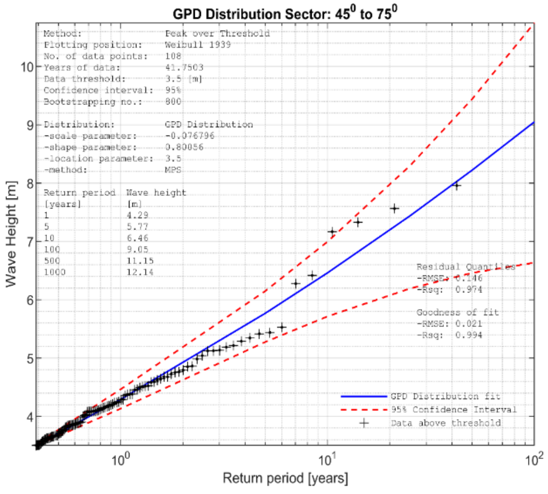
30deg:



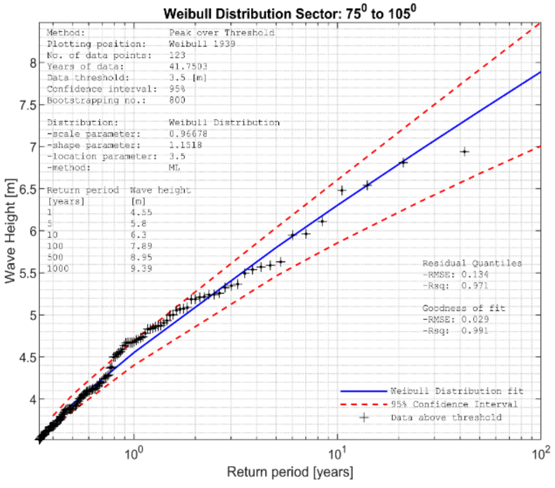


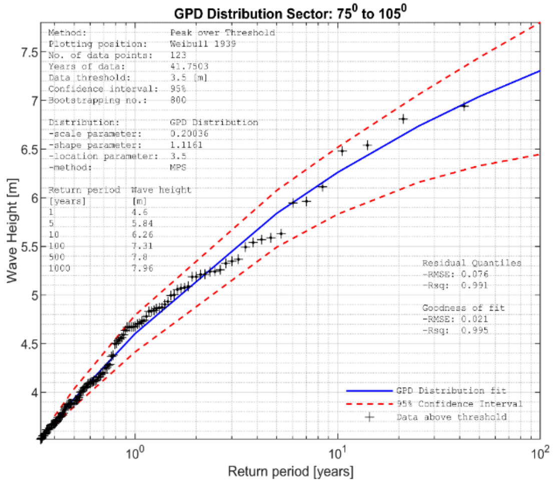
60deg:


Weibull Distribution Sector: 45^0 to 75^0
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 177
Years of data: 41.7503
Data threshold: 3 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 0.91127
-shape parameter: 0.98957
-location parameter: 3
-method: MPS
Return period [years] Wave height [m]
1 4.32
5 5.82
10 6.46
100 8.62
500 10.13
1000 10.78
Residual Quantiles
-RMSE: 0.113
-Rsq: 0.985
Goodness of fit
-RMSE: 0.018
-Rsq: 0.996
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]

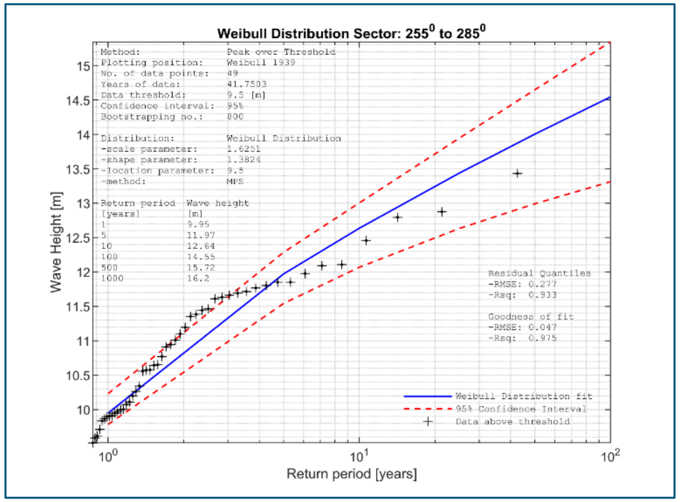

GPD Distribution Sector: 45^0 to 75^0
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 108
Years of data: 41.7503
Data threshold: 3.5 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: -0.076796
-shape parameter: 0.80056
-location parameter: 3.5
-method: MPS
Return period [years] Wave height [m]
1 4.29
5 5.77
10 6.46
100 9.05
500 11.15
1000 12.14
Residual Quantiles
-RMSE: 0.146
-Rsq: 0.974
Goodness of fit
-RMSE: 0.021
-Rsq: 0.994
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]

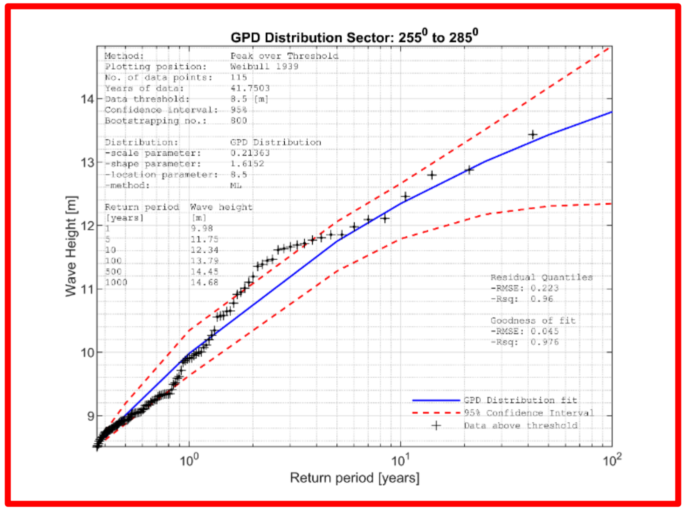
90deg:


Weibull Distribution Sector: 75^0 to 105^0
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 123
Years of data: 41.7503
Data threshold: 3.5 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 0.96678
-shape parameter: 1.1518
-location parameter: 3.5
-method: ML
Return period [years] Wave height [m]
1 4.55
5 5.8
10 6.3
100 7.89
500 8.95
1000 9.39
Residual Quantiles
-RMSE: 0.134
-Rsq: 0.971
Goodness of fit
-RMSE: 0.029
-Rsq: 0.991
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]

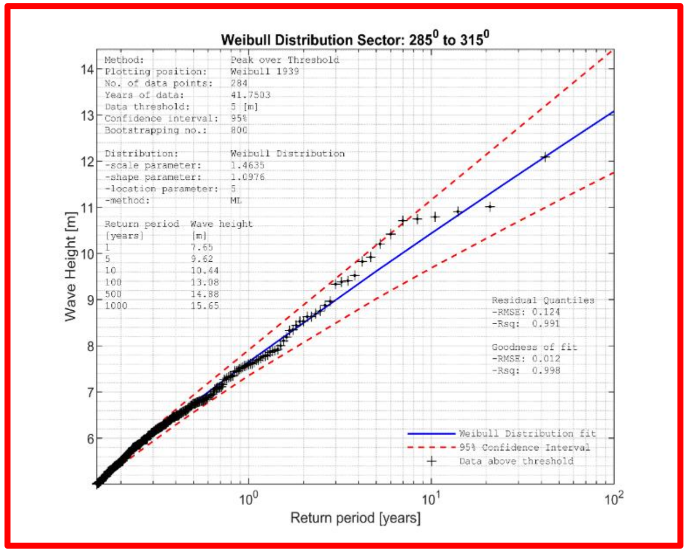

GPD Distribution Sector: 75^0 to 105^0
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 123
Years of data: 41.7503
Data threshold: 3.5 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: 0.20036
-shape parameter: 1.1161
-location parameter: 3.5
-method: MPS
Return period [years] Wave height [m]
1 4.6
5 5.84
10 6.26
100 7.31
500 7.8
1000 7.96
Residual Quantiles
-RMSE: 0.076
-Rsq: 0.991
Goodness of fit
-RMSE: 0.021
-Rsq: 0.995
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]

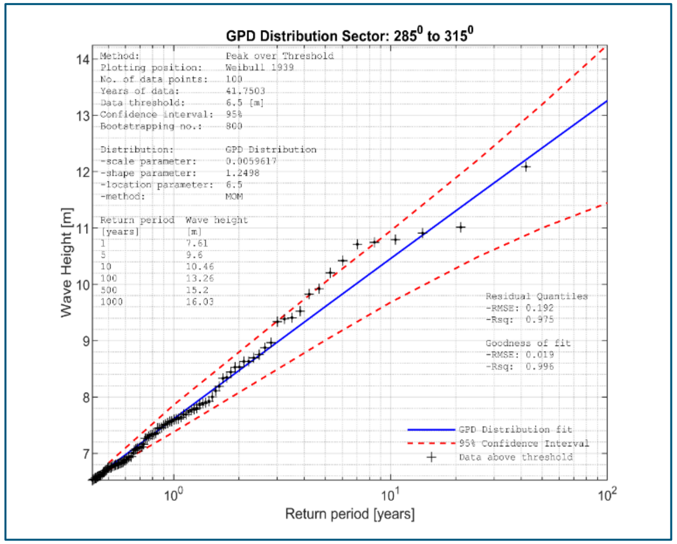
270deg:



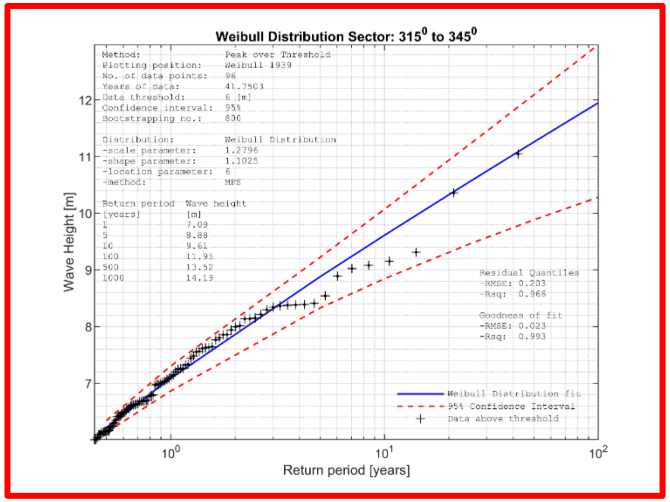


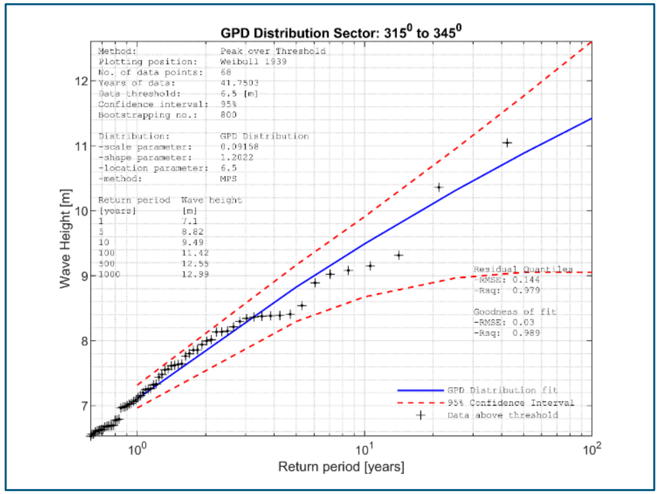
300deg:





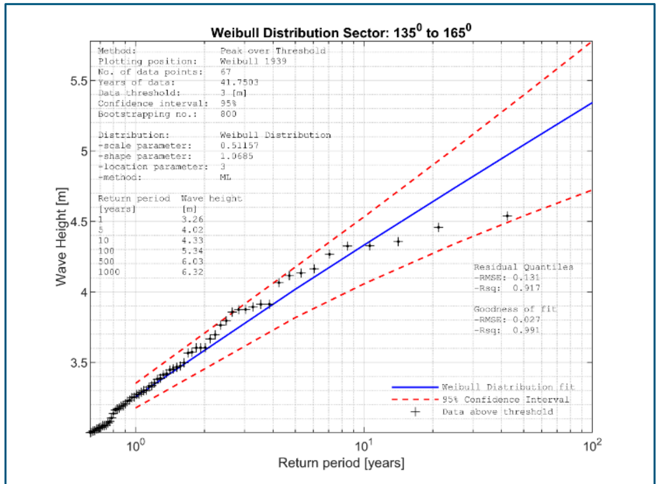
330deg:

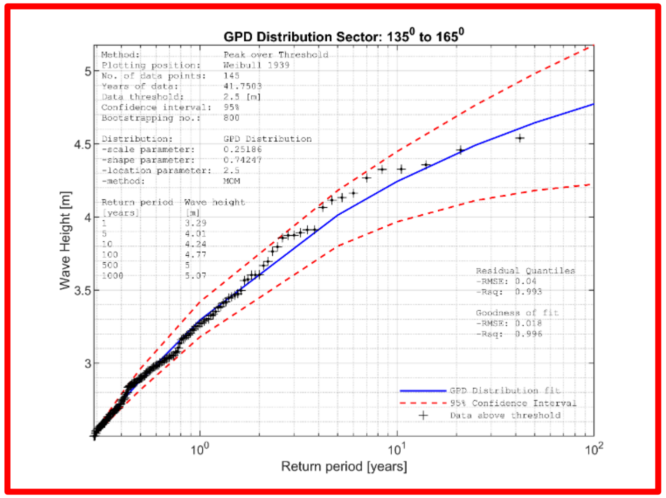




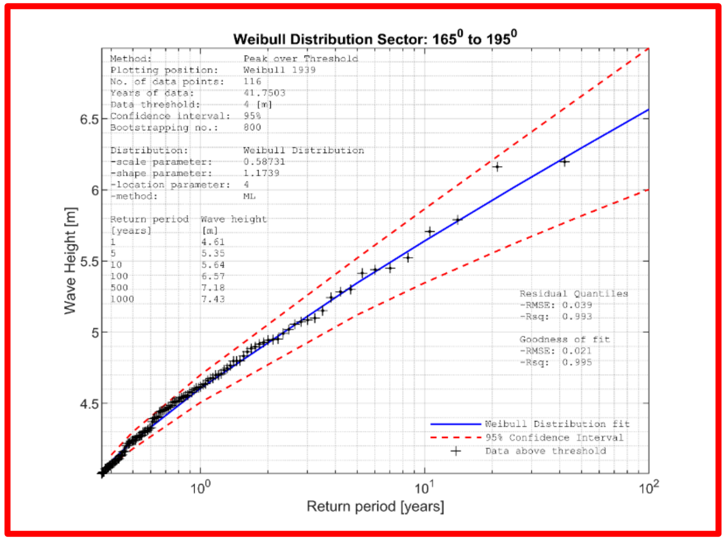
Extreme Wave Height fitting – ERA5 Point 4

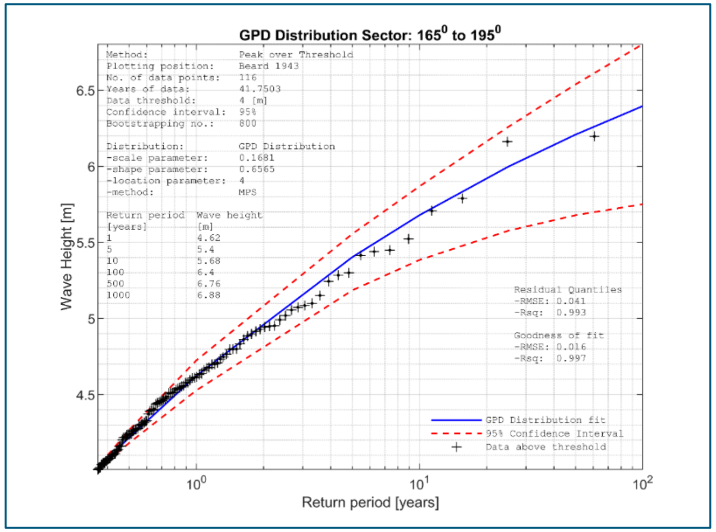
150deg:



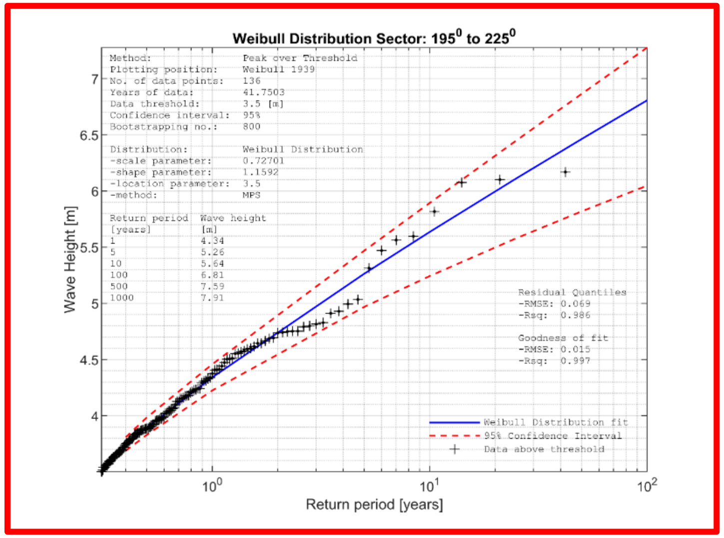


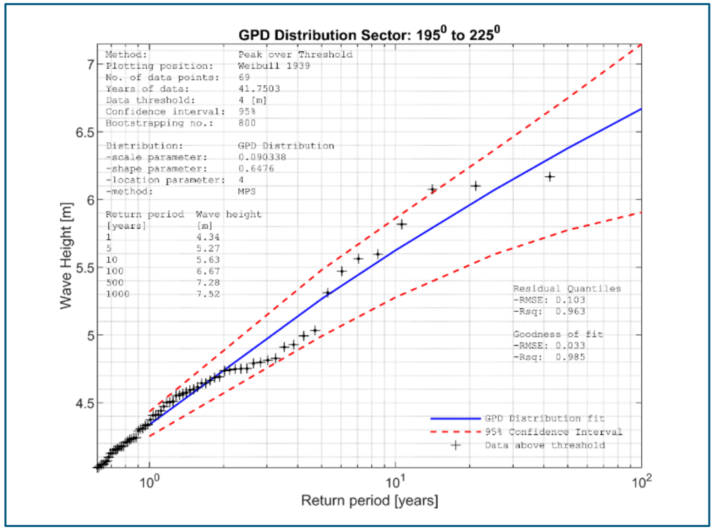
180deg:



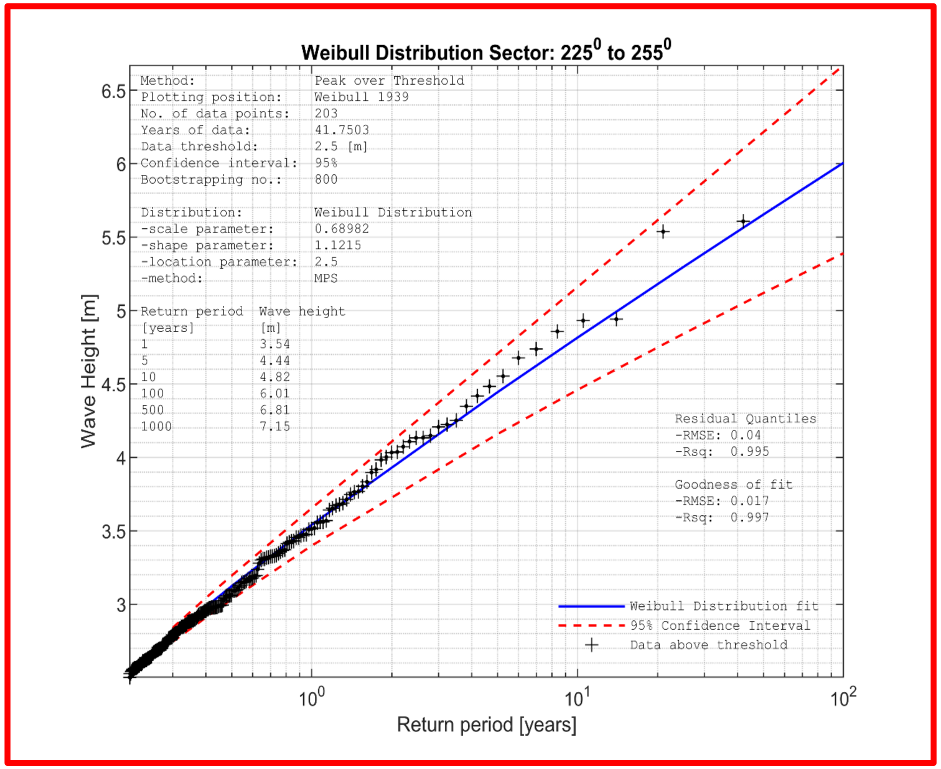


210deg:

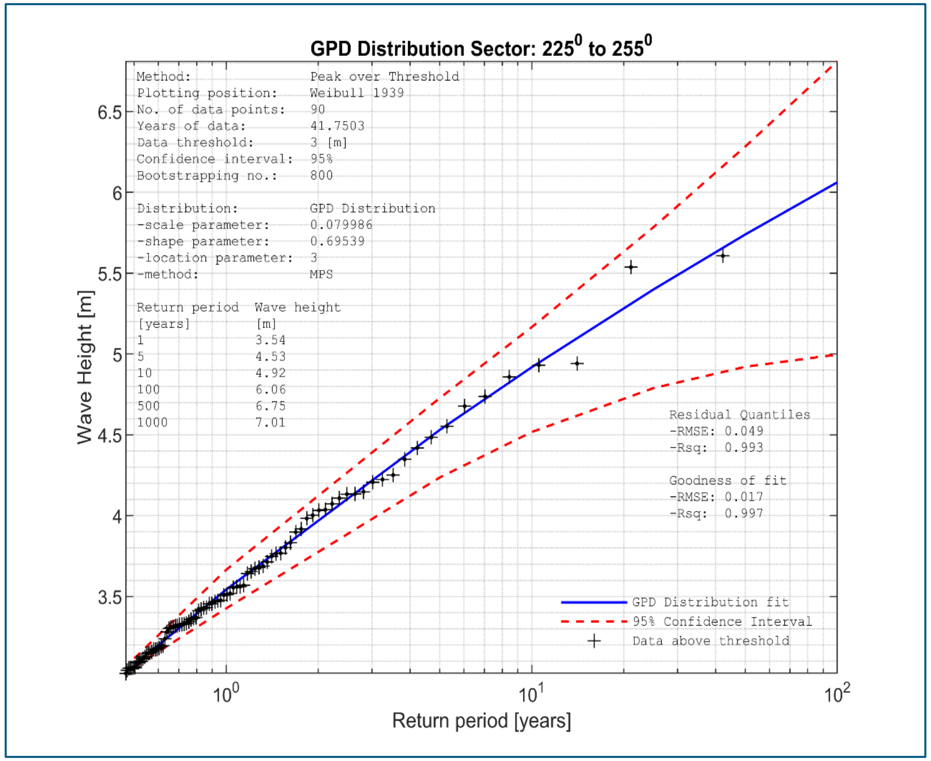




240deg:



Weibull Distribution Sector: 225⁰ to 255⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 203
Years of data: 41.7503
Data threshold: 2.5 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 0.68982
-shape parameter: 1.1215
-location parameter: 2.5
-method: MPS
Return period [years] Wave height [m]
1 3.54
5 4.44
10 4.82
100 6.01
500 6.81
1000 7.15
Residual Quantiles
-RMSE: 0.04
-Rsq: 0.995
Goodness of fit
-RMSE: 0.017
-Rsq: 0.997
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]



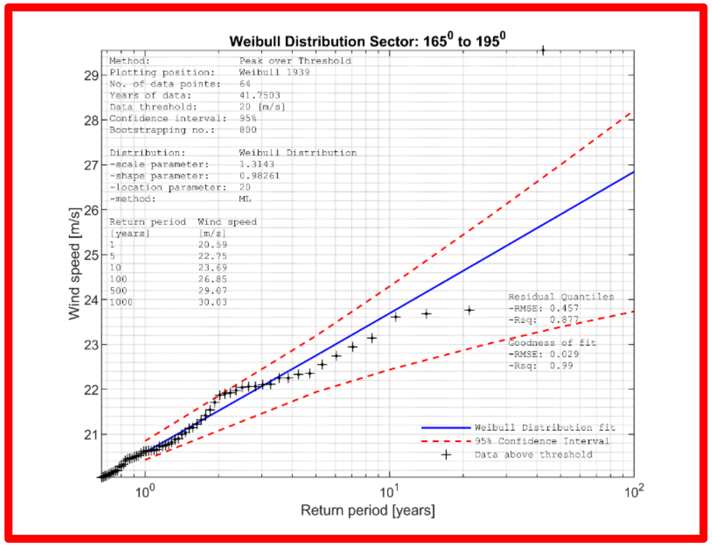
GPD Distribution Sector: 225⁰ to 255⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 90
Years of data: 41.7503
Data threshold: 3 [m]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: 0.079986
-shape parameter: 0.69539
-location parameter: 3
-method: MPS
Return period [years] Wave height [m]
1 3.54
5 4.53
10 4.92
100 6.06
500 6.75
1000 7.01
Residual Quantiles
-RMSE: 0.049
-Rsq: 0.993
Goodness of fit
-RMSE: 0.017
-Rsq: 0.997
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wave Height [m]
Return period [years]

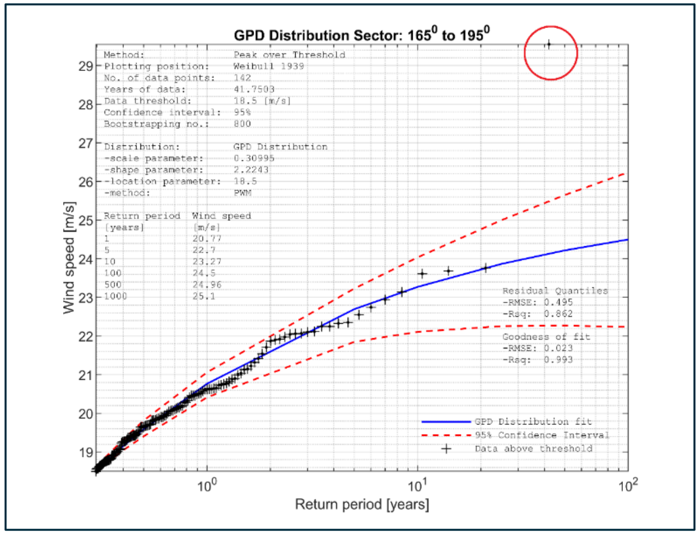
Appendix B – Extreme Value Analysis: Wind Distributions Fitting

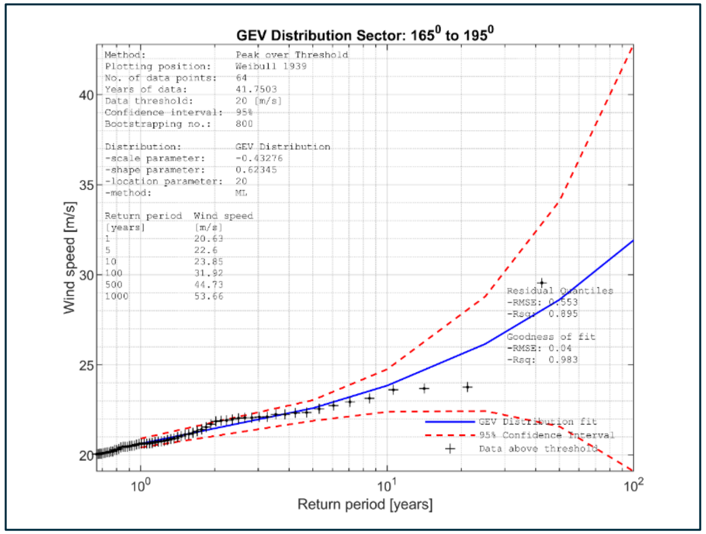
Plots in this Appendix present the distributions fitting for the four ERA5 data points resulting from the extreme value analysis of extreme wind speeds. Plots for each point are presented in a clockwise order of the directional sectors relevant for each point, with the selected distribution outlined in red.

Extreme Wind speed fitting – ERA5 Point 1

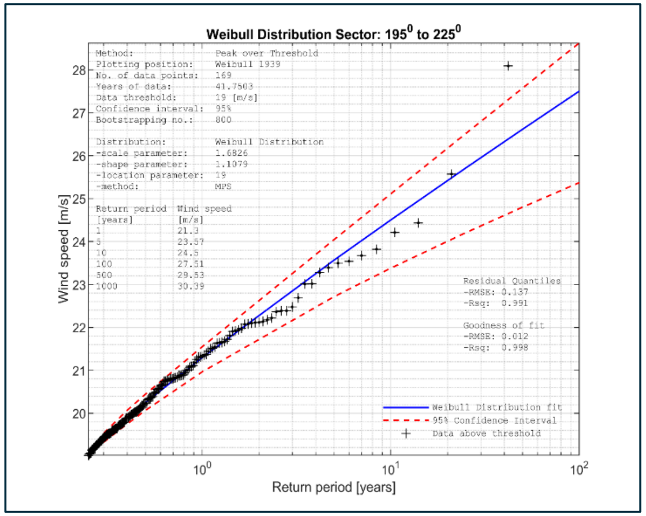
180deg:

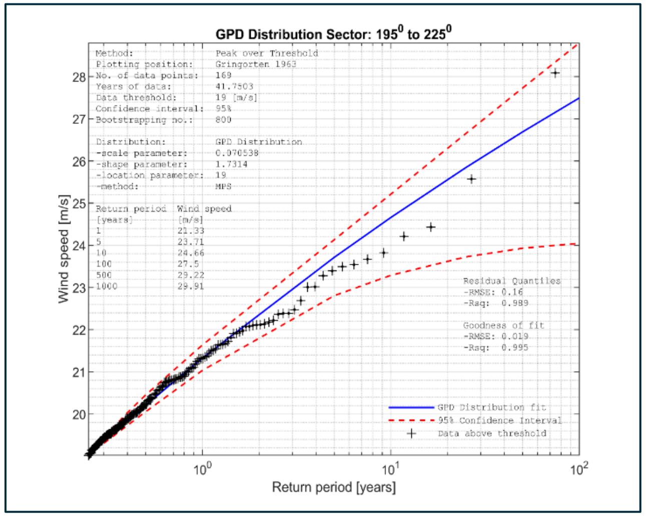


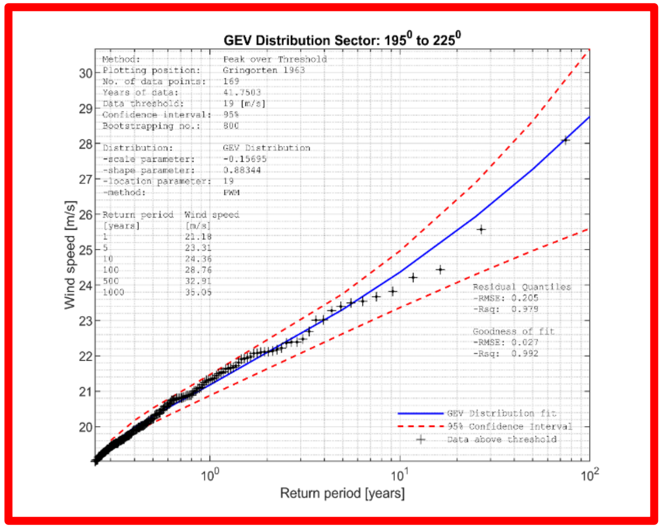




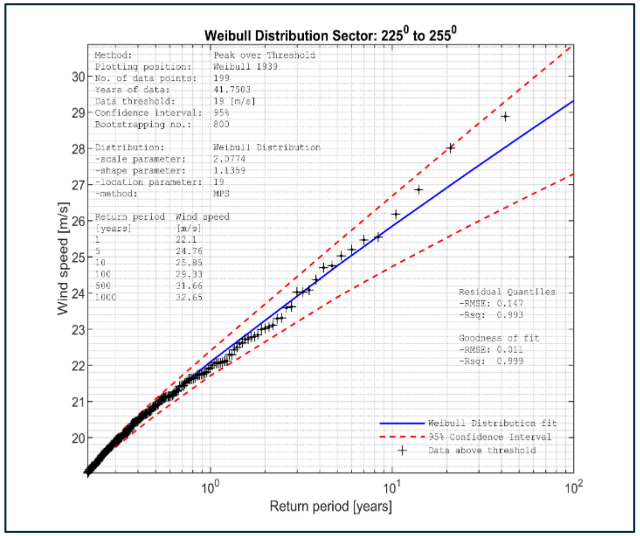
210deg:

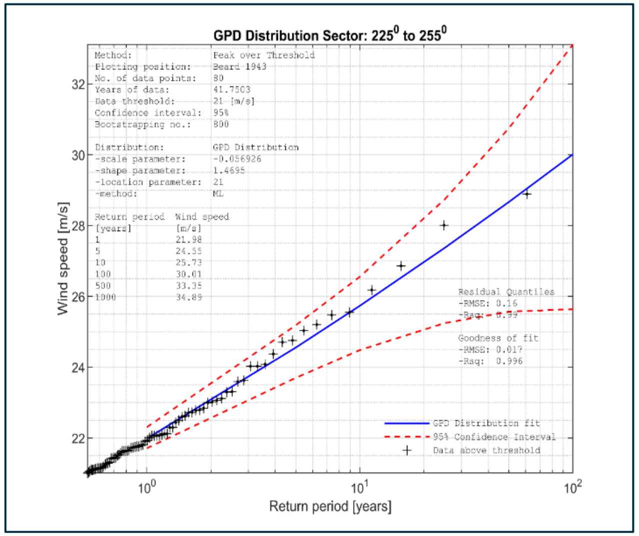


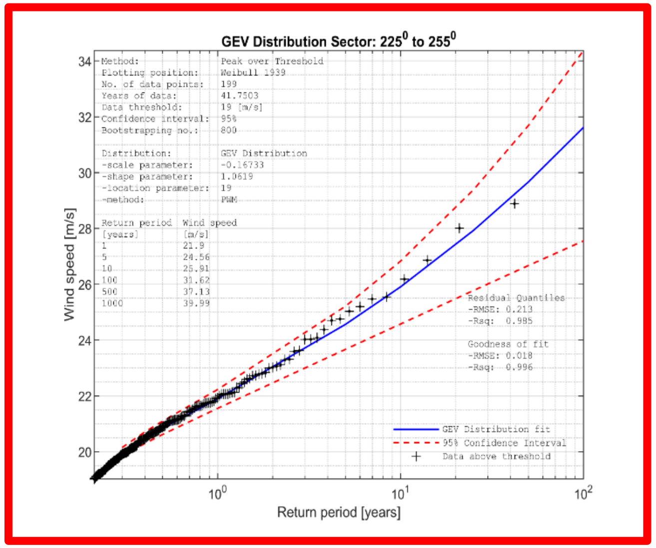




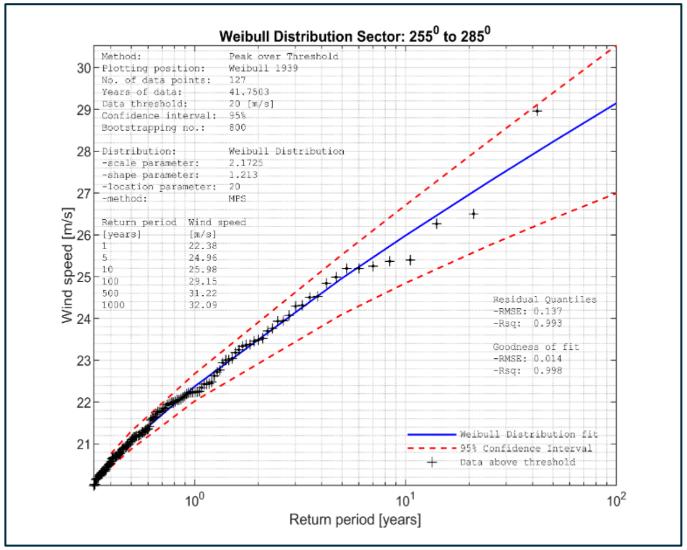
240deg:

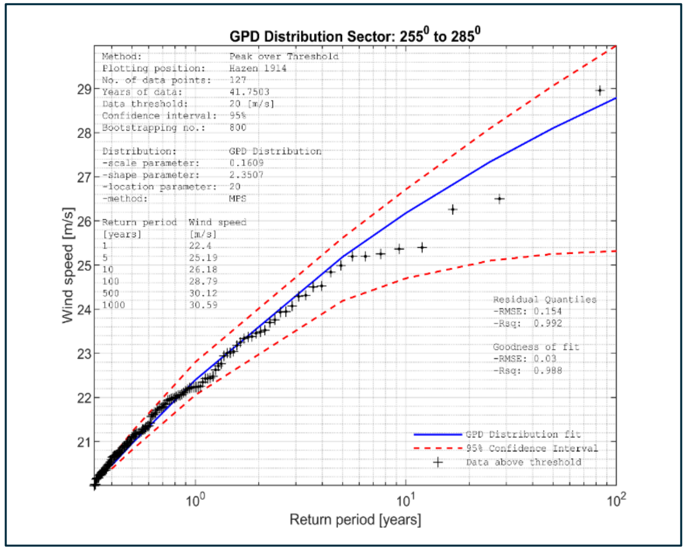


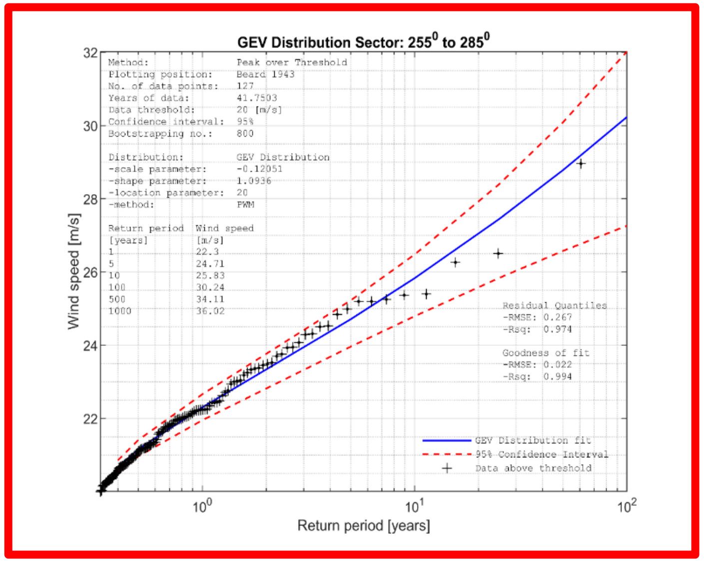




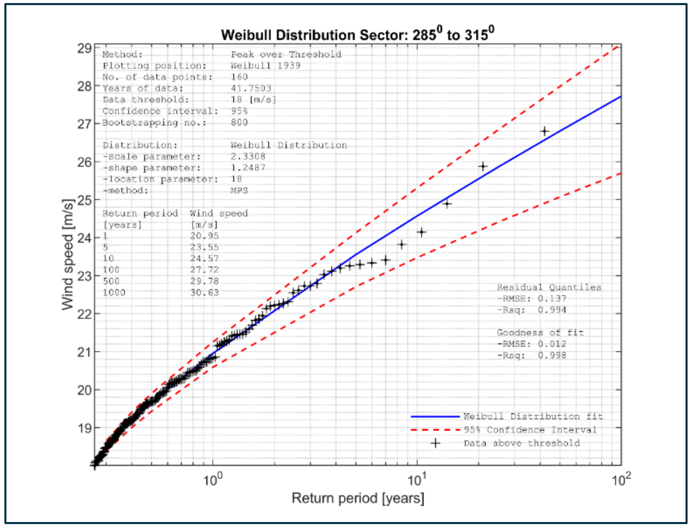
270deg:

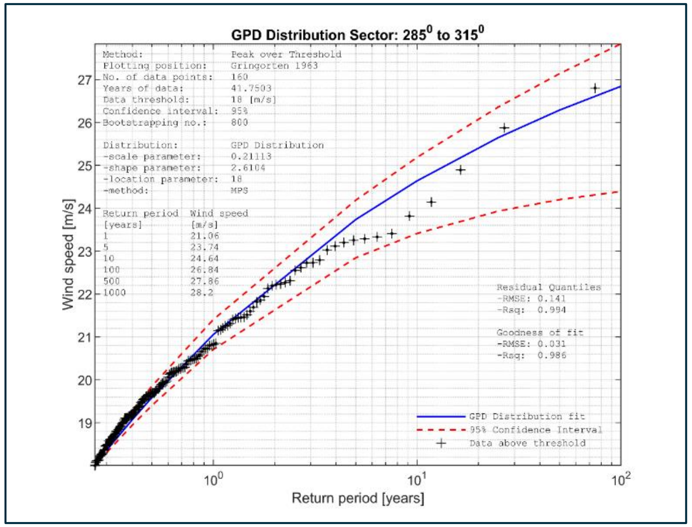


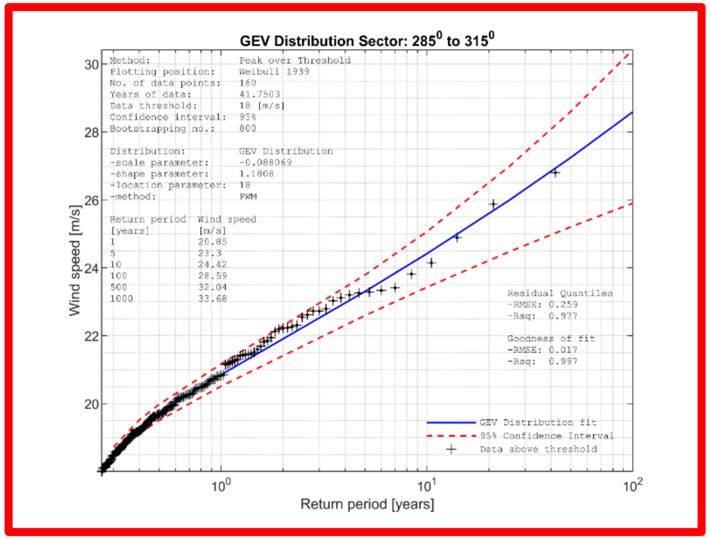




300deg:

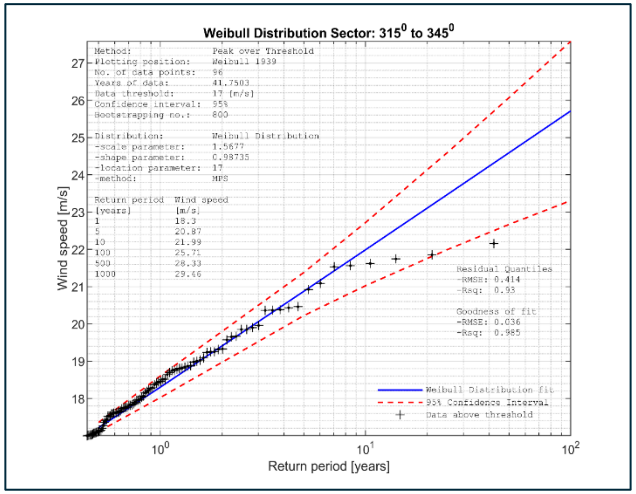


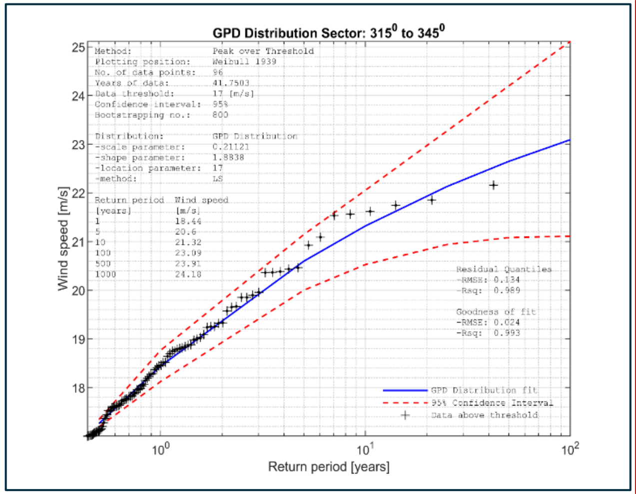


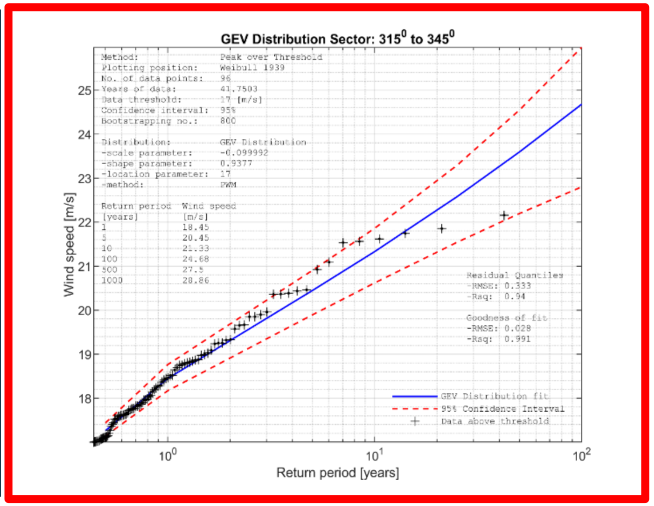


Royal HaskoningDHV

330deg:

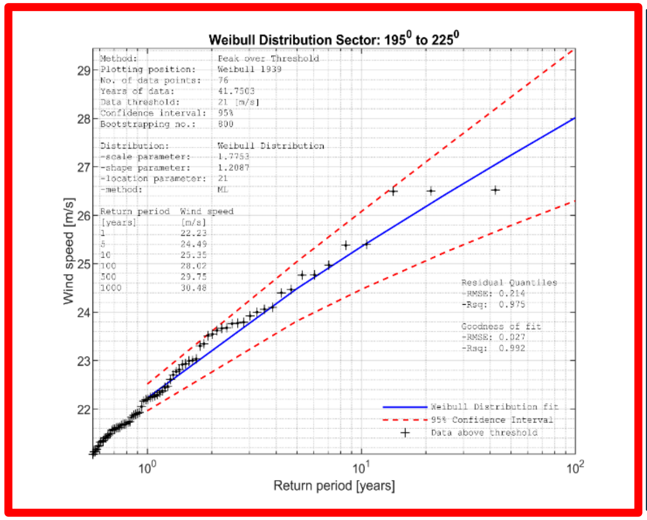


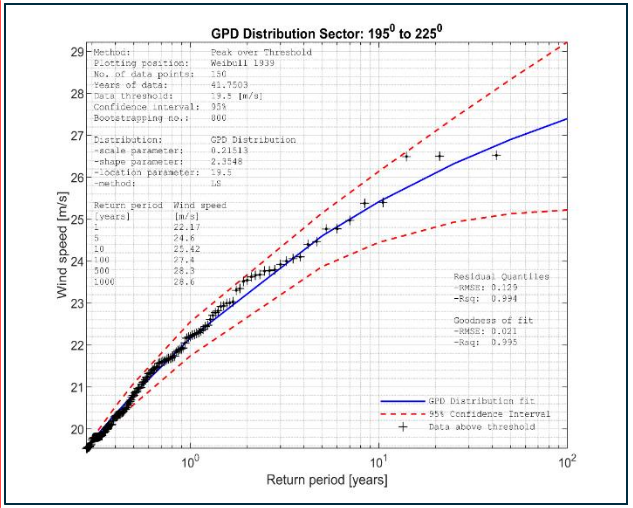


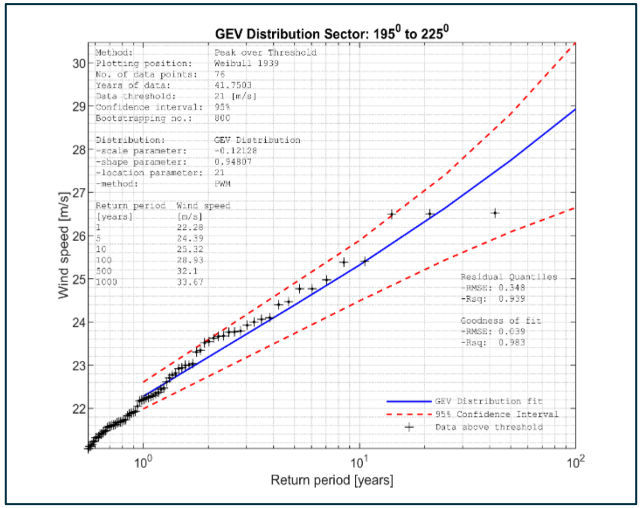


Extreme Wind speed fitting – ERA5 Point 2

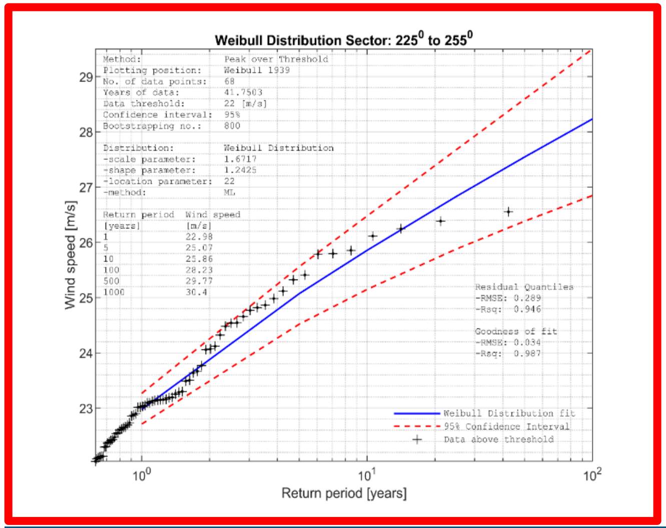
210deg:

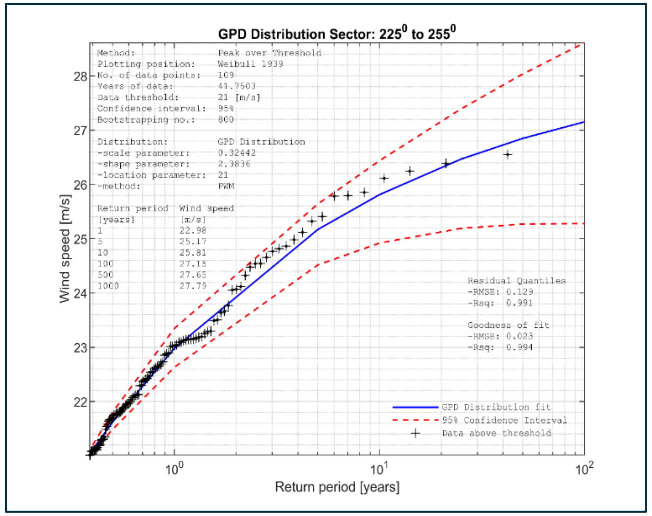


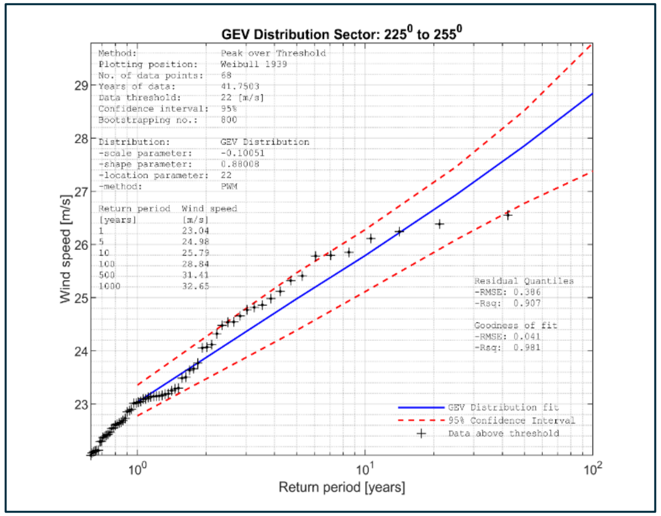




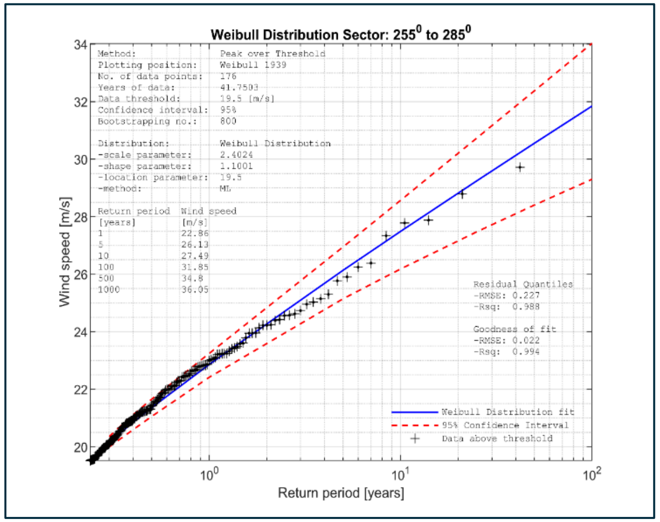
240deg:

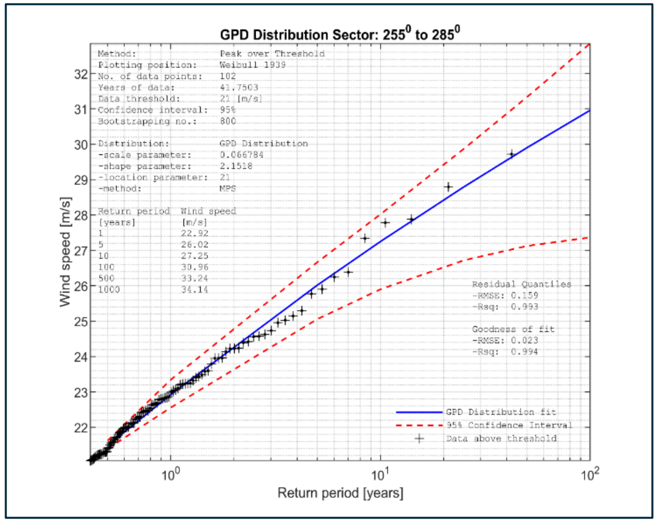


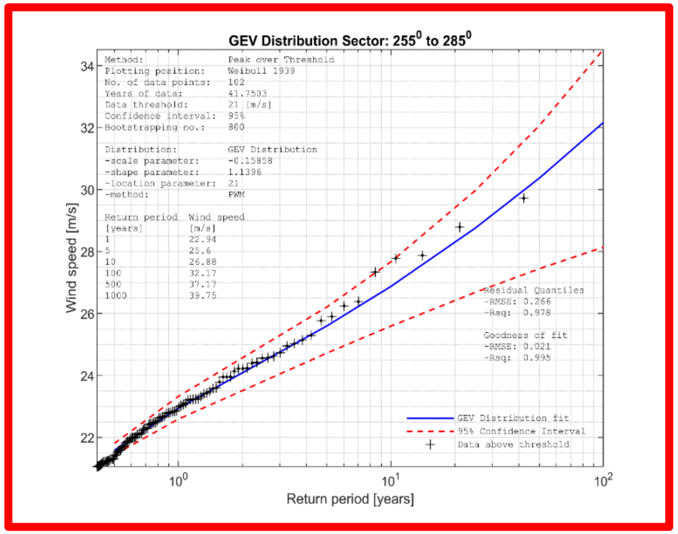




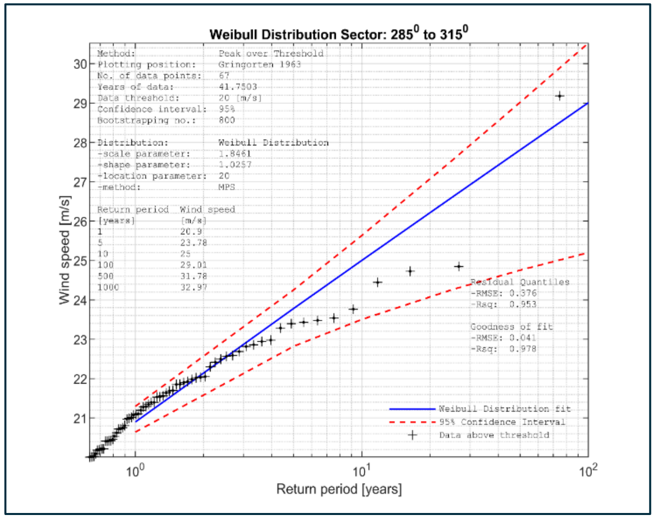
270deg:

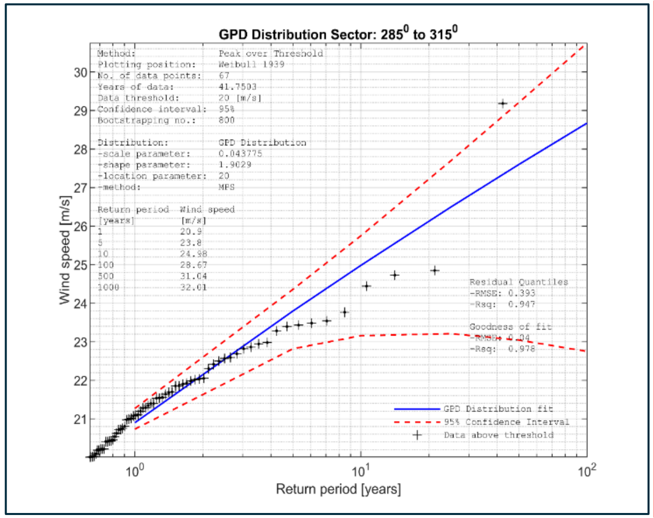


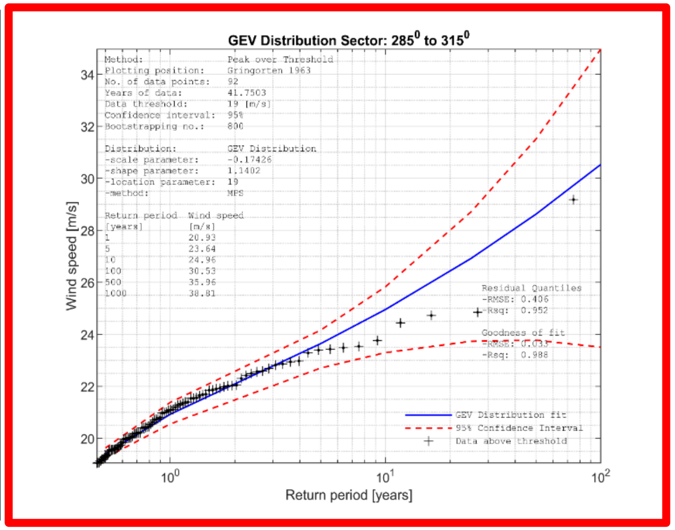




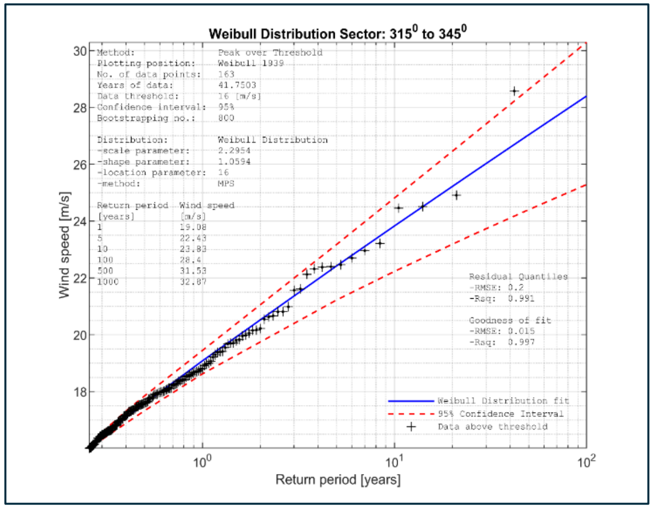
300deg:

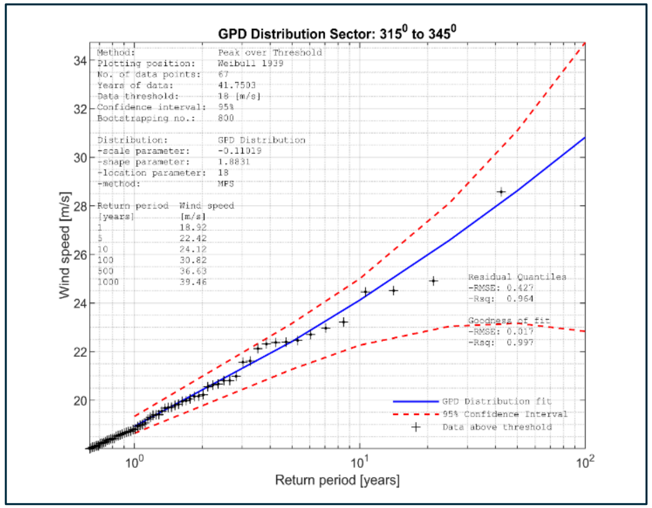


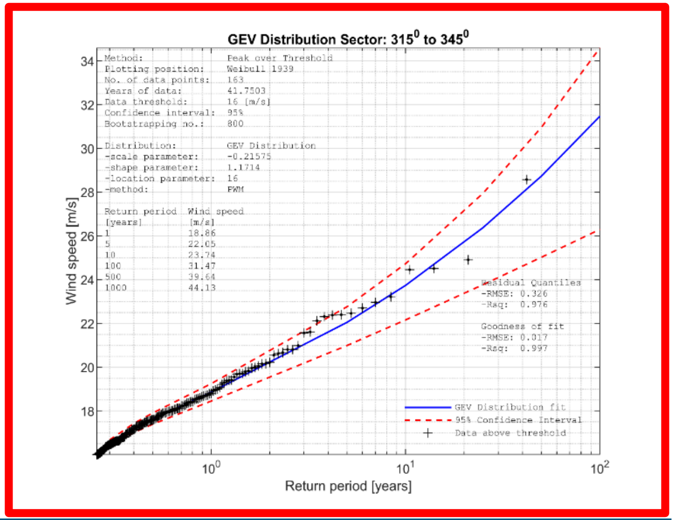




330deg:



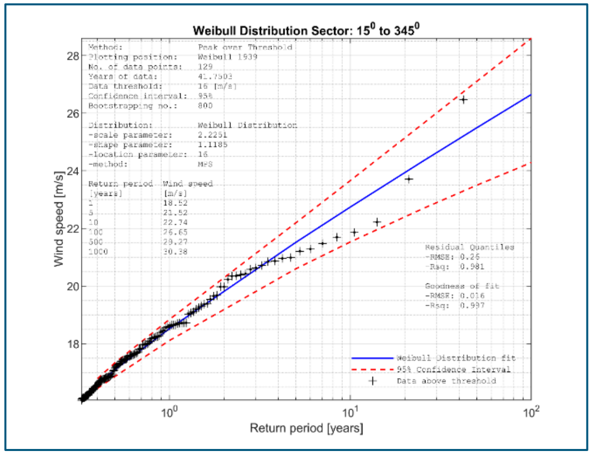


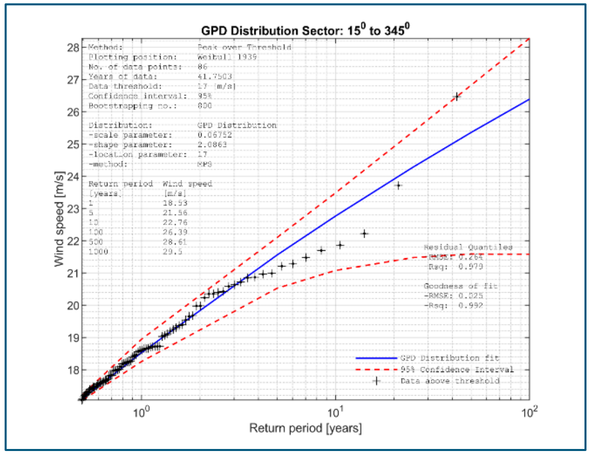


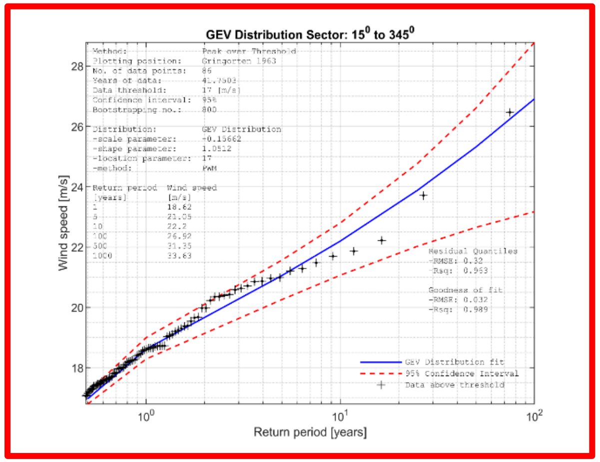
Royal HaskoningDHV

Extreme Wind speed fitting – ERA5 Point 2

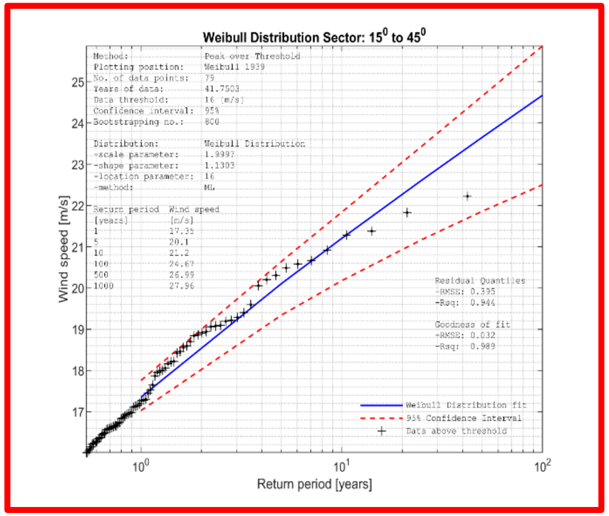
0deg:

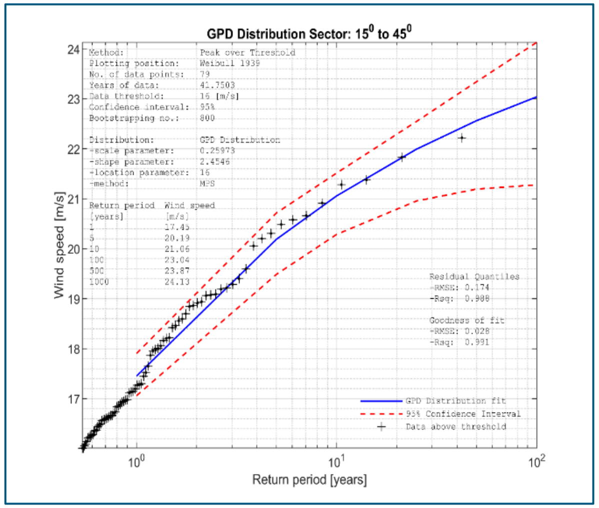


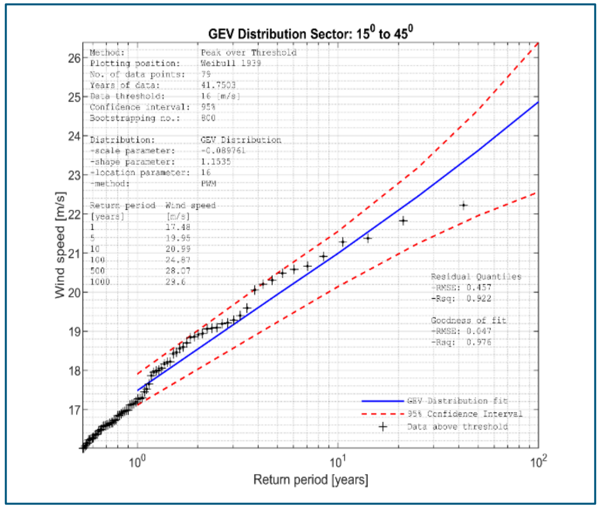




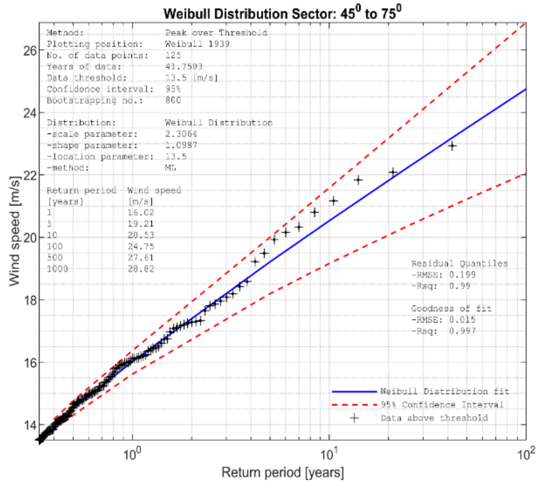
30deg:



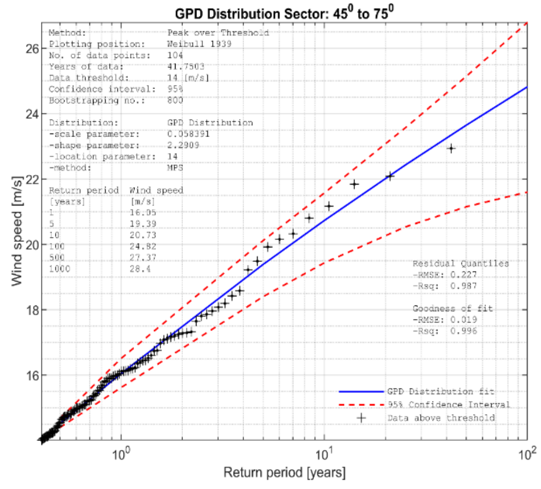




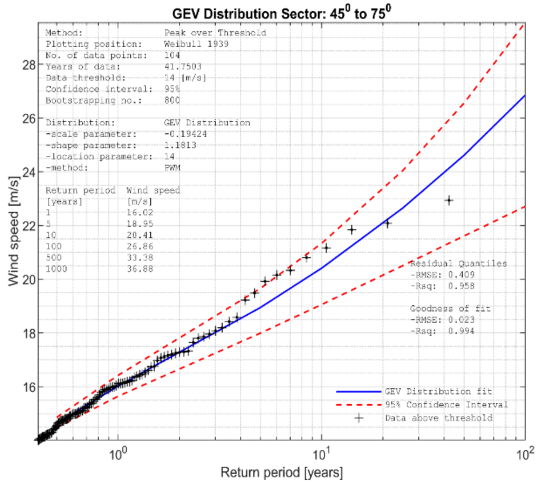
60deg:



Weibull Distribution Sector: 45⁰ to 75⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 125
Years of data: 41.7503
Data threshold: 13.5 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 2.3064
-shape parameter: 1.0987
-location parameter: 13.5
-method: ML
Return period [years] Wind speed [m/s]
1 16.02
5 19.21
10 20.53
100 24.75
500 27.61
1000 28.82
Residual Quantiles
-RMSE: 0.199
-Rsq: 0.99
Goodness of fit
-RMSE: 0.015
-Rsq: 0.997
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

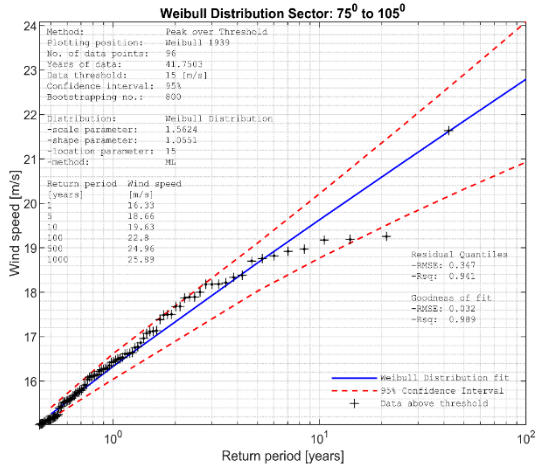


GPD Distribution Sector: 45⁰ to 75⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 104
Years of data: 41.7503
Data threshold: 14 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: 0.058391
-shape parameter: 2.2909
-location parameter: 14
-method: MPS
Return period [years] Wind speed [m/s]
1 16.05
5 19.39
10 20.73
100 24.82
500 27.37
1000 28.4
Residual Quantiles
-RMSE: 0.227
-Rsq: 0.987
Goodness of fit
-RMSE: 0.019
-Rsq: 0.996
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

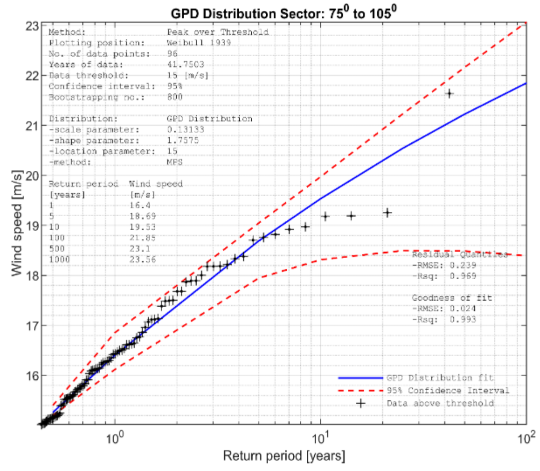


GEV Distribution Sector: 45⁰ to 75⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 104
Years of data: 41.7503
Data threshold: 14 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GEV Distribution
-scale parameter: -0.19424
-shape parameter: 1.1813
-location parameter: 14
-method: PWM
Return period [years] Wind speed [m/s]
1 16.02
5 18.95
10 20.41
100 26.86
500 33.38
1000 36.88
Residual Quantiles
-RMSE: 0.409
-Rsq: 0.958
Goodness of fit
-RMSE: 0.023
-Rsq: 0.994
GEV Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

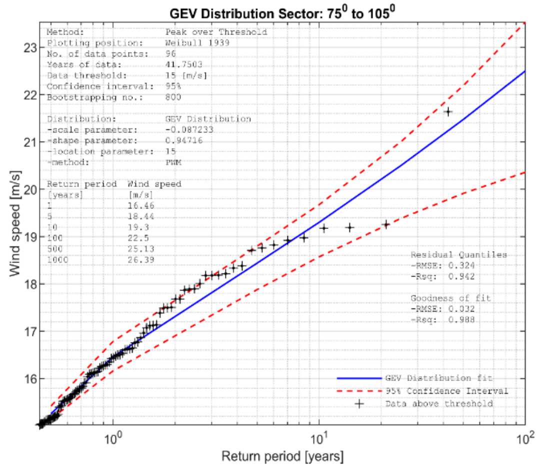
90deg:



Weibull Distribution Sector: 75⁰ to 105⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 96
Years of data: 41.7503
Data threshold: 15 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 1.5624
-shape parameter: 1.0551
-location parameter: 15
-method: ML
Return period [years] Wind speed [m/s]
1 16.33
5 18.66
10 19.63
100 22.8
500 24.96
1000 25.89
Residual Quantiles
-RMSE: 0.347
-Rsq: 0.941
Goodness of fit
-RMSE: 0.032
-Rsq: 0.989
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]



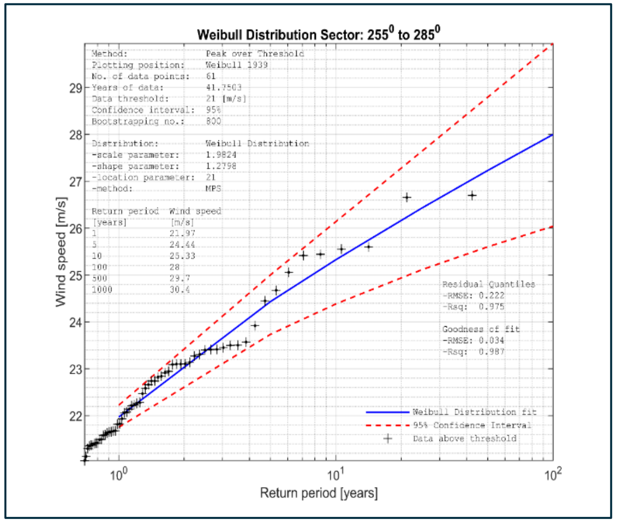
GPD Distribution Sector: 75⁰ to 105⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 96
Years of data: 41.7503
Data threshold: 15 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: 0.13133
-shape parameter: 1.7575
-location parameter: 15
-method: MPS
Return period [years] Wind speed [m/s]
1 16.4
5 18.69
10 19.53
100 21.85
500 23.1
1000 23.56
Residual Quantiles
-RMSE: 0.239
-Rsq: 0.969
Goodness of fit
-RMSE: 0.024
-Rsq: 0.993
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

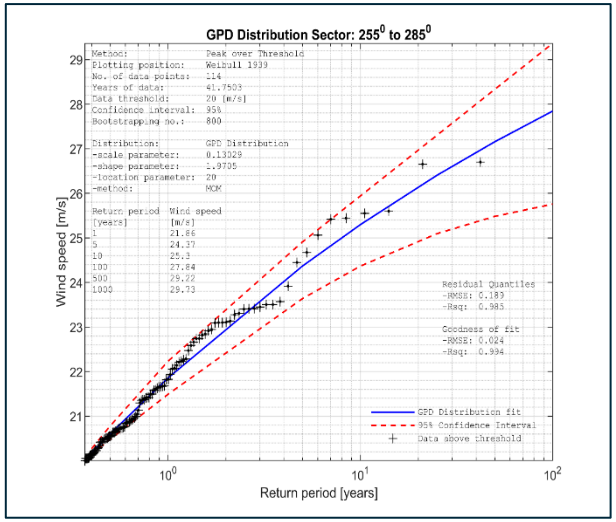


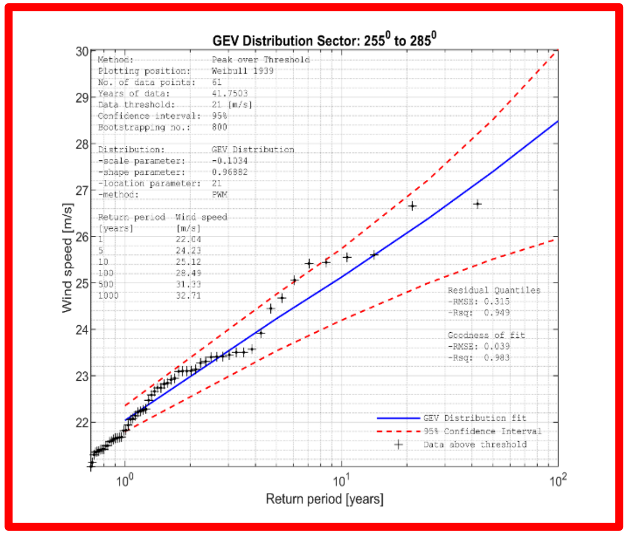
GEV Distribution Sector: 75⁰ to 105⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 96
Years of data: 41.7503
Data threshold: 15 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GEV Distribution
-scale parameter: -0.087233
-shape parameter: 0.94716
-location parameter: 15
-method: PWM
Return period [years] Wind speed [m/s]
1 16.46
5 18.44
10 19.3
100 22.5
500 25.13
1000 26.39
Residual Quantiles
-RMSE: 0.324
-Rsq: 0.942
Goodness of fit
-RMSE: 0.032
-Rsq: 0.988
GEV Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

Royal HaskoningDHV

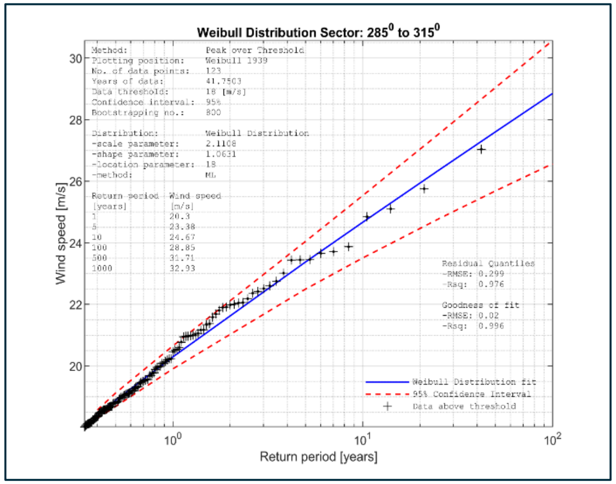
270deg:

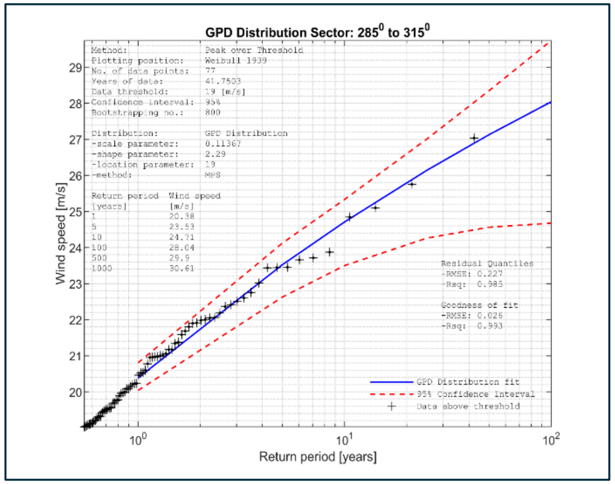


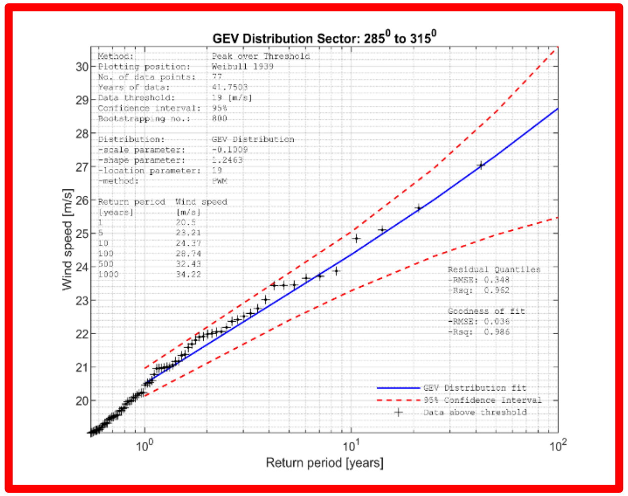




300deg:

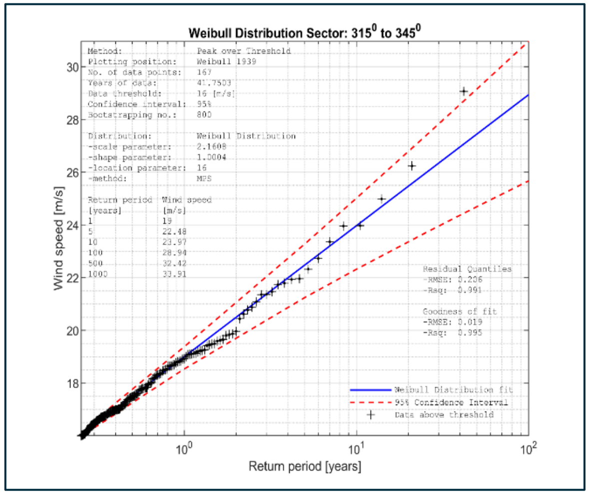


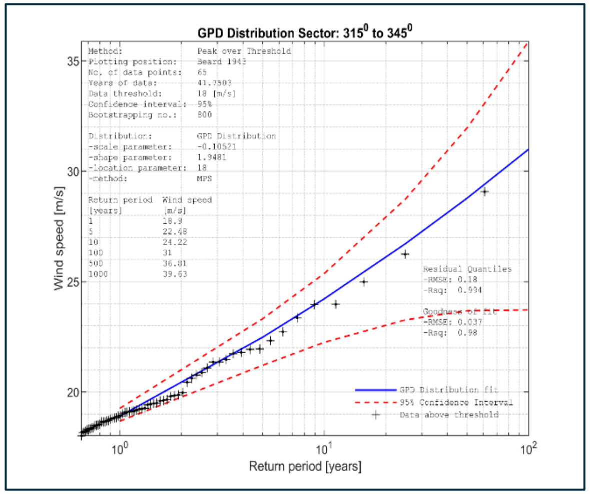


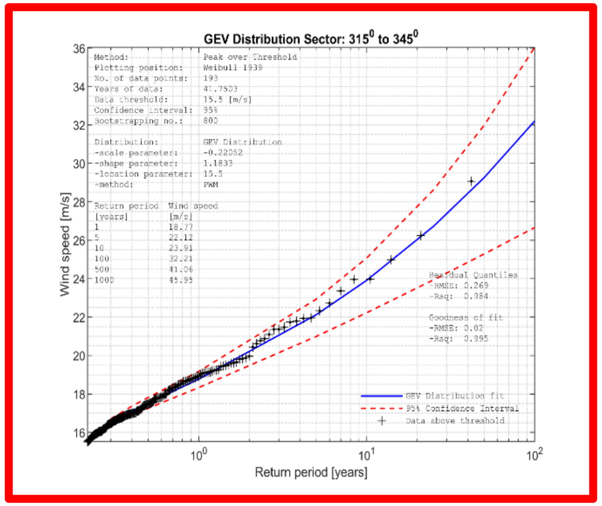


Royal HaskoningDHV

330deg:

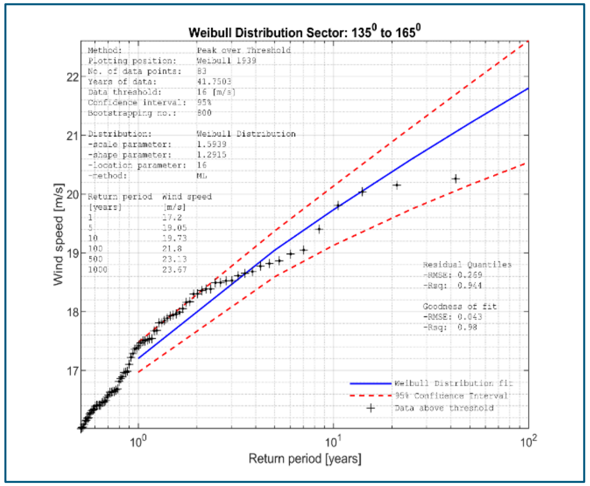


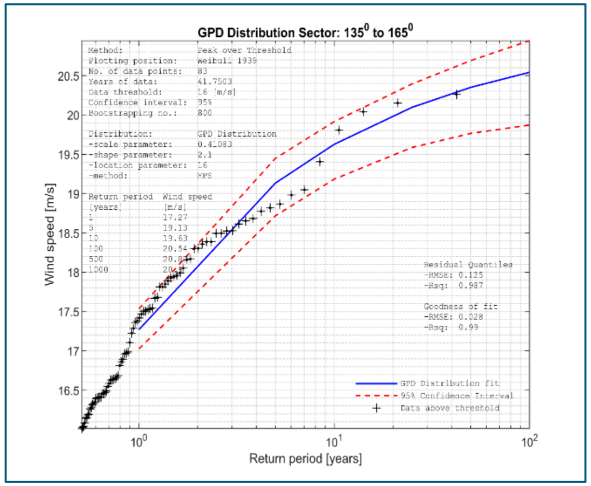


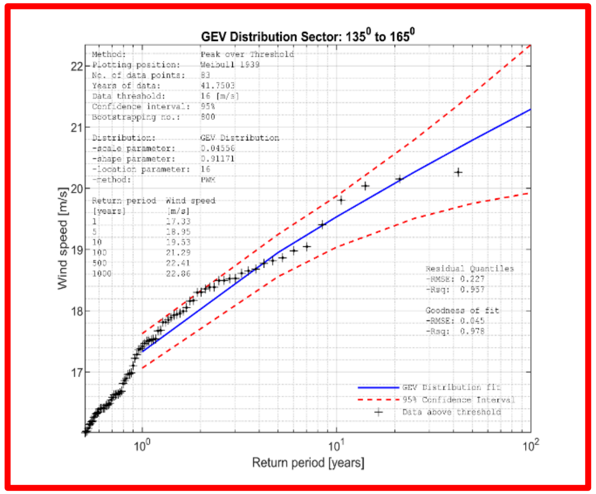


Extreme Wind speed fitting – ERA5 Point 4

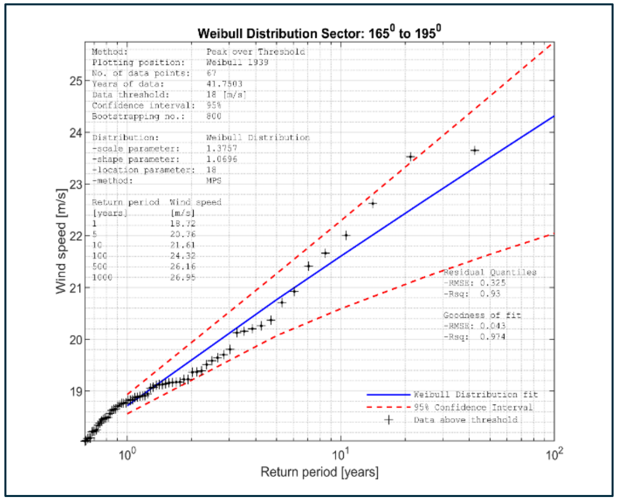
150deg:

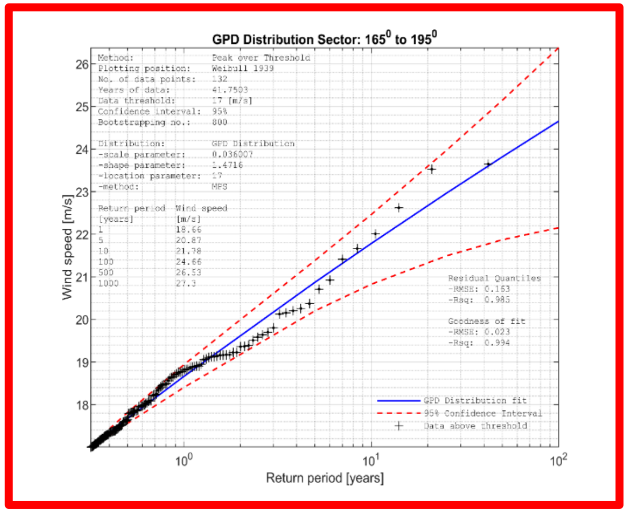


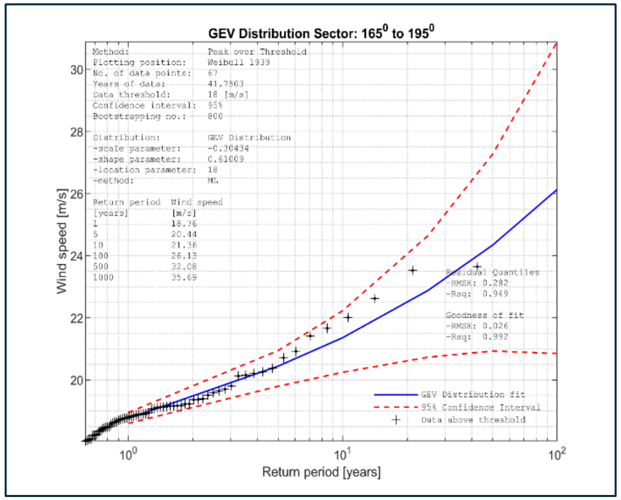




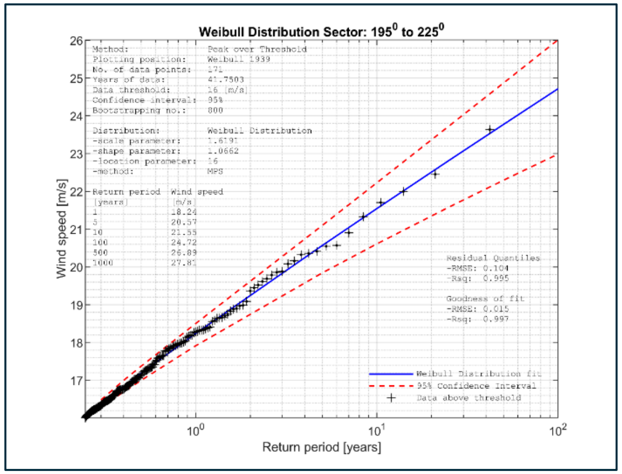
180deg:

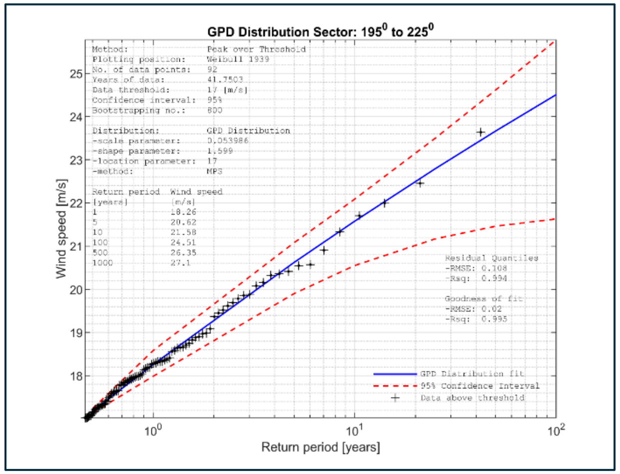


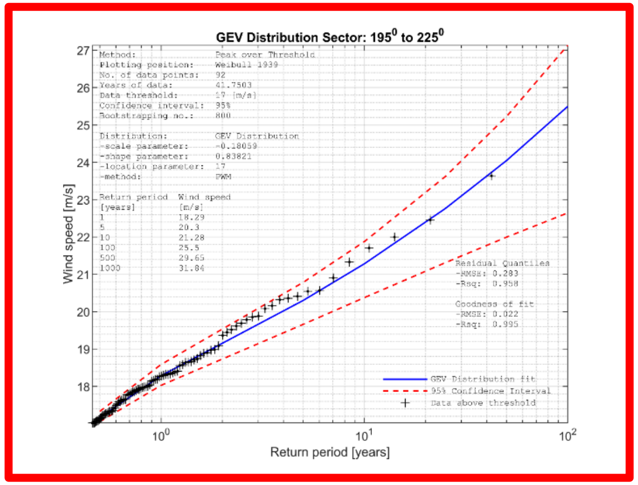




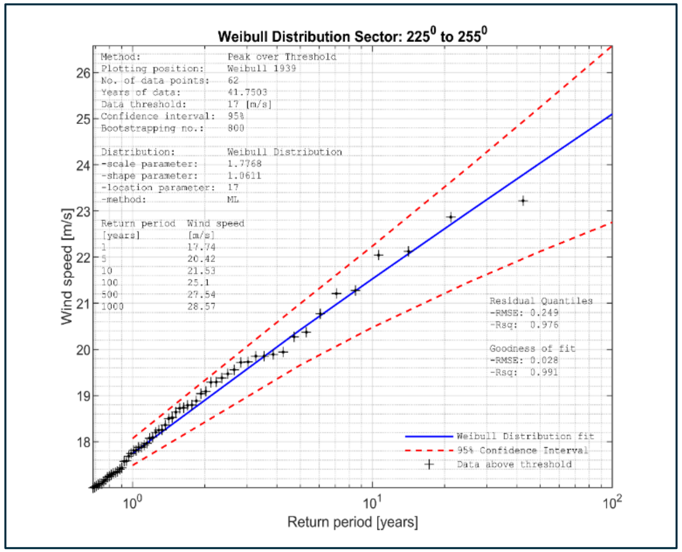
210deg:



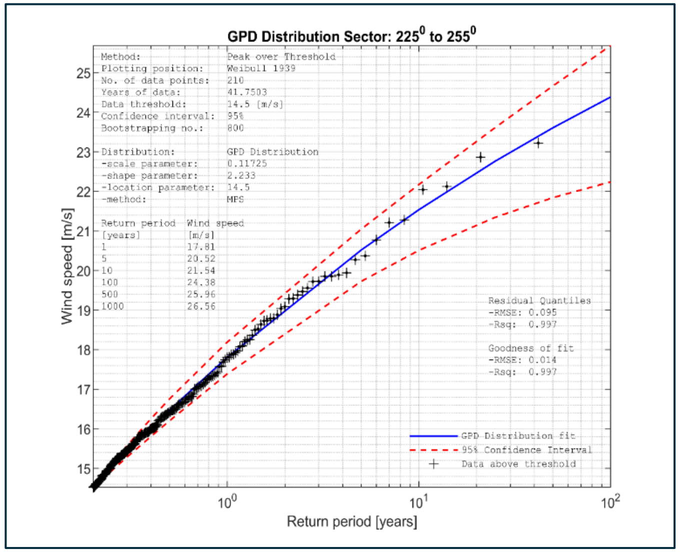




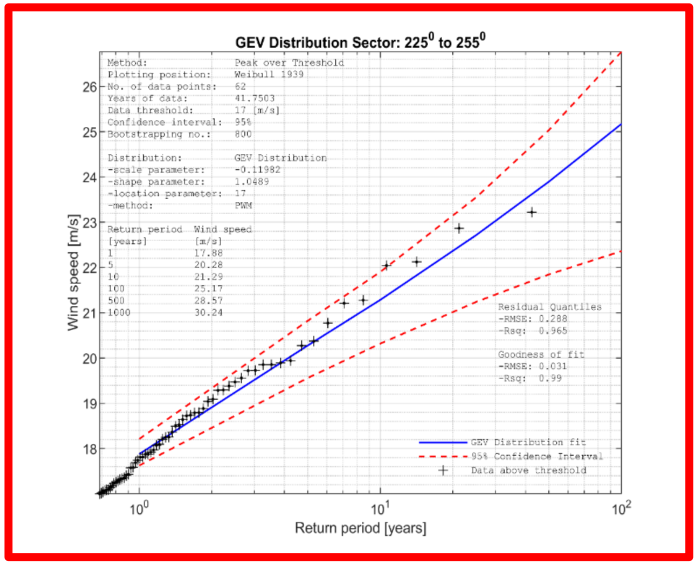
240deg:



Weibull Distribution Sector: 225⁰ to 255⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 62
Years of data: 41.7503
Data threshold: 17 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: Weibull Distribution
-scale parameter: 1.7768
-shape parameter: 1.0611
-location parameter: 17
-method: ML
Return period [years] Wind speed [m/s]
1 17.74
5 20.42
10 21.53
100 25.1
500 27.54
1000 28.57
Residual Quantiles
-RMSE: 0.249
-Rsq: 0.976
Goodness of fit
-RMSE: 0.028
-Rsq: 0.991
Weibull Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]



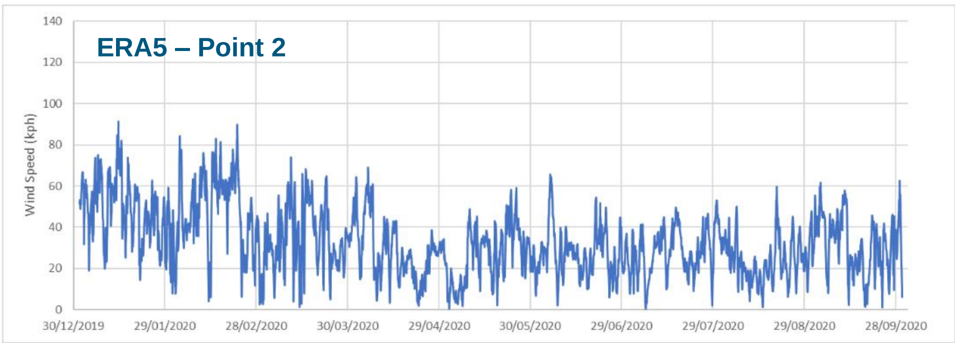
GPD Distribution Sector: 225⁰ to 255⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 210
Years of data: 41.7503
Data threshold: 14.5 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GPD Distribution
-scale parameter: 0.11725
-shape parameter: 2.233
-location parameter: 14.5
-method: MPS
Return period [years] Wind speed [m/s]
1 17.81
5 20.52
10 21.54
100 24.38
500 25.96
1000 26.56
Residual Quantiles
-RMSE: 0.095
-Rsq: 0.997
Goodness of fit
-RMSE: 0.014
-Rsq: 0.997
GPD Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

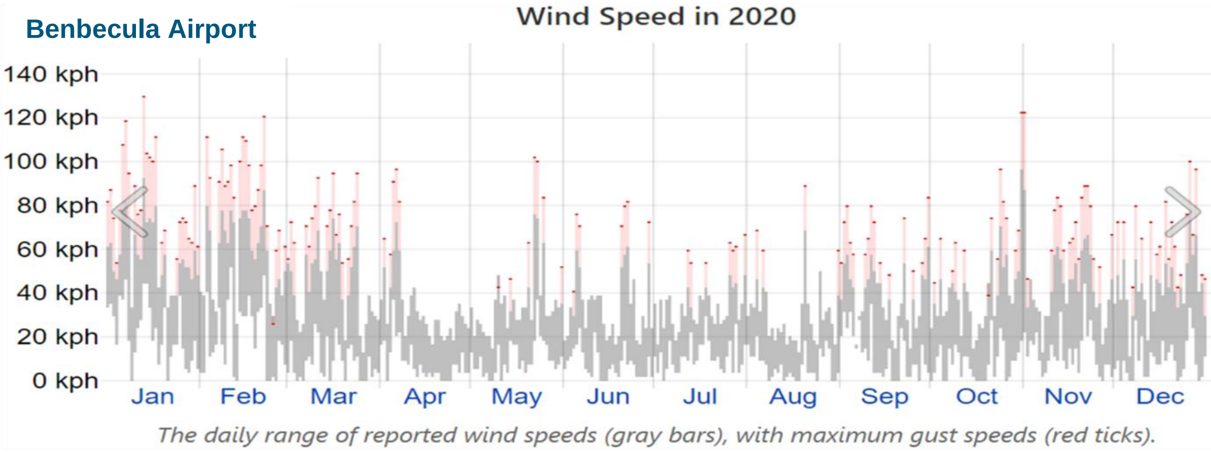


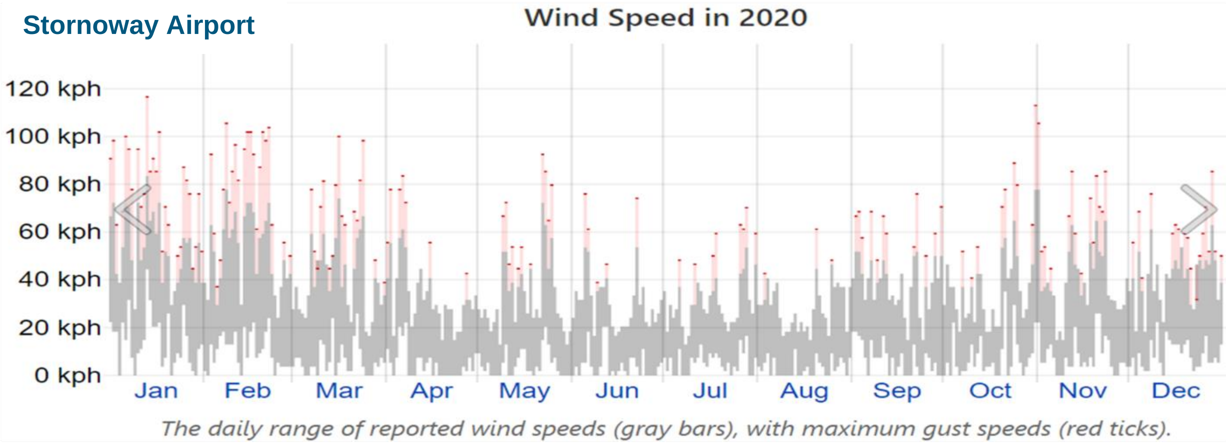
GEV Distribution Sector: 225⁰ to 255⁰
Method: Peak over Threshold
Plotting position: Weibull 1939
No. of data points: 62
Years of data: 41.7503
Data threshold: 17 [m/s]
Confidence interval: 95%
Bootstrapping no.: 800
Distribution: GEV Distribution
-scale parameter: -0.11982
-shape parameter: 1.0489
-location parameter: 17
-method: PWM
Return period [years] Wind speed [m/s]
1 17.88
5 20.28
10 21.29
100 25.17
500 28.57
1000 30.24
Residual Quantiles
-RMSE: 0.288
-Rsq: 0.965
Goodness of fit
-RMSE: 0.031
-Rsq: 0.99
GEV Distribution fit
95% Confidence Interval
Data above threshold
Wind speed [m/s]
Return period [years]

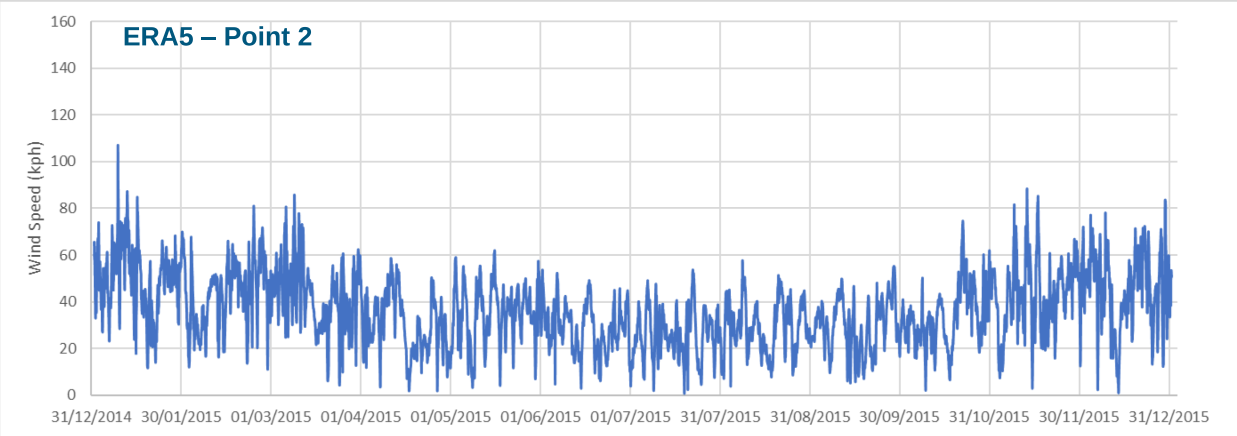
Appendix C – Comparison with measured wind conditions

Plots in this Appendix present comparison between winds speeds from the ERA5 data Point 2 and the measured wind speeds at the Benbecula and Stornaway Airports. The recorded wind speeds at the Benbecula and Stornoway Airports were accessed from WeatherSpark.com. For this comparison selected years with highest wind speeds identified in the ERA5 data were chosen and are presented from latest to oldest. As such the first plots presents comparison for year 2020 and the last plot for year 1989.

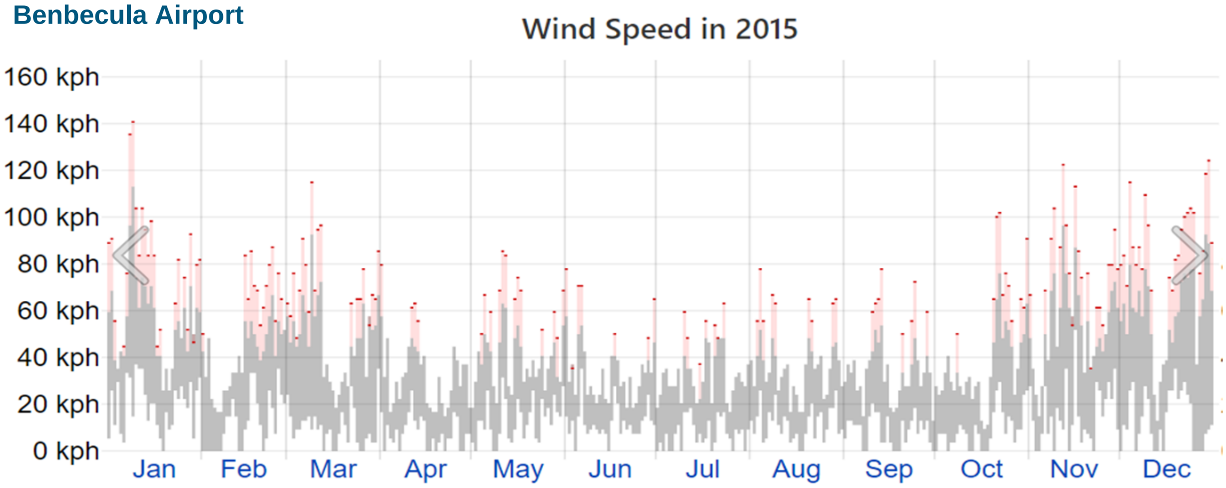






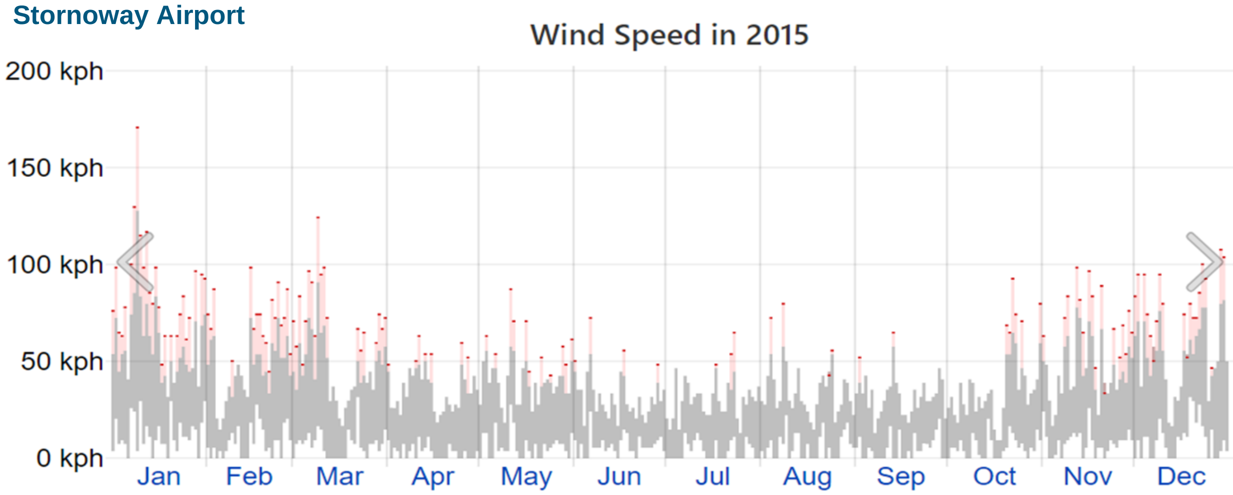


Benbecula Airport

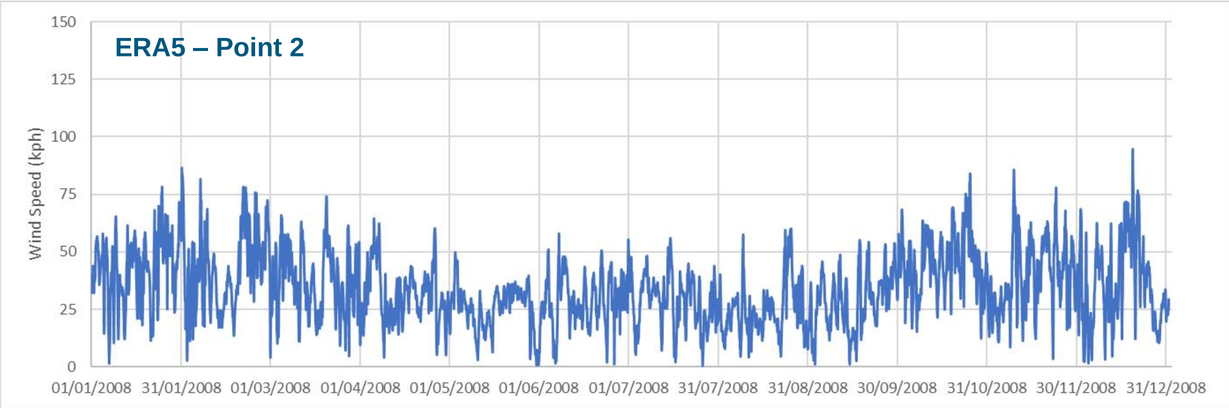


The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

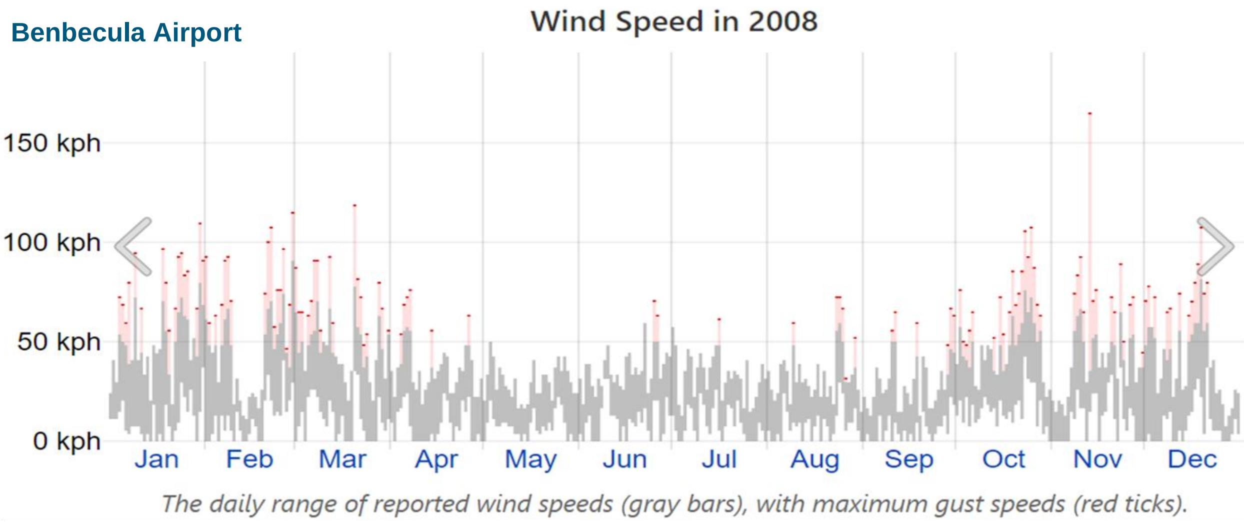
Stornoway Airport



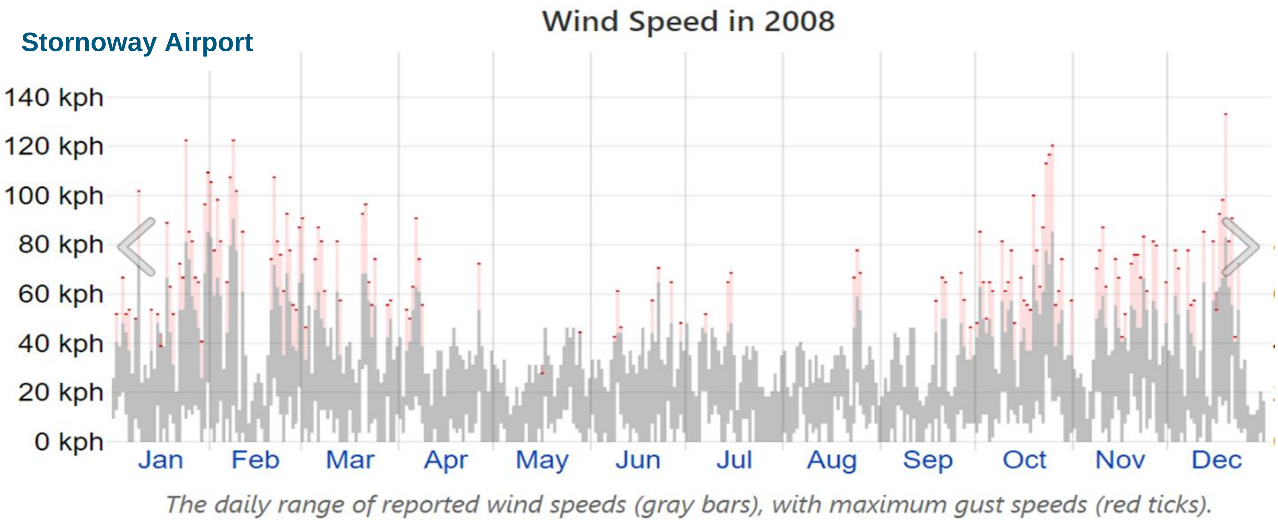
The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

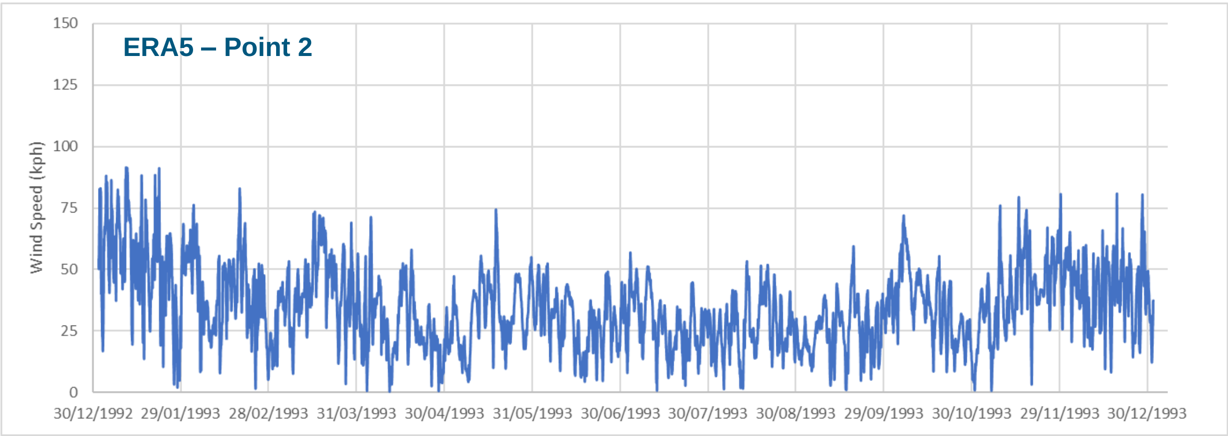


Benbecula Airport

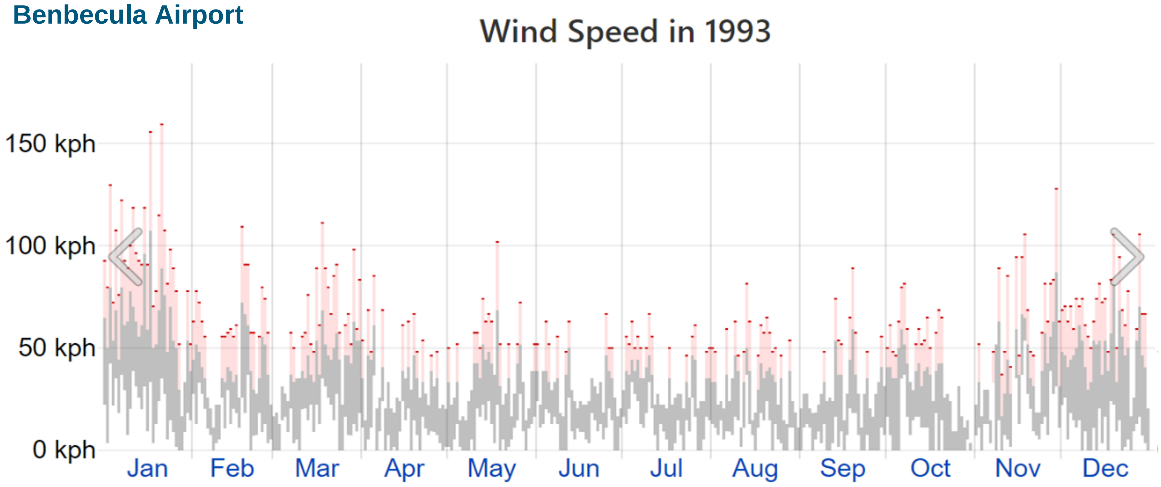


Stornoway Airport



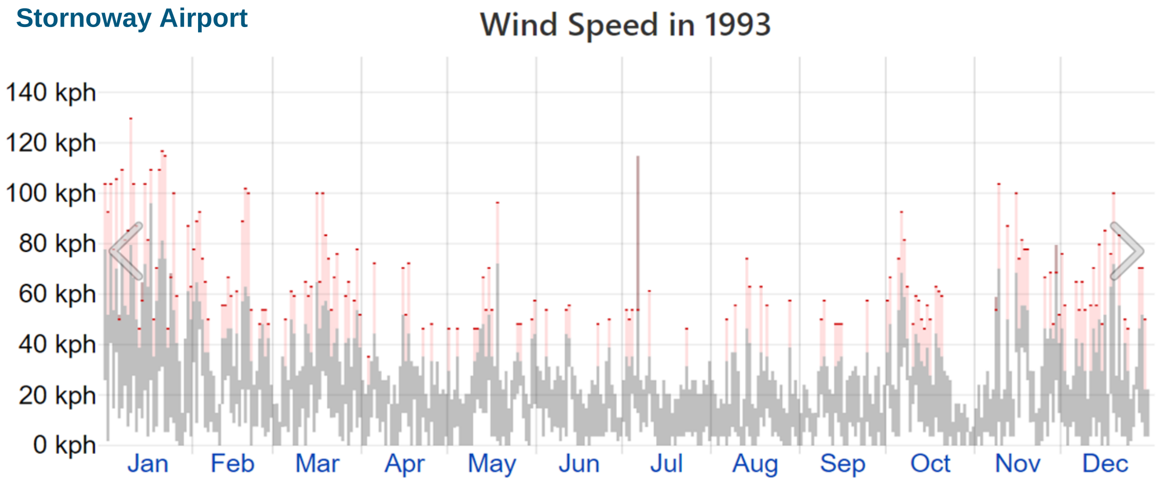


Benbecula Airport

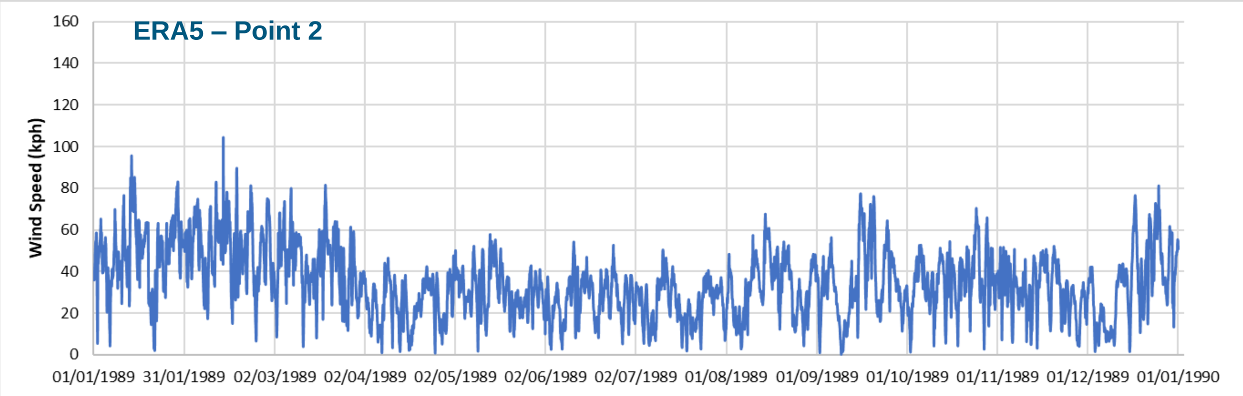


The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

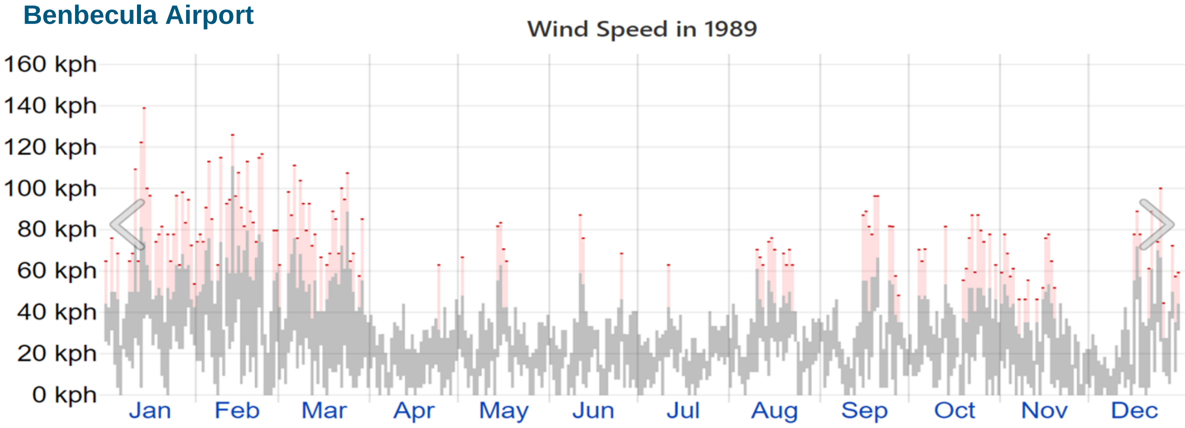
Stornoway Airport



The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

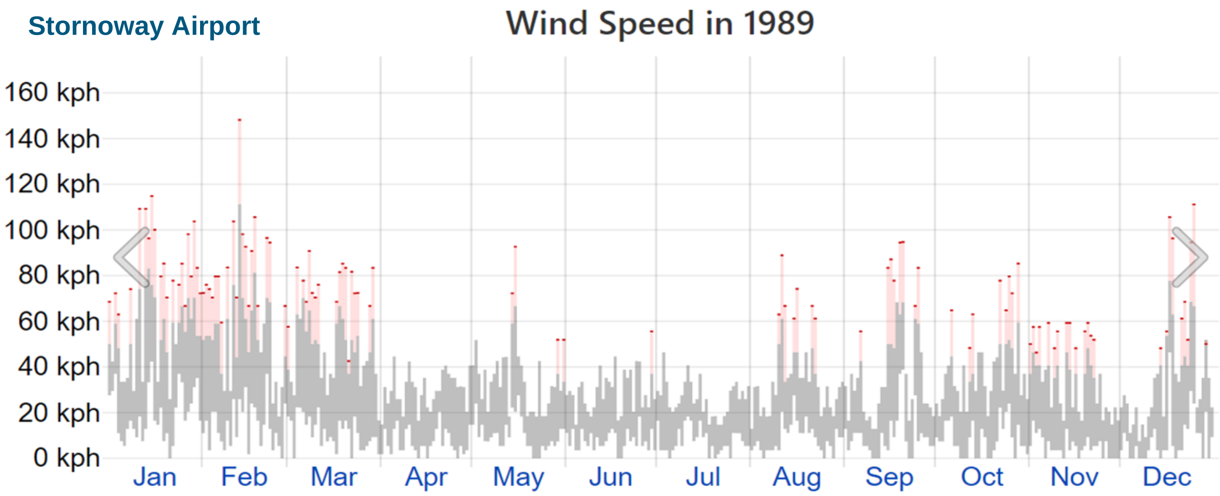


Benbecula Airport



The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

Stornoway Airport



The daily range of reported wind speeds (gray bars), with maximum gust speeds (red ticks).

Appendix D – Contour plots of the wave model results

This Appendix presents contour plots of the wave modelling results for the required return period events (**Figure D-1** to **Figure D-16**). The 1 in 50-year event is presented in **section 7.2** of this report.

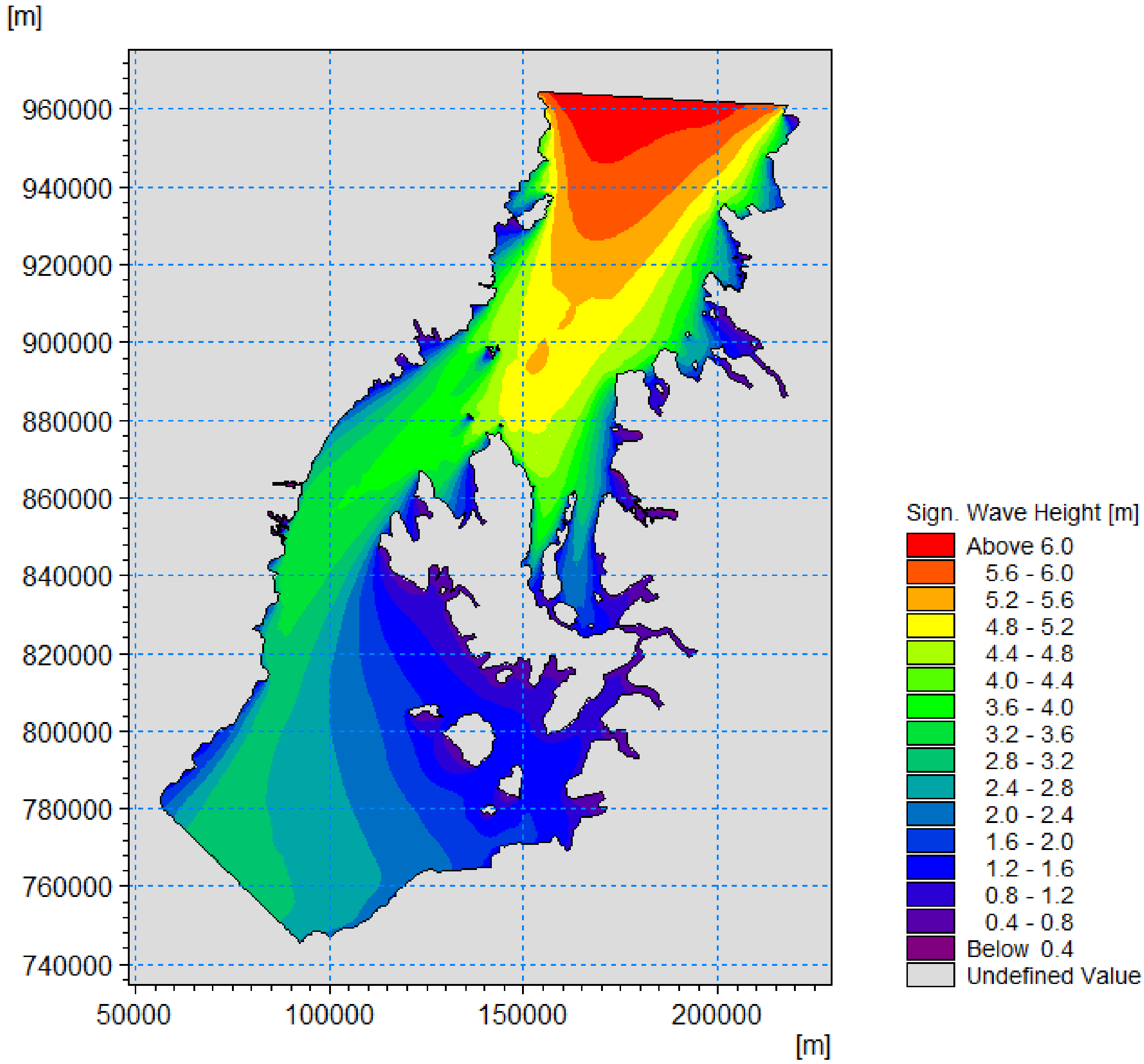


Figure D-1: Contour plot of significant wave height within model Domain 1 – 1 in 1-year return period event

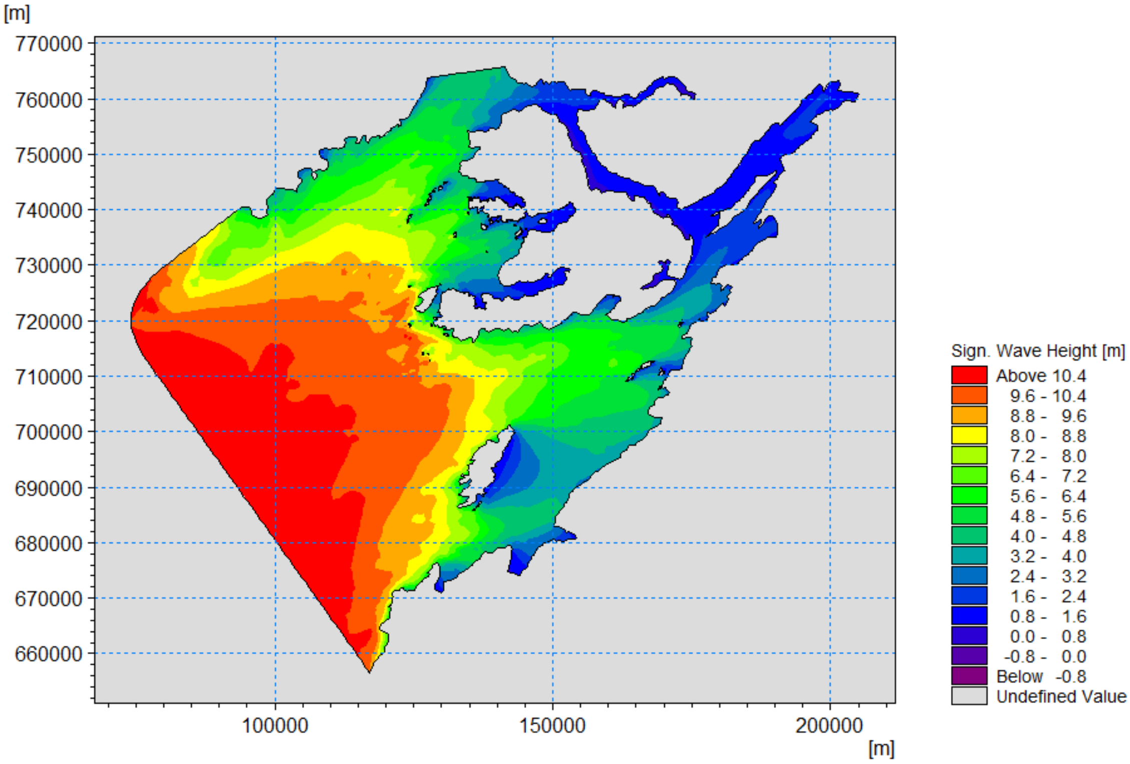


Figure D-2: Contour plot of significant wave height within model Domain 2 – 1 in 1-year return period event

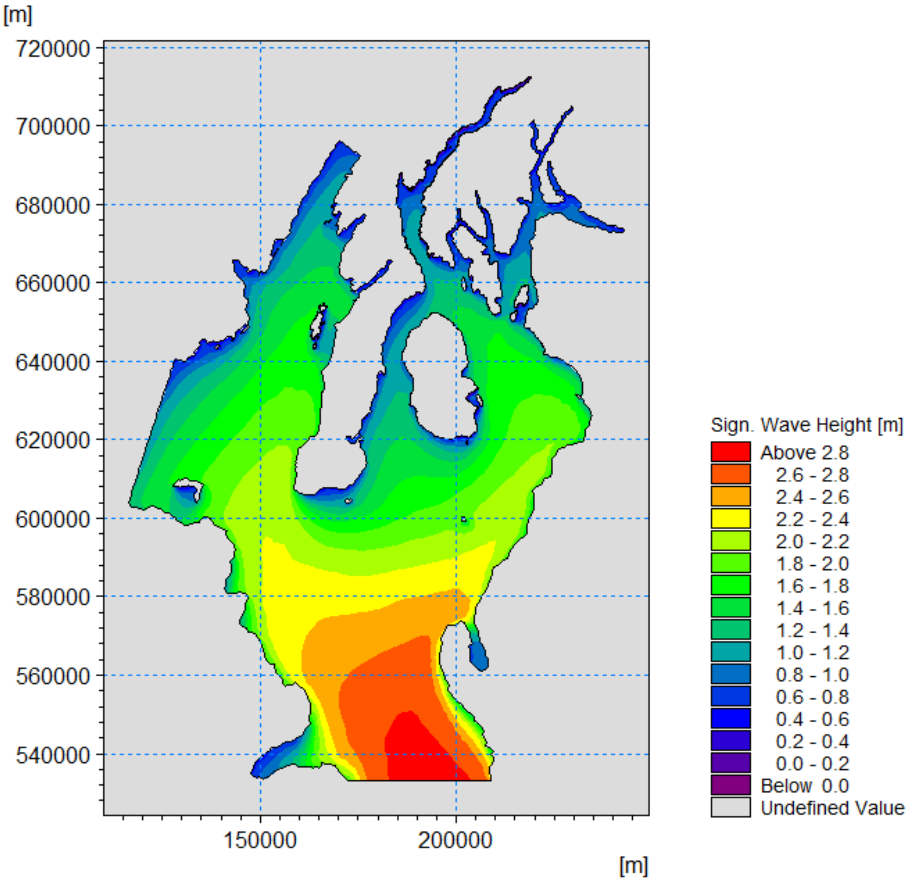


Figure D-3: Contour plot of significant wave height within model Domain 3 – 1 in 1-year return period event

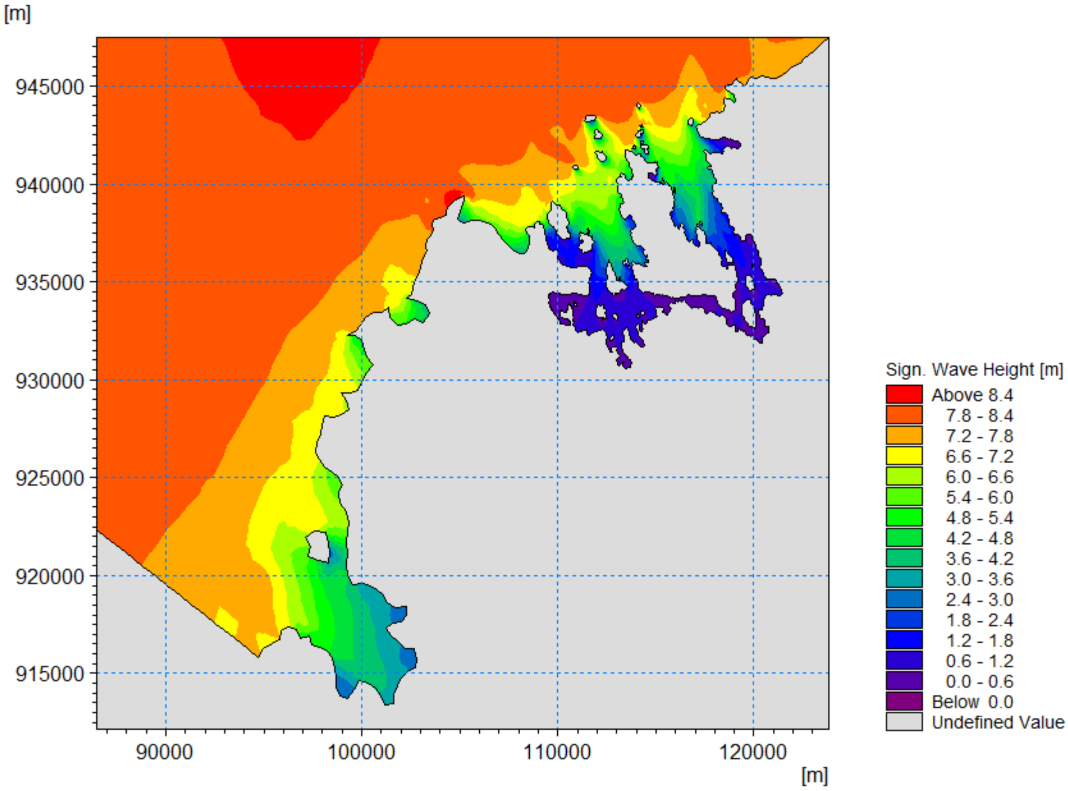


Figure D-4: Contour plot of significant wave height within model Domain 4 – 1 in 1-year return period event

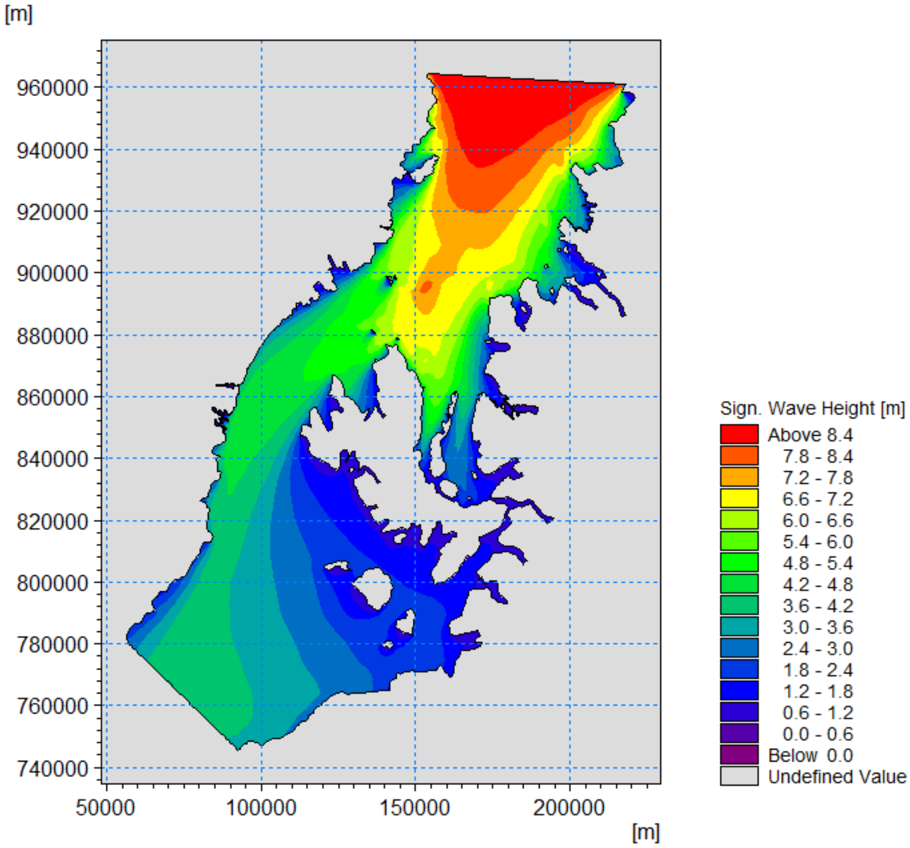


Figure D-5: Contour plot of significant wave height within model Domain 1 – 1 in 10-year return period event

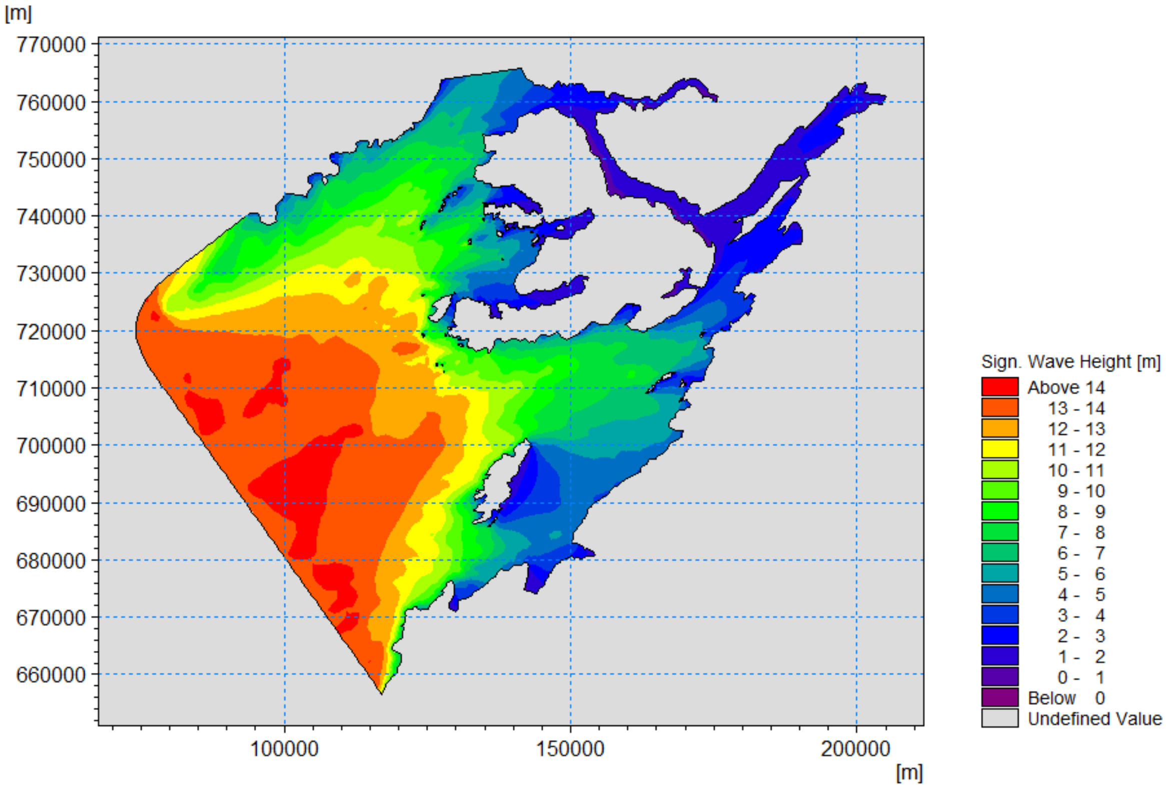


Figure D-6: Contour plot of significant wave height within model Domain 2 – 1 in 10-year return period event

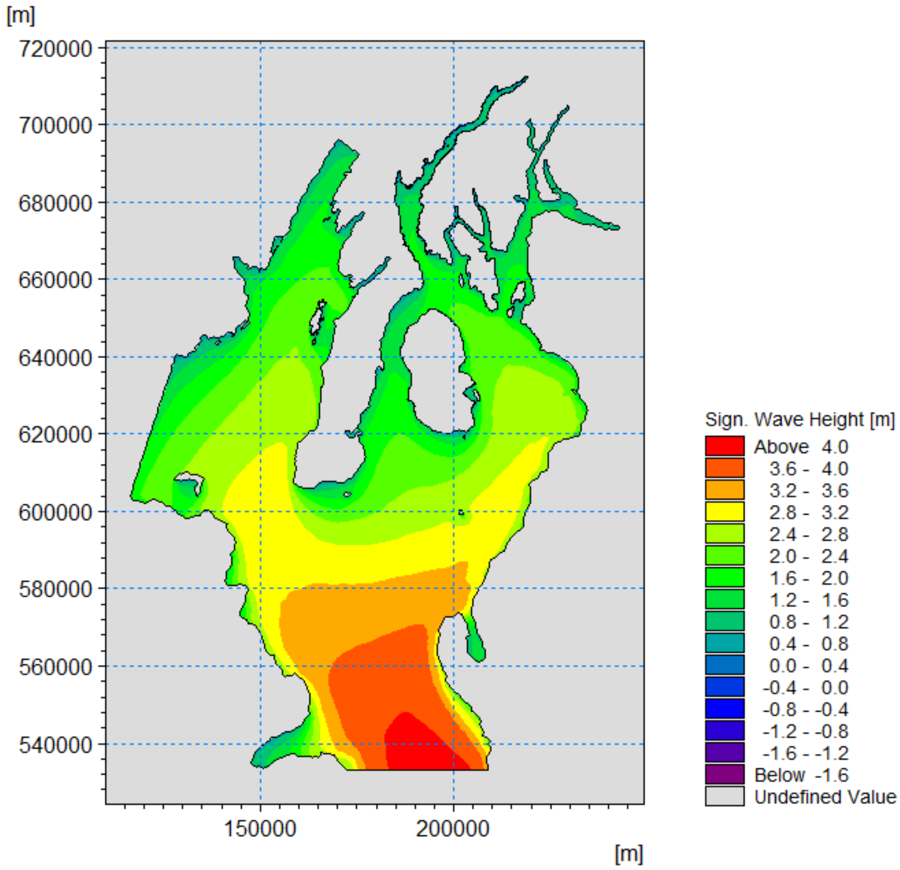


Figure D-7: Contour plot of significant wave height within model Domain 3 – 1 in 10-year return period event

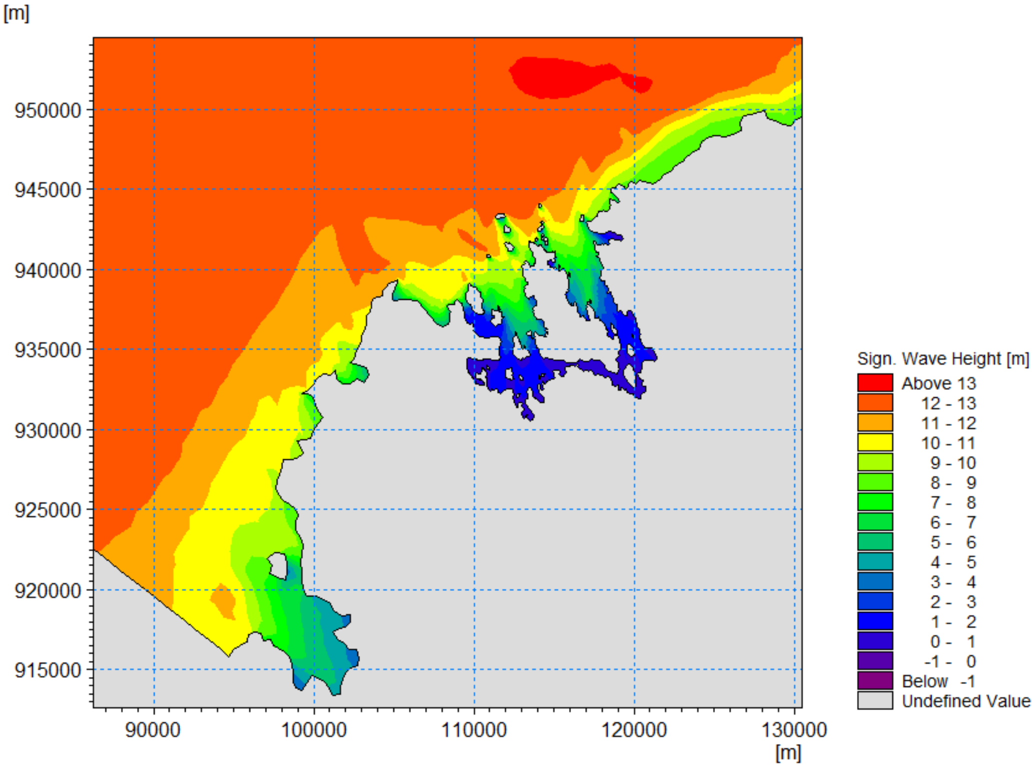


Figure D-8: Contour plot of significant wave height within model Domain 4 – 1 in 10-year return period event

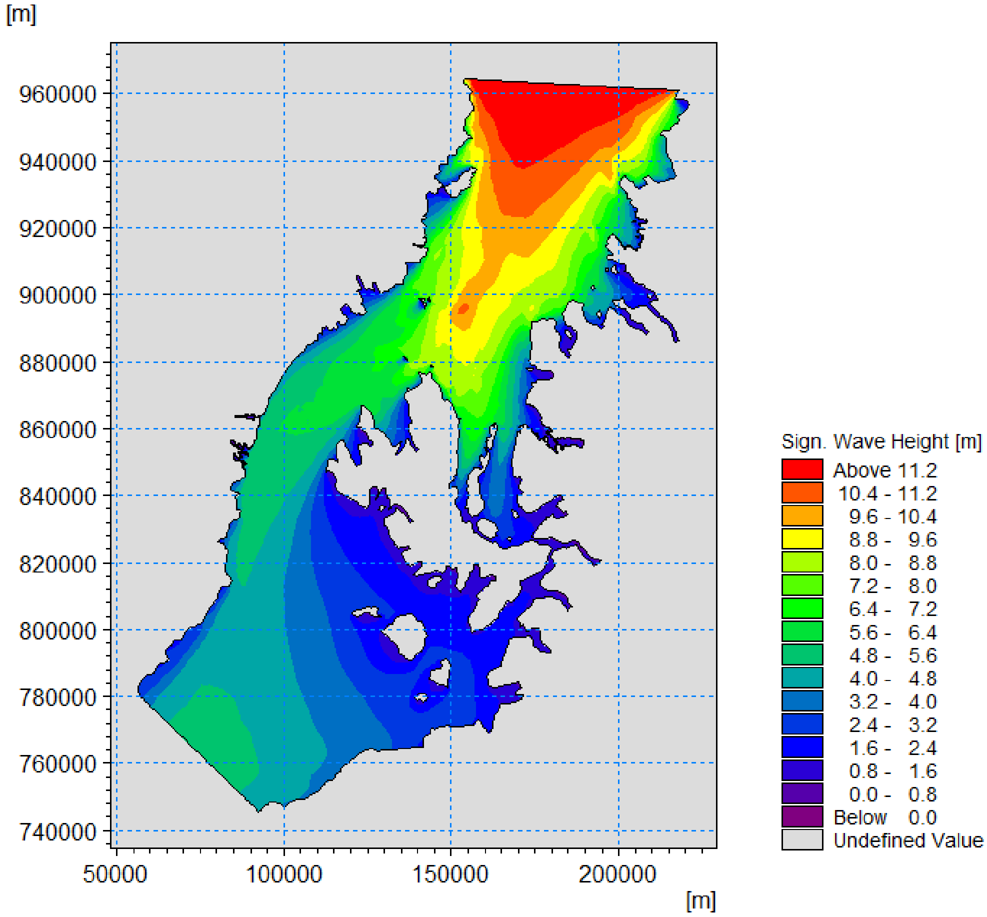


Figure D-9: Contour plot of significant wave height within model Domain 1 – 1 in 100-year return period event

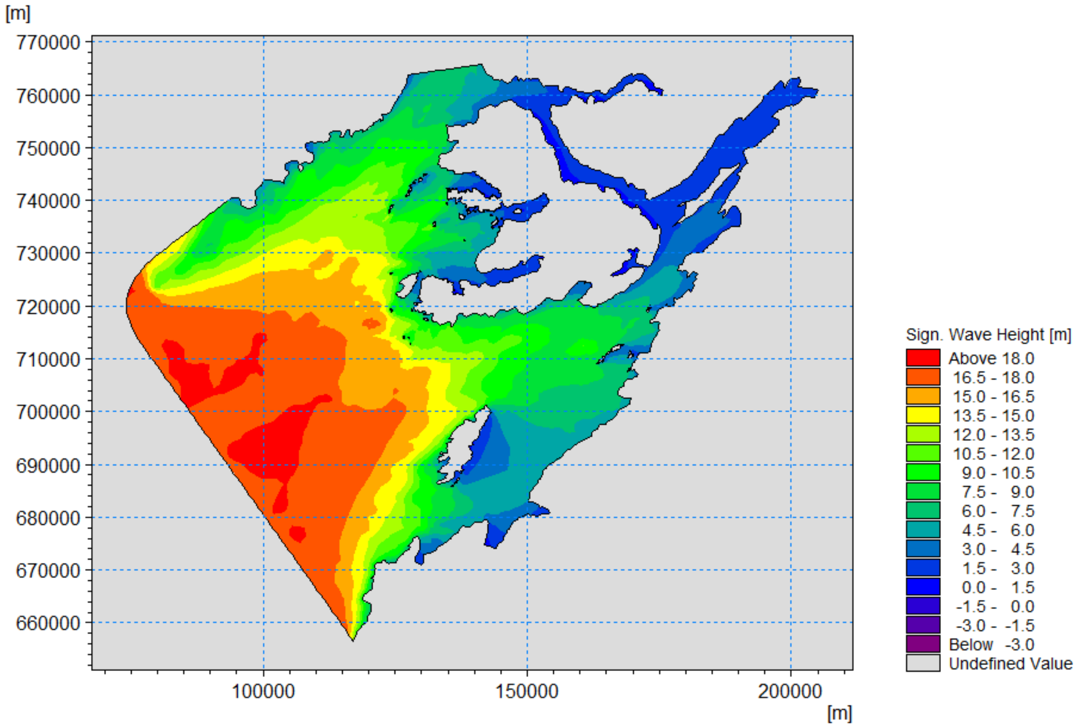


Figure D-10: Contour plot of significant wave height within model Domain 2 – 1 in 100-year return period event

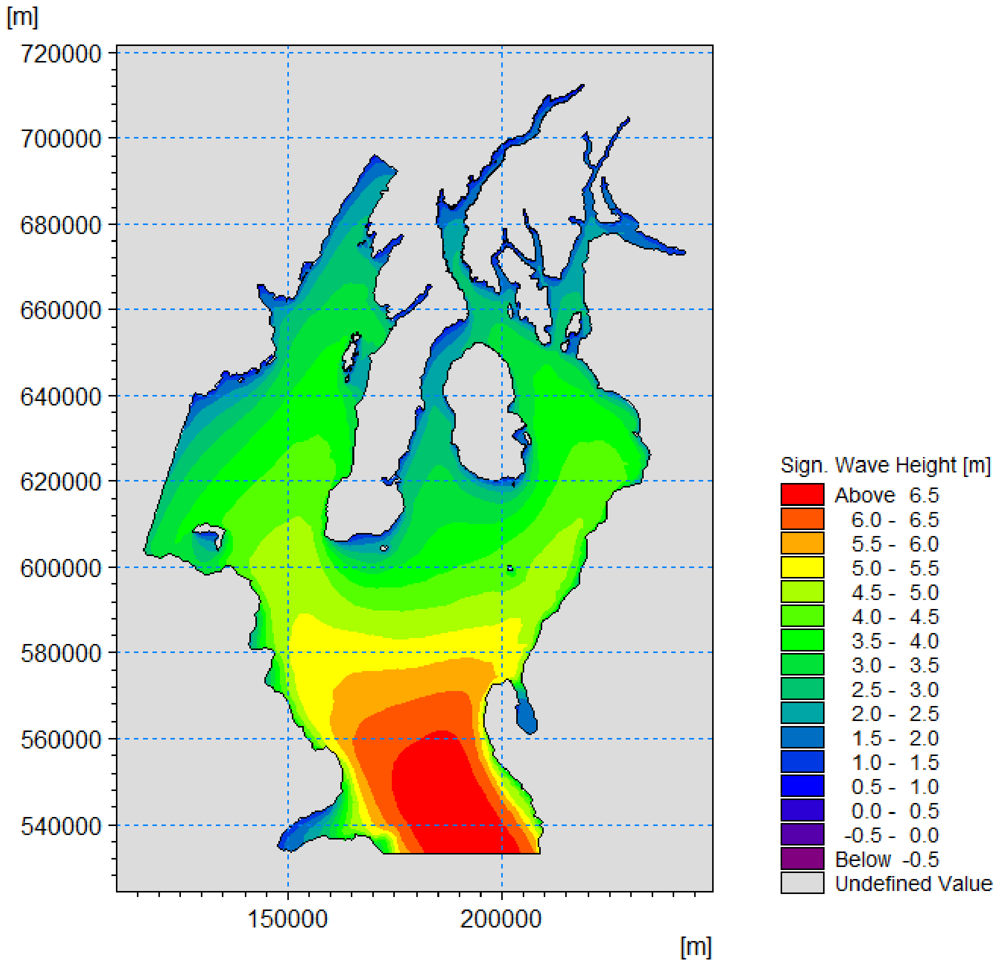


Figure D-11: Contour plot of significant wave height within model Domain 3 – 1 in 100-year return period event

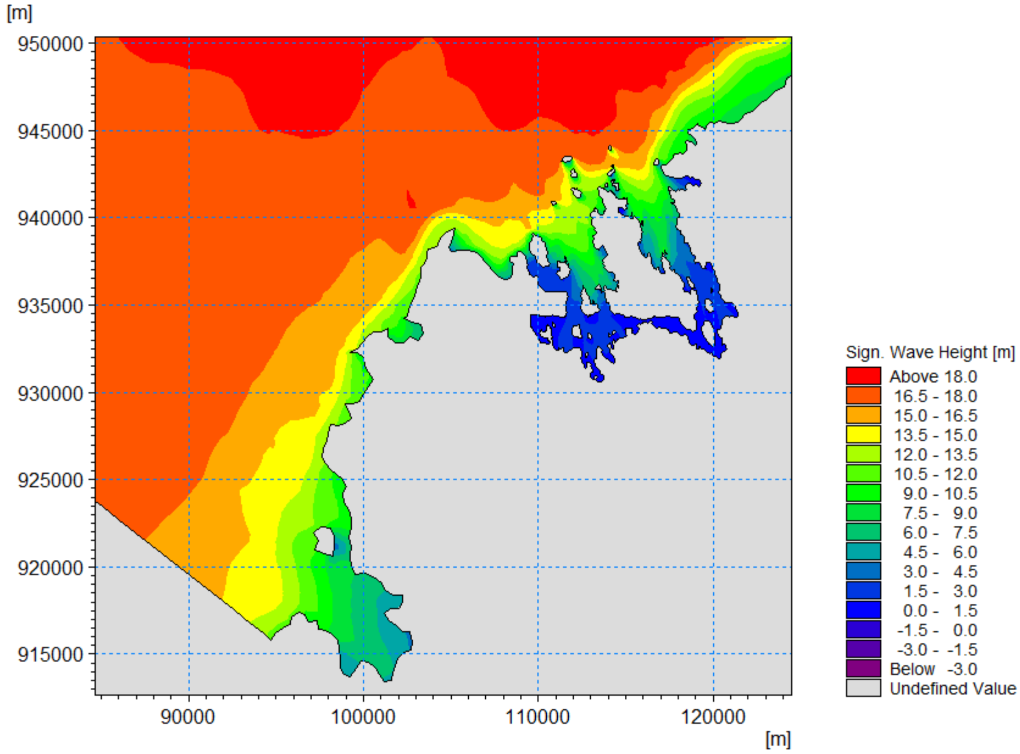


Figure D-12: Contour plot of significant wave height within model Domain 4 – 1 in 100-year return period event

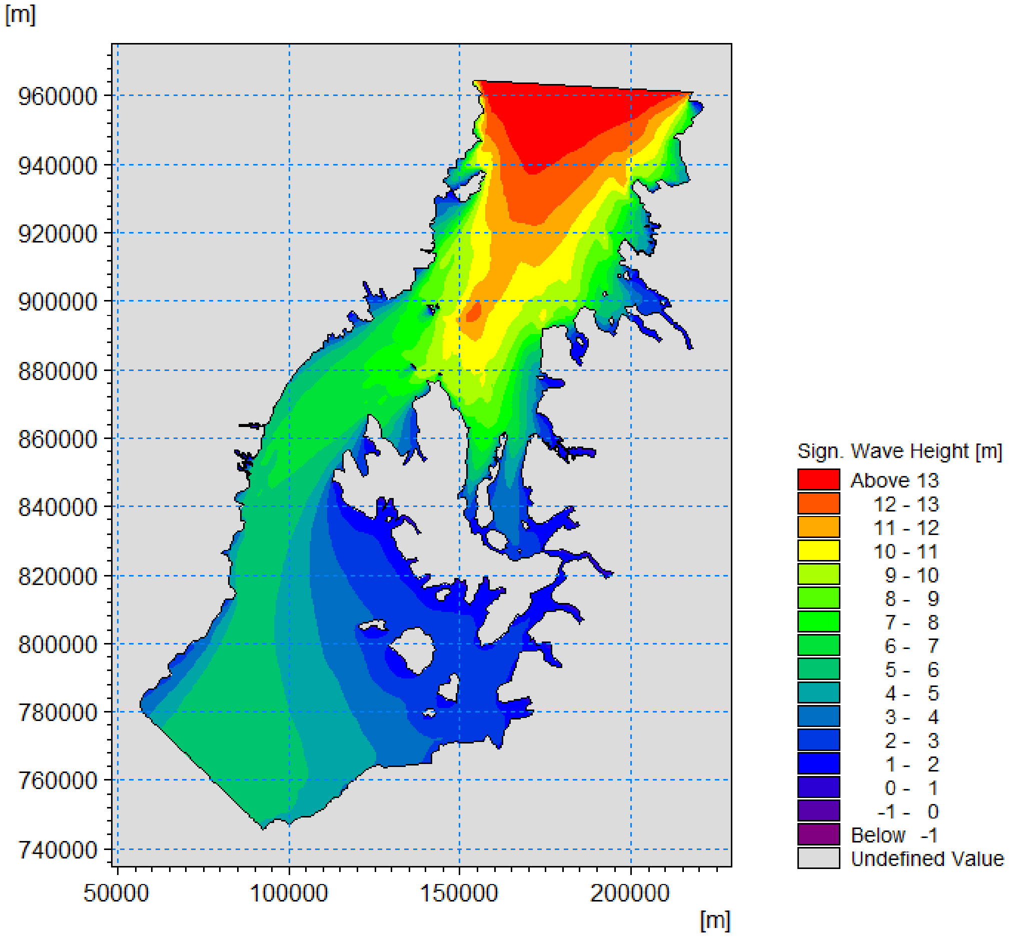


Figure D-13: Contour plot of significant wave height within model Domain 1 – 1 in 500-year return period event

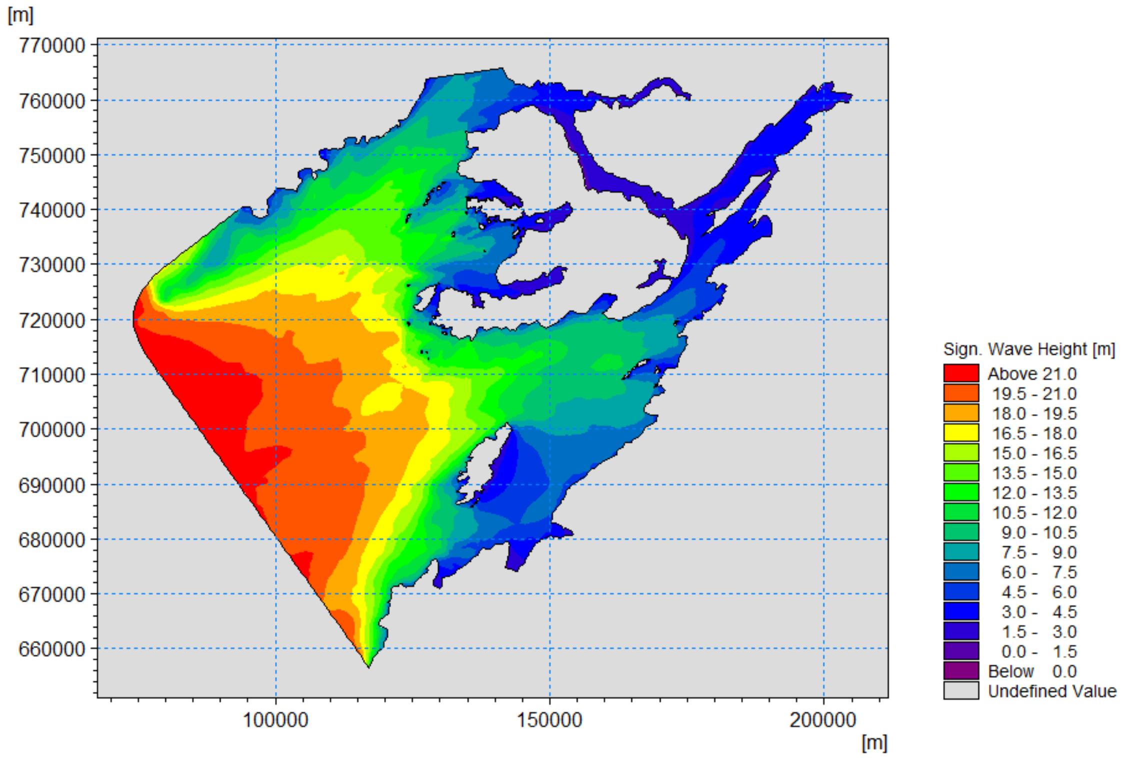


Figure D-14: Contour plot of significant wave height within model Domain 2 – 1 in 500-year return period event

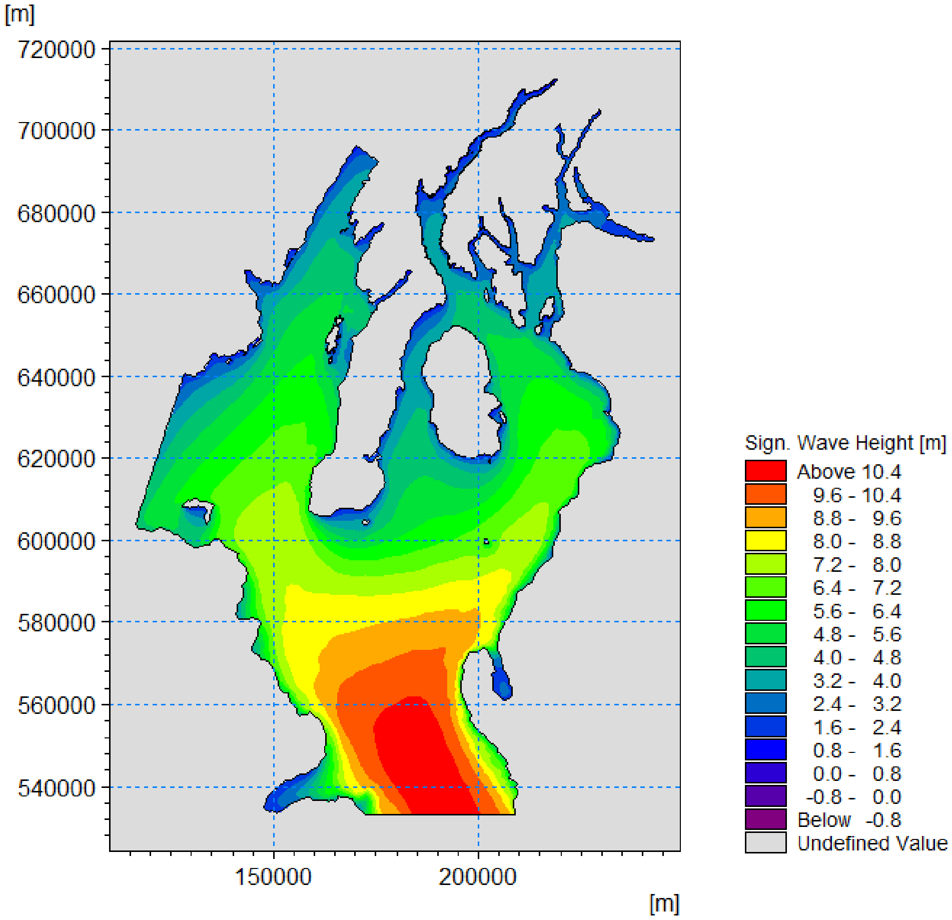


Figure D-15: Contour plot of significant wave height within model Domain 3 – 1 in 500-year return period event

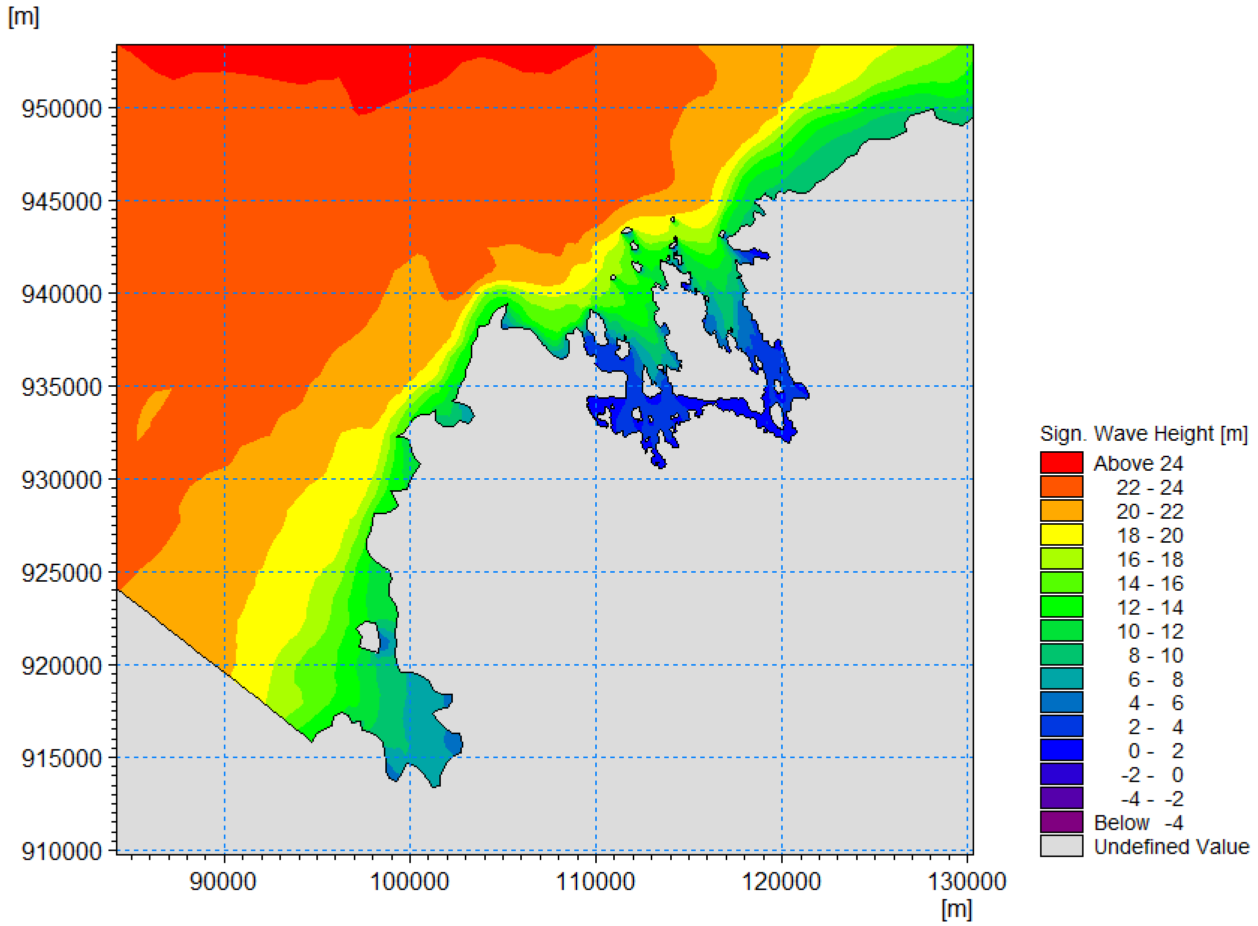


Figure D-16: Contour plot of significant wave height within model Domain 4 – 1 in 500-year return period event