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Logo of “**Dobrogea-Litoral Constanta Water Basin Administration**”

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Study on the modelling of wave transformation

DOCUMENT NO.: **64210030-EBD-ENG-RE-004**

DOCUMENT NAME: **Coastal erosion reduction Phase II (2014-2020) Lot 2 – Mamaia Area**
PROJECT NO.: **64210030**

CLIENT NAME: **“Dobrogea Litoral” Water Basin Administration**

Logo of "**Dobrogea-Litoral Constanta Water Basin Administration**"

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Change log

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1.0	All	Initial transmission

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1. INTRODUCTION

1.1. Project background

The Romanian coastline along the Black Sea is subject to erosion. Coastal erosion contributes to the loss of particularly valuable land, losses that can affect coastal ecosystems and generate economic and social damage to such an area. Therefore, the „Dobrogea Litoral” Water Basin Administration (ABADL) within the National Administration of Romanian Waters (ANAR) defines the Masterplan "Protection and rehabilitation of the coastal zone". The Mamaia area (Lot 2) is one of the 11 lots identified as part of Phase II Coastal Erosion Reduction (2014-2020) within this Masterplan.

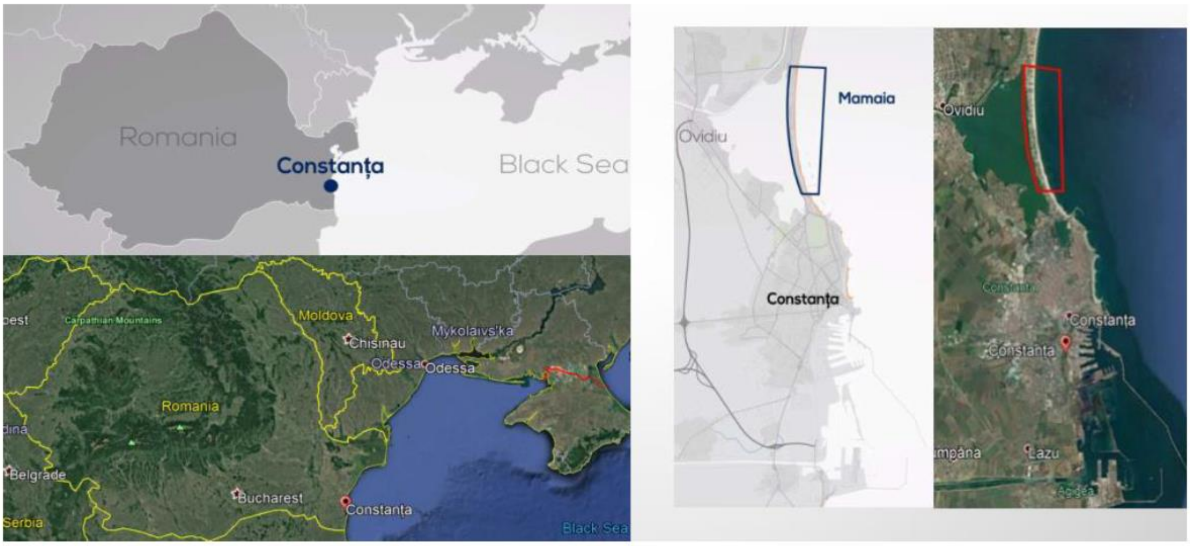


Figure 1.1 – Project location

The main objective of this project is to protect and rehabilitate the Romanian coastal area and environmental factors, through engineering works to combat the phenomenon of coastal erosion, supporting the revival of the marine ecosystem and the development of some species that, at a given moment, had disappeared from the ecosystem, protecting marine biodiversity and the littoral zone and the sustainable development of the coastal zone, respectively.

The works are financed by means of the Cohesion Fund of the European Union - Large Infrastructure Operational Program (POIM) 2014-2020.

1.2. Activity field

The project area is located between the ports of Constanța and Midia, delimited by the location of the Arcadia restaurant in the north, and in by the dike perpendicular to the Mamaia Sud shoreline the south.
The activity field consists in the design and construction of the following elements:

- Removal of coastal marine structures MM5, MM6 and MM7
- Extension of the RJ1 coastal structure by 65m
- Removal of the pedestrian pier made of concrete
- Widening of the beach north of the coastal structure RJ1 on a length of 6,950m, to create a beach with a width of 100m
- Temporary works

Similarly, in accordance with the urban planning certificates, the necessary documentation will be prepared to obtain the relevant permits.

1.3. Scope of the document

A Design Basis must be prepared for the design and construction of the works as part of the detailed design phase of the project. The scope of this study on the modelling of wave transformation involves the analysis of the Metocean conditions for the Mamaia shoreline, which will provide information for the Design Basis. The study on the modelling of wave transformation is being conducted for the „Coastal erosion reduction Phase II (2014-2020) Lot 2 – Mamaia Area” project to determine the nearshore operational conditions, projected water levels and projected wave conditions.

The report summarizes the methodology used to analyse Metocean conditions in Chapter 2, and thereafter offshore wave and wind conditions and water levels are discussed in Chapters 3 and 4. Analysis of Extreme Values (AVE) is covered in Chapter 5. AVE is performed for wind speed and wave height variables. For the wave height variable, the wave crest period and associated wind speed are determined. The projected water levels are determined from specialized literature. The setup of the wave transformation model and the transformation from offshore to nearshore, is described in chapter 6 and finally, the results are presented in chapter 7. Conclusions are presented in chapter 8.

2. METHODOLOGY

2.1. Approach

2.1.1. Waves

The operational and design wave conditions will be transformed from offshore to nearshore conditions. The offshore wave climate is acquired from Infoplaza Marine Weather BV [1] with the location 44.0°N, 29.5°E, see figure 3.3. A SWAN (Simulation of Waves Nearshore) spectral wave model was created to transform offshore wave conditions to nearshore wave conditions using bathymetry consisting of digitized marine charts and survey data.

SWAN is a state-of-the-art wave model developed by Delft University of Technology, and it is widely used in the engineering industry to determine designed wave conditions. The model includes the processes of wave propagation, refraction, shoaling due to spatial variations of the seabed and current, wave transmission and reflection from obstacles, wave dissipation by white-capping, depth-induced breaking and friction with the bottom of the sea. This model was verified using results from both field measurements and physical model testing [2].

To determine the design conditions for the Mamaia area, an analysis of extreme values (AVE) is carried out. AVE is performed on offshore wave data to determine offshore design conditions. The offshore design conditions are then transformed to the shoreline with the wave model. Coastal structures will be included in the numerical models. The approach is in accordance with the methodology proposed in the Contractor Proposal 38[A.1].

2.1.2. Wave levels

Local design water levels during storm conditions are determined from the literature. Bondar [3] has conducted extensive research which is used to obtain water levels and various components. Local measurements from Port Constanța were used to validate the water levels obtained by Bondar.

2.2. Contractual requirements

An overview of the Beneficiary's main requirements relevant to this Study on the Modelling of Wave Transformation is presented in this paragraph [A.1]:

- The offshore wind and wave dataset covers at least a 33-year time period;
- The calibrated offshore wind and wave data set includes the most recent events;
- Data are available at a time interval of 1 hour;
- Data were processed in directional collection tanks to at least 30 degrees;
- All sound and water level data will be reduced to the reference local geodetic elevation, respectively the mean level of the Black Sea in 1975 (MN75);
- Design conditions with a return period between 1 and 100 years at the dike, as information for coastal protection works;
- In the design activities, the Contractor must consider 3.3 mm/year for sea level rise, resulting in a sea level rise of 0.165 m for a 50-year lifetime.

3. DATA ANALYSIS

3.1. Specialty informational material

Various Metocean papers and studies are used as reference and to provide information for this Study on wave transformation. The following specialty informational materials are used.

Previous wave modelling studies performed in the same region:

- Halcrow's wave transformation study [4];
- The feasibility study carried out by ROMAIR in association with Arcadis [5];

Papers on Metocean conditions along the Romanian coast:

- Study on the variation of the water level in the Black Sea carried out by Bondar [3];
- Spectral partitioning and surge in the Black Sea by Van Vledder [6] used to verify the settings used in the undulatory model.

3.2. Bathymetry

Bathymetric data is a key component of a undulatory model, as the wave transformation process is dependent on water depth. Two sources of bathymetric data were available. The bathymetry of this model consists of a combination of digitized marine charts and raw data from measurements [B.1]. Figure 3.1 shows the bathymetric data used for the undulatory model.

All horizontal coordinates refer to the UTM 35N zone. All vertical levels are relative to the local MN75 system.

Figure 3.1: Bathymetric data used for the wave model. Research data obtained (left) and samples from digitized marine charts (right)

3.3. Data regarding measurements

Nearshore wave data were measured off the coast of Mamaia as part of the JICA (2007) study. The measurement data recorded from the JICA wave measuring device was provided by the Client. The location of the presented measuring device has the coordinates UTM35N 632088m E 4902263m N at a water depth of approximately 11m. The measuring device measured data over three periods of different durations:

- 17 March 2006 – 27 May 2006;
- 16 October 2006 – 9 January 2007;
- 2 April 2007 – 5 November 2010.

The time intervals of the measured significant wave height (Hs), significant wave duration ($T_{1/3}$) and mean wave direction are shown in Figure 3.2. For a comparison between wave durations, the observed significant wave duration ($T_{1/3}$) was converted to peak-wave duration (Tp), which is calculated in the model using the relationship Tp = 1,075 * T1 / 3 from [7].

The average wave direction measurements on the JICA website are questionable, as they show that the waves generally come from a fairly narrow band, where the offshore wave / wind data shows otherwise. There are periods during the observational dates, where the wave direction clearly shows problematic values, especially the large waves directed offshore between September 2008 and March 2009. This is also confirmed by the Halcrow wave transformation study, which observes the same phenomenon [4]. Therefore, the undulatory model will be calibrated and validated for the parameters of significant wave height and peak-wave duration, while wave direction will be removed.

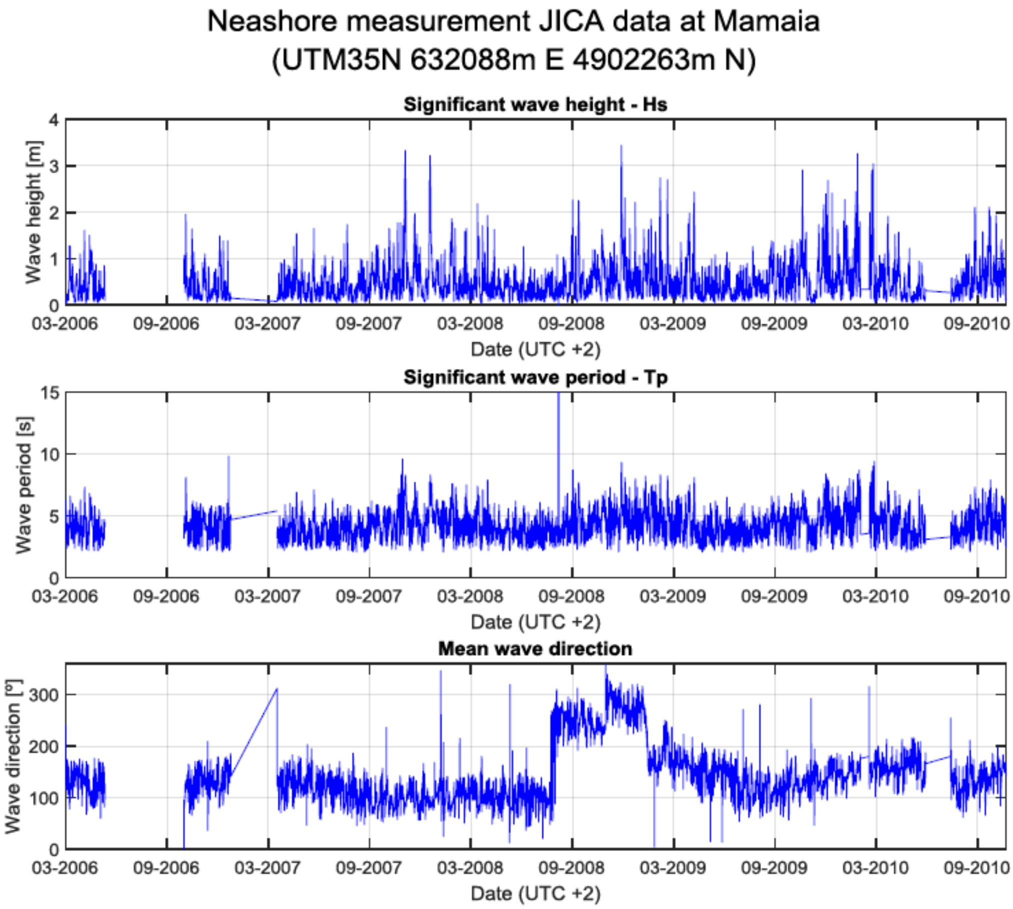


Figure 3.2: Available measurement data with variables for significant wave height, significant wave duration and mean wave direction from the JICA study in Mamaia

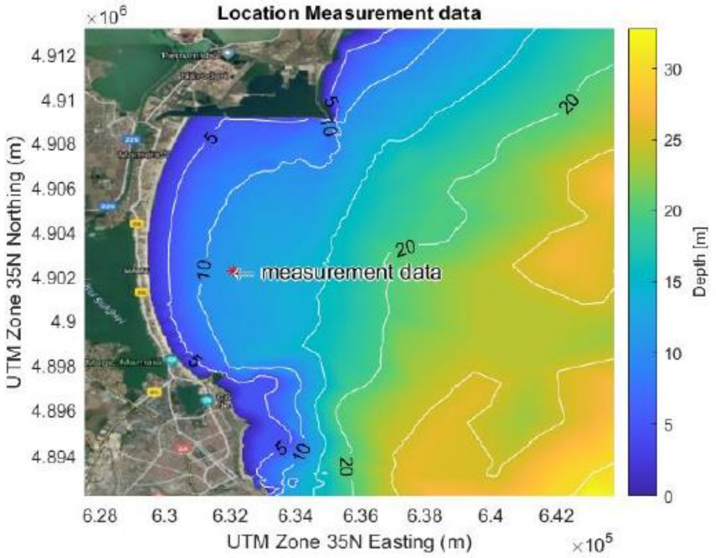


Figure 3.3: Location measurement data from the JICA study UTM35N 632088m E 4902263m N

3.4. Metocean dataset measured offshore

Wind and wave range data are purchased from Infoplaza Marine Weather BV [1], which is a registered trademark of BMT Argoss BV. Data are acquired for the location 44.0°N 29.5°E (UTM35 700438m E 4874911m Y) at a depth of 69 m MSL and at a distance of 74 km from the project location, see figure 3.3. The data set consists of modelled 40-year time series (January 1979 – October 2019) with a 1-hour interval. These data regarding the reconstruction by calculation of some situations (hindcast data) were calibrated by Infoplaza for the altimeter data. Acquired wave and wind data comply with the contractual requirements as stated in [A.1]. The time series contain several Metocean parameters, including significant wave height (Hs), associated peak-wave spectral duration (Tp), zero-crossing period (Tz), and input directions for the total sea state. Wind speed and direction at 10m height (U10) are also included. The fact sheet presented in Annex 10.1 contains more information on calibrated wave and wind data for computational reconstruction of some situations.

Additional wave parameters from the same offshore measured data set are available with a 3-hour interval. This additional information was used to analyse the climate and offshore wave characteristics in more detail.

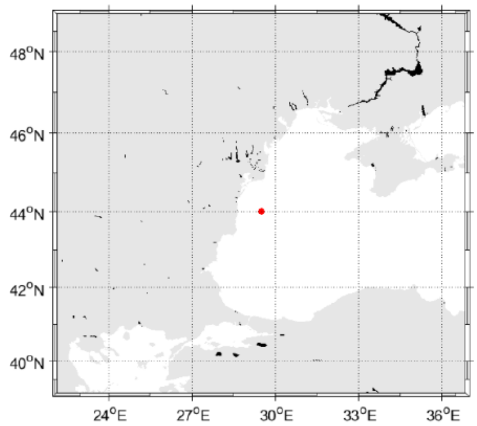


Figure 3.4: Location data on offshore waves and winds

4. METOCEAN OFFSHORE OPERATIONAL CONDITIONS

4.1. Wind

The wind direction indicates two dominant directions from NNW to ENE and from S to SSW, see Figure 4.1. We can observe that the wind direction is relatively similar to the wind direction, which indicates that the area is predominantly one with sea wind climate.

The monthly probability of exceeding the wind speed is indicated in Figure 4.2 (left). Seasonal variation is present, with the lowest wind speeds in the summer months from April to September and the highest wind speeds occurring in the winter months from October to March. The time series plot is visible in Figure 4.2, where clear seasonal variations are observed over the years.

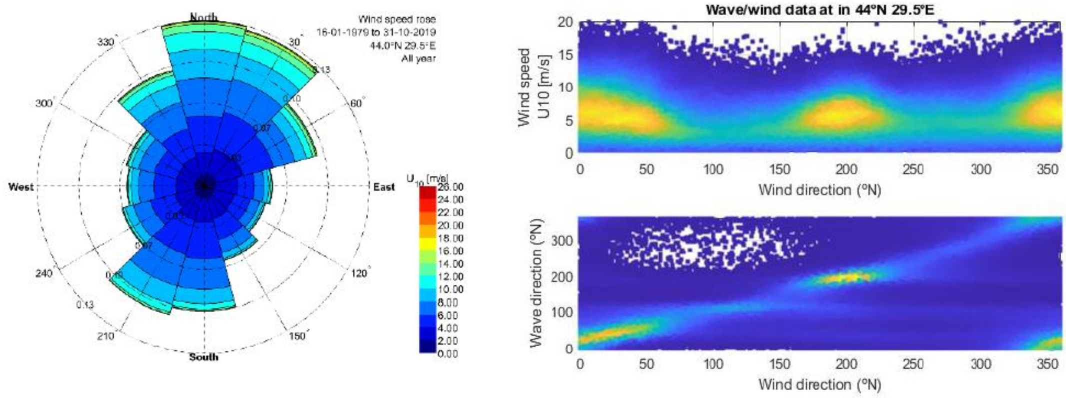


Figure 4.1: Mean annual wind increase (left) and wind density dispersion versus wind direction (top right) and wind direction versus wave direction (bottom right)

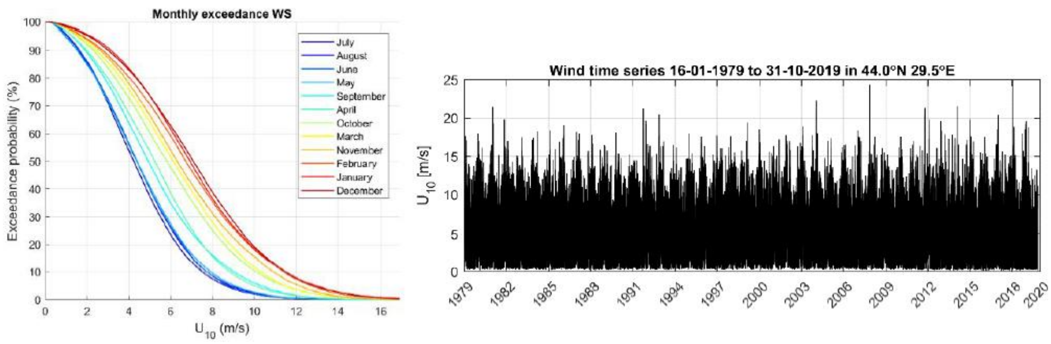


Figure 4.2: Monthly WS exceedance curve (left) and wind speed time series (right)

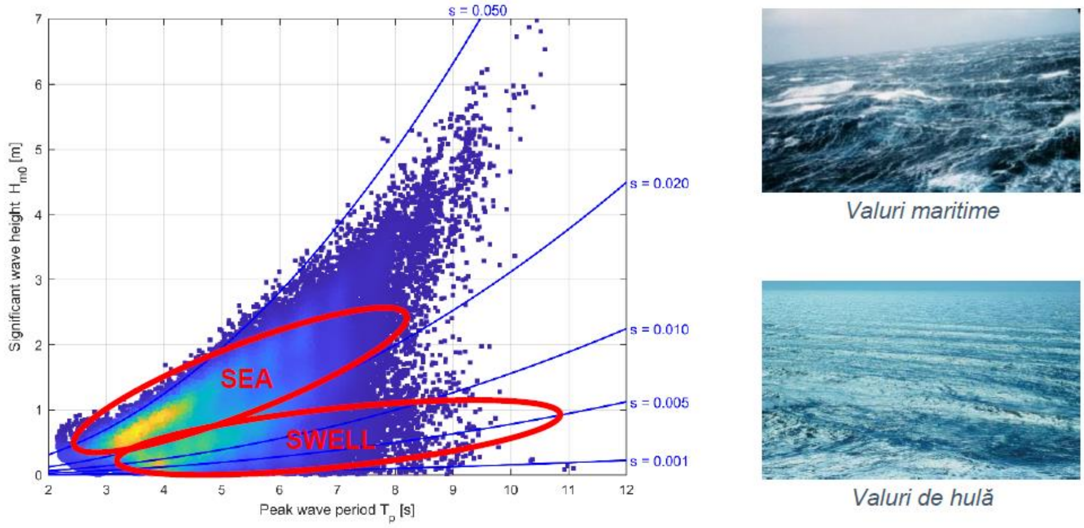
4.2. State of the sea

The 3-hour interval data set for the calculation of some situations is composed of several components of the waves, namely sea waves, swell waves and total waves, the last one being the combination of the sea wave and swell wave. An evaluation of offshore wave data was performed to determine which component(s) govern the wave climate. Sea wind conditions can be characterized as relatively steep, wind-generated waves in the area of interest, which is why sea wave conditions are strongly correlated with wind conditions. These conditions generally lead to the highest wave heights. Swell waves are waves generated over long distances and are characterized as lower but longer waves. Swell waves generally have no correlation with local wind conditions. As the origin of sea waves and swell waves and their correlation with wind are different, this aspect could also affect the modelling approach. Therefore, it is important to identify which wave type is governing this specific situation.

One way to tell the difference between sea and swell waves is to assess the curvature of the wave. Figure 4.3 shows significant wave height versus peak-wave duration for offshore data, along with a number of lines of equal curvature. The difference between sea waves and swell waves can be made at the curvature line of 0.02. Where the curvature of the S_0 wave is given by:

1) $$S_0 = \frac{2*\pi*H_{m0}}{g*T_p^2}$$

Where H_{m0} is the significant spectral height of the wave (m), hereinafter referred to as the significant wave height, and T_p is the peak-wave duration (s).



Sea waves / Swell waves

Figure 4.3: Significant wave height [m] versus peak wave duration [a] at the location in the offshore data. Wave curvature lines [-] are displayed in blue

In Figure 4.4, the scatterplots for significant wave height H_{m0} and peak-wave duration Tp for the total sea state, and conditions for sea waves and swell waves are shown on the left side. In addition, wave rosettes are provided for wave height and peak-to-wave duration for total sea state, sea waves, and swell wave conditions for the mean wave direction. Sea waves have two dominant directions, mainly from ENE and from S to SSW. Swell waves have two main directions, namely from ENE and SE. Wave durations are similar for both sea wave and swell wave conditions.

Only the wave height for marine waves is significantly higher. The fact that the duration of waves designated as swell waves has a similar magnitude to that of sea waves is probably related to the limited distance that swell waves have travelled. Large distances are required before a wavefield begins to display the typical well-sorted, large-crested waves that surge waves display. Travel distances on the Black Sea are not long enough.

We can therefore conclude that the wave climate is dominated by marine waves and the wave conditions can be described by the total sea state.

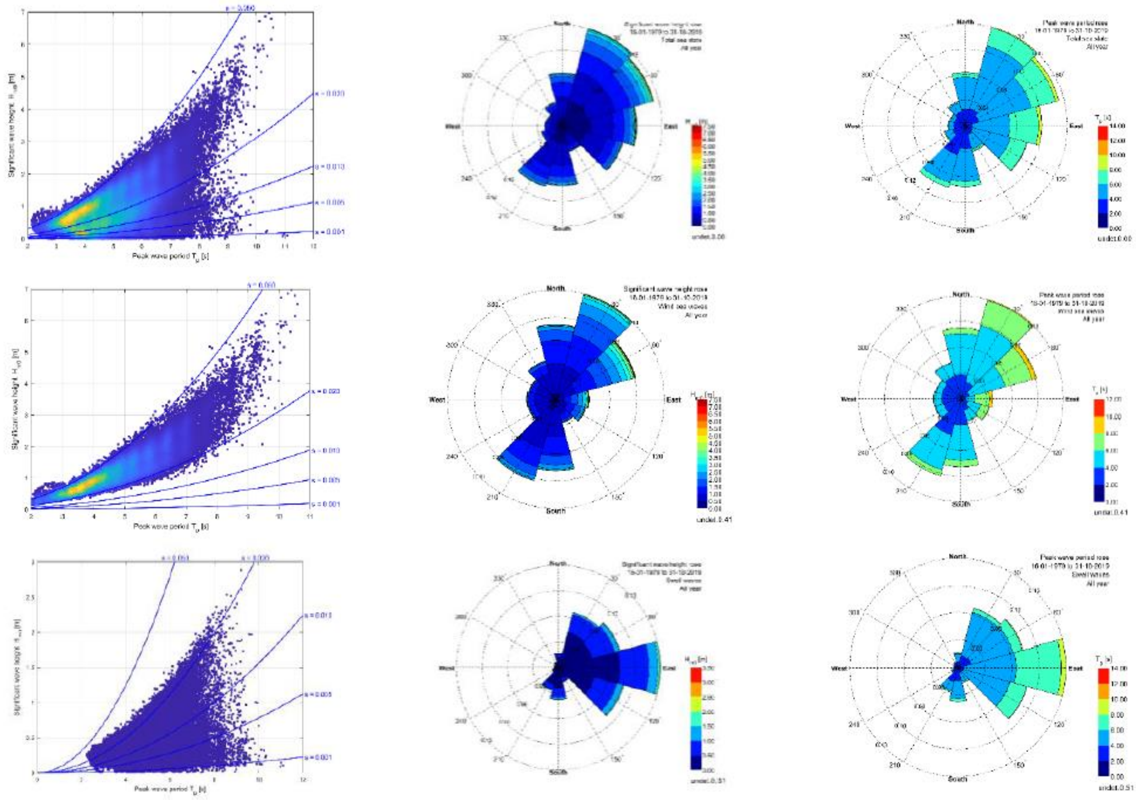


Figure 4.4: Density scattering H_{m0} versus Tp (left), wave rosettes (middle) and wave duration rosettes (right) for the total sea state (top), sea wind conditions (middle) and swell waves (left) for the offshore location 44.0°N 29.5°E

4.3. Spectral data

Offshore wave data contain spectral information in the form of wave spectral energy and wave propagation. The spectral energy of the waves and the directional propagation of the waves are shown in Figure 4.5 and Figure 4.6. Most of the wave energy is present around the wave frequency of 0.09-0.15 Hertz; corresponding to a wave duration of approximately 6.5 – 11.0 seconds. The spectral shape corresponds to a Jonswap spectrum with a factor of 3.3.

Directional wave propagation is shown in figure 4.6 for the total sea state, sea waves and swell waves. Wave propagation versus wave direction, versus wave height, and versus wave duration are indicated. Wave propagation varies between 10 - 30°. The graph in figure 4.5 (right) confirms that the wave propagation for waves with a duration of 10-11s have a propagation of 18-20°.

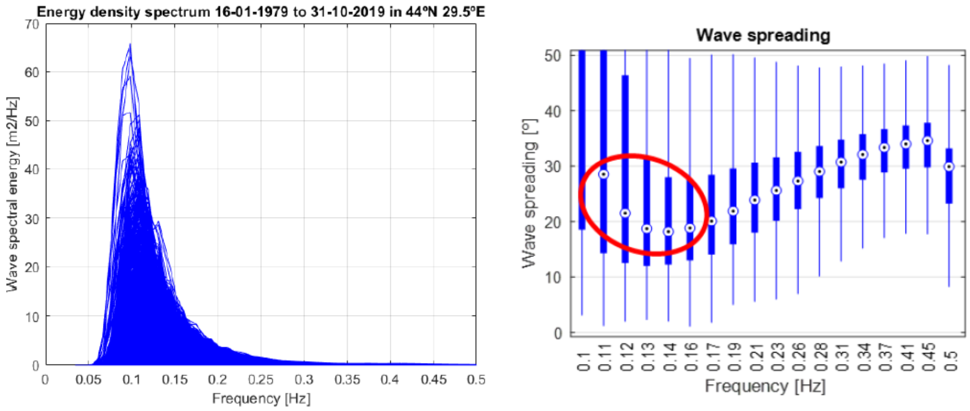


Figure 4.5: Wave spectral energy from the data set collected offshore 44.0°N 29.5°E

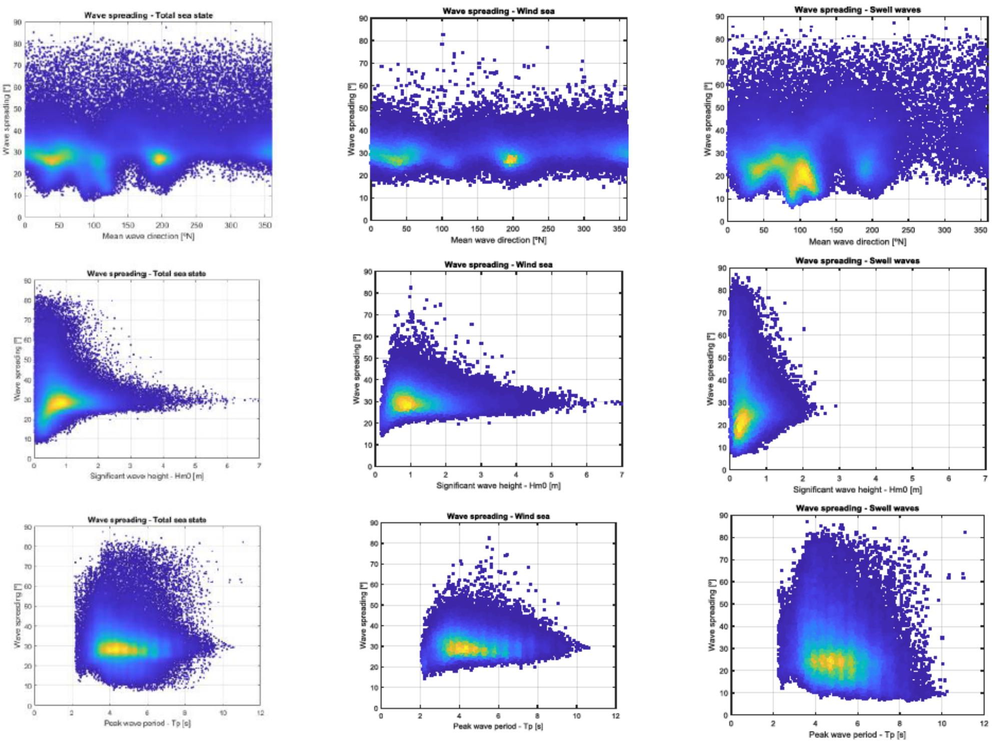


Figure 4.6: Propagation of waves from the data set collected offshore 44.0°N 29.5°E

4.4. Waves

Based on the section we present the waves described by the total sea state. The wave climate at the offshore location shows two dominant directions that are visible in figure 4.7 (left). The main wave direction is from NNE to ESE or 30-120°N. Secondary wave directions are mainly from S to SSW. Directional rosettes of peak-wave duration are visible in figure 4.7 (right). The directions correspond to the direction of the wave.

The monthly probability of wave height exceedance is shown in Figure 4.8 (left). Seasonal variation is present, with the lowest waves in the summer months from April to September and the highest waves in the winter months from October to March. The density plot for wave height versus wave duration is shown in Figure 4.8 (right). Most waves have a curvature between s equals 0.020 to 0.050. The difference between swell and sea waves would be made at the 0.02 curvature line.

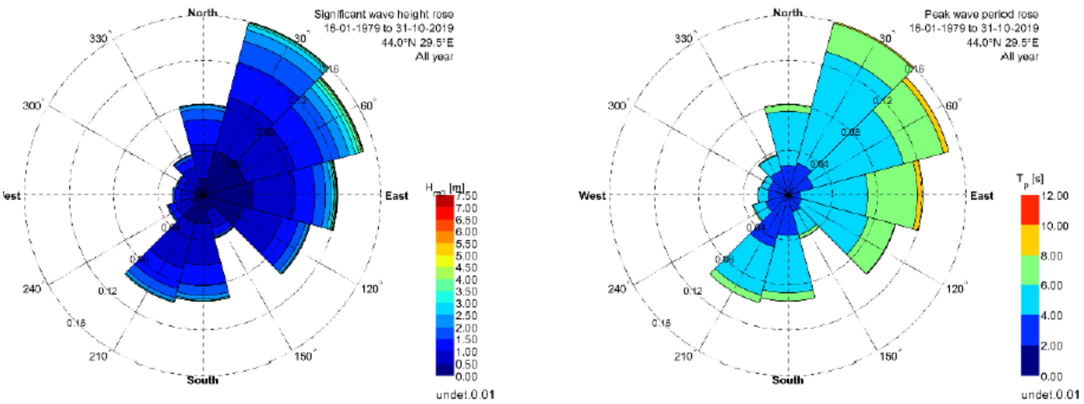


Figure 4.7: Rose for waves (left) and rose for peak-wave duration for the entire data set (right)

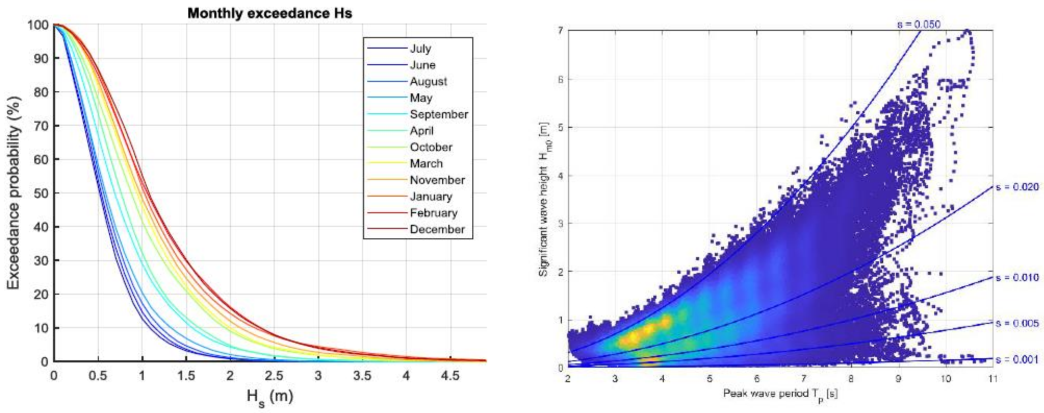


Figure 4.8: Monthly exceedance curve Hs (left) and wave dispersion Hs versus Tp, including wave curvature (right)

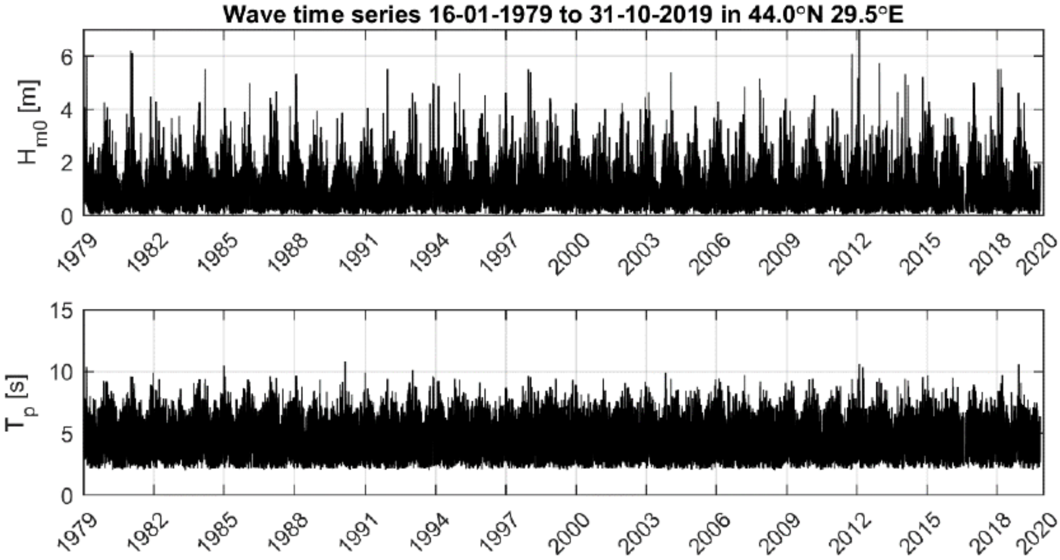


Figure 4.9: Time series plot of Hm0 wave height (top) and wave duration (bottom) from 1979 to in 2019 at the location 44N 29.5E

The time series plot for wave height and wave duration is shown in Figure 4.9, where clear seasonal variations are observed over the years. Directional scatter plots for wave duration versus wave height per 30° directional basin (345 to 15°N, 15 to 45°N, …, 315 to 345°N) are shown in Figure 4.10. A significant variation in wave height is observed. The biggest waves are from the direction 15° to 135°N.

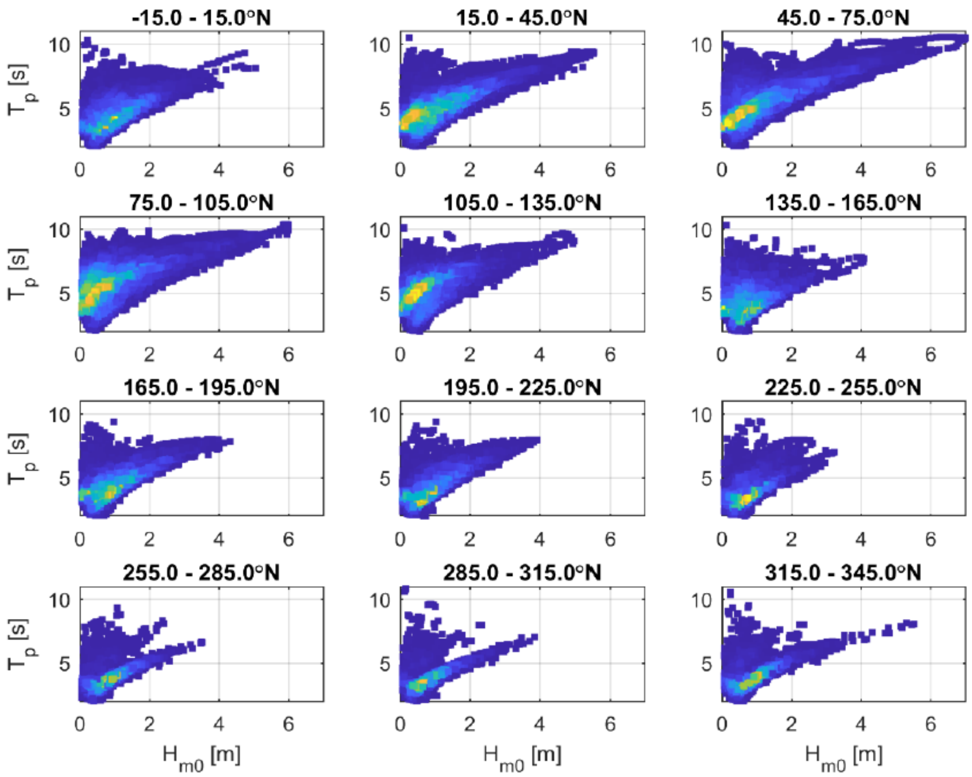


Figure 4.10: Directional scatter plots for wave duration (T_p) versus wave height (H_{m0}) per 30° directional basin (345 la 15°N, 15 la 45°N, …, 315 la 345°N)

As an input for detailed design, the shape of the storm is also important. Based on the data collected offshore, the shape of the storm is shown in Appendix 10.4 for the 10 largest waves. Storms generally last approximately one to three days. The ten largest waves are between 5.5 and 7 meters high, with wave durations ranging from 8 to 10.5 seconds. The extreme conditions simulated in the SWAN wave model are shown in Table 6-2 in Section 6.4.2.

4.4.1. Validation of offshore wave datasets

Offshore wave data is received from the Beneficiary. This data does not meet the design requirements because the length of the data set is 12 years (1991-2002) with a 6-hour interval, however this set can be used for validation purposes. The time series data source is WAM data from ECMWF at the location 29°E 44°N. This location is 40 kilometres to the west, closer to the shoreline compared to data acquired from Infoplaza. Comparison of wave heights from both time series shows a correlation coefficient of 0.91 and RMSE of 0.29 (root mean square error) – see Figure 4.11. The wave height exceedance curves also show a good match. Although the location is different, the wave heights are still quite similar. Although both data sets are hindcast data, their similarity makes us confident about the accuracy of the data.

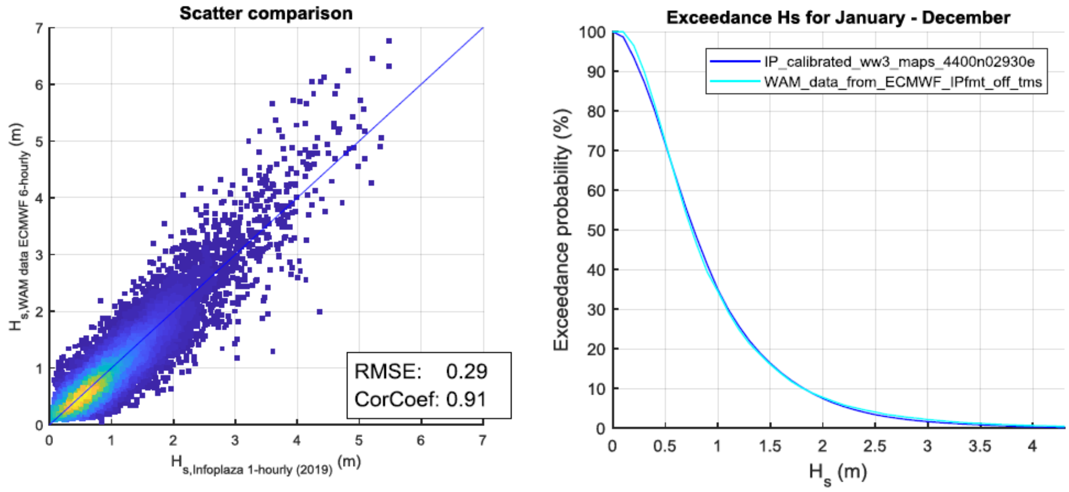


Figure 4.11: Comparison of wave height dispersion from client offshore data and inland data (left) and comparison of wave height exceedance curve (right)

4.5. Stagnant water levels

The highest water level (daily average) ever recorded was 0.902 m on 19 February 1979 [4]. The highest water levels are observed in Constanța, when strong easterly winds blow towards the coast. Westerly winds can lower the coastal water level by a smaller amount (up to 0.6m).

Measured tide data is available in Constanța Port. The water levels were recorded by the OTT sea level recorder in the period 1993 – 2004. Figure 4.12 shows the time series of the water level measured in Constanța Port. The water level varies between a minimum value of -0.20 m and a maximum value of 0.79 m MN75.

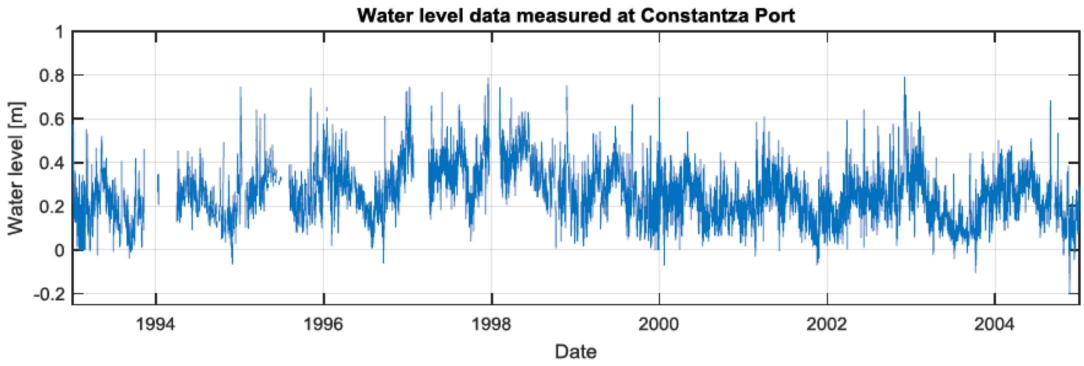


Figure 4.12: Data regarding the measurement of the water level recorded in the port of Constanța in the period 1993-2004

The conversion of the reference mean sea level (MSL) to the local reference level MN75 is depicted in Figure 4.13, and the difference between MSL and MN75 is 0.11 m [5].

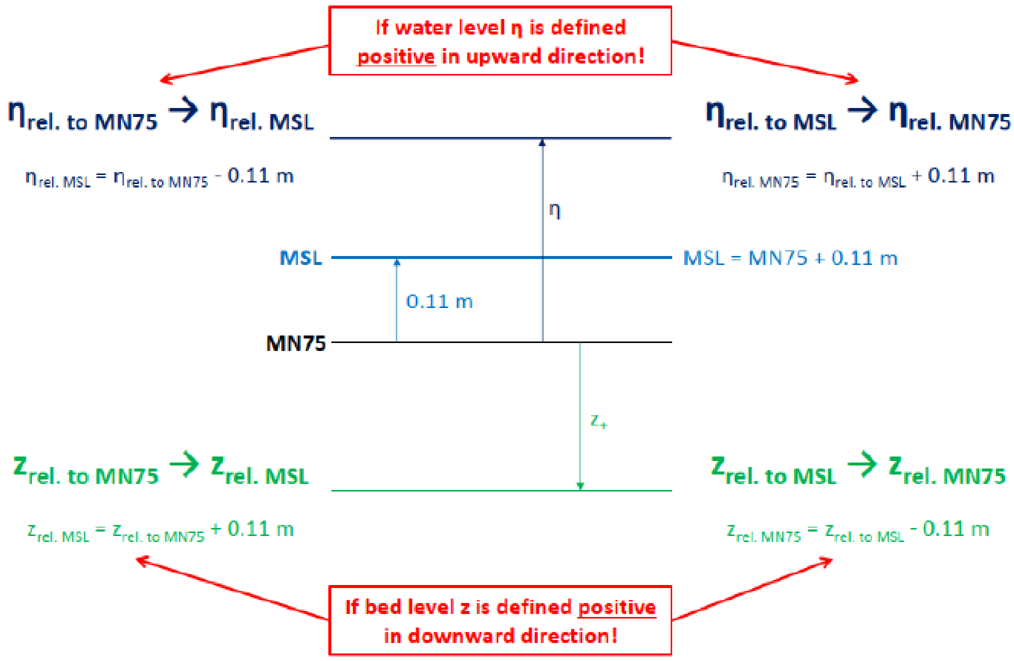


Figure 4.13: Definition of reference levels MSL and MN75

5. <u>METOCEAN DESIGN CONDITIONS</u>

To determine the design conditions for the Mamaia area, an analysis of extreme values (AVE) is carried out. AVE is performed on the total sea state from offshore wave and wind speed data. Since the wave climate consists mainly of sea waves, it is justified to perform AVE on the total sea state. Offshore design conditions are transformed to onshore using SWAN in Chapter 6.

AVE uses a peak-over-threshold analysis with generalized Pareto distribution (DPG) on the data. DGP is often used to model another distribution curve. Design values are calculated for recurrence values of 1, 5, 10, 25, 50 and 100 years. Directional basins are processed into 30-degree directional basins (345 to 15°N, 15 to 45°N, …, 315 to 345°N, all directions).

5.1. Offshore wind design conditions

Offshore wind design conditions are determined for recurrence values (RV) of 1, 5, 10, 25, 50, and 100 years (see Table 5-1). Directional collection basins are processed into 30-degree directional collection basins. The AVE report, including remaining directional collection basins, recurrence values and adjustments are presented in Annex 10.2. The highest wind conditions are coming from the 315–345°N directional collection basin, which is an offshore-oriented wind direction. The highest onshore wind conditions are coming from the directional basin 15-45° and 45-75°N, so from NNE to NE.

Table 5-1: Offshore wind design conditions for omnidirectional and 30-degree directional basins

	0-360º	345-15º	15-45º	45-75º	75-105º	105-135º	135-165º	165-195º	195-225º	225-255º	255-285º	285-315º	315-345º
1yr	17.84	15.73	15.22	13.64	11.09	10.55	10.70	12.91	13.30	10.22	11.47	12.68	14.62
5yr	20.28	18.51	17.74	17.37	14.45	13.64	13.71	15.43	15.55	13.11	14.75	15.21	17.78
10yr	21.48	19.54	18.80	18.54	15.37	14.80	14.65	16.21	16.44	13.87	16.22	16.03	19.38
25yr	23.21	20.78	20.15	19.79	16.26	16.19	15.65	17.03	17.57	14.58	18.20	16.92	21.73
50yr	24.65	21.63	21.16	20.55	16.75	17.15	16.26	17.53	18.37	14.97	19.73	17.48	23.73
100yr	26.21	22.40	22.14	21.18	17.13	18.04	16.76	17.93	19.14	15.26	21.30	17.95	25.92

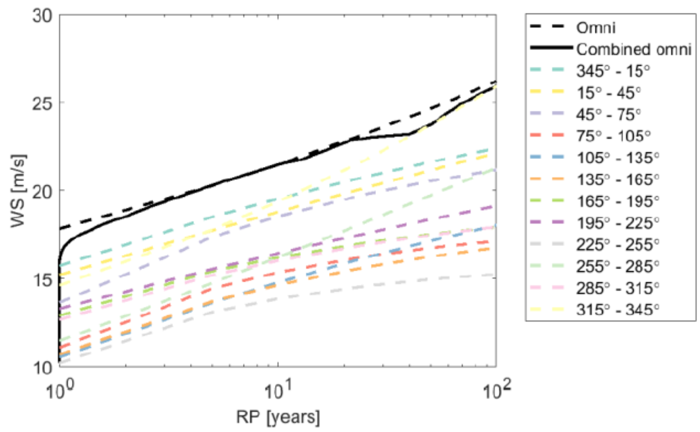


Figure 5.1: Directional and omnidirectional recurrence values for wind

5.2. Offshore wave design conditions

Design conditions for offshore waves are determined for recurrence values of 1, 5, 10, 25, 50 and 100 years. Directional collection basins are processed into 30-degree directional collection basins. Table 5-2 shows the offshore wave design conditions. The conditions for the highest waves are from the 45-75°N directional collection basin, NE direction.

The AVE report, including more detailed information, is presented in annex 10.2. Directional and omnidirectional recurrence values are shown in figure 5.2.

Table 5-2: Design conditions for offshore waves for omnidirectional and 30-degree directional collection basins

	0-360º	345-15º	15-45º	45-75º	75-105º	105-135º	135-165º	165-195º	195-225º	225-255º	255-285º	285-315º	315-345º
1yr RV	4.48	2.42	3.25	3.83	3.46	2.34	1.32	2.72	2.40	-	1.30	1.02	1.71
5yr RV	5.52	3.24	4.24	5.15	4.85	3.39	2.34	3.54	3.09	-	2.22	1.92	2.69
10yr RV	5.94	3.58	4.65	5.65	5.22	3.78	2.72	3.79	3.32	-	2.56	2.22	3.19
25yr RV	6.45	4.02	5.17	6.26	5.57	4.24	3.18	4.05	3.56	-	2.97	2.56	3.95
50yr RV	6.82	4.34	5.55	6.68	5.76	4.56	3.49	4.21	3.72	-	3.25	2.77	4.59
100yr RV	7.17	4.65	5.92	7.07	5.90	4.85	3.79	4.35	3.85	-	3.50	2.95	5.31

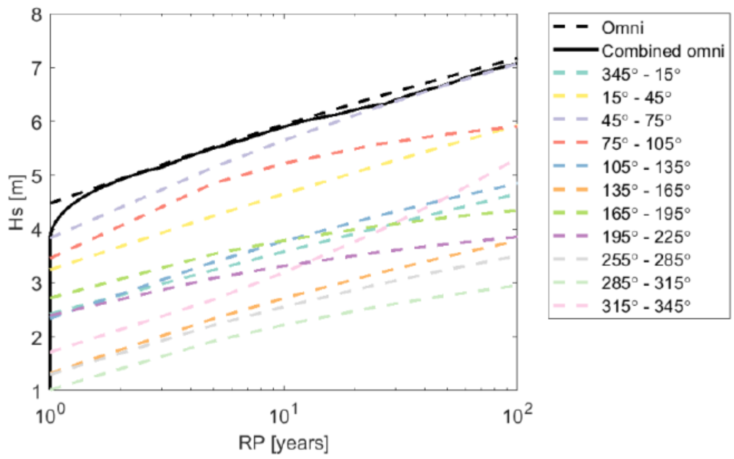


Figure 5.2: Directional and omnidirectional recurrence values for wave height

5.2.1. Associated variables

The wave input conditions for the designed modelling study are based on the AVE analysis for wave height. As an input condition for modelling the wave transformation, the associated P-50 Tp and U_{10} values are calculated for each wave height. The associated P-50 and U_{10} value is used instead of the 1/100-year wind condition because it leads to a uniform wave height near the boundary of the undulatory model. Strong wave growth at the model boundary is not desired because the deep-water wave field can be expected to be a fully developed wave field in equilibrium with the wind strength. The constant wave height at the boundary is visible in the spatial wave height plots presented in paragraph 6.3 Model performance. Conditional distributions are modelled with a bivariate copula for the dependence of wave height on the associated variable and a univariate distribution for the associated variable. The family of the copula function is selected based on the AIC criterion of Gauss, t, Gumbel, Frank or Clayton. Using the same criterion, the univariate distribution family is selected from the generalized Pareto, generalized extreme value, and Weibull.

Table 5-3 shows the designed offshore wave heights for recurrence periods of 1 and 100 years, including the associated variables Tp and U_{10}.

Table 5-3: Design conditions for offshore location Latitude 44.0°N Longitude 29.5°E

Recurrence value 1/1 year				Recurrence value 1/100 years		
Directional collection basin [°N]	Wave height H_{m0} [m]	Associated Tp [s] (P50 value)	Associated U_{10} [m/s] (P50 value)	Wave height H_{m0} [m]	Associated Tp [s] (P50 value)	Associated U_{10} [m/s] (P50 value)
345-15	2.42	5.96	13.30	4.65	9.78	21.50
15-45	3.25	7.26	14.56	5.92	9.53	20.54
45-75	3.83	7.84	14.06	7.07	10.97	19.78
75-105	3.46	7.94	9.14	5.90	9.88	16.54
105-135	2.34	7.06	7.84	4.85	8.95	15.32
135-165	1.32	4.71	7.76	3.79	7.70	11.90
165-195	2.72	6.63	12.68	4.35	8.25	15.66

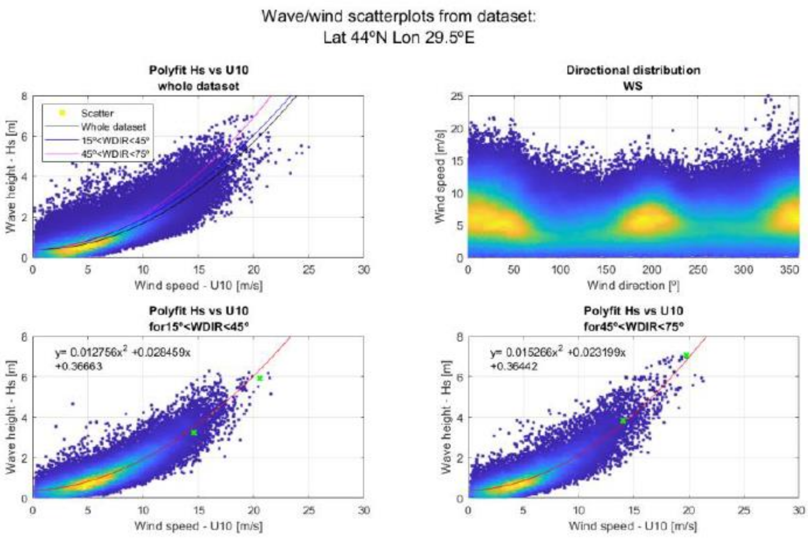


Figure 5.3: Wave/wind dispersion plots including the polynomial regression for omnidirectional collections basins 15-45° and 45-75°

The climate of the winds is mainly dominated by wind and maritime conditions. Since waves are mainly dominated by wind speed, a good correlation between the two parameters is to be expected. Figure 5.3 shows density plots of wind speed versus wave height for the entire data set (top left), for the 15–45° directional collection basin (bottom left) and the 45–75° directional collection basin (bottom right). Designed values are plotted with green crosses at the bottom of the two figures. One can observe that the design values follow the polynomial line quite precisely. This confirms the correlation between wind speed and wave height.

5.3. Designed water levels

The designed water levels in the Mamaia area are derived from specialized literature, as extensive research has already been carried out in the past [3] for several components that make up the total water level. The time series available for the measured water level (Section 4.5) is considered too short for us to accurately derive the designed water levels.

According to [3], the extreme water levels in the littoral area of Constanța include the following components:

- Seasonal variation
- Tidal variation
- MSL (reference mean sea level) versus MN75
- Barometric pressure and resulting convulsions
- Sea level rise
- Wind adjustment

The seasonal variation of the water level in the Black Sea is mostly caused by river discharges in winter/spring and relatively low discharges in summer/autumn. The average seasonal variation is 16 cm/year, respectively +0.08 m in summer and -0.08 m in winter [3]. As extreme wave conditions occur in the winter season, the contribution of seasonal variation to the total designed water level used in wave modelling is taken at the value of -0.08m. The variation caused by the Black Sea tides is very limited to only a few centimetres; the tidal range is MSL – 0.05m to MSL +0.05m [3].

The conversion of the reference level MSL to the local reference level MN75 is 0.11m (MSL = MH75 + 0.11m), explained in more detail in paragraph 4.5.

Black Sea seiches are caused by sudden changes in atmospheric pressure. The resulting fluctuation in water level causes a long wave (seiche), which propagates throughout the Black Sea with an ordinal wave speed of 125 m/s. The seiche travels back and forth across the Black Sea in about 4.5 hours. A seiche amplitude of MSL +/- 0.10 m was applied with respect to designed water levels [3].

The long-term sea level rise in the Constanța region is a prescribed value of 3.3 mm/year, provided by the Beneficiary as a requirement. For the entire service time of the works of 50 years, this will total 0.165m. Storm wave levels for various onshore wind directions were taken from the literature [3]. Storm wave levels are shown in Table 5-4.

Table 5-4: Storm wave level as a function of recurrence interval and wind direction class [5].

Recurrence interval (1/year) Wind direction from the shore (°N)

Perioada de recurență (1/an)	Direcția vântului dinspre mal (°N)							
	0	30	60	90	120	150	180	210
1	0.22	0.31	0.29	0.24	0.17	0.15	0.15	-0.09
5	0.29	0.42	0.41	0.32	0.24	0.20	0.18	-0.13
10	0.31	0.47	0.46	0.36	0.26	0.22	0.19	-0.14
25	0.35	0.54	0.53	0.39	0.30	0.24	0.20	-0.16
50	0.38	0.59	0.58	0.42	0.33	0.26	0.21	-0.17
100	0.40	0.64	0.64	0.45	0.37	0.28	0.22	-0.18

The designed water level is used as information for coastal protection works. Three design levels are defined for hydraulic loading:

1) Surf: wave conditions VR 1 n + water level conditions VR 1 year
2) Surf/Reinforcement stability: wave condition VR 100 years + water level conditions VR 100 years
3) Downstream post stability: wave condition VR 100 years + low water level conditions VR 100 years

The various contributions to the three designed water levels are shown in Table 5-5.

Table 5-5: Various contributions to the designed water level at Constanța for hydraulic loading conditions: surf, reinforcement stability and downstream post stability

Contribution	(1) Surf	(2) Surf/ Reinforcement stability	(3) Downstream post stability
Seasonal variation (winter)	-0.08 m	-0.08 m	-0.08 m
Variation caused by tides	+0.05 m	+0.05 m	-0.05 m
MSL in MN75	+0.11 m	+0.11 m	+0.11 m
Barometric pressure / seiche	+0.10 m	+0.10 m	-0.10 m
Sea level rise	+0.165 m	+0.165 m	+0.00 m
Subtotal [m MN75]	**+0.345 m**	**+0.345 m**	**-0.120 m**
Storm wave	Varies (see Table 5-4)	Varies (see Table 5-4)	Varies (see Table 5-4)

The designed water level (including the sea level rise over a 50-year period) for different recurrence intervals and different direction classes for the respective high-water conditions are shown in Table 5-6, and low water conditions are shown in table 5-7. The designed water levels correspond to the numbers from the feasibility study carried out by ROMAIR Consulting [5].

Table 5-6: Designed water levels [m MN75] for different recurrence intervals and different wind direction classes, high water level

Recurrence interval (1/year) / Wind direction from the shore (°N)

Perioadă de recurență (1/an)	Direcția vântului dinspre mal (°N)							
	0	30	60	90	120	150	180	210
1	0.57	0.65	0.63	0.58	0.52	0.50	0.50	0.25
5	0.63	0.77	0.75	0.67	0.58	0.54	0.52	0.22
10	0.66	0.82	0.81	0.70	0.61	0.56	0.53	0.21
25	0.69	0.88	0.88	0.74	0.65	0.58	0.55	0.19
50	0.72	0.93	0.93	0.77	0.68	0.60	0.56	0.18
100	0.75	0.98	0.98	0.79	0.71	0.62	0.56	0.17

Table 5-7: Designed water levels [m MN75] for different recurrence intervals and different wind direction classes, low water level

Recurrence interval (1/year) / Wind direction from the sea (°N)

Perioadă de recurență (1/an)	Direcția vântului dinspre larg (ºN)							
	0	30	60	90	120	150	180	210
1	0.10	0.19	0.17	0.12	0.05	0.03	0.03	-0.21
5	0.17	0.30	0.29	0.20	0.12	0.08	0.06	-0.25
10	0.19	0.35	0.34	0.24	0.14	0.10	0.07	-0.26
25	0.23	0.42	0.41	0.27	0.18	0.12	0.08	-0.28
50	0.26	0.47	0.46	0.30	0.21	0.14	0.09	-0.29
100	0.28	0.52	0.52	0.33	0.25	0.16	0.10	-0.30

6. NEARSHORE WAVE TRASNFORMATION MODEL

6.1. Calculation grid and bathymetry

The conversion of offshore wave conditions to a nearshore wave climate is achieved with the SWAN numerical undulatory model. The model bathymetry consists of a combination of digitized marine charts and research data. Research data are presented in section 3.2. Depth is shown at local reference level MN75. The undulatory model consists of four calculation grids, visible in figure 6.1 and figure 6.2 (left).

- Grid A: Unprocessed grid with a resolution of 1000 x 1000 m (dx dy)
- Grid B: Intermediate grid with a resolution of 200 x 200 m (dx dy)
- Grid C: Precise grid with a resolution of 50 x 50 m (dx dy)
- Grid D: Precise grid with a resolution of 10 x 10 m (dx dy)

The largest model is 85 x 156 km in size, extending to the offshore hindcast data point. The smallest model is 2 x 1.5 km in size focusing on Mamaia beach and pier. Breakwaters are modelled as obstacles in the undulatory model. The SWAN model is simulated in stationary state. The offshore data is located 70 km from the project site, which is within the validity limits of stationarity. The spectral resolution consists of 72 equally spaced directional collection basins with a width of 5° and 41 logarithmically distributed frequencies in the range 0.05 Hz – 2.5 Hz. The relatively high upper frequency was chosen to improve accuracy for low wind speeds.

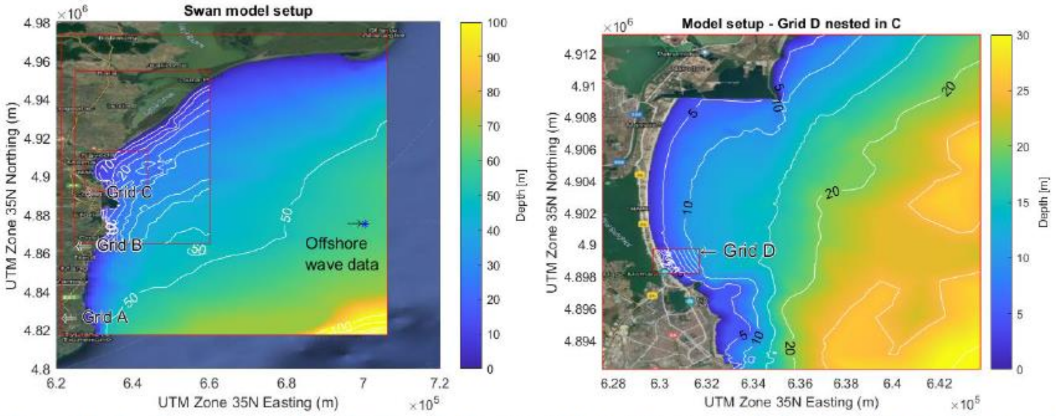


Figure 6.1: SWAN model setup, grid B imbricated in A and C and imbricated in B (left) and grid D imbricated in C (right)

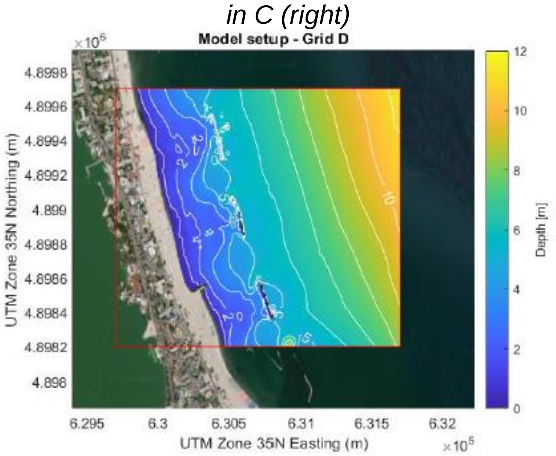


Figure 6.2: SWAN model setup, grid D (left)

6.2. Output locations

Output locations are chosen at various isobaths along the proposed location of the new beach and extended breakwater. All nearshore output locations are shown as green dots in Figure 6.3. Wave conditions at two output locations are discussed in detail in the main report, namely:

Table 6-1: Output locations for the wave model

Output location	Location [UTM35N]	Location [Krasovsky/Stereo 70]	Depth [m MN75]
Loc01	632089.0m E 4902262.0m N	791911.0m E 313468.8m E	11.8
Loc110	630419.4m E 4898632.3m N	790331.8m E 309795.9m N	3.2

The coordinates for the other 139 locations can be found in annex...

Figure 6.3: Output locations for the undulatory model

6.3. Model performance

Numerical settings in the undulatory model are studied to improve the model performance. This paragraph describes the calibration and validation of the wave pattern. The nesting and convergence of the wave pattern is also studied, checked and confirmed to be within the rules. The nesting and convergence figures of the model are presented in Appendix 10.5.

6.3.1. Validation – stormy event

The presented storm that occurred between 10 and 17 February 2010 is used to calibrate the wave undulatory. The coordinates from the measuring device correspond to the output location Loc01 of the wave pattern. This location is used for wave pattern calibration and validation.

The physical settings used in the wave model are the following, corresponding to the settings found in specialized literature on Black Sea-based modelling [6]:

```
GEN3 KOMen
OFF DIFFRAC
WCAP KOM DELTA=1.0
PROP BSBT
OFF BNDCHK
FRICTION JONSWAP CONSTANT 0.038
BREaking CONstant 1.0 0.73
NUMERIC ACCUR 0.01 0.01 0.01 99.5 STAT 50
```

Two simulations with the above settings are simulated while the directional dispersion is varied for sensitivity purposes. The first simulation uses a directional dispersion (DSPR) of 18° and the second simulation a DSPR of 30°. Generally, a value of 30° is used for sea wave conditions, while DSPR values of 5-10° are used for swell wave conditions.

The comparison of Hs and Tp parameters from the wave model and measurement data is shown in Figure 6.4. Results from both simulations show comparable results. The simulation with a directional dispersion of 18° shows a higher peak wave height. Wave height and duration have the same trend as in the measurement data. The wave model will be simulated with a directional dispersion of 18° as this is conservative and corresponds to the spectral analysis described in paragraph 4.3. Validation of the entire measurement time series is presented in paragraph 6.3.2.

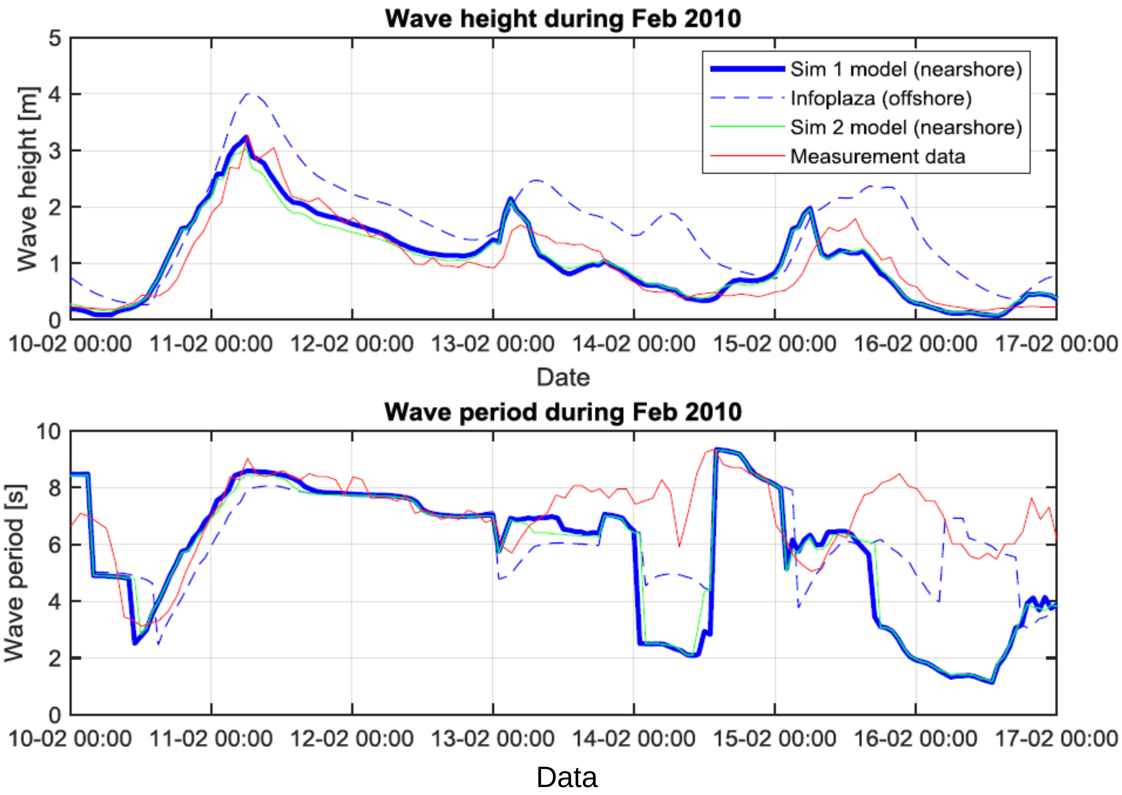


Figure 6.4: Comparison of wave model results and measurement data for Hs and Tp

6.3.2. Validation – bulk data

Since the entire offshore wave time series is converted to nearshore wave time series, the nearshore time series contains data from 16 January 1979 to 31 October 2019. This overlaps the period for which measurement data is available, visible in Figure 6.7. The entire measurement campaign lasts from March 2006 to October 2010, with interruptions, without measured data. For the wave height, wave duration and wave direction parameters, the root mean square error (RMSE) and the correlation coefficient (CorCoef) are calculated.

The root mean square error (RMSE) is calculated as (1):

1. $$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}$$

The correlation coefficient (CorCoef) is calculated as (2):

2. $$r = \frac{n(\sum xy - (\sum x)(\sum y)}{\sqrt{(n\sum x^2 - (\sum x)^2 * (n \sum y^2 - (\sum y)^2}}$$

The measurement data is recorded at different times compared to the wave pattern. The time series data from the wave pattern are interpolated onto the time axis of the measurement data to obtain equal data and to make scatter plots of measured data versus modelled data, see Figure 6.5.

Dispersion comparison for wave height and peak period were indicated. The wave height has a very good match with the beacon measured data, resulting in a root mean square error (RMSE) of 0.22 and a CorCoef correlation coefficient of 0.88. Wave duration has a lower correlation of 0.66 and RMSE (root mean square error) of 1.21. The peak-to-wave duration is generally less than one second from the measured values. Similar to the results obtained by Halcrow [4] the wave model produces shorter peak-to-wave durations than the JICA observations during periods of low wave activity due to attenuation of the pressure signal and therefore not being able to measure wave durations below 2 seconds. For these cases, the undulatory model is considered to produce more realistic results than the data. In general, the wave model is considered to satisfactorily reproduce the peak-wave durations. It is concluded that the wave model is suitable to determine the design conditions.

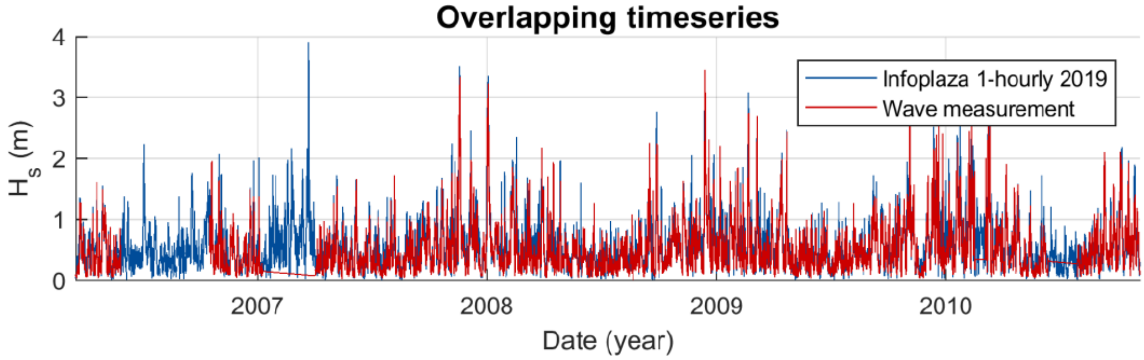


Figure 6.5: Overlapping of timeseries plot for wave height

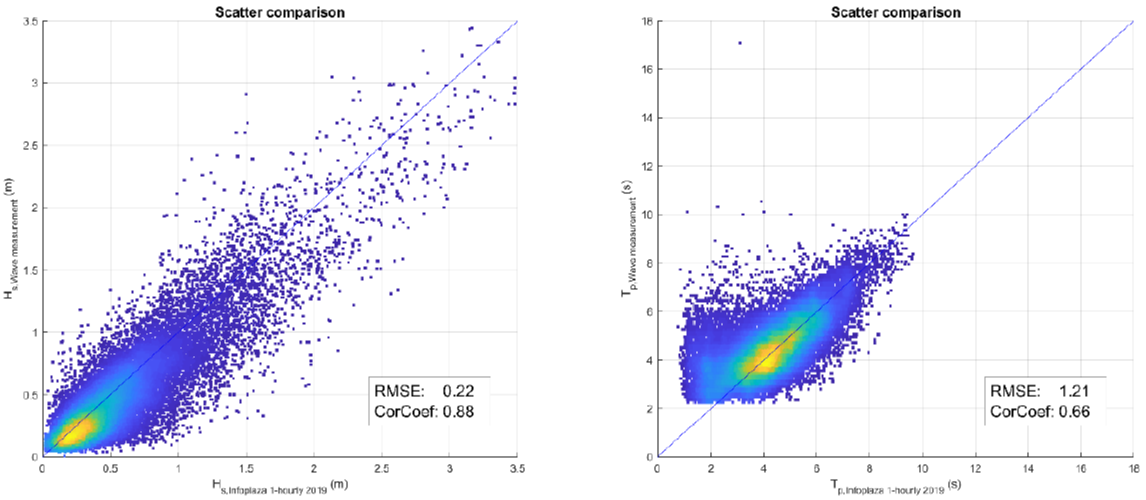


Figure 6.6: Comparison of wave height dispersion (left) and wave duration (right)

6.4. Delimitation conditions

6.4.1. Operating conditions

The operational nearshore wave climate is calculated by simulating a matrix of wind/wave scenarios that are subsequently interpolated to convert the 40-year time series of offshore wave conditions to nearshore wave conditions in the project area. The method is called the transformation matrix method. Offshore climate discretization is described in this chapter. The total sea state is simulated to determine the operational conditions of the waves. For each parameter (Hm0, Tp, Theta, u10, water level), the collection reservoirs selected to discretize the climate are shown below.

- Hm0 (m): [0.1 0.5 1 1.5 2 2.5 3 4.5 6 7.5]
- θ (degrees): [0 30 60 90 120 150 180 210 240 270 300 330]
- Tp (s): [2 4 6 8 10 16.5]
- Water level (m MN75): [0]
- U_{10} (m/s): 0.1 3.25 6.5 9.75 13 19.5 26
- Propagation (degrees): [18]

The total number of runs based on this discretization is 2697. The number of disabled nodes is equal to 2343. An example of climate discretization is shown in Figure 6.6 (right); the red dots represent the nodes of the transformation matrix and the blue dots show those that are disabled.

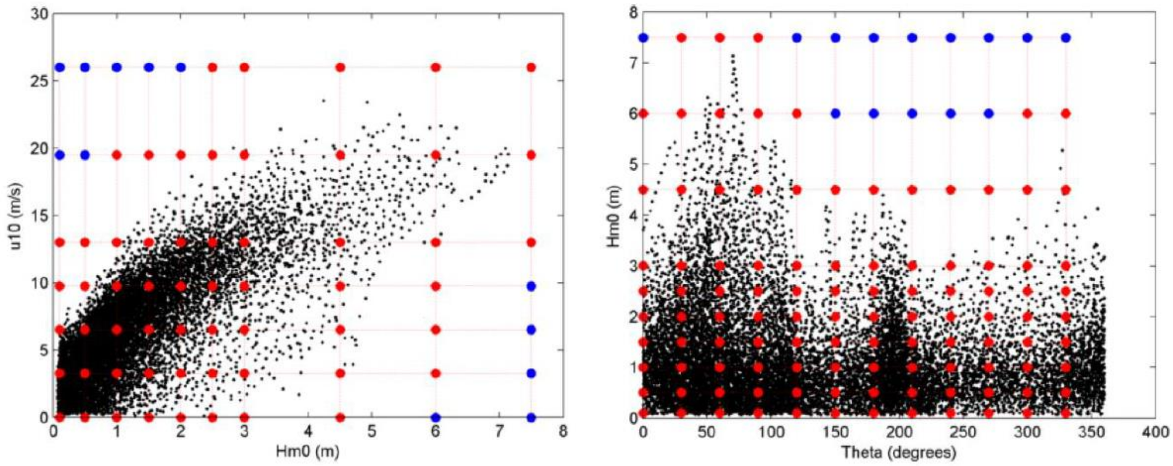


Figure 6.7: Climate discretization for u10/Hm0 (left) and Hm0 / θ (right)

6.4.2. Extreme conditions

The applicable offshore design conditions that are simulated in SWAN are shown in Table 6-2. The conditions consist of the main variable, wave height and associated P-50 variables, wave duration and wind speed. The condition for the highest wave with a recurrence period of 100 years during high water is from the direction of 60°N, which is equal to 7.07 m. The associated wave duration is 10.97 seconds with a wind speed of 19.78 m/s. The associated variables Tp and u10 are presented in paragraph 5.2.1. The Jonswap factor is equal to 3.3 and the directional spread is set to 18° for all conditions described in paragraph 4.3.

Table 6-2: Overview of offshore design conditions simulated in the undulatory model

Condition	Recurrence value [1/y]	Wave direction [°N]	H_{m0} [m]	Tp [s]	Water level [m]	U_{10} [m/s]	Wind direction [°N]	Jonswap factor [-]	Directional propagation [°]
Condiție	Valoare de recurență [1/y]	Direcția valului [ºN]	H_{m0} [m]	Tp [s]	Nivelul apei [m]	U_{10} [m/s]	Direcția vântului [ºN]	Factorul Jonswap [-]	Propagare direcțională [º]
1	1	0	2.42	5.96	0.57	13.30	0	3.3	18
2		30	3.25	7.26	0.65	14.56	30	3.3	18
3		60	3.83	7.84	0.63	14.06	60	3.3	18
4		90	3.46	7.94	0.58	9.14	90	3.3	18
5		120	2.34	7.06	0.52	7.84	120	3.3	18
6		150	1.32	4.71	0.50	7.76	150	3.3	18
7		180	2.72	6.63	0.50	12.68	180	3.3	18
8	100	0	4.65	9.78	0.75	21.50	0	3.3	18
9		30	5.92	9.53	0.98	20.54	30	3.3	18
10		60	7.07	10.97	0.98	19.78	60	3.3	18
11		90	5.90	9.88	0.79	16.54	90	3.3	18
12		120	4.85	8.95	0.71	15.32	120	3.3	18
13		150	3.79	7.70	0.62	11.90	150	3.3	18
14		180	4.35	8.25	0.56	15.66	180	3.3	18
15	100	0	4.65	9.78	0.28	21.50	0	3.3	18
16		30	5.92	9.53	0.52	20.54	30	3.3	18
17		60	7.07	10.97	0.52	19.78	60	3.3	18
18		90	5.90	9.88	0.33	16.54	90	3.3	18
19		120	4.85	8.95	0.25	15.32	120	3.3	18
20		150	3.79	7.70	0.16	11.90	150	3.3	18
21		180	4.35	8.25	0.10	15.66	180	3.3	18

7. <u>RESULTS</u>

7.1. Nearshore operating conditions

The nearshore time series are calculated with the wave model and transformation matrix method presented in Section 6.4. The output locations are chosen along the stretch of the beach, covering depths between 3m and 14m. The output locations are visible in Figure 6.3 and appendix 10.3. In the breakwater area, several locations are chosen on the sides of the wall and in the transverse direction of the breakwater. Operational wave conditions from two representative locations, Loc01 and Loc110, are presented in this report. The coordinates of these locations are shown in Table 6-1.

The density dispersion for wave height versus wave duration for loc01 covering the entire period is shown in Figure 7.1 (left). Two dominant wave directions are observed from ENE to E and SSE, visible in pink for waves and wave duration plot, see Figure 7.1 (middle + right).

Location loc110 closer to shore shows a more uniform wave direction, from ENE to E due to refraction towards the coast, see Figure 7.2. (middle + right). Due to wave breaking at shallower depths, wave heights decreased significantly near the breakwater. The density dispersion for wave height versus wave duration for site 110 covering the entire period is shown in Figure 7.2 (left).

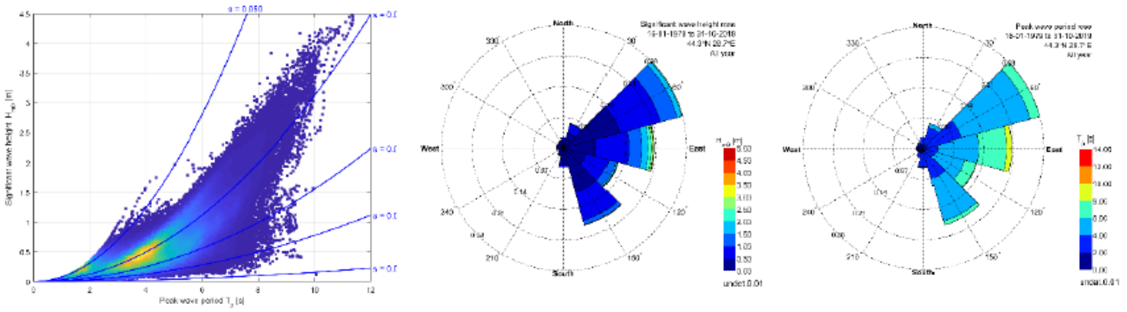


Figure 7.1: Dispersion of wave height density versus peak-wave duration (left) wave rose (middle) and wave duration rose (right) for location loc01

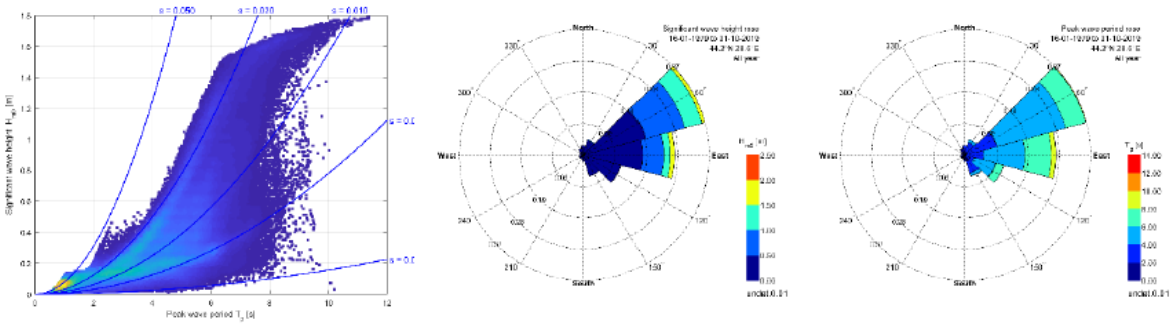


Figure 7.2: Dispersion of wave height density versus peak-wave duration (left) wave rose (middle) and wave duration rose (right) for location loc110

7.2. Nearshore design conditions

Design conditions for the nearshore are determined for recurrence periods of 1, 10, 25, 50, and 100 years. For locations loc01 and loc110, results for recurrence periods of 1 and 100 years are shown in Table 7-1 and Table 7-2. Results for other locations or recurrence periods are available on request.

Table 7-1: Design conditions for waves for location loc01

Condition	Recurrence period [years]	Offshore wave/ wind direction [°N]	Water level [m MN75]	Average wave direction [°]	Wave crest direction [°]	Significant wave height H_{m0} [m]	Wave crest duration T_p [s]	Mean absolute wave duration T_{mm10} [s]	Directional propagation [°]
Condiție	Perioadă de recurență [ani]	Direcție val/vânt în larg [ºN]	Nivelul apei [m MN75]	Direcția medie a valului [º]	Direcția vârfului valului [º]	Înălțimea semnificativă a valului H_{m0} [m]	Durata vârfului valului T_p [s]	Durata medie a valului absolut T_{mm10} [s]	Propagare direcțională [º]
1	1/1 HWL	345-15	0.57	49.3	62.5	1.30	5.80	4.49	3.52
2		15-45	0.65	68.5	72.5	2.04	6.99	5.91	4.75
3		45-75	0.63	82.9	82.5	2.63	8.34	7.08	5.76
4		75-105	0.58	98.3	92.5	2.25	8.43	7.72	6.36
5		105-135	0.52	113.7	117.5	1.64	7.44	6.69	5.35
6		135-165	0.50	133.6	137.5	0.86	5.25	4.17	3.22
7		165-195	0.50	141.5	142.5	1.59	7.35	5.60	4.15
8	1/100 HWL	345-15	0.75	55.6	72.5	2.37	7.42	5.95	4.65
9		15-45	0.98	76.8	82.5	3.48	9.44	8.02	6.43
10		45-75	0.98	89.0	87.5	4.77	11.28	10.41	8.83
11		75-105	0.79	99.8	97.5	4.55	10.37	9.79	8.48
12		105-135	0.71	113.7	117.5	3.93	9.46	8.83	7.54
13		135-165	0.62	127.5	132.5	2.14	8.44	7.01	5.37
14		165-195	0.56	137.3	137.5	2.34	9.04	7.17	5.20
15	1/100 LWL	345-15	0.28	55.9	72.5	2.34	7.42	5.93	4.63
16		15-45	0.52	77.4	82.5	3.46	9.50	8.04	6.44
17		45-75	0.52	89.3	87.5	4.65	11.28	10.46	8.91
18		75-105	0.33	99.9	97.5	4.47	10.37	9.82	8.54
19		105-135	0.25	113.5	117.5	3.92	9.46	8.86	7.61
20		135-165	0.16	127.0	132.5	2.14	8.40	7.04	5.40
21		165-195	0.10	136.9	137.5	2.32	8.73	7.17	5.18

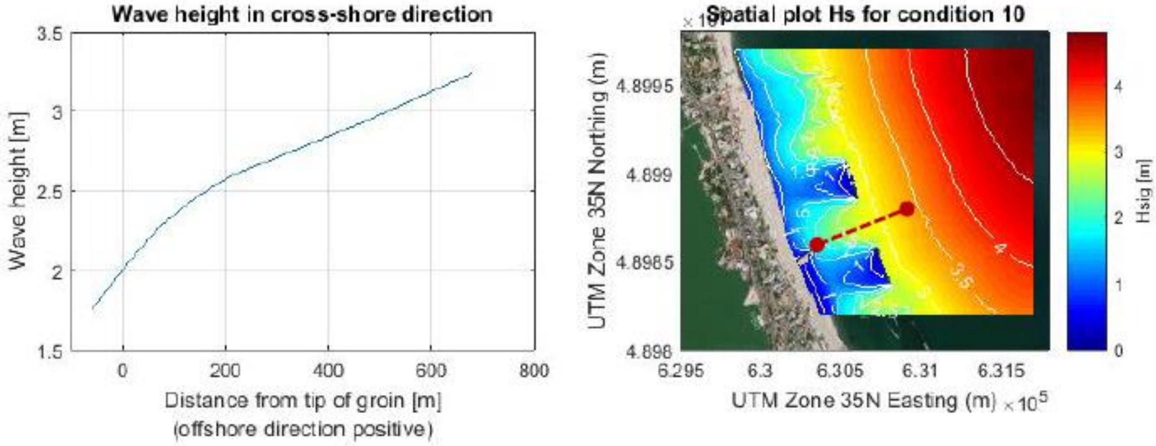


Figure 7.3: Wave height evolution perpendicular to the beach (left) and Hs spatial plot (right) for condition 10; section perpendicular to the beach indicated by red dotted line

The wave height for condition 10 – 1 / 100 year storm with Hs = 7.07 m, Tp = 10.97 s, u10 = 19.78 m/s, WL = 0.98 m and Dir = 60° – is shown in Figure 7.3. A cross section of the wave height is shown in Figure 7.3 (left) and the spatial variation is indicated in the figure on the right. The decrease in wave height is due to shallower depths leading to wave breaking and partly due to the displaced offshore breakwaters, MM3 and MM4. The direction of waves near the shore is about 70-75°, a direction that is perpendicular to the coast. Table 7-2 shows the design conditions at the loc110 location.

Table 7-2: Design conditions for waves for location loc110

Condition	Recurrence period [years]	Offshore wave/ wind direction [°N]	Water level [m MN75]	Average wave direction [°]	Wave crest direction [°]	Significant wave height H_{m0} [m]	Wave crest duration T_p [s]	Mean absolute wave duration T_{mm10} [s]	Directional propagation [°]
Condition	Perioadă de recurență [ani]	Direcție val/vânt în larg [°N]	Nivelul apei [m MN75]	Direcția medie a valului [°]	Direcția vârfului valului [°]	Înălțimea semnificativă a valului H_{m0} [m]	Durata vârfului valului T_p [s]	Durata medie a valului absolut T_{mm10} [s]	Propagare direcțională [°]
1	1/1 HWL	345-15	0.57	61.8	67.5	1.22	6.24	5.24	4.09
2		15-45	0.65	71.5	72.5	1.84	7.39	6.73	6.01
3		45-75	0.63	76.4	77.5	1.93	8.39	7.76	7.07
4		75-105	0.58	80.0	82.5	1.75	8.41	8.00	6.93
5		105-135	0.52	85.3	87.5	0.98	7.42	6.57	4.42
6		135-165	0.50	100.6	92.5	0.37	5.28	3.44	1.79
7		165-195	0.50	102.9	92.5	0.59	7.56	5.32	2.17
8	1/100 HWL	345-15	0.75	69.2	72.5	1.92	7.75	7.25	6.22
9		15-45	0.98	75.5	77.5	2.18	9.75	9.02	8.21
10		45-75	0.98	78.9	82.5	2.28	11.3	10.94	9.99
11		75-105	0.79	81.3	82.5	2.10	10.36	10.18	9.09
12		105-135	0.71	85.4	87.5	1.88	9.43	8.93	7.34
13		135-165	0.62	90.9	92.5	1.01	8.44	6.90	3.68
14		165-195	0.56	96.2	92.5	0.90	10.93	7.19	2.95
15	1/100 LWL	345-15	0.28	70.1	72.5	1.74	7.76	7.32	6.39
16		15-45	0.52	75.7	77.5	1.98	9.81	9.07	8.32
17		45-75	0.52	78.9	82.5	2.06	11.31	10.97	10.05
18		75-105	0.33	81.0	82.5	1.90	10.37	10.20	9.10
19		105-135	0.25	85.0	87.5	1.71	9.44	8.98	7.41
20		135-165	0.16	89.6	87.5	1.02	8.42	7.02	3.79
21		165-195	0.10	94.9	92.5	0.90	10.94	7.28	3.03

8. CONCLUSION

Metocean operational conditions and coastal design conditions are studied in this report. The wave climate is dominated by marine wave conditions. Two dominant directions are observed ENE (~ 60°N) and SSE (~ 150°N). The biggest waves are observed in the winter period, from November to March. At structure RJ1, the waves show a more uniform wave direction from the east (~90°N) due to refraction towards the coast. Due to wave breaking at shallower depths, wave heights decreased significantly near structure RJ1.

The operational conditions for the waves calculated with the undulatory model are compared with the measurement data. The wave height shows a relatively good match with the beacon-measured data, resulting in a root mean square error value of 0.22 and a correlation coefficient of 0.88. Wave duration has a lower correlation of 0.66 and RMSE (root mean square error) of 1.21. The peak-to-wave duration is generally less than one second from the measured values. It is concluded that the wave model is suitable to determine the design conditions.

Offshore design conditions were determined for recurrence values of 1, 5, 10, 25, 50 and 100 years. The main variable is wave height and the associated P-50 Tp and U10 values are calculated. Offshore design conditions are converted to nearshore conditions with the SWAN wave model.

Extreme value analysis (AVE) uses a peak-over-threshold analysis with generalized Pareto distribution (DPG) on the data. The highest condition for offshore waves with PR of 1/100 years has Hs = 7.07m, Tp = 10.97s, u10 = 19.78 m/s, WL = 0.98m, and Dir = 60°N.

Nearshore wave data are derived with the SWAN numerical wave model along the stretch of the beach, covering depths between ~3m and 14m. In the area of the breakwater, several locations are chosen on the sides of the wall and in the transverse direction of the RJ1 structure. Conditions for the highest waves with a PR (recurrence period) of 1/100 years in the nearshore area at 44.3°N 28.7°E have a Hs = 4.77m, Tp = 11.3s and a mean wave direction of 89.0° N. At structure RJ1, location 44.2°N 28.6°E, the condition with a PR of 1/100 years was reduced to a Hs = 2.28m, Tp = 11.3s, and a mean wave direction of 78.9°N.

9. REFERENCES, ABBREVIATIONS, DEFINITIONS

9.1. References

Client's documents

No.	Document no.	Document title
[A.1]		Contractual requirements

Boskalis' documents

No.	Document no.	Document title
[B.1]	64210030-GEN-SUR-RE-014	Report on bathymetry design measurements

Third party documents

No.	Document reference

[1] Infoplaza Marine Weather BV, „Wind and wave data for a location in the Black Sea,” (Date despre vânt și valuri pentru o locație din Marea Neagră) 2019.

[2] Delft University of Technology, [Online]. Available: swanmodel.sourceforge.net.

[3] C. Bondar, „The Black Sea level variations and the river-sea interactions,” (Variațiile nivelului Mării Negre și interacțiunile râu-mare) 2007.

[4] Halcrow Romania S.R.L., „Wave Modelling Report,” (Raport privind modelarea valurilor) 2011.

[5] ROMAIR Consulting, „Wave Propagation from Offshore to Nearshore Report – Mamaia,” (Raport privind propagarea valurilor dinspre larg către linia țărmului – Mamaia) 2015.

[6] G. van Vledder and A. Akpinar, „Spectral partinioning and swells in the black sea,” *Proceedings of the 35th International Conference on Coastal Engineering, (Partiționare spectrală și hule în Marea Neagră, „Proces-verbal al ediției 35 a Conferinței Internaționale pentru Inginerie Costieră”)* vol. 35, pp. 199-212, 2016.

[7] Y. Goda, „Random seas and design of maritime structures,” *Advanced series on ocean engineering, (Mări aleatorii și proiectarea structurilor maritime, „Serie avansată despre ingineria oceanică) World Scientific Publications*, vol. 15, 2000.

[8] S. Grishin, „Conceptual design of a development scheme for blocks in the Romanian sector of the Black Sea,” (Proiectarea conceptuală a unei scheme de dezvoltare a blocurilor din sectorul românesc al Mării Negre) Universitatea din Stravanger, 2014.

[9] Boskalis, „DECLARAȚIE PRIVIND METODA DE LUCRU,” 2017.

9.2. Abbreviations

Abbreviation	Full definition
RV	Recurrence value
RP	Recurrence period (/interval)
DSWBA	„Dobrogea Litoral” Water Basin Administration

Abbreviation	**Full definition**
RWNA	The National Administration of Romanian Waters
LIOP	Large infrastructure operational program
EVA	Analysis of extreme values
GPD	Generalized Pareto distribution
RMSE	Root-Mean-Square-Error
CorCoef	Correlation coefficient

9.3. Definitions

Definition	**Full definition**
°N	Direction in nautical convention
Hs	Significant wave height
Tp	Period of extreme waves
$T_{1/3}$	Period of significant waves
U_{10}	Wind speed at an altitude of 10 meters

10. <u>ANNEXES</u>

10.1. Offshore data fact sheet

10.2. Analysis of extreme values

10.3. Output locations

10.4. Checking the shape of the storm

10.5. Model performance

-Translation from Romanian-

Offshore wind and wave data as information for the detailed design stage of Romanian beaches – Mamaia area (lot 2)

Fact Sheet

Prepared for:	**Boskalis**
Care of:	**Jordi Hoek**
Date:	**16/12/2019**
Your reference:	-/-
Our reference:	**2019-032x**

Document status page

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Author(s):	Joris de Vroom
Examiner(s):	Peter Groenewoud
Title:	Offshore wind and wave data as information for the stage of detailed design of Romanian beaches - Mamaia area (lot 2)
Subtitle:	Fact Sheet
Our reference:	2019 – 032x
Issue date:	16/12/2019
Prepared for:	Boskalis
Care of:	Jordi Hoek
Your reference:	-/-
Comments:	

Delivery factsheet
This document was prepared by Infoplaza Marine Weather (Infoplaza).

Title
Offshore wind and wave data as information for the detailed design stage of Romanian beaches – Mamaia area (lot 2).

Description
We provide wind and wave time series for a location in the Black Sea. Hourly wind and wave data were taken from our back-estimated data with the WaveWatch III code for the Black Sea (15' x 15" resolution).

Location and area of interest
The output model point used to provide the data is characterized in Table 1 and Figure 1. Based on an evaluation, this location is considered the best for the project area.

Table 1 WW3 The global grid point and area used to provide the data

Description	Latitude	Longitude	Depth (m)	Grid	Resolution
Point on the wave model grid	44°00'N	29°30'E	69	Black Sea	15'x15'

Image source: Google Earth

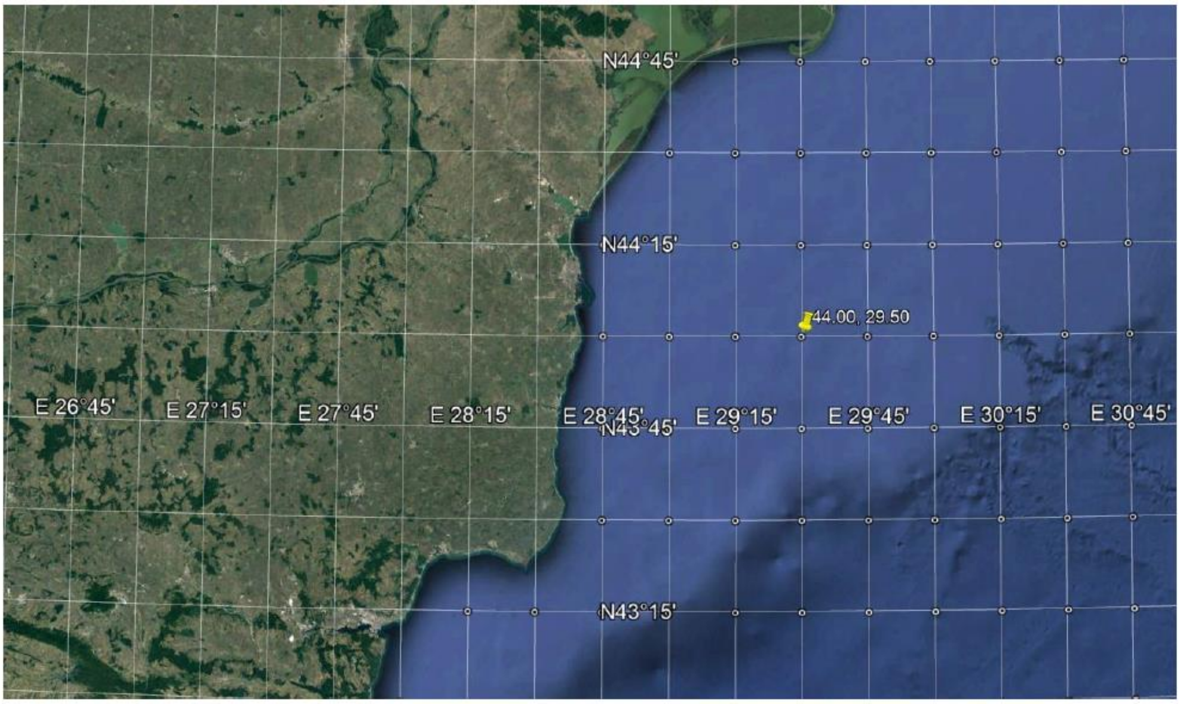


Figure 1 WW3 point on the model grid providing wind and wave date (yellow marker) and all points on the wave model grid in the area (white circles)

Frame of reference

(a) Definitions and notation

- **2D *S*-wave spectrum**
  The 2D spectral energy density describes how the sea surface elevation variation is distributed over spectral frequency and spectral direction. It is often referred to as a fully real 2D wave spectrum. There are 35 spectral frequencies (equally distributed on a logarithmic axis between 0.0345 and 0.8827 Hz) and 36 spectral directions (centers with 10-degree-wide bins) expressed in radians.

- **Quasi-2D / 1D wave spectrum**
  The 1D spectral energy density describes how the sea surface elevation variation is distributed over frequency f. It is often referred to as the 1D wave spectrum. Along with the mean wave direction and directional propagation per frequency basin, the 1D wave spectrum is also referred to as the quasi-2D wave spectrum. This is related to the fact that real 2D spectra can be simulated from quasi-2D spectra assuming a cosine-squared directional distribution of energy density based on directional propagation around the mean wave direction per frequency.

- **Spectral moment m_p**
  For any integer p (number), m_p is the integral over the frequency f of f^p multiplied by the wave spectrum with the frequency f in cycles per unit of time. Observation: m_0 is the total variation in the sea surface elevation.

- **Wave height *H***
  This is the crest-to-trough height of an individual wave between two consecutive crossings of the standing water level.

- **Significant wave height *Hs***
  Average H-wave height for 1/3 of the tallest waves. Except in shallow water, *Hs* is closely approximated by *Hm0*, defined as 4 times the standard deviation of the surface vertical displacement (4 x square root of the spectral moment m0). In this report and all the files of results, we have approximated *Hs* using *Hm0.*

- **Main wave direction *Hsd***
  The direction derived from the first-order directional Fourier moments (weighted sine and cosine moments) of the directional wave spectrum. Wave direction is defined as "coming from". It can also be defined for (a) limited range(s) of frequencies and plotted as a function of frequency.

Zero level crossing period T
The time elapsed between two consecutive crossings of the standing water level.

Average Zero Crossing Periods (Tz)
Average zero crossing periods T for a given sea state. Tz is approximated by Tz ≈ Tm0.2 (see moment-based wave duration).

- **Wave duration based on spectral moments $Tm_{p,q}$**
  $Tm_{p.q} = (m_p/\ m_q)^{1/(q-p)}$ with spectral moments m_p and m_q, with p and q as two distinct integers. Here, $Tm_{-1,0}$ and $Tm_{0,2}$ are referred to as the mean wave durations (***Tm***) and the mean zero-crossing periods (***Tz***), respectively.

- **Zero crossing period T**
  The time elapsed between two consecutive crossings of the standing water level.

- **Average of the crossing periods at zero level *Tz***
  The average of the **zero crossing periods** *T* for a given sea state. Tz is approximated by $Tz \approx Tm_{0,2}$ (see moment-based wave duration).

- **Peak-wave frequency *Fp***
  This is the frequency at which the wave spectrum reaches its maximum value.

- **Duration of the peak-wave *Tp***
  The duration corresponding to the frequency at which the spectral density reaches its maximum value.

- **The direction of the peak-wave *Pd***
  This is the direction of the waves that corresponds to the peak-wave frequency.

- **Wave length** λ
  The horizontal distance between two consecutive crossings of the standing water level in the direction of wave propagation.

- **Wave curvature parameter *s***
  A dimensionless parameter defined as the ratio of the significant wave height Hs to the deep water wavelength corresponding to the wave period $Tm_{-1,0}$, for example, $Tm_{-1,0}$, ex., $s= (2\pi/g)\ Hs/(Tm_{-1,0})^2$

- **Directional propagation**
  This is the weighted average of the directional propagation of energy for the total spectrum (**propagared**) or the directional propagation at the peak-wave frequency (**propagarep**).

- **Wind waves**
  When using a separator based on wave curvature, a spectral component (distinct peak) is classified as a wind wave if the wave curvature is s > 0.025. Note that this "engineering" definition does not take wind into account; just the curvature of the wave. Alternatively, a spectral peak is classified as a wind wave, if its group velocity is lower than the component of the wind velocity along its direction, i.e. the component is continuously increasing due to wind energy input. Most separators assume a single wind wave peak, but multiple wind wave peaks are possible. Corresponding parameters for the wind wave, such as ***Hs_sea***, ***Tp-sea***, etc., are found by applying the definitions of these parameters only to a particular peak of the wind wave. The total wind wave parameters can be found after summing the wave energy with the wind wave crests. In this study we used our standard separator based on wave curvature.

- **Swell waves**
  Any spectral component (distinct peak) that does not classify as a wind wave is classified as a swell wave component. Separators can find multiple wind wave peaks. The corresponding swell wave parameters, such as ***Hs_swl***, ***Tp_swl*** etc., are found by applying the definitions of these parameters to that specific storm wave peak only. The total parameters of the storm wave can be found by summing the wave energy with all components of the storm wave. In this study we used our standard separator based on wave curvature.

- **Wind speed u10 and wind direction *u10d***
  Sustained wind speed at 10 m above the surface (sea) and associated direction. Wind direction is defined as "coming from". "Sustained" means the average for 1 hour.

- **Gravitational acceleration *g***
  On Earth, taken equal to 9.81 m/s^2

(b) Units and Conventions

- Spectral density (2D) is expressed in m2/Hz/rad; spectral density (1D) is expressed in m2/Hz/rad
- Unless otherwise specified, units are expressed using the SI convention:
  - Length or distance (wave height, surface elevation, water depth) in meters,
  - Period (wave durations) in seconds,
  - Speed in meters per second,
  - Direction in degrees clockwise from North.
- Wind and wave (spectral) directions are defined as "coming from" relative to the applicable true north clockwise.
- Unless otherwise explicitly stated, coordinates are expressed in degrees of latitude and longitude, assuming a WGS84 coordinate system.

Conformity and fitness for purpose

If necessary, the data and methods proposed in this document comply with the relevant standards and guidelines (e.g. API 2Int-Met[1], ISO 19901-1[2], the ISO standard governing metocean activities for the offshore industry).

The paper was drafted by a qualified metocean data specialist and technically reviewed before publication. Infoplaza's quality management process is accredited to ISO 9001-2008.

Infoplaza offers a series of Metocean services, each with its own proposed purpose. It is important for the end user to assess the "fitness for purpose" of any particular service to avoid using the results beyond their originally intended limits.

The offshore wind and wave data provided in this delivery, in the context of the information available to us, is considered adequate to serve as input for further modelling and studies of ambient climate and severe climate for offshore locations. In this project we used satellite observation data to calibrate offshore wind speed and back-estimated data for wave height. In the absence of in situ observational data, this is generally accepted as a reliable way to validate the quality of offshore wind and wave modelling data.

For modelling studies and detailed design applications, additional validation with in situ observations near the actual study location is usually prescribed by certification authorities and/or warranty inspectors. Such in situ data were not available to Infoplaza at the time of the study. Additional modelling based on provided offshore conditions, quality control (based on in situ observations) and subsequent data analysis are the sole responsibility of the party performing such work and subsequently the end user.

If you have any doubts about the suitability of the information contained in this document for your specific purpose, or if you would like to discuss alternative services, please contact us at (info@infoplaza.nl), and an advisor with experience in Metocean will be happy to help you.

[1] American Petroleum Institute, 2007. Interim Guidance on Hurricane Conditions in the Gulf of Mexico. API Bulletin 2INT-MET, May 2007.

[2] ISO, 2005. Petroleum and natural gas industries, Specific requirements for offshore structures, Part 1 – Metocean design and operating considerations. ISO / FDIS 19901-1:2005 (E).

Calibration method

a) Retrospective estimated data for offshore

Infoplaza operates a third-generation wave prediction model based on the WaveWatch III code on a global network as well as several regional networks for hindcast and forecast data. The global model used by Infoplaza has a resolution of ½ºx½º. The model uses CFSR wind data provided by the Marine Modelling Division of the National Center for Environmental Prediction (NCEP).

In addition to the global model, Infoplaza also generated several retrospectively estimated regional data for the European continental shelf, the Mediterranean, the Black Sea, the Caspian Sea, the Red Sea, the Persian Gulf, Indonesia, the South China Sea, and Northwest Australia. Where appropriate, Metocean conditions from these higher-resolution retrospectively estimated regional data are used.

For the present study we used data from the Black Sea model. All models provide 3-h time series of wave spectra and hourly time series of integrated parameters (data for maps) covering a period of over 40 years (1979–near present, back-estimated data updated monthly) . For this hourly study, back-estimated data from map files were extracted for the years 1979-2019.

The retrospectively estimated data has been validated/recalibrated by Infoplaza (see next section).

b) Calibration of offshore wind and wave data

Systematic errors between significant ambient wave height and model and satellite wind speed are removed from the model by assuming a linear error model. Satellite measurements (1992–2018) were used to calibrate back-estimated model wind speed and significant wave height at the model point for the period (1979–2019).

Satellite observations were collected within a radius of 50 km around the model point. Satellite data collected over such a small region in a single satellite pass is highly correlated. To account for this, we only use the sample from the nearest satellite at each pass. The model data are then linearly interpolated in time to form matching pairs of satellite measurement data / modelled data that can be compared. The slope and intercept are calculated for each point on the waveform grid using the least squares method for the sorted data. This calibration results in a significant wave height and unbiased wind speed for the model compared to in situ satellite observations.

Figure 2 below shows the comparison of Probability of Exceedance (PoE) of significant wave height from proximity altimeter observations and retrospectively estimated calibrated data. Figure 3 provides a similar comparison between satellite-derived wind speed (scatterometer and altimeter) and retrospectively estimated calibrated data.

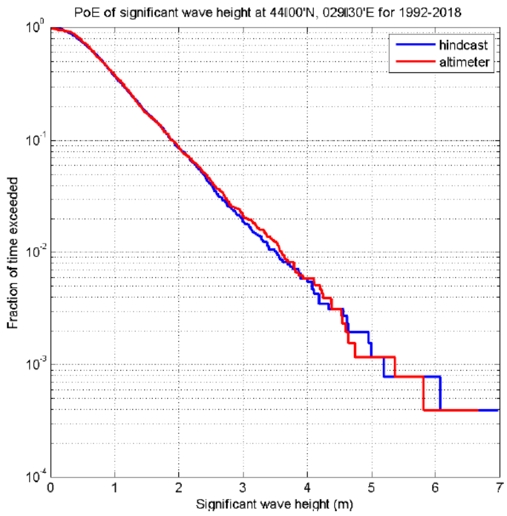


Figure 2: PoE of significant wave height from altimeter and retrospectively estimated data.

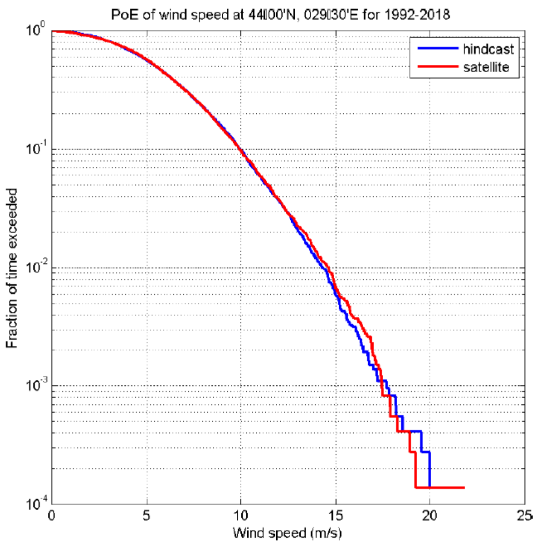


Figure 3: PoE of satellite-derived wind speed (scatterometer and altimeter) and retrospectively estimated data

Results

The time series for the integrated wind and wave parameters were written to the following file:

- calibrated_ww3_maps_4400n02930e.mat

The MATLAB file contains hourly time series records for the period 1979-2019. The location label refers to the coordinates of the location of interest. Wave and wind directions are labelled *„Hsd", „pd"* and *„u10d"*. The first data record refers to January 16, 1979, 00:00 (due to the rotation of the model), and the last data record to October 31, 2019, 21:00.

The file contains a MATLAB structure named 'S' with the following fields (if present, the symbol used in the reference frame is enclosed in parentheses):

- lon – Longitude of the location in degrees;
- lat – Latitude of the location in degrees north;
- t – Date and time as MATLAB serial number of date, with time in UTC;
- u10 – Wind speed, sustained for 1 hour, at 10 m above the surface (u10);
- u10d – Corresponding wind direction (u10d);
- hs – Significant wave height in meters (Hs);
- hsd – Main wave direction (Hsd);
- tm – Period of energy waves (Tm);
- tp – Wave peak duration (Tp);
- pd – Wave crest direction (Pd);
- depth – The water depth at the location, in meters;

-Translation from Romanian-

ANALYSIS OF EXTREME VALUES FOR
WAVE AND WIND CLIMATE

AVE Mamaia – 44N 29.5E

Author(s): J. Hoek
Contributor(s): -
Examiner(s): W. Jager

12 February, 2020

Table of Contents

1 Introduction

A short introductory paragraph about the scope of the report.

Table 1: Nomenclature

Abbreviation	Full name
RP	Recurrence period
RV	Return value
yr	Year

2 Project location and data

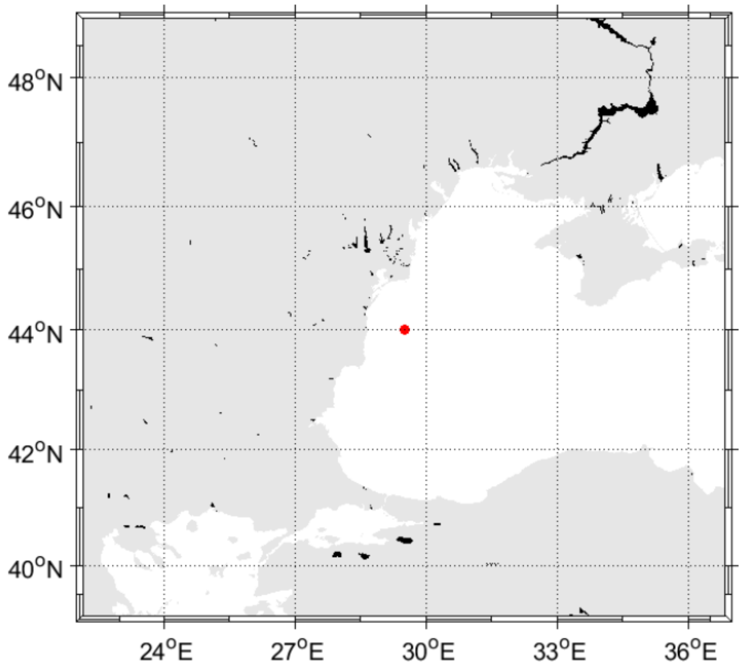
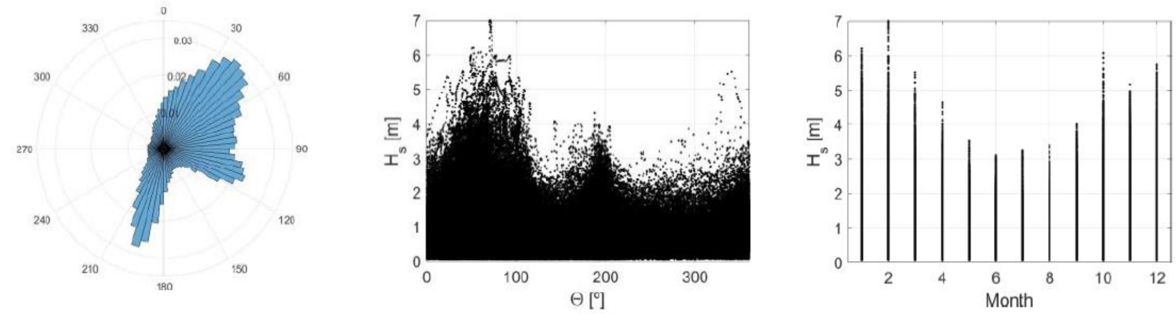


Figure 2: Data location

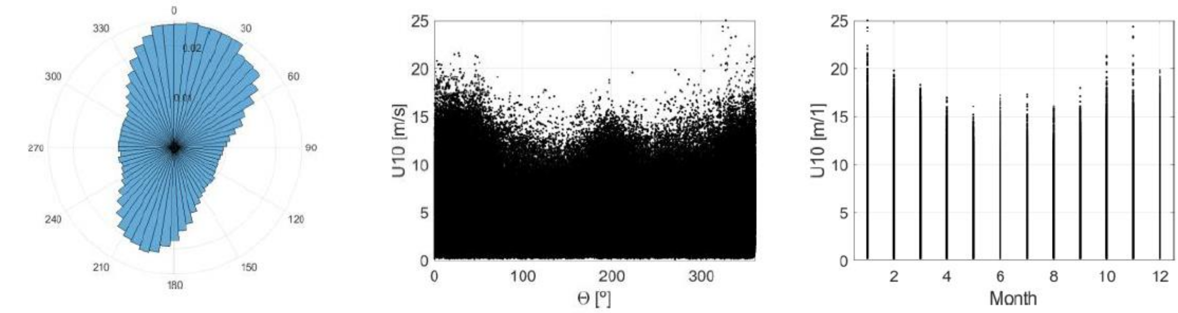
The data are available from Infoplaza. The data are retrospective estimates and have been calibrated by Infoplaza against the altimeter data. The location used is at Lon 29.5°E, Lat 44°N, at a depth of 69m. The time ranges consist of hourly data for a period of 41 years of data (1979-2019). The series includes significant wave height (Hs), associated spectral peak duration (Tp), zero crossing period (Tz), and input directions for total sea state. Also included are wind speed and direction at 10m height (U10).



(a) Wave direction

(b) Wave direction vs. *Hs*

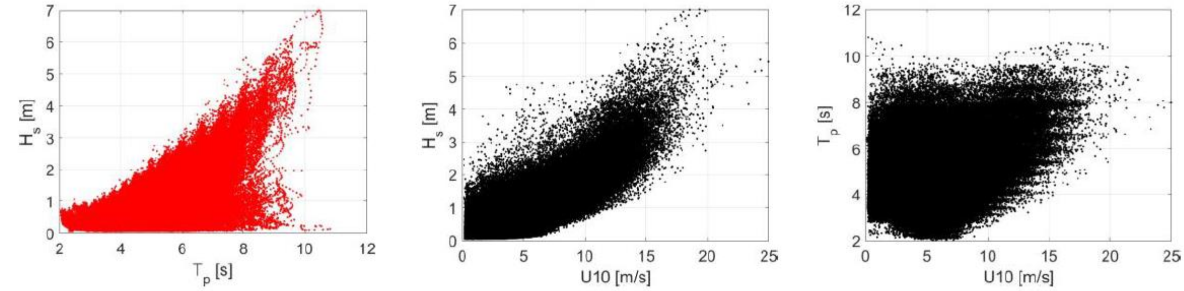
(c) Month vs. *Hs*



(a) Wind direction

(b) Wind direction vs. U_{10}

(c) Month vs. U_{10}



(a) Total sea state H_s vs T_p

(b) H_s vs. U_{10}

(c) T_p vs. U_{10}

3 Return values

3.1 Univariate recurrence values

3.1.1 Main variable values (Ws)

This section shows the results of a peak-over-threshold univariate analysis for Hs. Table 2 shows the recurrence values for different recurrence periods in each directional sector. An omnidirectional estimate is also included. Table 3 presents the 90% uncertainty intervals for all estimates, and Table 4 presents the selected thresholds, sample sizes, and parameters of the GPD distributions for each directional sector. More details on the concordance can be found in appendix A.1.

Table 2: Recurrence values for different directional sectors.

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
Data max.	24.98	22.30	21.58	21.31	17.52	17.82	17.06	17.81	19.60	16.78	19.85	21.34	24.98
1yr RV	17.84	15.73	15.22	13.64	11.09	10.55	10.70	12.91	13.30	10.22	11.47	12.68	14.62
5yr RV	20.28	18.51	17.74	17.37	14.45	13.64	13.71	15.43	15.55	13.11	14.75	15.21	17.78
10yr RV	21.48	19.54	18.80	18.54	15.37	14.80	14.65	16.21	16.44	13.87	16.22	16.03	19.38
25yr RV	23.21	20.78	20.15	19.79	16.26	16.19	15.65	17.03	17.57	14.58	18.20	16.92	21.73
50yr RV	24.65	21.63	21.16	20.55	16.75	17.15	16.26	17.53	18.37	14.97	19.73	17.48	23.73
100yr RV	26.21	22.40	22.14	21.18	17.13	18.04	16.76	17.93	19.14	15.26	21.30	17.95	25.92

Table 3: 90% uncertainty intervals for recurrence values for different directional sectors

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RV	[17.5,18.3]	[15,16.8]	[15.1,15.3]	[13.3,14.2]	[10.7,11.6]	[10.4,10.8]	[10.5,11]	[12.1,14]	[13.3,13.4]	[9.55,11.2]	[11.3,11.8]	[12.6,12.8]	[14.6,14.7]
5yr RV	[18.7,23.5]	[16.6,21.5]	[16.4,20.7]	[15.3,21.1]	[12.5,18]	[11.9,17]	[12.2,16.3]	[13.6,18.4]	[14.5,17.5]	[11.2,16.4]	[12.7,19.4]	[13.9,18]	[16.1,21.7]
10yr RV	[19.1,27]	[17.1,23.6]	[16.7,23.9]	[15.8,24]	[12.9,20.3]	[12.3,20.3]	[12.6,18.4]	[14,20]	[14.9,19.8]	[11.5,18.2]	[13.2,24.5]	[14.1,20.5]	[16.5,26.8]
25yr RV	[19.6,33.2]	[17.7,26.5]	[17,29.3]	[16.2,27.7]	[13.2,23.1]	[12.7,25.2]	[13,21.1]	[14.3,22]	[15.2,23.2]	[11.7,20.2]	[13.6,33.8]	[14.4,24]	[17.1,37]
50yr RV	[19.9,39.7]	[18,28.7]	[17.2,34.5]	[16.4,30.4]	[13.3,25]	[13,29.4]	[13.2,23.1]	[14.5,23.3]	[15.4,26.2]	[11.9,21.4]	[13.8,43.4]	[14.5,26.8]	[17.4,48.4]
100yr RV	[20.2,48.1]	[18.2,31]	[17.4,40.8]	[16.6,33.1]	[13.4,26.8]	[13.1,34.2]	[13.3,24.9]	[14.6,24.5]	[15.6,29.7]	[11.9,22.5]	[14,56.1]	[14.6,29.8]	[17.7,64.3]

Table 4: Thresholds, sample size and GPD parameters (shape and scale) for different directional sectors

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
Threshold	17.00	13.00	15.00	12.50	10.00	10.00	10.00	10.00	13.20	8.00	11.00	12.50	14.50
Sample size	77	154	47	60	59	53	55	143	44	88	52	45	44
Shape parameter	0.11	-0.12	-0.03	-0.27	-0.38	-0.12	-0.27	-0.28	-0.07	-0.42	0.03	-0.24	0.14
Scale parameter	1.29	2.24	1.61	3.16	3.21	2.17	2.50	2.76	1.48	3.40	1.98	1.94	1.74

Figure 7 shows estimates of directional and omnidirectional recurrence values. There are two estimates of omnidirectional recurrence rates:

1. the recurrence values represented by the dashed black line are based on a match for the data points in all directional recipients.

2. the recurrence values represented by the solid black line are based on the mathematical combination of the directional recurrence values.

In theory, the two estimates should be identical and at least as large as the largest directional estimates. In practice, discrepancies cannot be avoided due to sample size uncertainties. However, large differences indicate that either the omnidirectional match (dotted line) or at least one of the directional matches is inadequate.

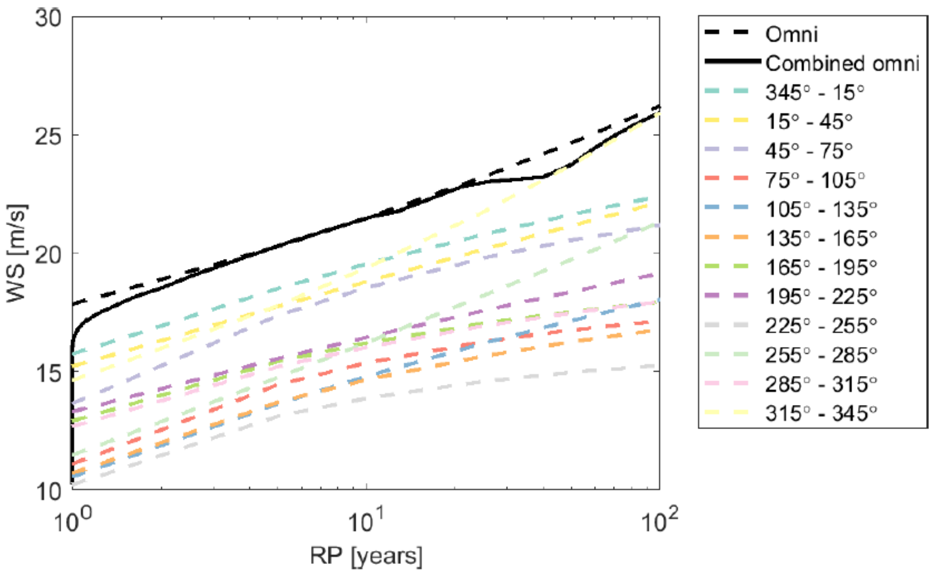


Figure 7: Directional and omnidirectional recurrence values

References

S. Coles, *An Introduction to Statistical Modeling of Extreme Values,* Vol. 208. London: Springer, 2001.

A. Diagnostic charts for concordance assessment

A.1 Main Variables (Ws)

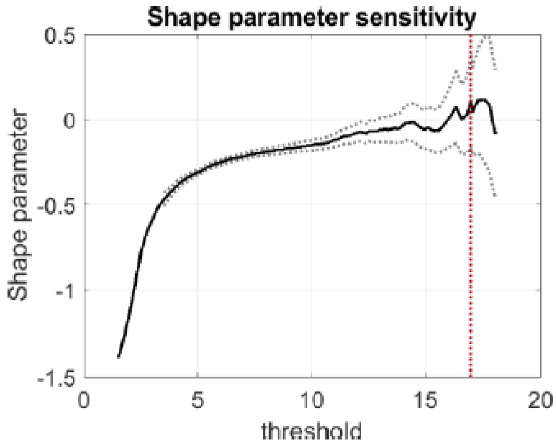
Concordance is assessed by six diagnostic charts. The first four charts evaluate the choice of threshold. The last two charts evaluate the quality of GPD concordance for the selected threshold. The first four plots show the shape parameter, scale parameter, mean residual lifetime, and recurrence value as a function of threshold. The optimal threshold is as low as possible, meeting the following criteria: Above the threshold

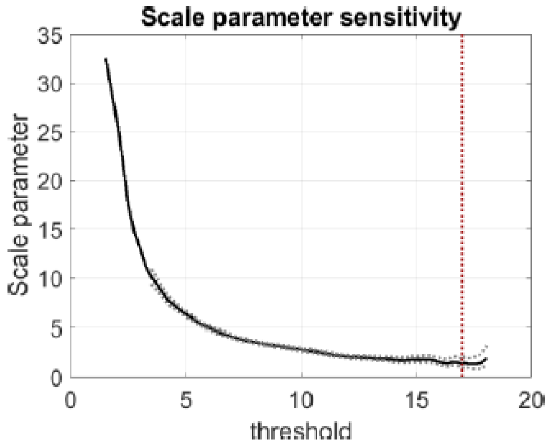
1. the shape parameter must be approximately constant,
2. the scale parameter must behave approximately linearly,
3. the average excess must behave approximately linearly and
4. the recurrence value must be approximately constant.

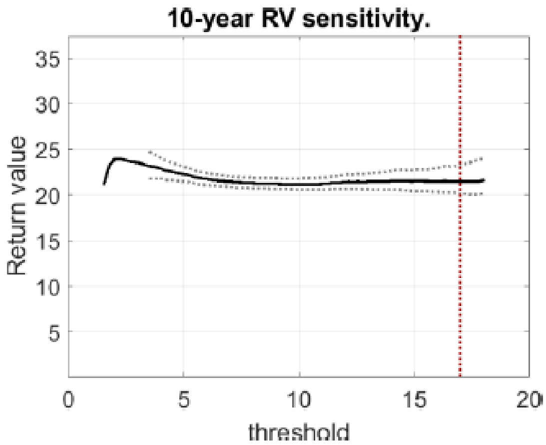
For very large thresholds, the information in the charts becomes unreliable because the sample size will be small. This is visible in the extended uncertainty ranges.

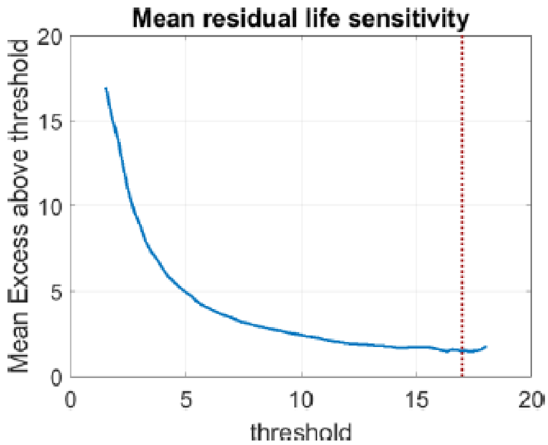
The last two charts are a qq-plot and a recurrence-value chart. In the qq plot, the quantiles of the empirical distribution and the GPp distribution are plotted against each other (blue crosses). The better the match, the closer the points are to the x = y line (red line). If the points are below the line, the adjusted GP distribution tends to overestimate the recurrence values. If the points are above the line, the adjusted GP distribution tends to underestimate the recurrence values. The recurrence value plot shows the GP recurrence values for their recurrence periods (black solid line). A 90% confidence interval is also shown (dotted grey lines) as well as empirical recurrence levels (blue crosses). The better the adjustment, the closer the empirical recurrence levels are to the GP recurrence values.

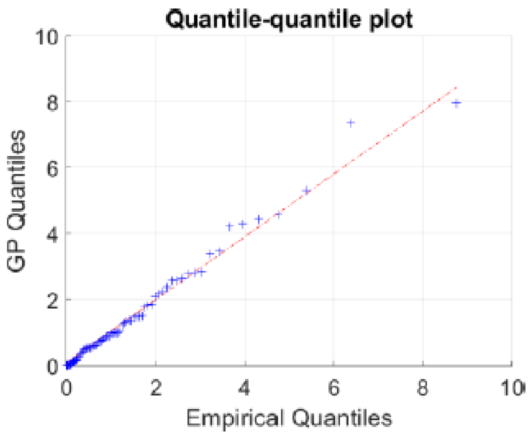
A.1.1 **Directional sector:** 0°-360°

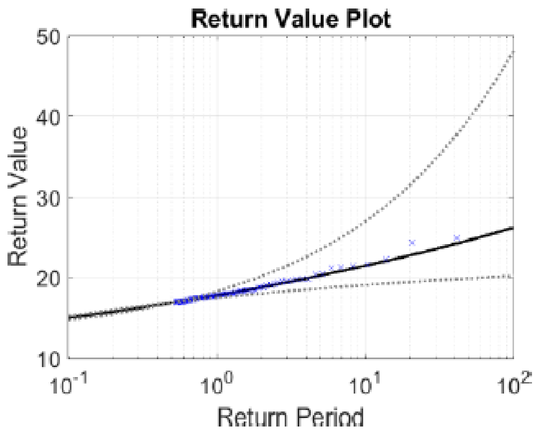




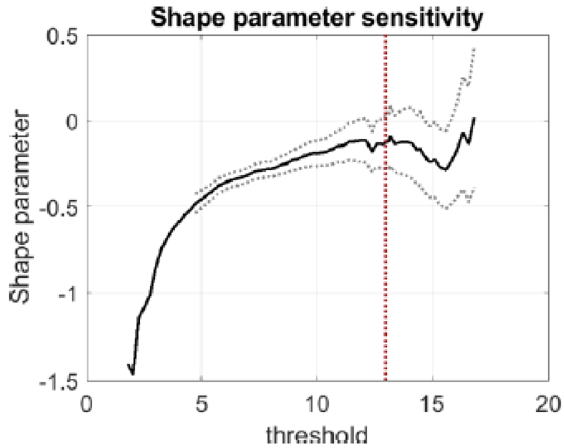


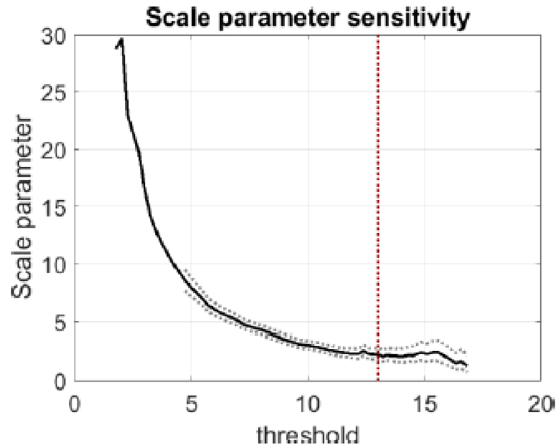


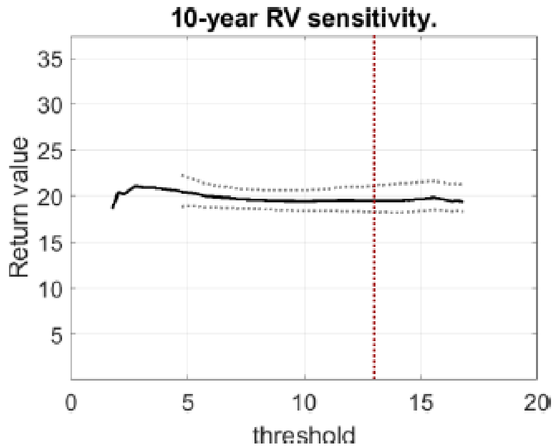


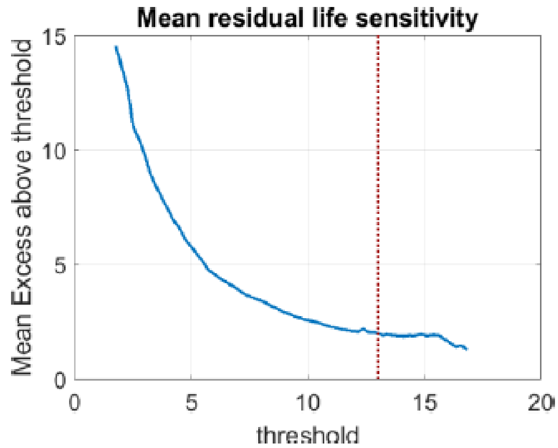


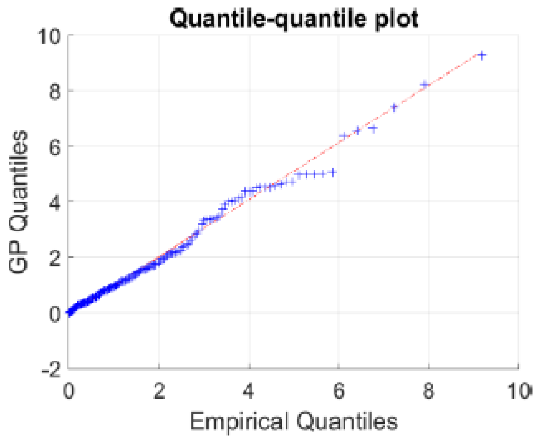
A.1.2 **Directional sector:** 345°-15°

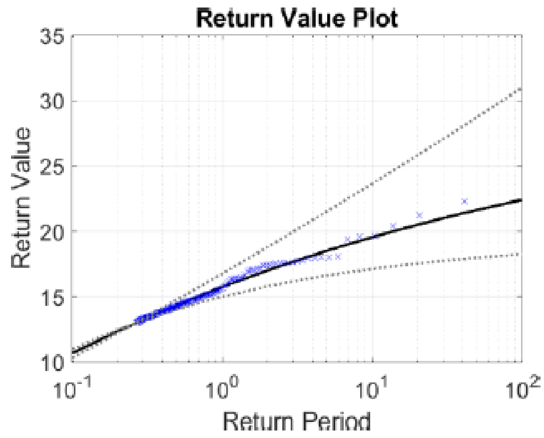




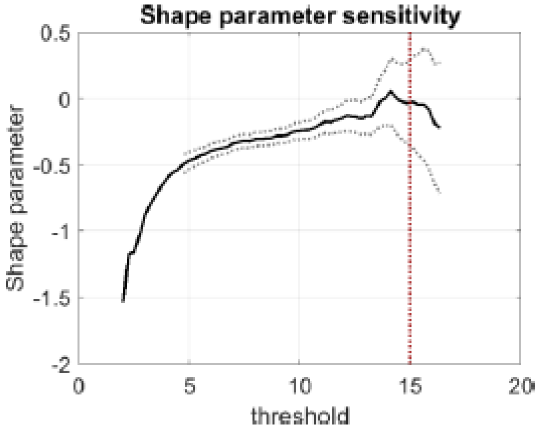


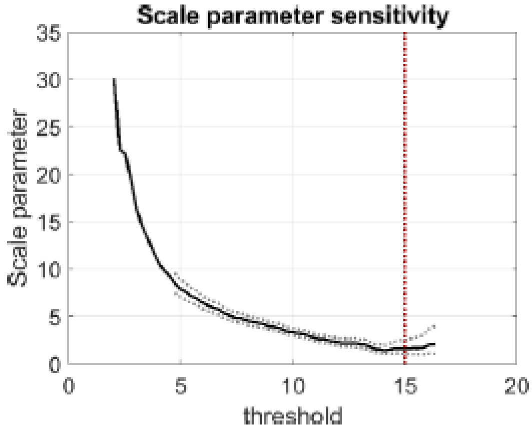


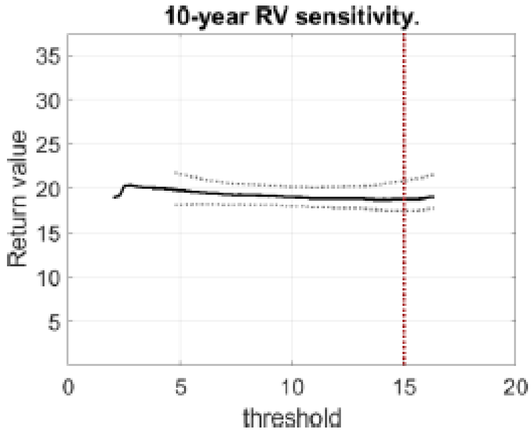


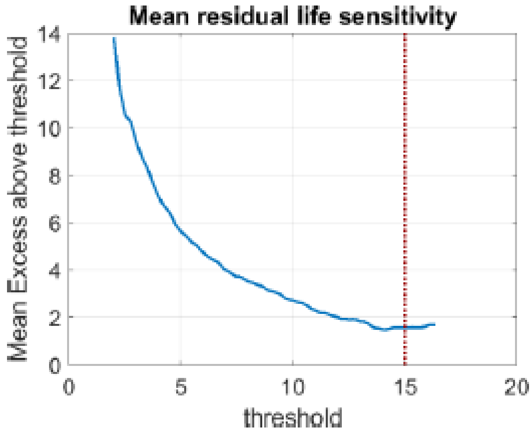


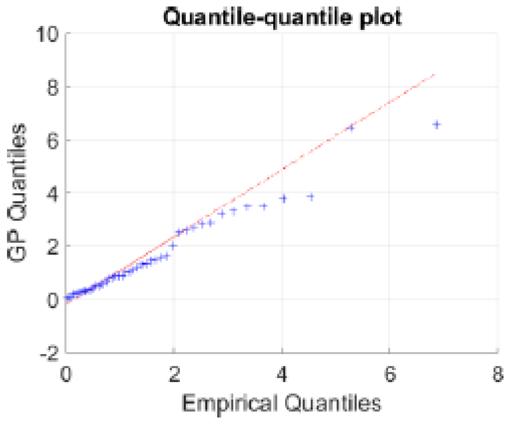
A.1.3 **Directional sector:** 15°-45°

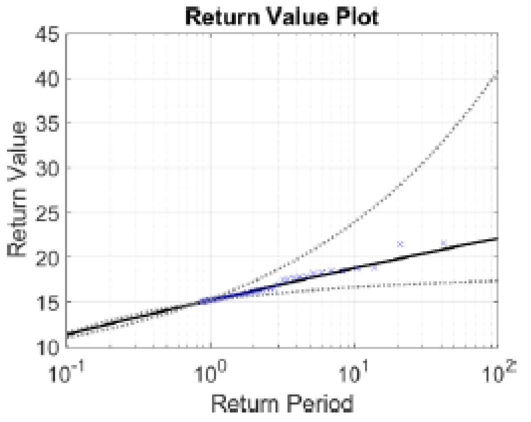




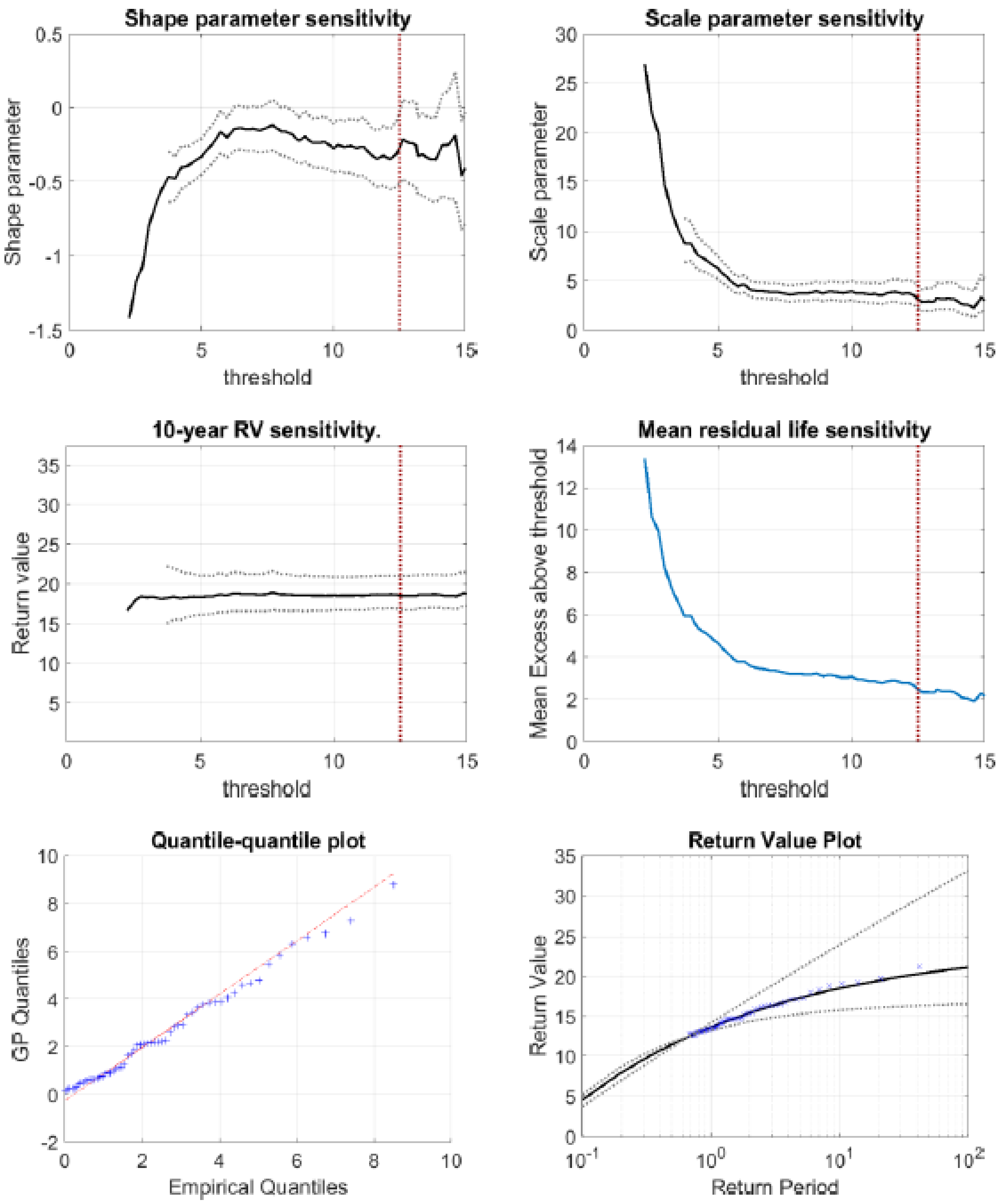




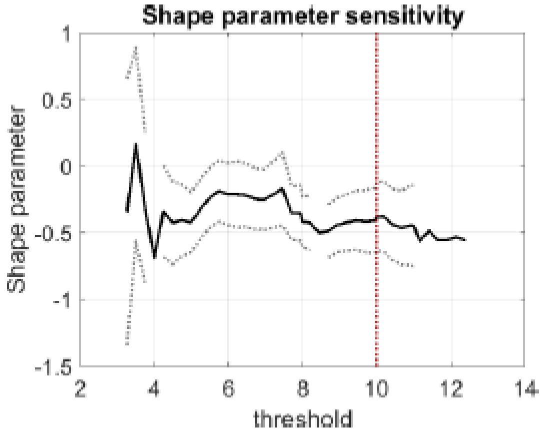


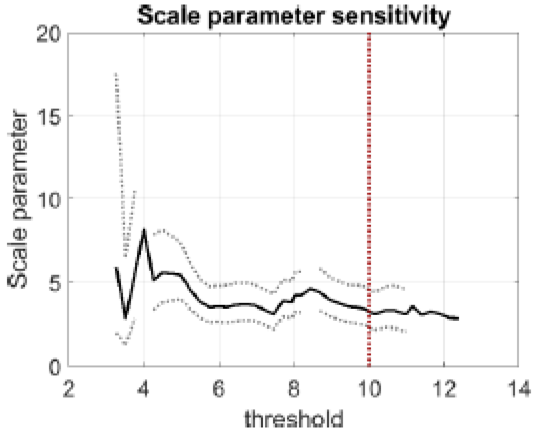


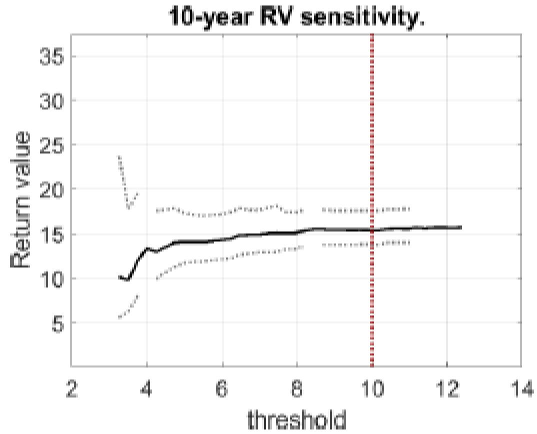
A.1.4 **Directional sector:** 45°-75°

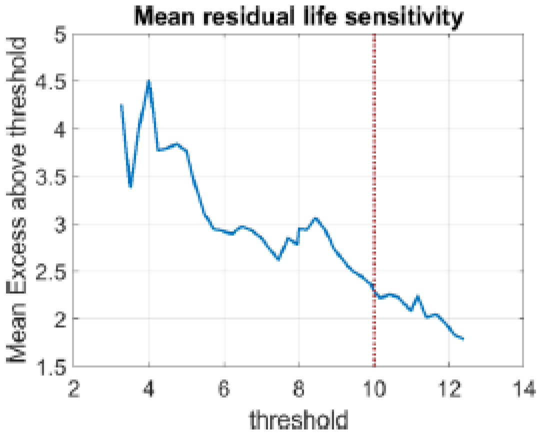


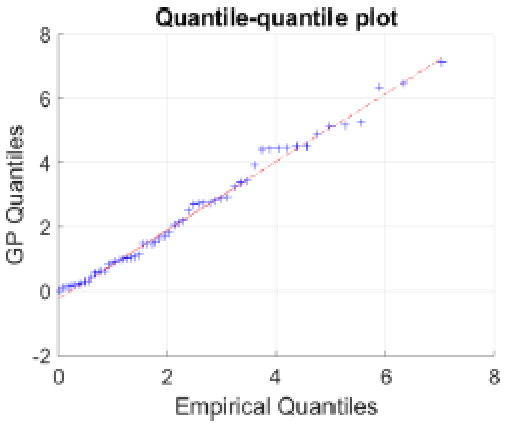
A.1.5 Directional sector: 75°-105°

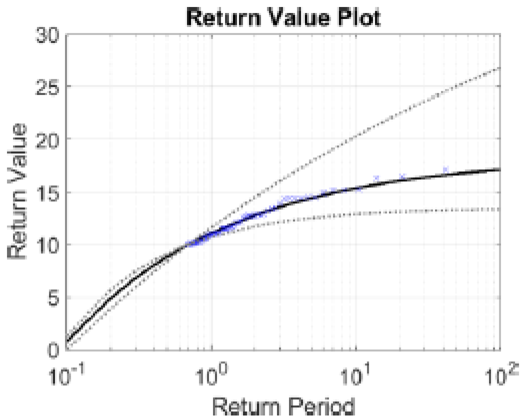




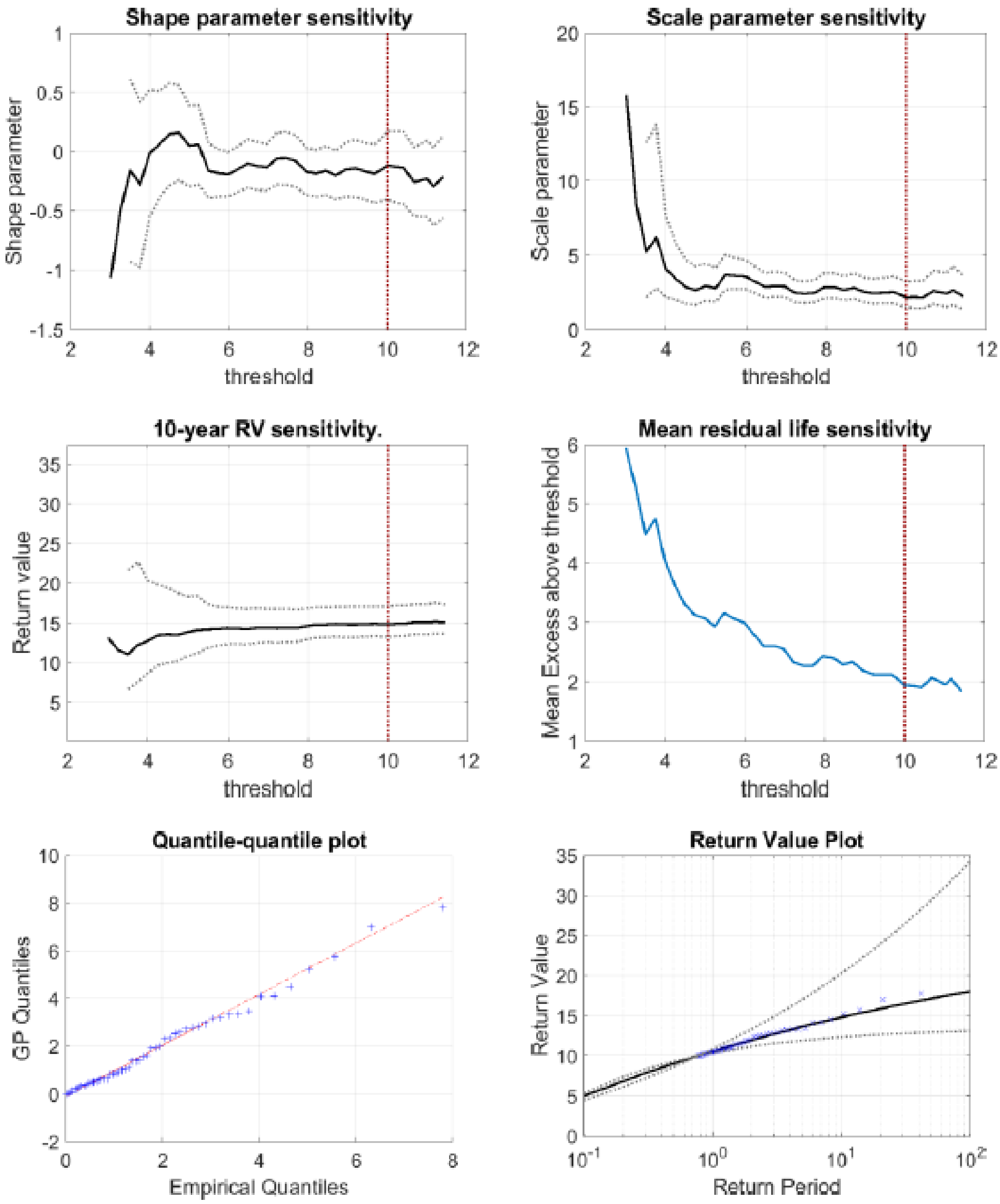




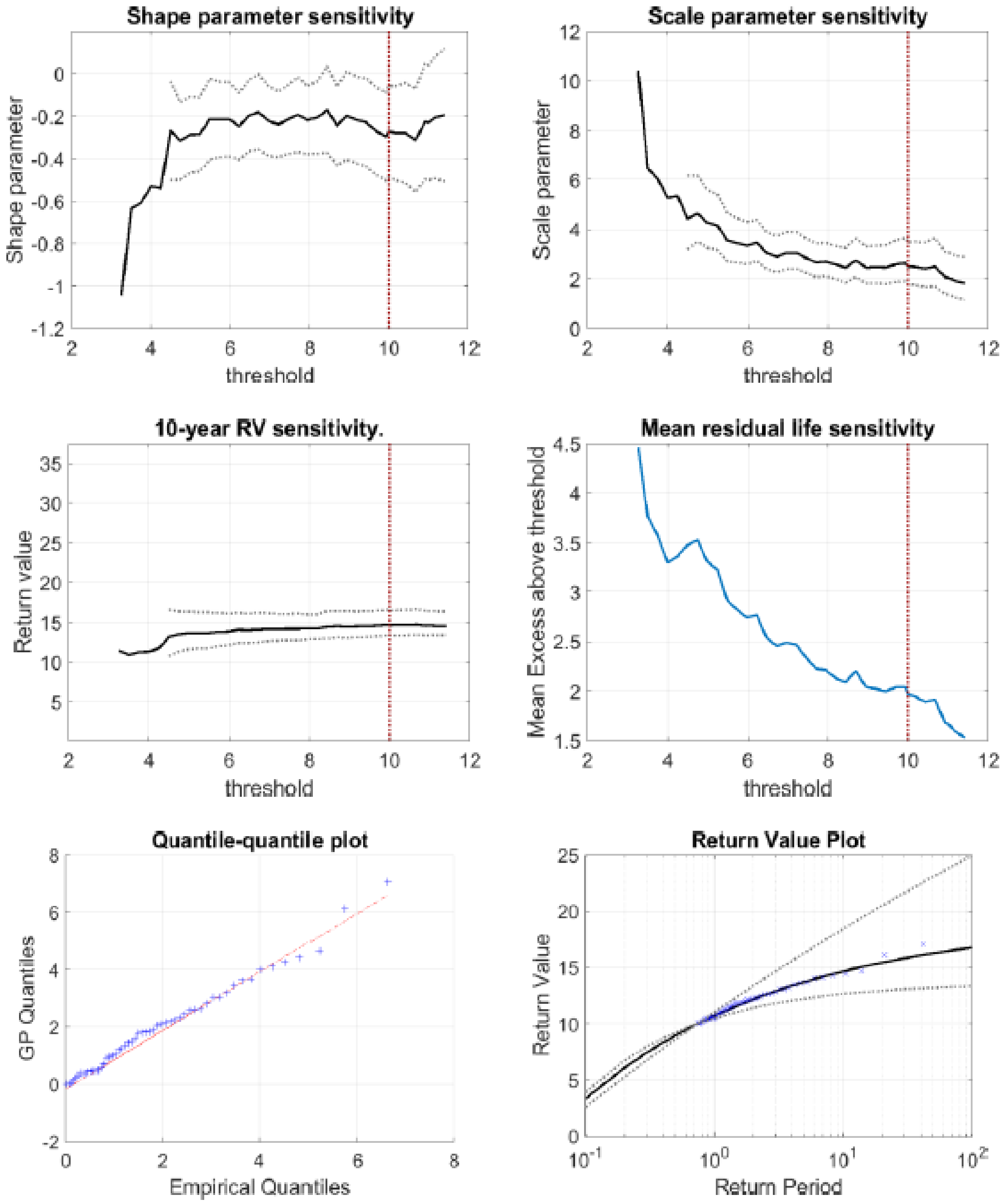




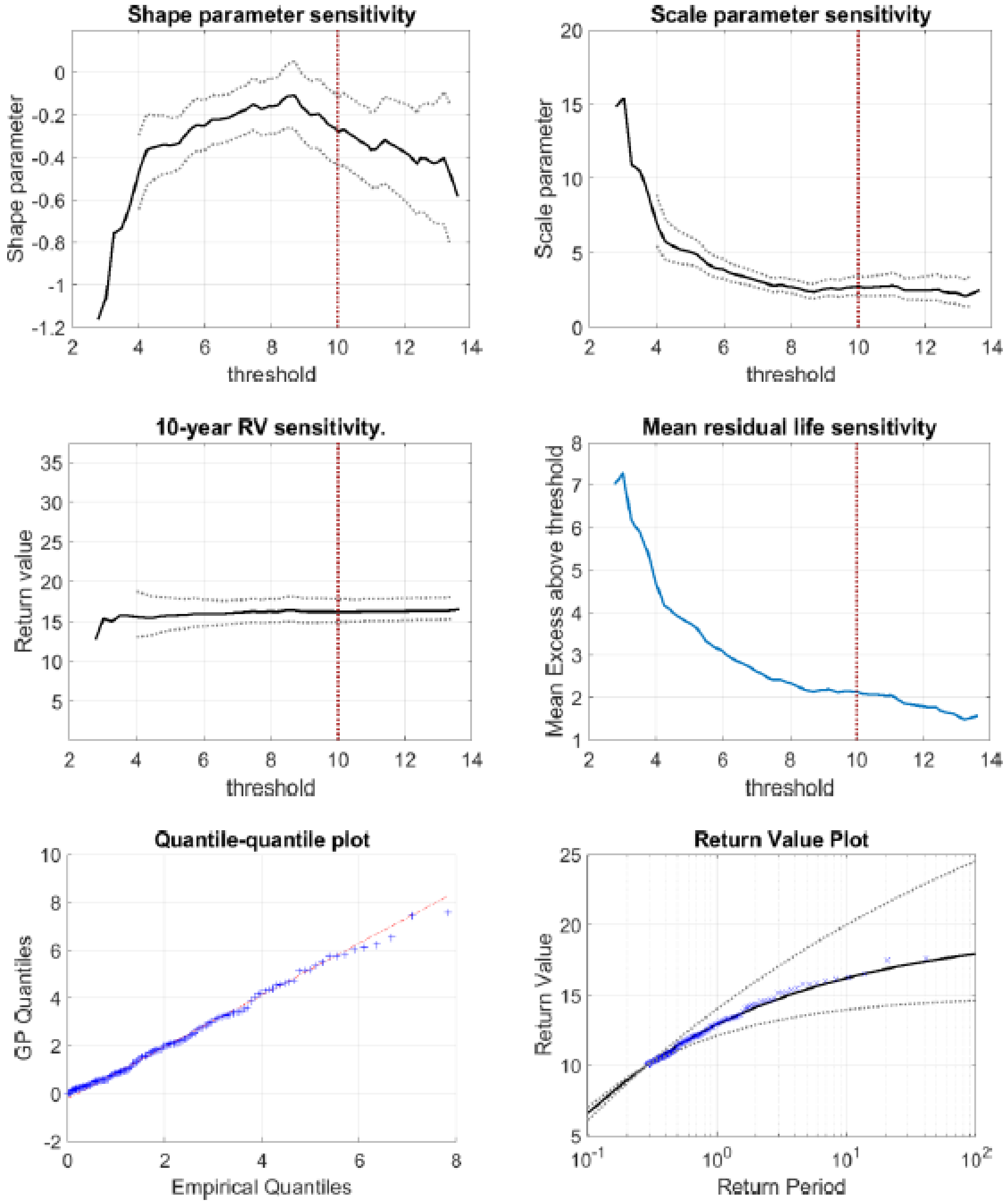
A.1.6 Directional sector: 105°-135°



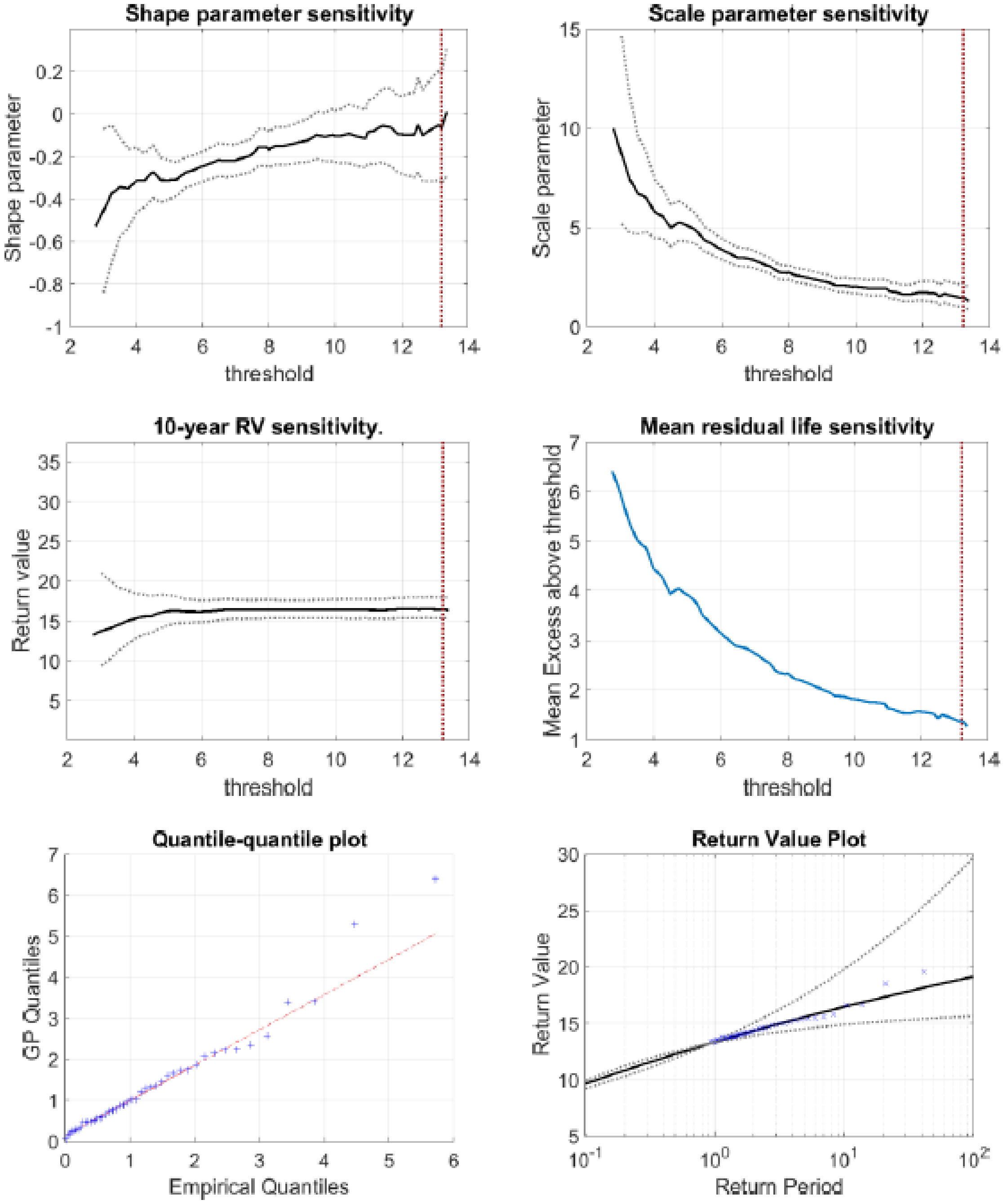
A.1.7 **Directional sector:** 135°-165°



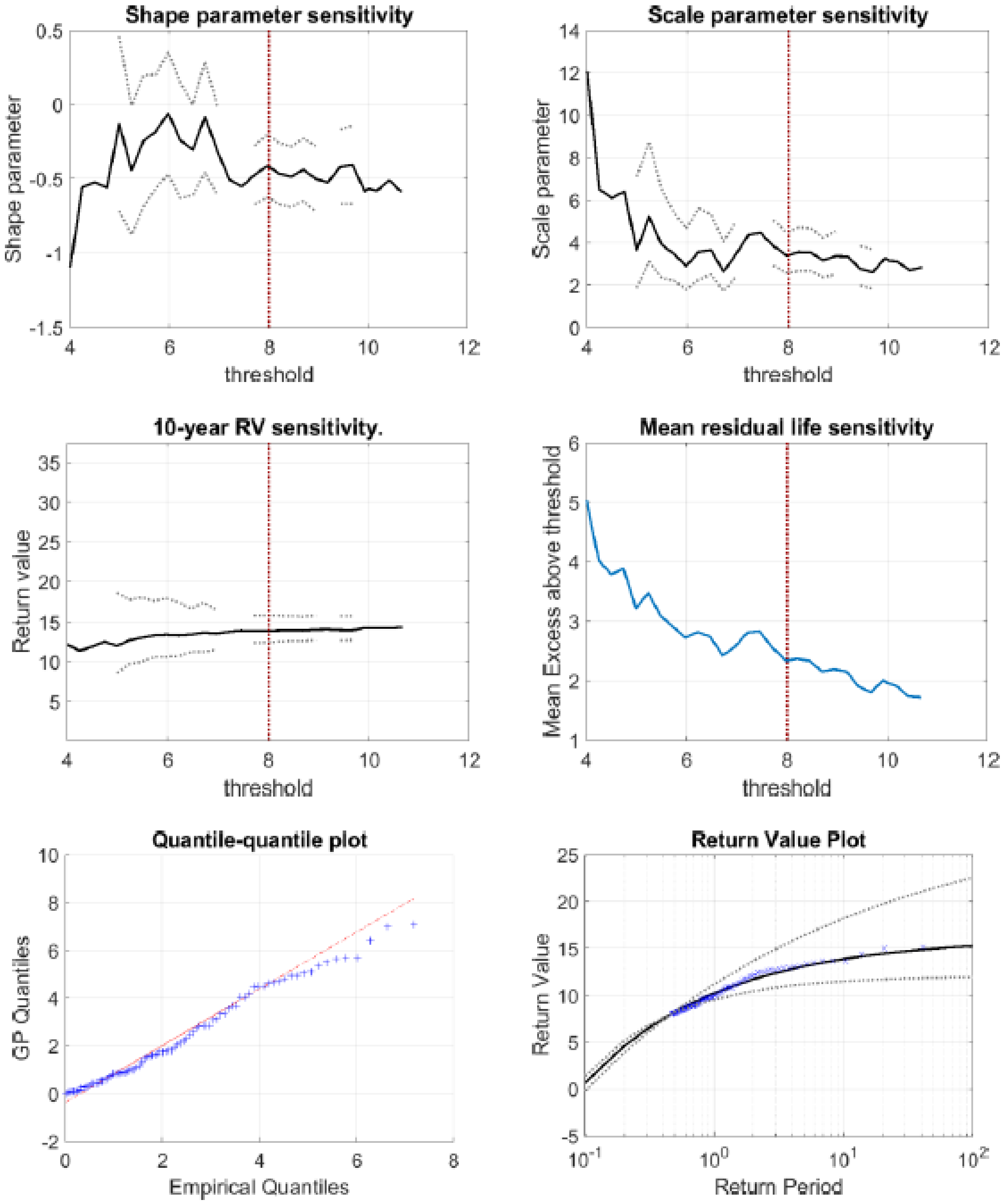
A.1.8 **Directional sector:** 165°-195°



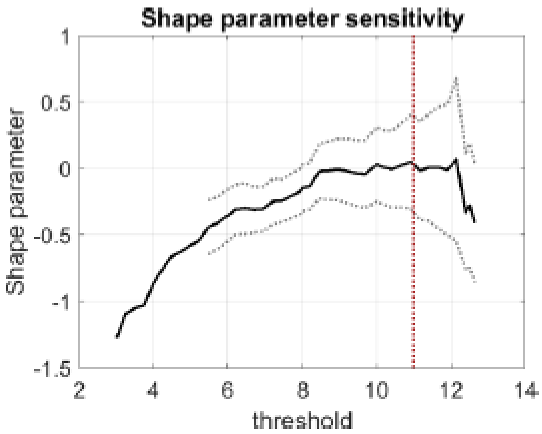
A.1.9 **Directional sector:** 195°-225°

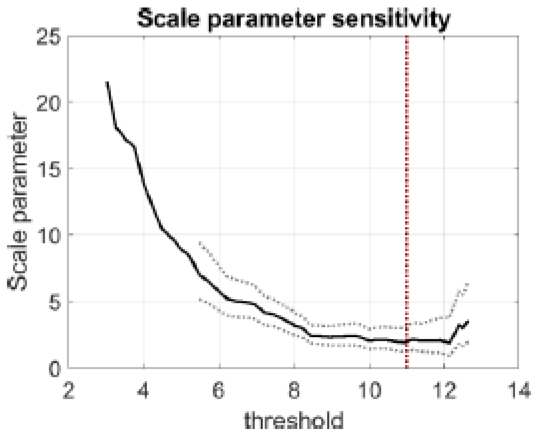


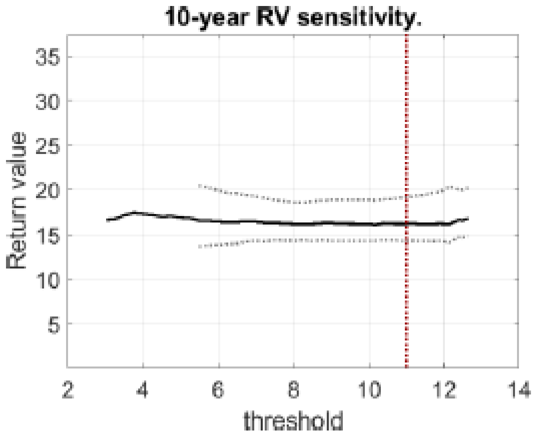
A.1.10 **Directional sector:** 225°-255°

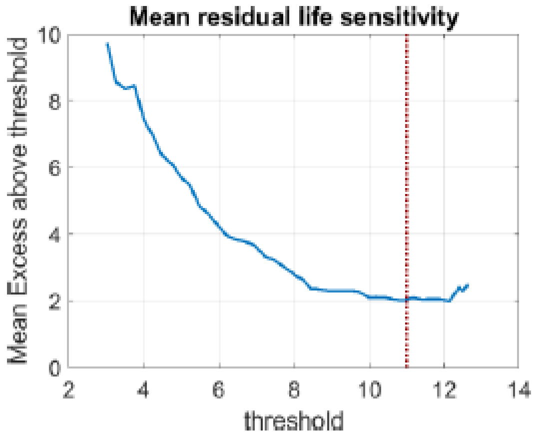


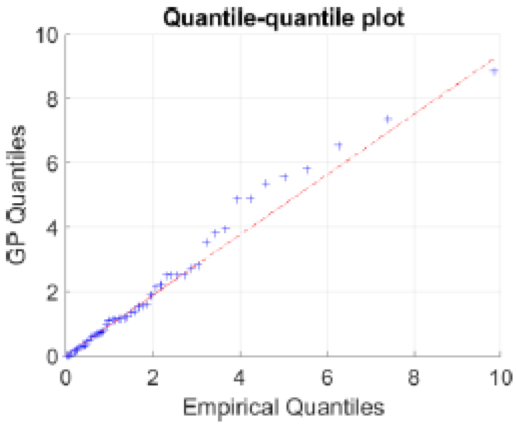
A.1.11 **Directional sector:** 255°-285°

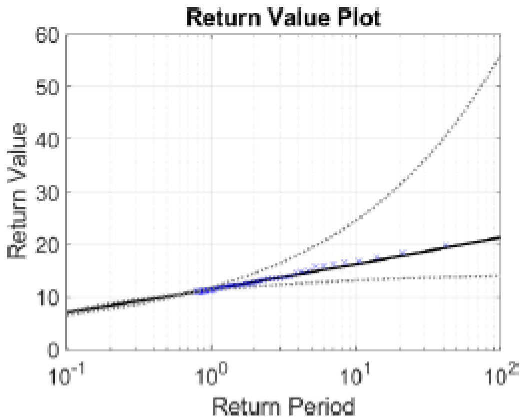




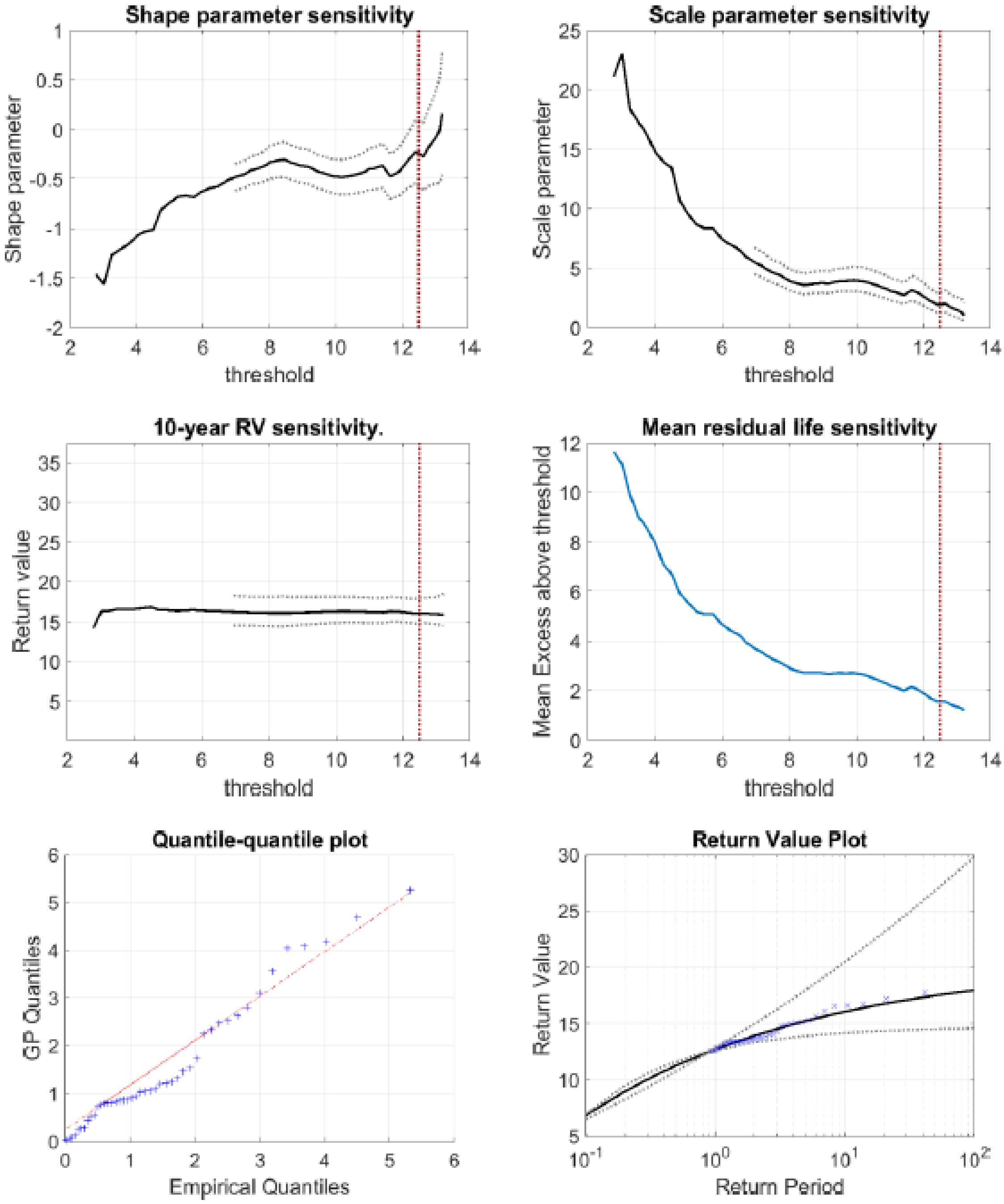




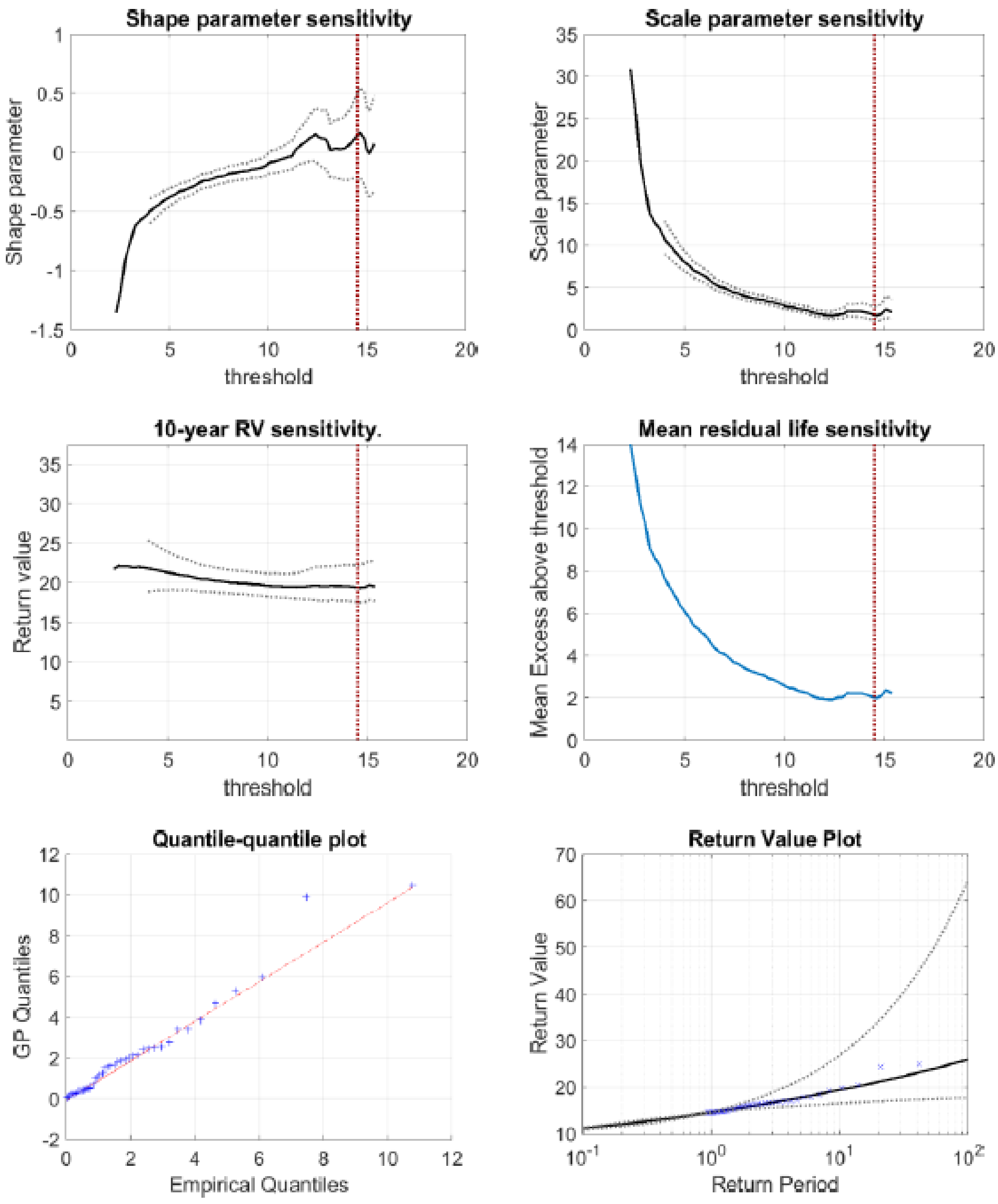




A.1.12 **Directional sector:** 285°-315°



A.1.13 Directional sector: 315°-345°



-Translation from Romanian-

ANALYSIS OF EXTREME VALUES FOR WAVE AND WIND CLIMATE

AVE Mamaia – 44N 29.5E

Author(s): J. Hoek
Contributor(s): -
Examiner(s): **Wiebke Jäger**

10 January 2020

Table of Contents

1 Introduction

A short introductory paragraph about the scope of the report.

Table 1: Nomenclature

Abbreviation	Full name
RP	Recurrence period
RV	Return value
yr	Year

2 Project location and data

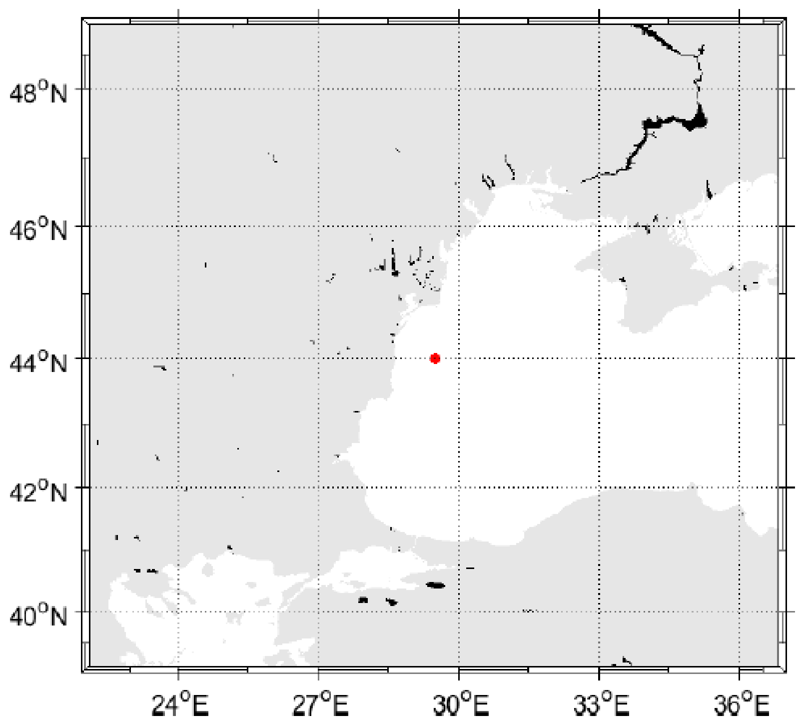
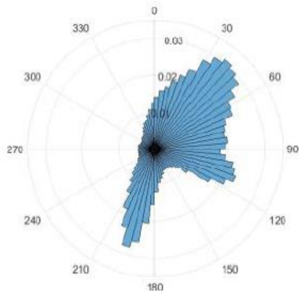
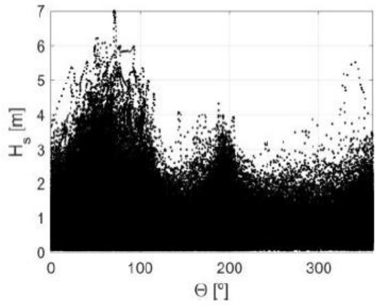


Figure 2: Data location

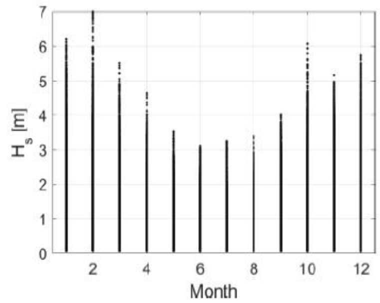
The data are available from Infoplaza. The data are retrospective estimates and have been calibrated by Infoplaza against the altimeter data. The location used is at Lon 29.5°E, Lat 44°N, at a depth of 69m. The time ranges consist of hourly data for a period of 41 years of data (1979-2019). The series includes significant wave height (Hs), associated spectral peak duration (Tp), zero crossing period (Tz), and input directions for total sea state. Also included are wind speed and direction at 10m height (U10).



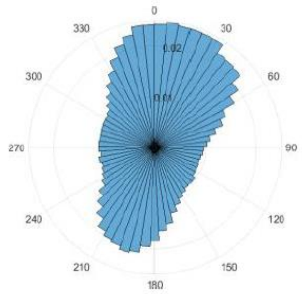
(a) Wave direction



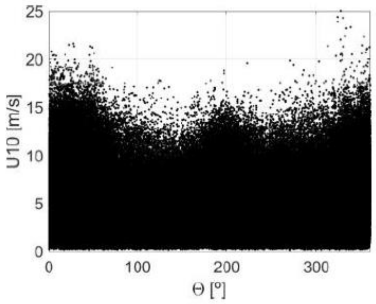
(b) Wave direction vs. *Hs*



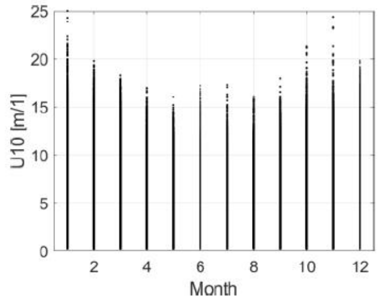
(c) Month vs. *Hs*



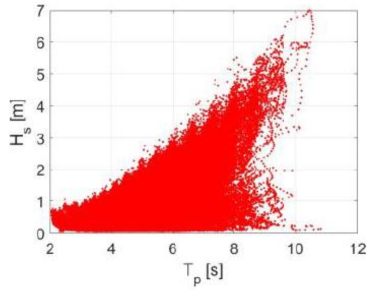
(a) Wind direction



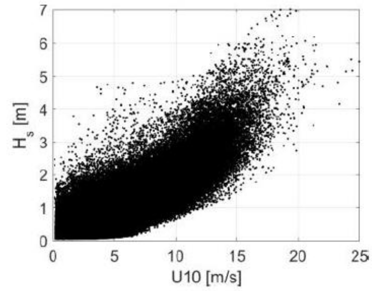
(b) Wind direction vs. U_{10}



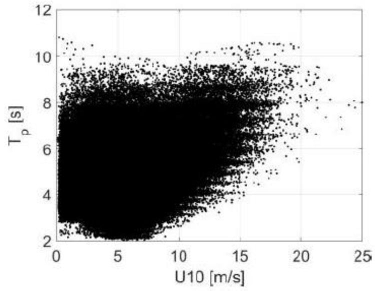
(c) Month vs. U_{10}



(a) Total sea state H_s vs T_p



(b) H_s vs. U_{10}



(c) T_p vs. U_{10}

3 Return values

3.1 Univariate recurrence values

3.1.1 Main variable values (Ws)

This section shows the results of a peak-over-threshold univariate analysis for Hs. Table 2 shows the recurrence values for different recurrence periods in each directional sector. An omnidirectional estimate is also included. Table 3 presents the 90% uncertainty intervals for all estimates, and Table 4 presents the selected thresholds, sample sizes, and parameters of the GPD distributions for each directional sector. More details on the concordance can be found in appendix A.1.

Table 2: Recurrence values for different directional sectors.

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
Data max.	6.99	5.06	5.52	6.99	5.99	4.98	4.07	4.30	3.92	3.21	3.51	3.86	5.51
1yr RV	4.48	2.42	3.25	3.83	3.46	2.34	1.32	2.72	2.40	-	1.30	1.02	1.71
5yr RV	5.52	3.24	4.24	5.15	4.85	3.39	2.34	3.54	3.09	-	2.22	1.92	2.69
10yr RV	5.94	3.58	4.65	5.65	5.22	3.78	2.72	3.79	3.32	-	2.56	2.22	3.19
25yr RV	6.45	4.02	5.17	6.26	5.57	4.24	3.18	4.05	3.56	-	2.97	2.56	3.95
50yr RV	6.82	4.34	5.55	6.68	5.76	4.56	3.49	4.21	3.72	-	3.25	2.77	4.59
100yr RV	7.17	4.65	5.92	7.07	5.90	4.85	3.79	4.35	3.85	-	3.50	2.95	5.31

Table 3: 90% uncertainty intervals for recurrence values for different directional sectors

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RV	[4.09,4.97]	[2.17,2.77]	[2.94,3.67]	[3.5,4.3]	[3.44,3.48]	[2.04,2.73]	[1.28,1.38]	[2.56,2.96]	[2.28,2.56]	-	[1.26,1.36]	[1.01,1.02]	[1.64,1.82]
5yr RV	[4.8,6.52]	[2.65,4.19]	[3.51,5.41]	[4.26,6.57]	[4.23,5.98]	[2.73,4.32]	[1.84,3.26]	[3,4.49]	[2.68,3.77]	-	[1.71,3.29]	[1.52,2.63]	[2.14,3.76]
10yr RV	[5.05,7.19]	[2.81,4.89]	[3.71,6.25]	[4.5,7.6]	[4.38,6.88]	[2.96,4.99]	[1.99,4.19]	[3.1,5.1]	[2.78,4.27]	-	[1.82,4.33]	[1.65,3.34]	[2.33,5.08]
25yr RV	[5.35,8.09]	[3,5.9]	[3.94,7.44]	[4.76,9.03]	[4.49,7.94]	[3.21,5.86]	[2.15,5.57]	[3.19,5.87]	[2.88,4.91]	-	[1.92,5.96]	[1.77,4.3]	[2.57,7.52]
50yr RV	[5.54,8.78]	[3.13,6.73]	[4.09,8.42]	[4.92,10.1]	[4.55,8.66]	[3.36,6.5]	[2.23,6.73]	[3.24,6.43]	[2.93,5.37]	-	[1.98,7.4]	[1.83,5.04]	[2.73,10.1]
100yr RV	[5.72,9.47]	[3.24,7.63]	[4.22,9.47]	[5.06,11.3]	[4.58,9.3]	[3.49,7.14]	[2.3,8]	[3.27,6.96]	[2.97,5.82]	-	[2.02,9.07]	[1.88,5.79]	[2.88,13.5]

Table 4: Thresholds, sample size and GPD parameters (shape and scale) for different directional sectors.

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
Prag	2.50	1.50	2.10	2.60	3.40	1.00	1.20	2.20	2.00	-	1.20	1.00	1.50
Marime de mostra	557	228	228	150	43	218	49	86	83	-	48	42	62
Parametrul formei	-0.07	-0.03	-0.04	-0.10	-0.41	-0.13	-0.11	-0.28	-0.23	-	-0.12	-0.22	0.16
Parametru la scară	0.83	0.55	0.69	1.02	1.20	0.89	0.70	0.78	0.61	-	0.64	0.67	0.50

Figure 7 shows estimates of directional and omnidirectional recurrence values. There are two estimates of omnidirectional recurrence rates:

1. the recurrence values represented by the dashed black line are based on a match for the data points in all directional recipients.

2. the recurrence values represented by the solid black line are based on the mathematical combination of the directional recurrence values.

In theory, the two estimates should be identical and at least as large as the largest directional estimates. In practice, discrepancies cannot be avoided due to sample size uncertainties. However, large differences indicate that either the omnidirectional match (dotted line) or at least one of the directional matches is inadequate.

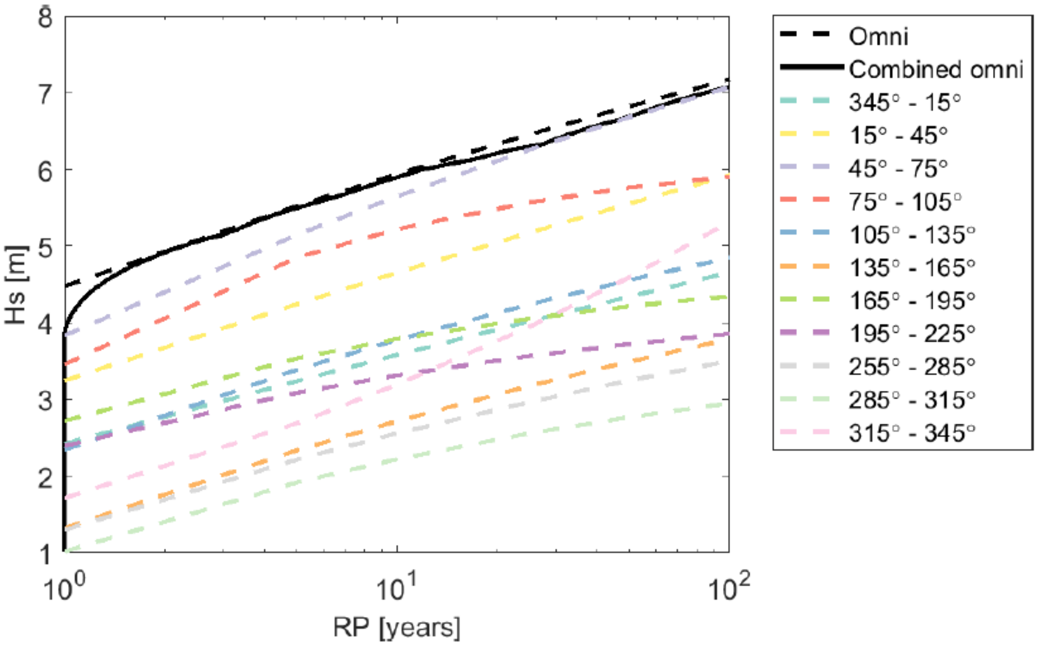


Figure 7: Directional and omnidirectional recurrence values

3.1.2 Associated values of other Tp variables

Table 5: Associated p25 values of Tp

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	8.11	5.77	7.08	7.63	7.68	6.60	4.56	6.45	6.11	-	4.33	3.78	4.91
5yr RL	9.03	6.72	7.92	8.66	8.79	7.41	5.74	7.16	6.85	-	5.28	4.93	5.65
10yr RL	9.41	7.21	8.26	9.10	9.07	7.75	6.15	7.42	7.12	-	5.69	5.23	6.05
25yr RL	9.87	7.98	8.70	9.72	9.38	8.14	6.68	7.73	7.45	-	6.31	5.52	6.72
50yr RL	10.14	8.61	9.03	10.20	9.58	8.42	7.09	7.94	7.66	-	6.84	5.65	7.35
100yr RL	10.47	9.33	9.35	10.61	9.75	8.65	7.49	8.12	7.89	-	7.46	5.73	8.05

Table 6: Associated p50 values of Tp

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	8.43	5.96	7.26	7.84	7.94	7.06	4.71	6.63	6.28	-	4.37	3.86	4.98
5yr RL	9.32	6.98	8.10	8.89	9.03	7.87	5.92	7.33	7.02	-	5.34	5.02	5.79
10yr RL	9.69	7.51	8.43	9.35	9.29	8.18	6.34	7.58	7.28	-	5.76	5.39	6.23
25yr RL	10.14	8.34	8.90	9.94	9.57	8.52	6.87	7.87	7.59	-	6.39	5.79	6.95
50yr RL	10.47	9.02	9.22	10.48	9.74	8.75	7.27	8.07	7.80	-	6.98	5.98	7.67
100yr RL	10.79	9.78	9.53	10.97	9.88	8.95	7.70	8.25	8.00	-	7.56	6.09	8.50

Table 7: Associated p75 values of Tp

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	8.71	6.16	7.43	8.04	8.22	7.47	4.87	6.80	6.45	-	4.41	3.93	5.06
5yr RL	9.59	7.26	8.28	9.10	9.24	8.21	6.10	7.49	7.17	-	5.41	5.13	5.95
10yr RL	9.94	7.79	8.60	9.58	9.47	8.48	6.52	7.72	7.42	-	5.84	5.61	6.42
25yr RL	10.47	8.61	9.03	10.20	9.71	8.79	7.06	8.01	7.72	-	6.49	6.18	7.20
50yr RL	10.79	9.33	9.35	10.77	9.86	8.95	7.44	8.18	7.92	-	7.09	6.44	7.94
100yr RL	18.02	10.63	9.84	11.27	9.98	9.13	7.84	8.35	8.11	-	7.68	6.60	8.97

WS

Table 8: Associated p25 values of WS

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	13.79	12.78	13.77	13.34	7.44	6.43	7.02	11.91	11.59	-	8.92	7.01	11.26
5yr RL	15.86	15.50	16.23	15.83	13.49	9.18	10.21	14.06	13.25	-	12.31	12.07	14.48
10yr RL	16.81	16.65	17.20	16.77	14.53	10.38	10.64	14.37	13.84	-	13.71	13.11	15.95
25yr RL	18.06	18.21	18.33	17.90	15.47	11.95	10.91	14.56	14.53	-	15.74	14.27	18.10
50yr RL	18.94	19.46	19.13	18.65	15.97	13.06	11.01	14.62	14.96	-	17.42	15.01	19.96
100yr RL	19.81	20.74	19.86	19.38	16.31	14.15	11.05	14.65	15.35	-	19.30	15.67	21.85

Table 9: Associated p50 values of WS

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	15.74	13.30	14.56	14.06	9.14	7.84	7.76	12.68	12.33	-	9.26	7.41	11.61
5yr RL	18.00	16.08	16.97	16.51	14.41	10.74	10.99	15.01	13.95	-	12.87	12.39	15.02
10yr RL	18.90	17.30	17.89	17.39	15.23	11.95	11.46	15.35	14.48	-	14.35	13.40	16.57
25yr RL	19.99	18.94	19.00	18.48	15.94	13.47	11.75	15.55	15.07	-	16.45	14.52	18.80
50yr RL	20.72	20.21	19.63	19.23	16.30	14.52	11.85	15.62	15.42	-	18.25	15.22	20.84
100yr RL	21.36	21.50	20.54	19.78	16.54	15.32	11.90	15.66	15.72	-	20.38	15.90	22.99

Table 10: Associated p75 values of WS

-	0°-360°	345°-15°	15°-45°	45°-75°	75°-105°	105°-135°	135°-165°	165°-195°	195°-225°	225°-255°	255°-285°	285°-315°	315°-345°
1yr RL	17.39	13.81	15.27	14.72	10.77	9.15	8.46	13.49	13.03	-	9.62	7.83	11.98
5yr RL	19.51	16.65	17.59	17.09	15.08	12.00	11.83	16.04	14.49	-	13.43	12.69	15.57
10yr RL	20.30	17.81	18.41	17.96	15.71	13.16	12.33	16.38	14.95	-	14.96	13.68	17.18
25yr RL	21.11	19.46	19.44	18.96	16.24	14.52	12.62	16.58	15.42	-	17.22	14.76	19.55
50yr RL	21.70	20.74	20.15	19.78	16.50	15.72	12.71	16.64	15.72	-	19.09	15.42	21.56
100yr RL	22.23	22.82	21.16	20.42	16.68	16.25	12.76	16.68	16.00	-	21.14	16.09	24.12

References

S. Coles, *An Introduction to Statistical Modeling of Extreme Values,* Vol. 208. London: Springer, 2001.

A. Diagnostic charts for concordance assessment

A.1 Main Variables (Hs)

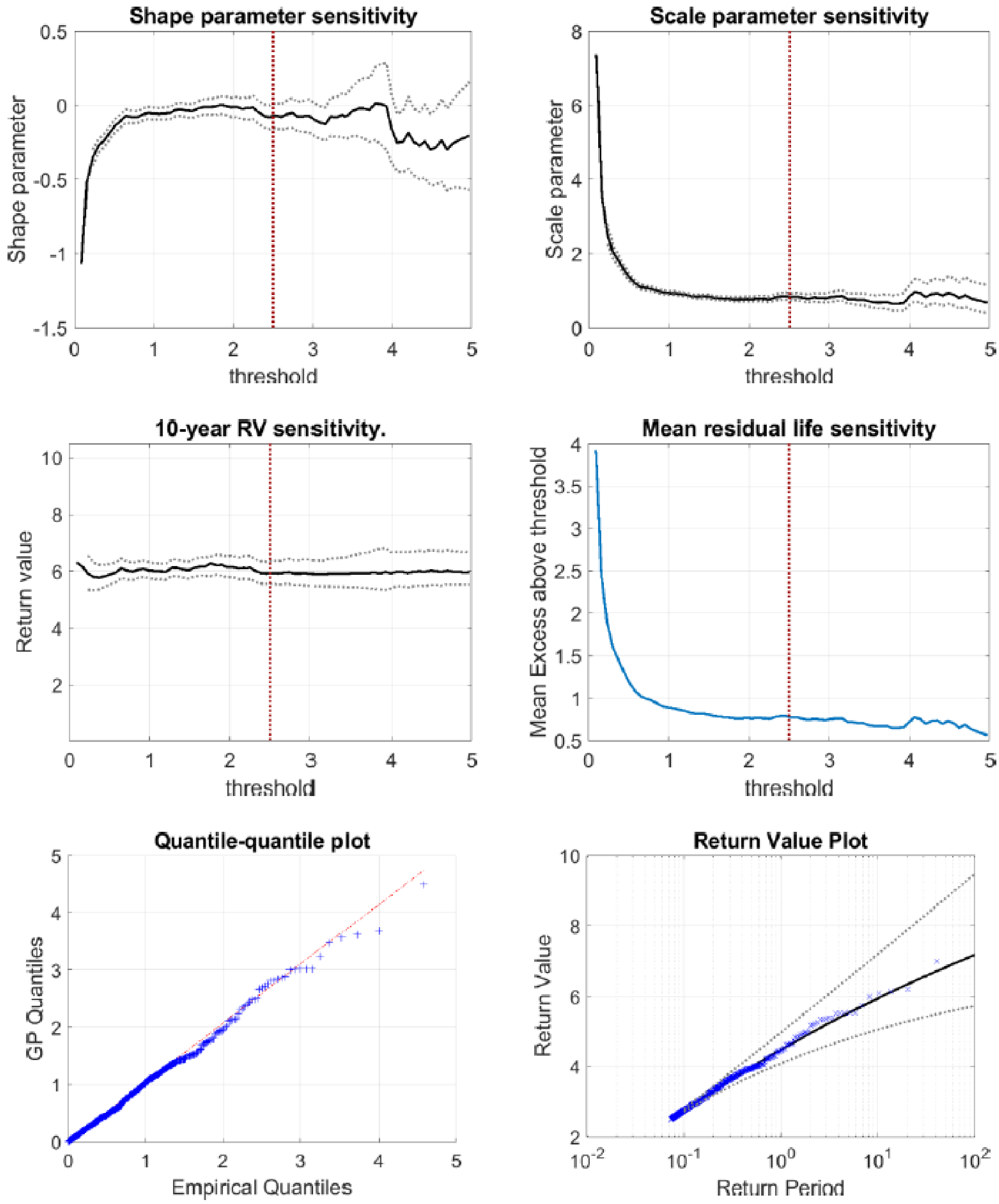
Concordance is assessed by six diagnostic charts. The first four charts evaluate the choice of threshold. The last two charts evaluate the quality of GPD concordance for the selected threshold. The first four plots show the shape parameter, scale parameter, mean residual lifetime, and recurrence value as a function of threshold. The optimal threshold is as low as possible, meeting the following criteria: Above the threshold

1. the shape parameter must be approximately constant,
2. the scale parameter must behave approximately linearly,
3. the average excess must behave approximately linearly and
4. the recurrence value must be approximately constant.

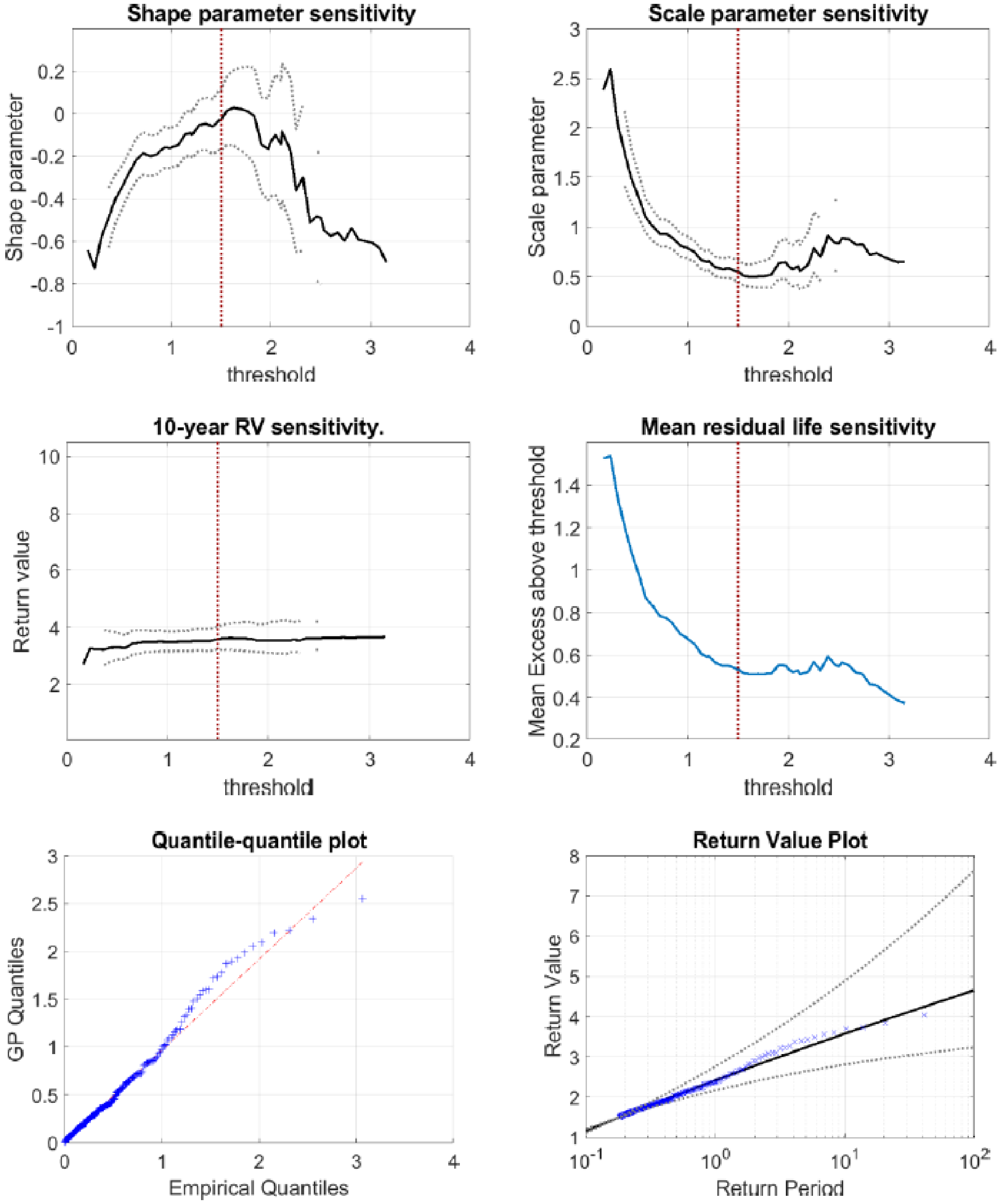
For very large thresholds, the information in the charts becomes unreliable because the sample size will be small. This is visible in the extended uncertainty ranges.

The last two charts are a qq-plot and a recurrence-value chart. In the qq plot, the quantiles of the empirical distribution and the GPp distribution are plotted against each other (blue crosses). The better the match, the closer the points are to the x = y line (red line). If the points are below the line, the adjusted GP distribution tends to overestimate the recurrence values. If the points are above the line, the adjusted GP distribution tends to underestimate the recurrence values. The recurrence value plot shows the GP recurrence values for their recurrence periods (black solid line). A 90% confidence interval is also shown (dotted grey lines) as well as empirical recurrence levels (blue crosses). The better the adjustment, the closer the empirical recurrence levels are to the GP recurrence values.

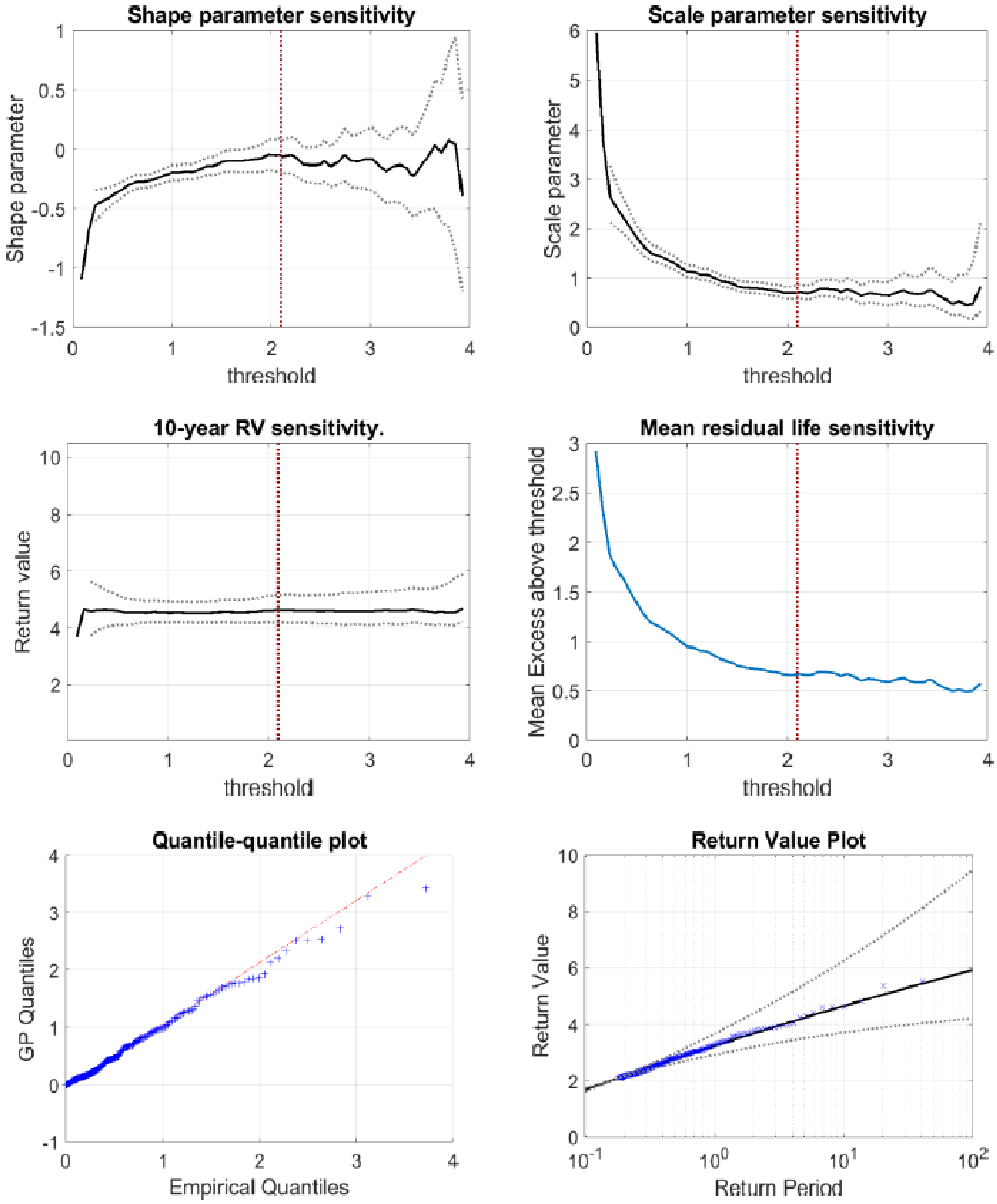
A.1.1 **Directional sector**: 0°-360°



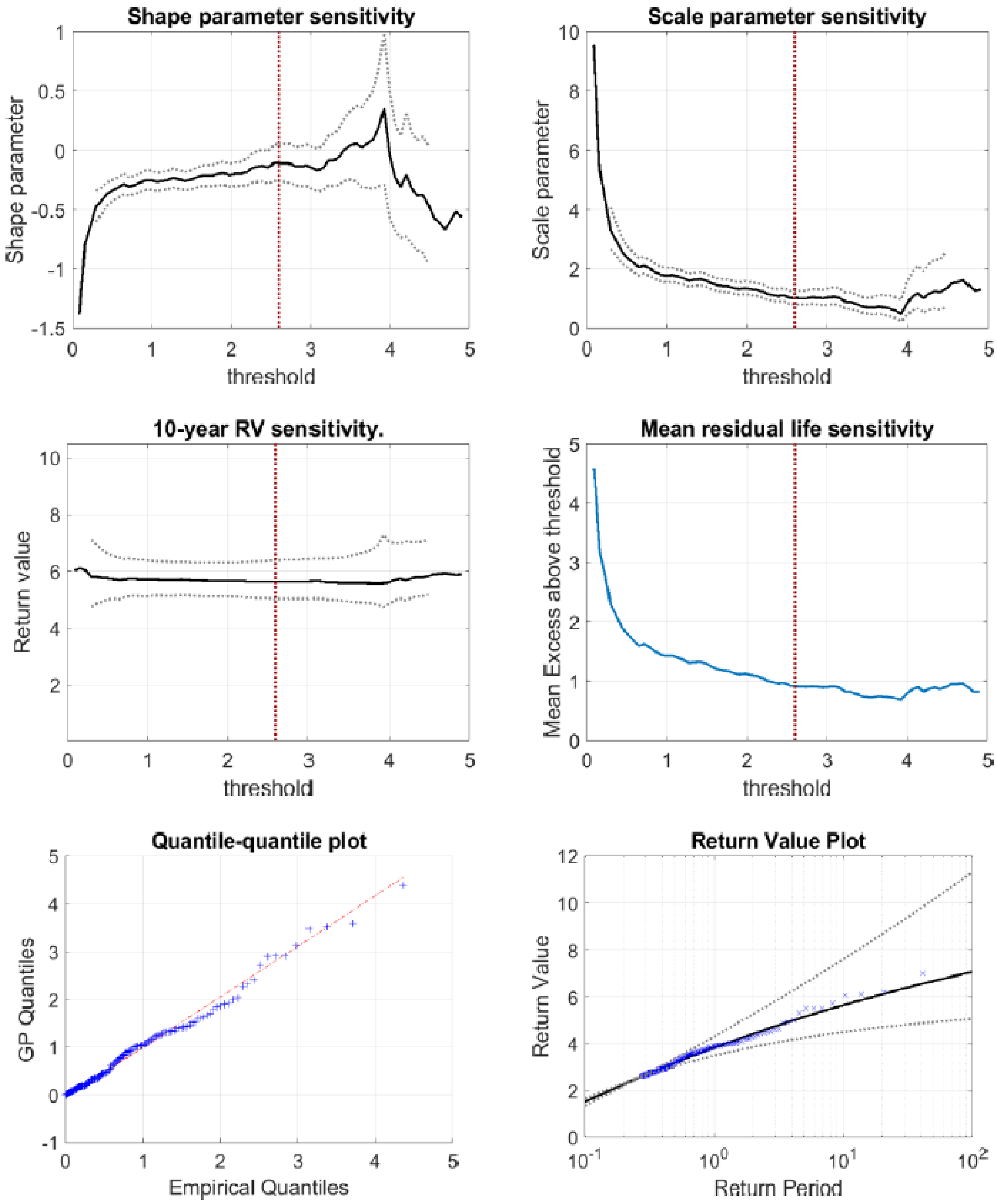
A.1.2 **Directional sector**: 345°-15°



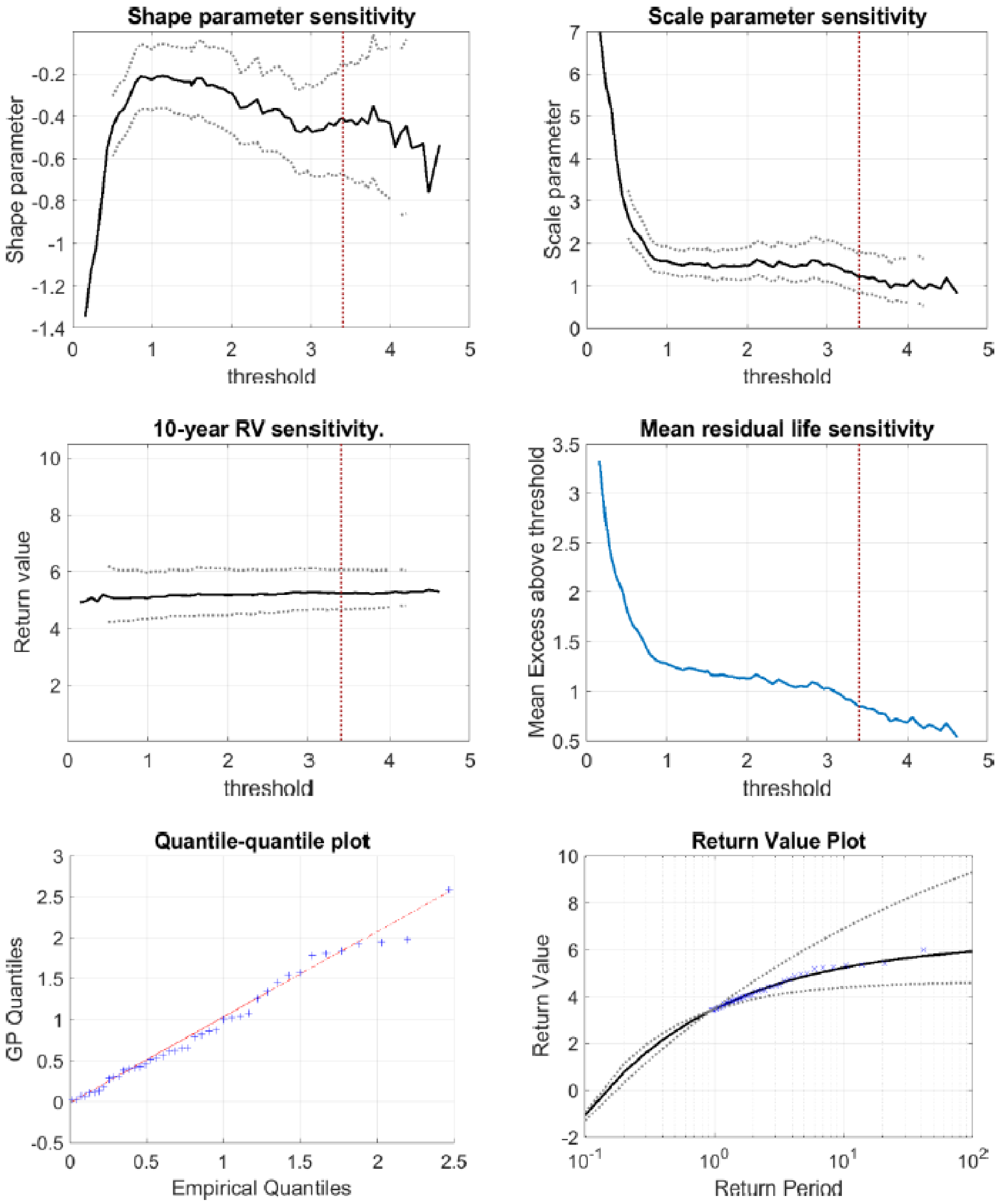
A.1.3 Directional sector: 15°-45°



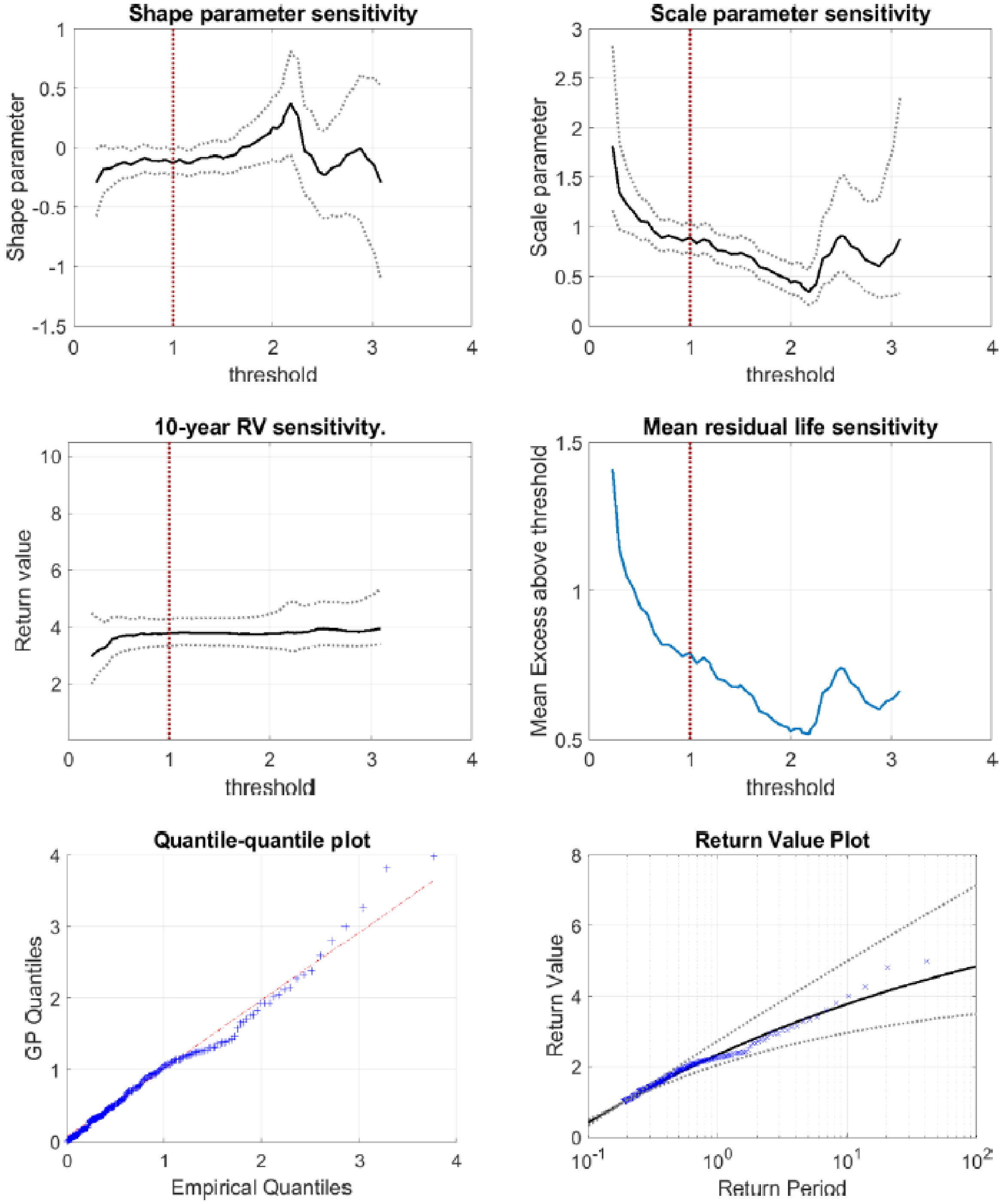
A.1.4 **Directional sector**: 45°-75°



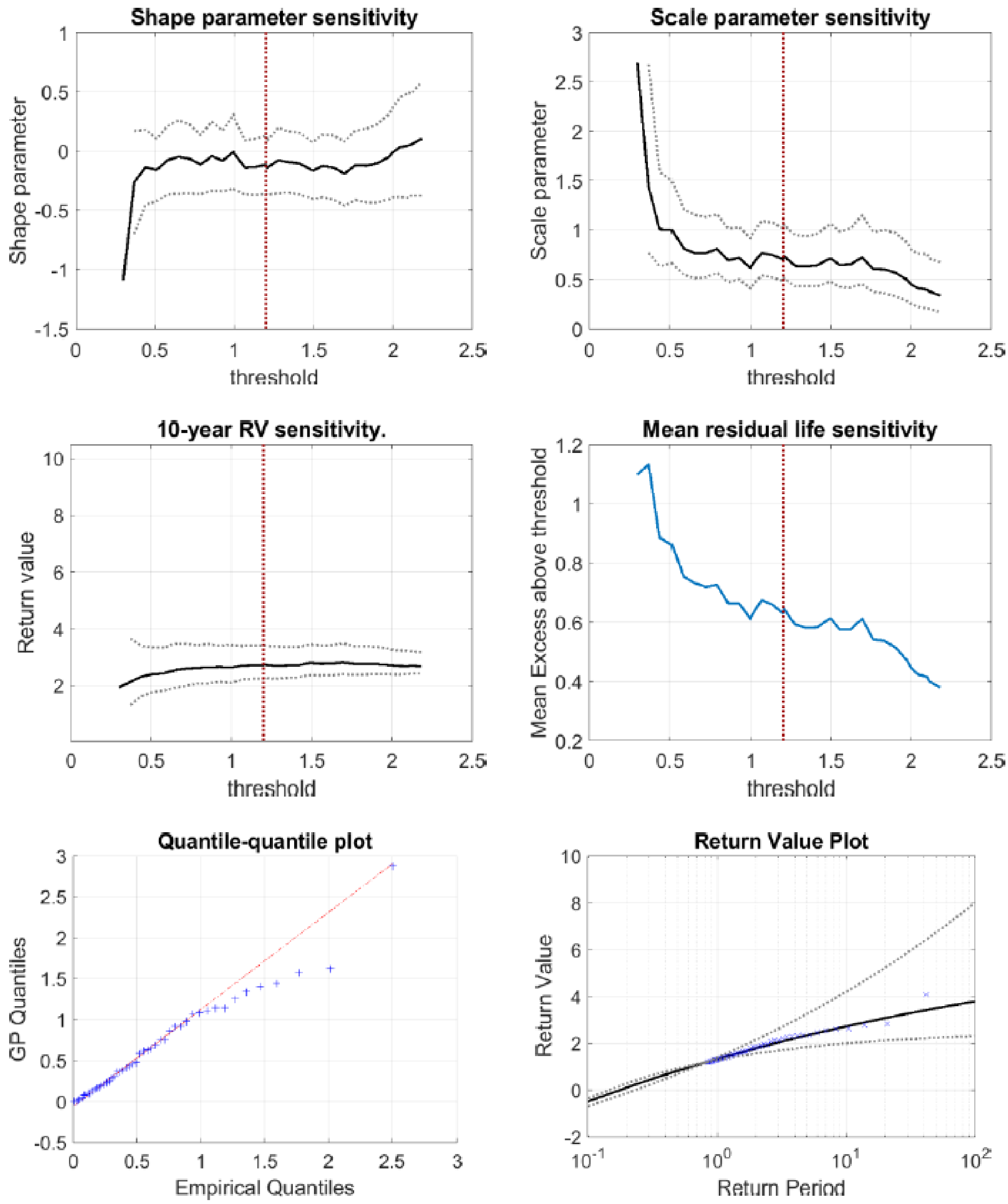
A.1.5 **Directional sector**: 75°-105°



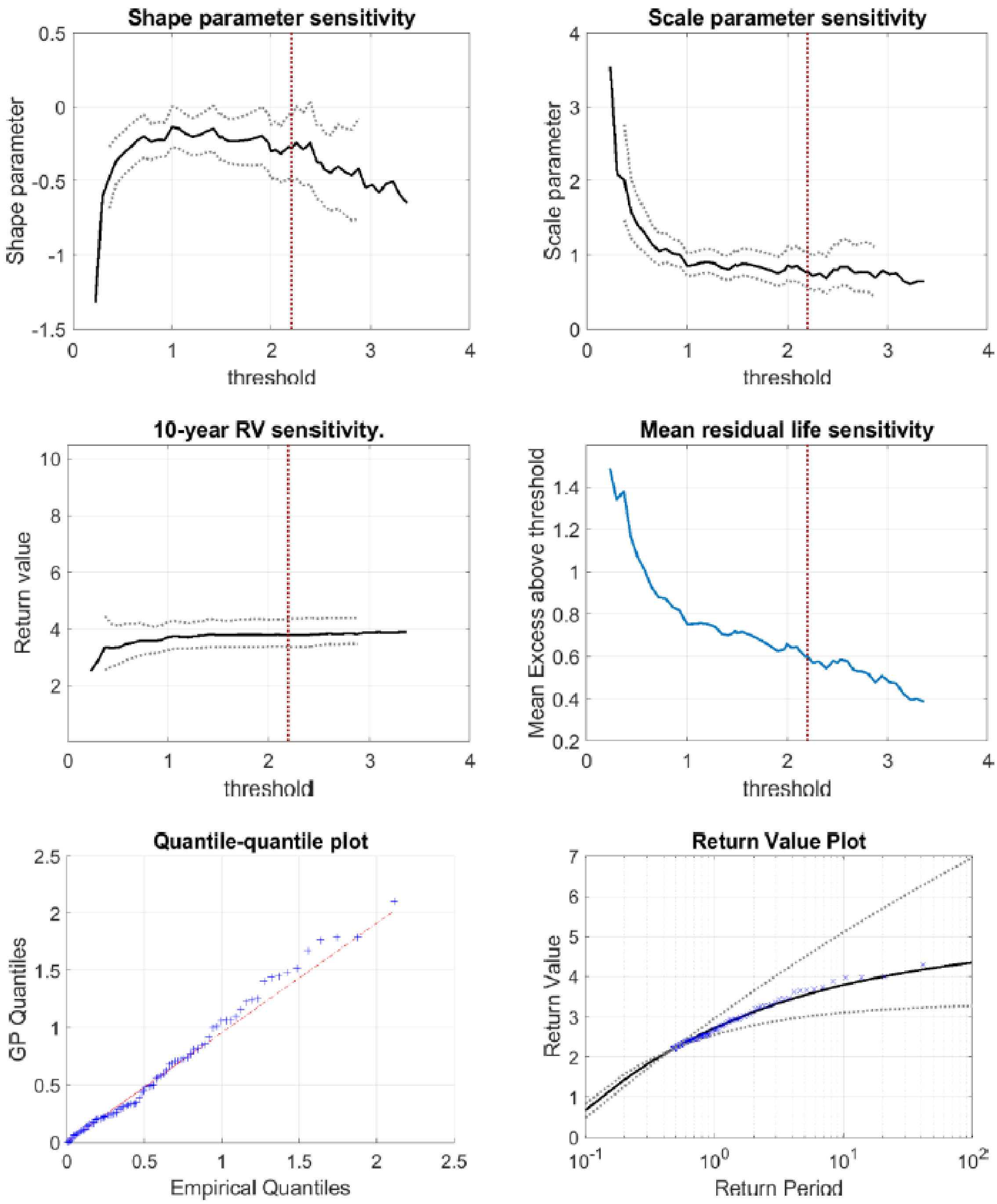
A.1.6 Directional sector: 105°-135°



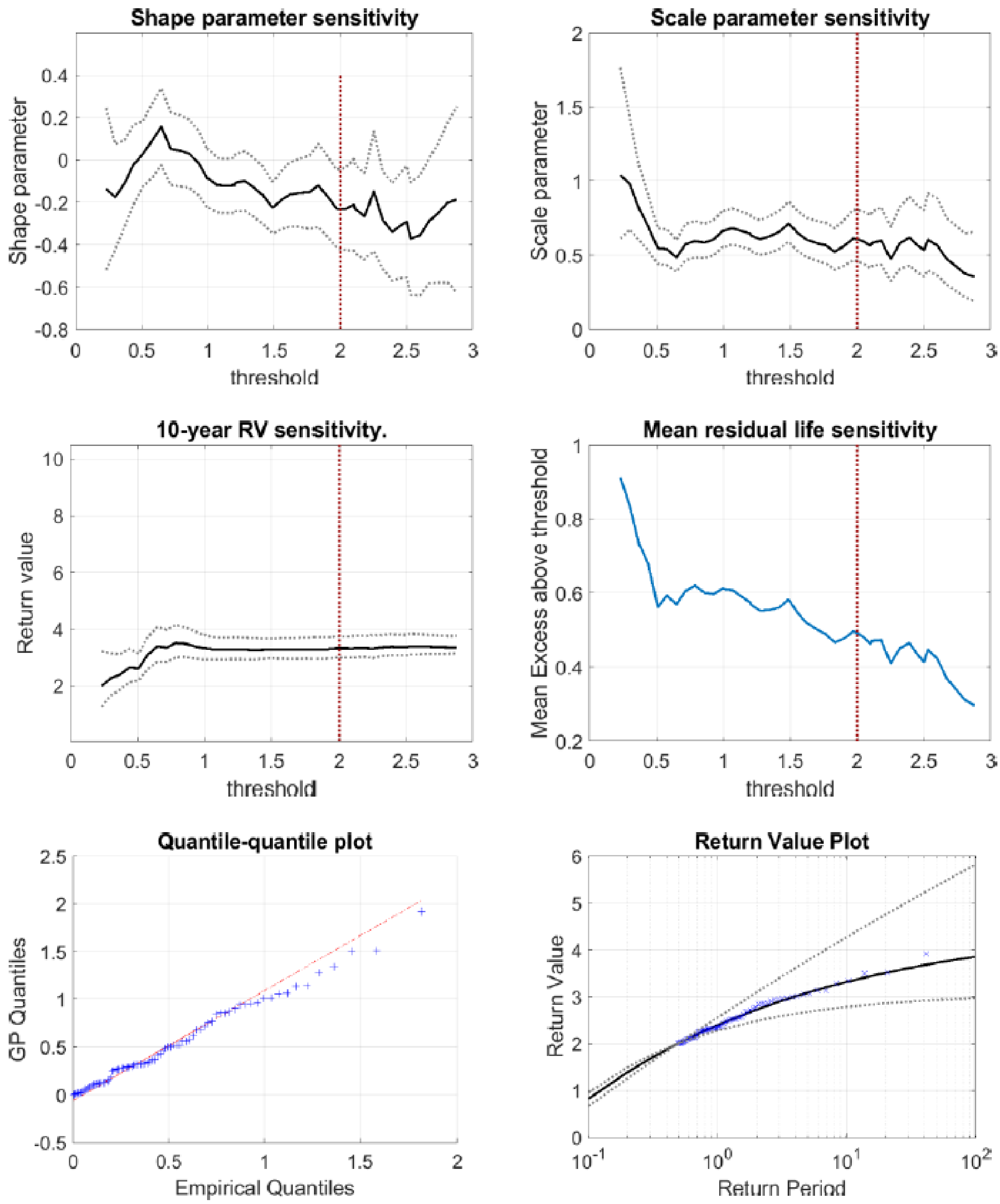
A.1.7 Directional sector: 135°-165°



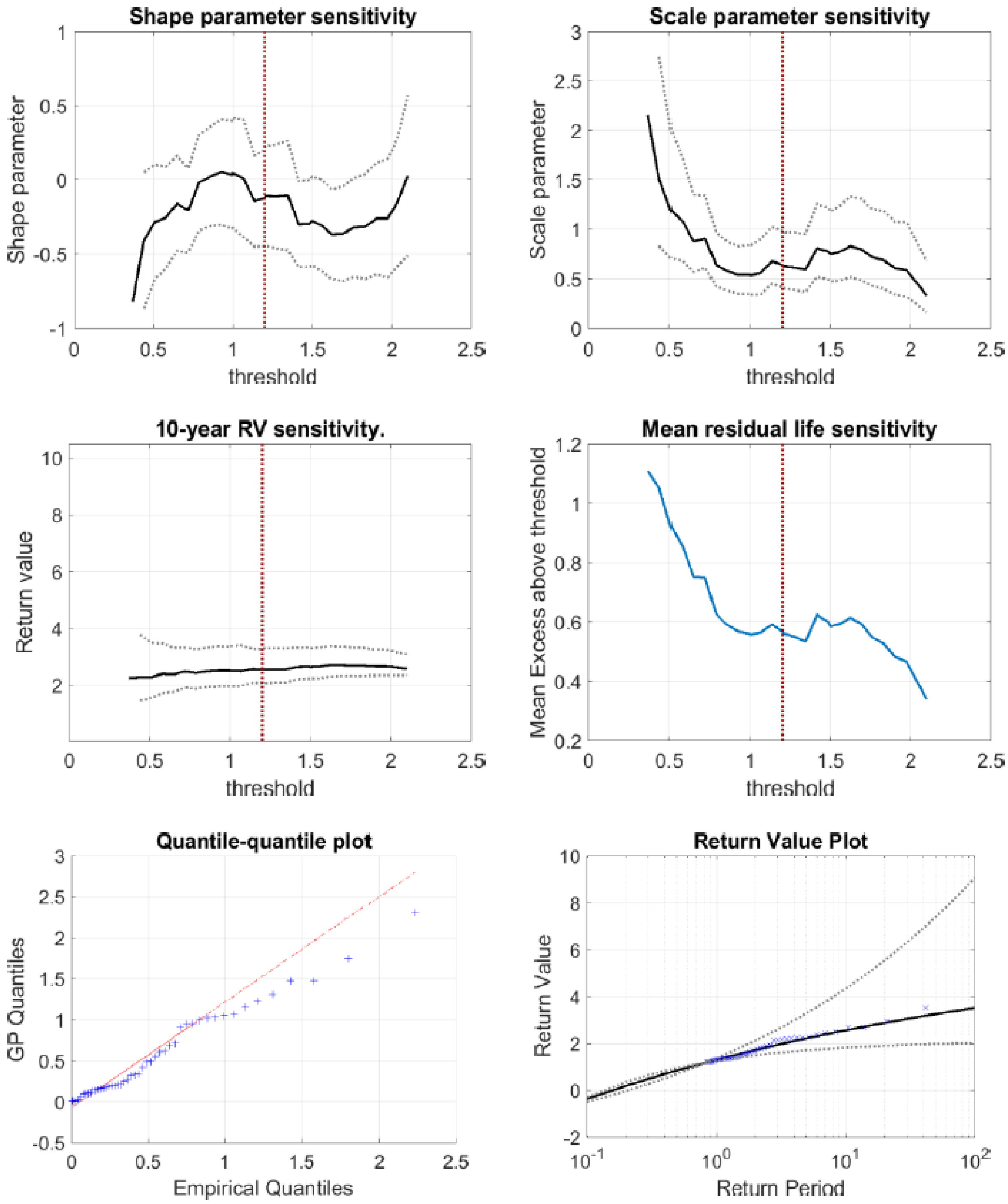
A.1.8 Directional sector: 165°-195°



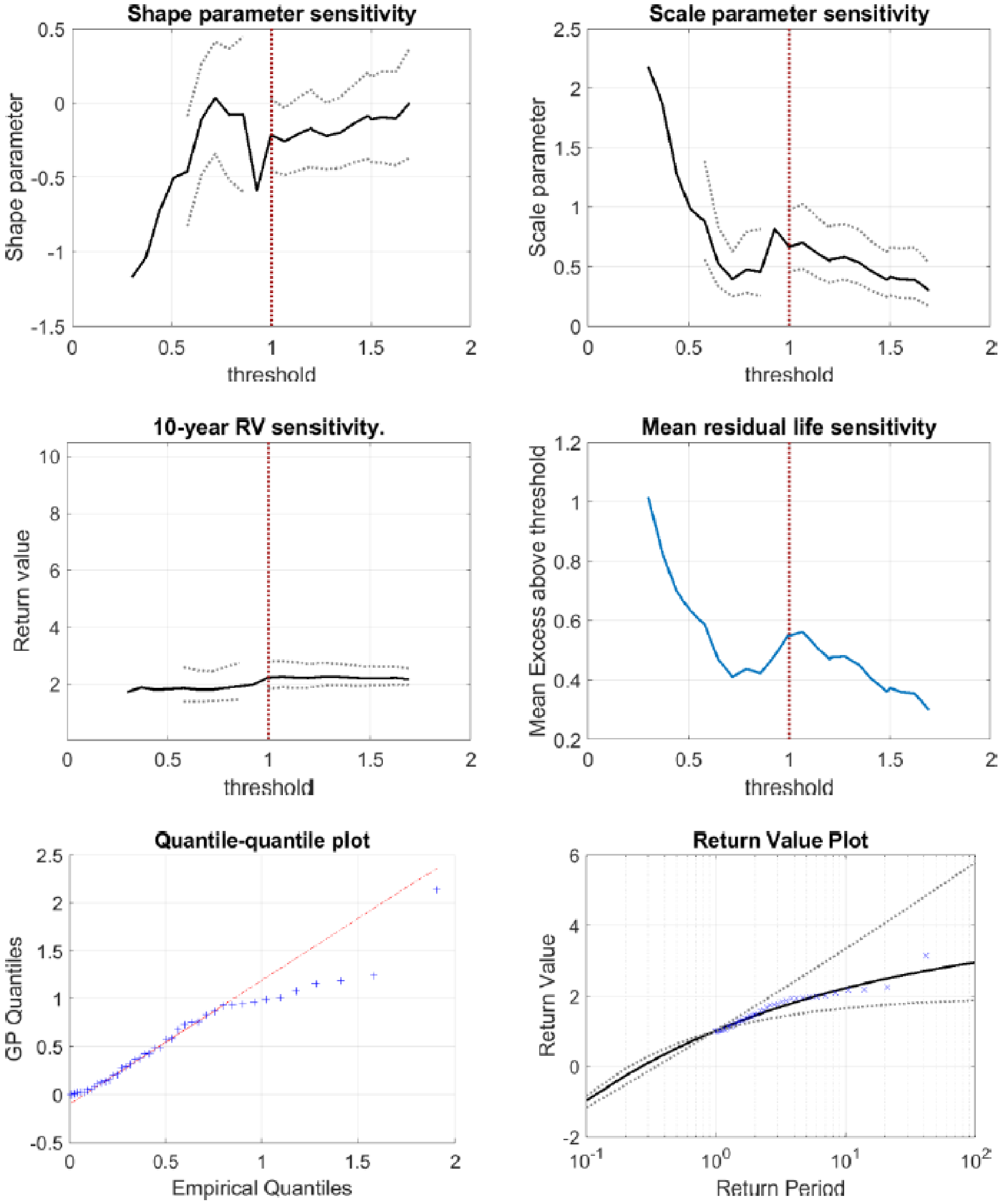
A.1.9 **Directional sector**: 195°-225°



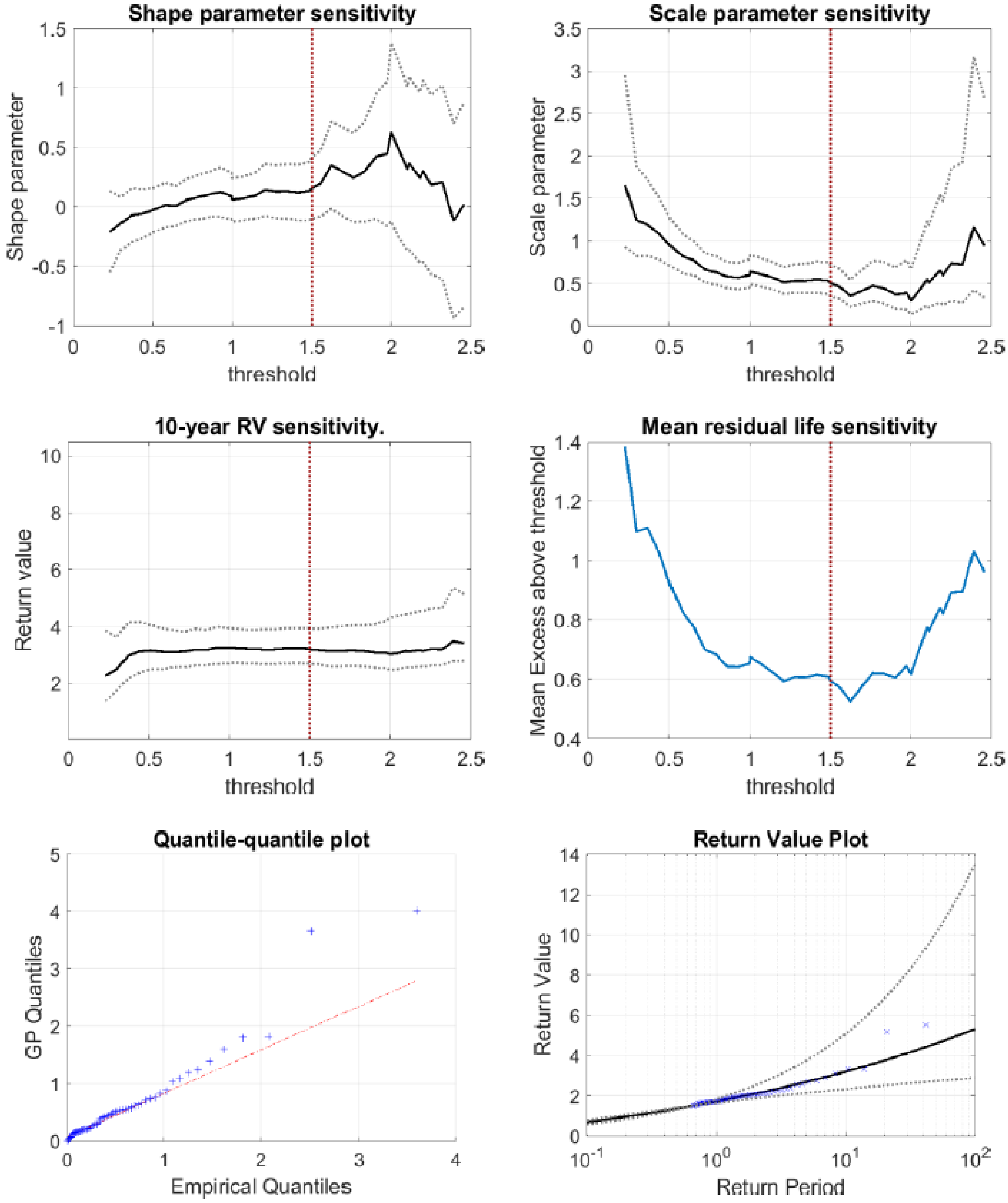
A.1.10 **Directional sector**: 255°-285°



A.1.11 Directional sector: 285°-315°

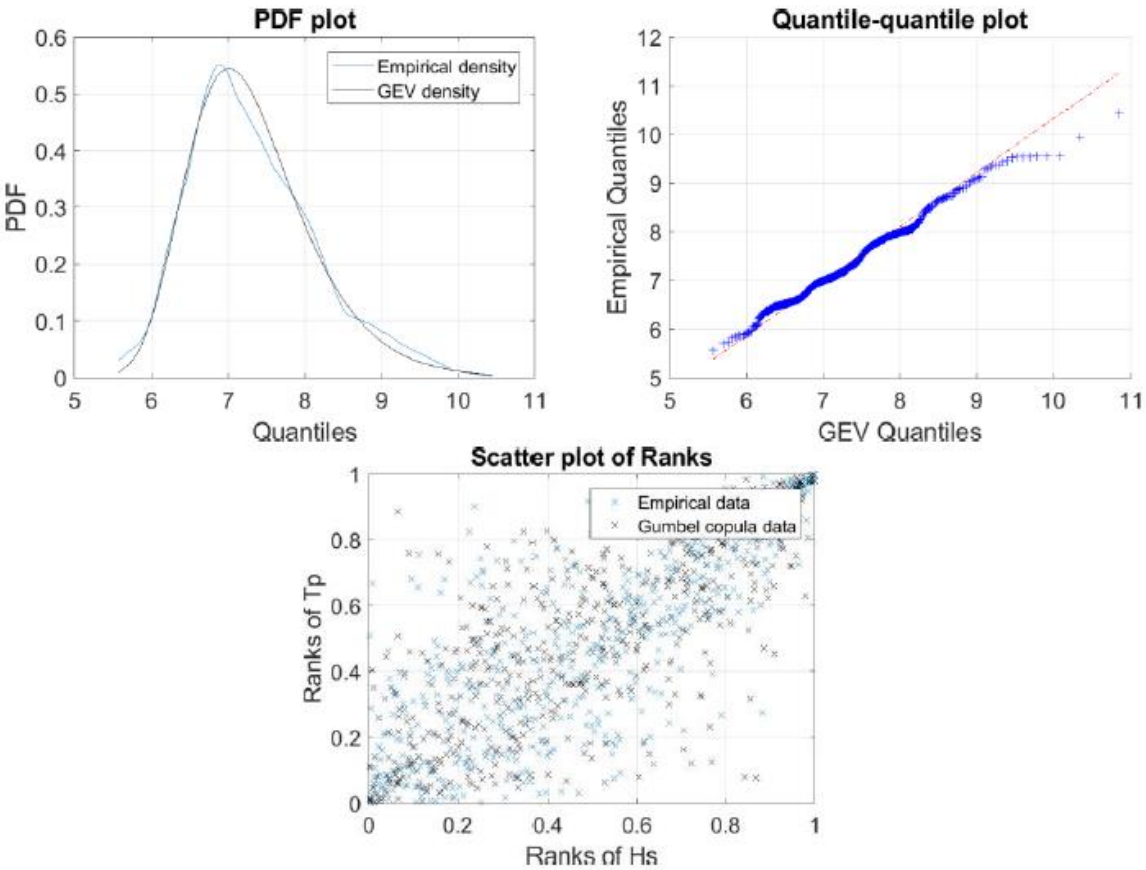


A.1.12 **Directional sector**: 315°-345°

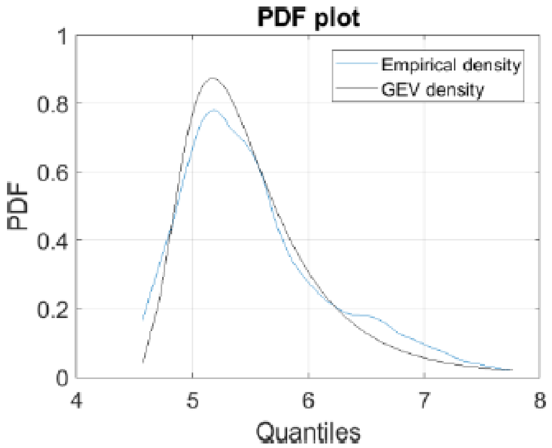


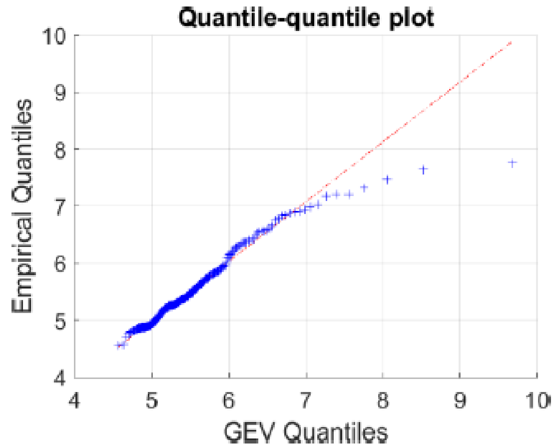
A.2 Associated variable (Tp)

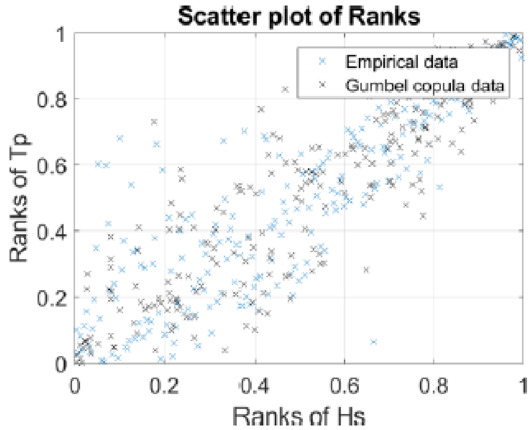
A.2.1 **Directional sector**: 0°-360°



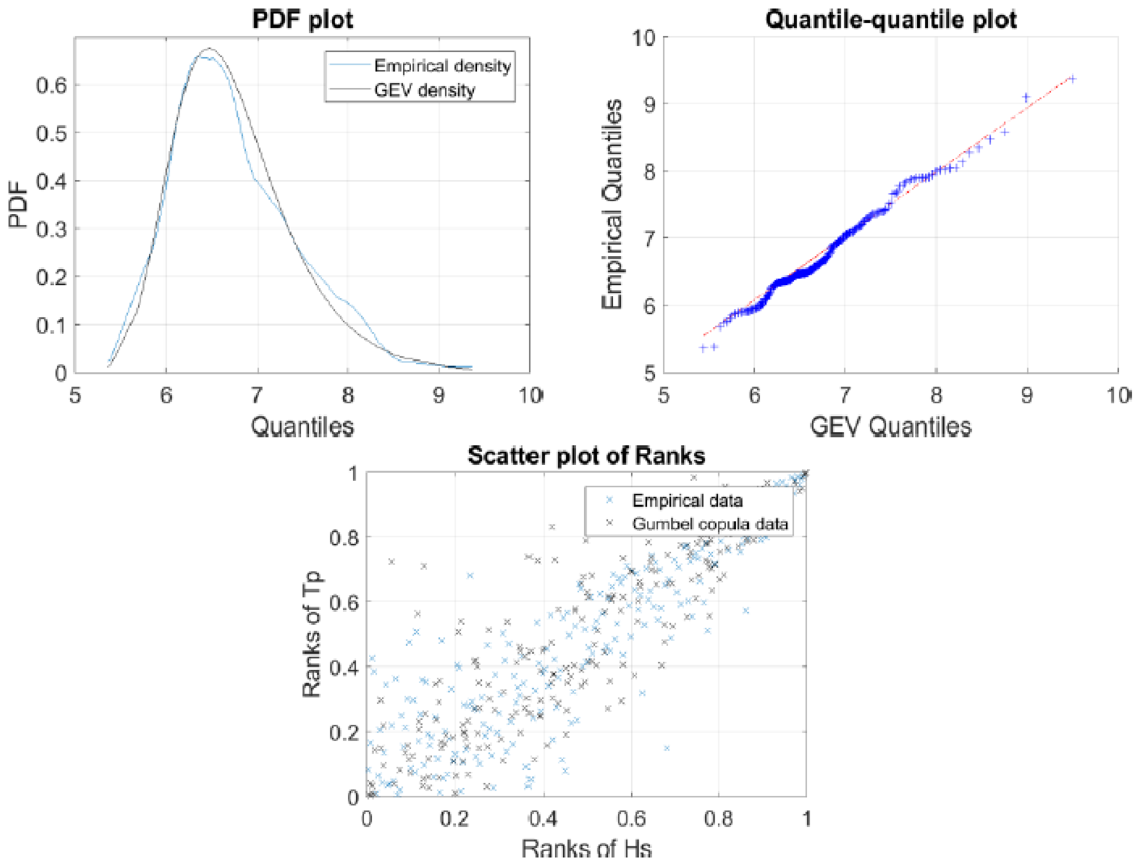
A.2.2 **Directional sector**: 345°-15°



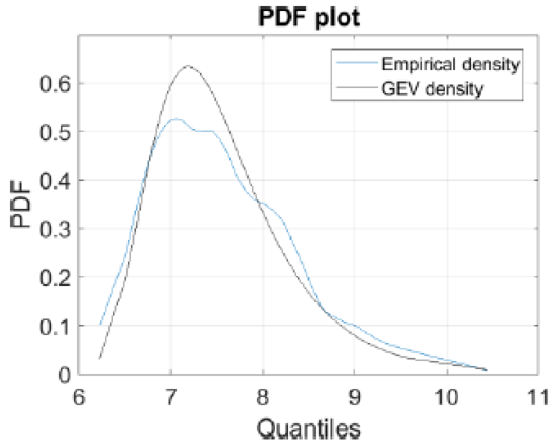


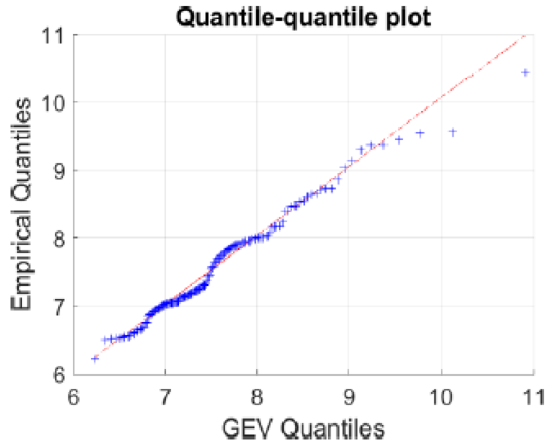


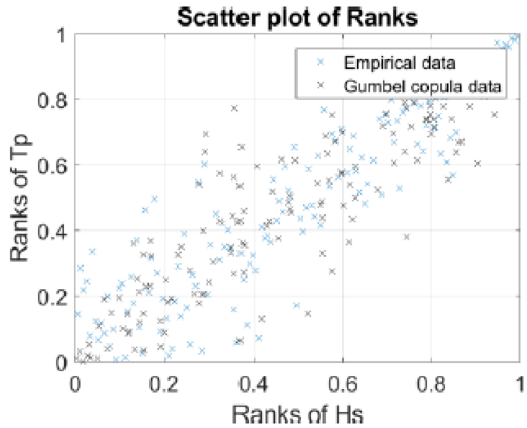
A.2.3 **Directional sector**: 15°-45°



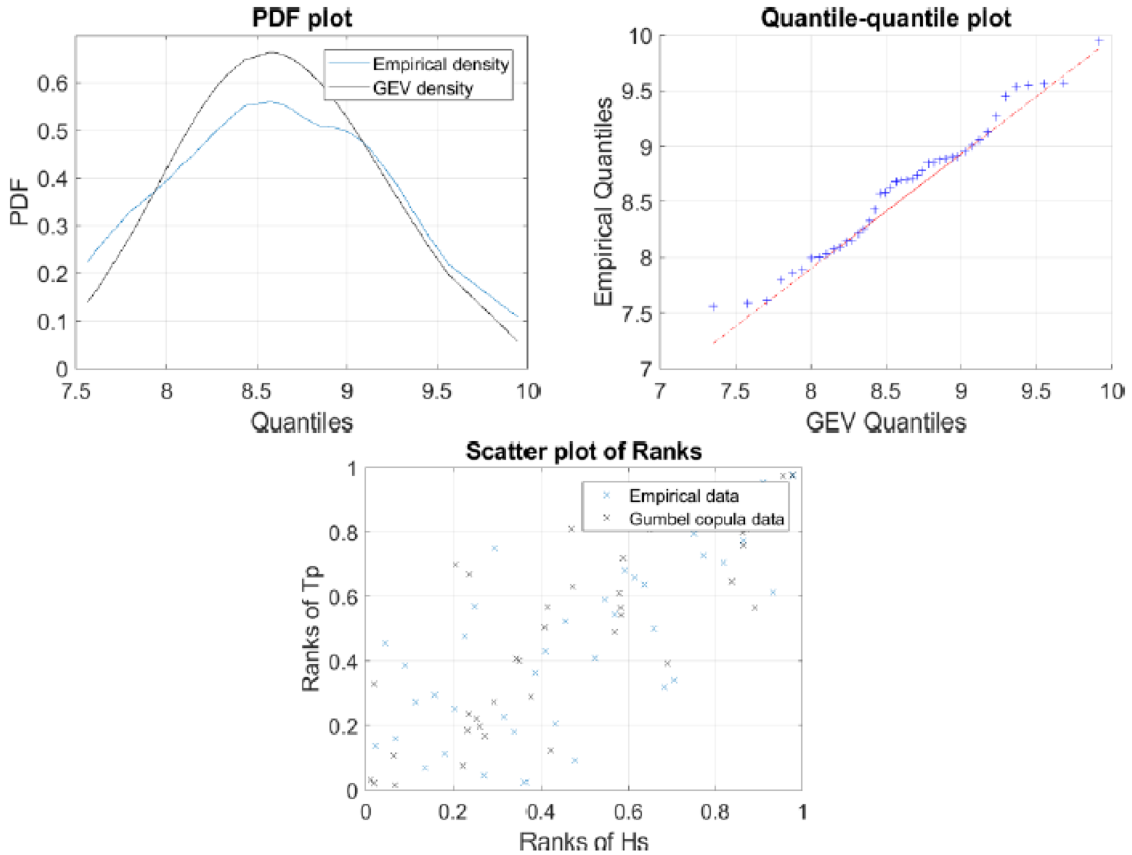
A.2.4 Directional sector: 45°-75°



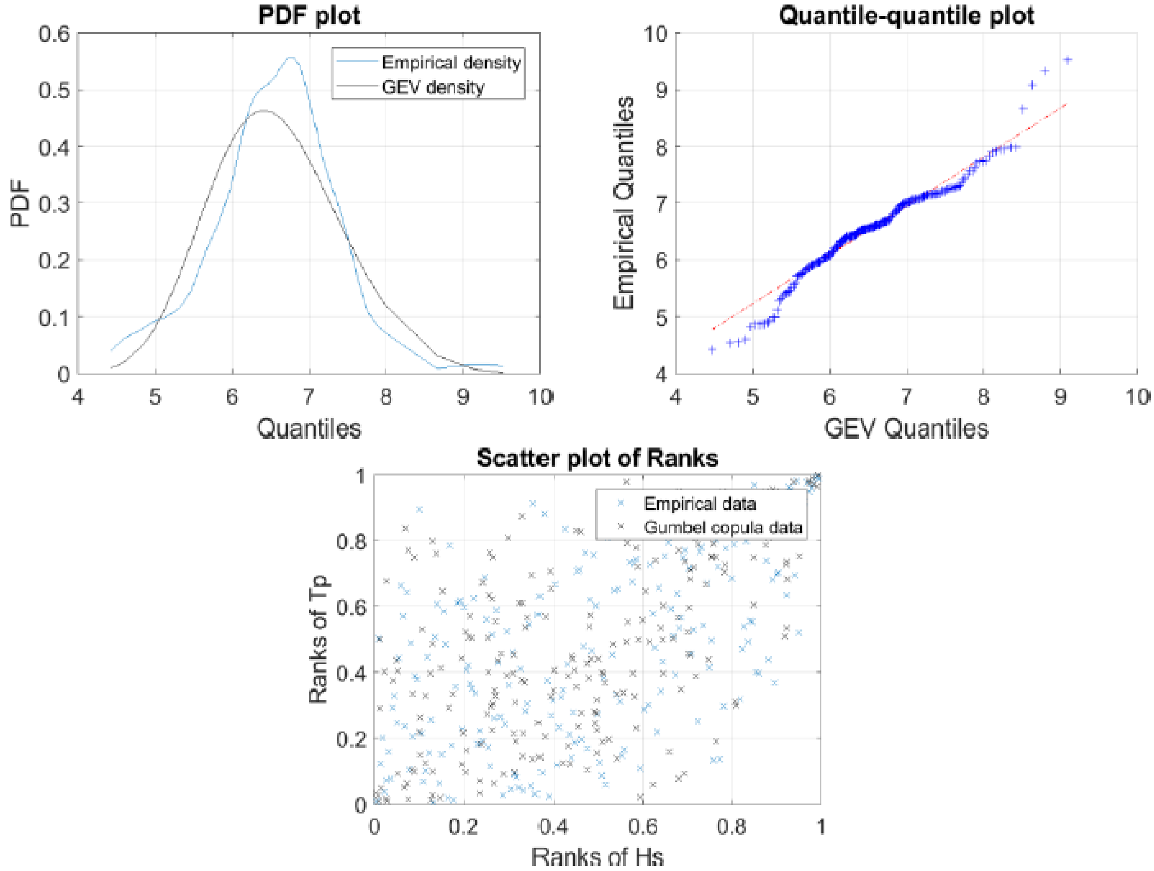




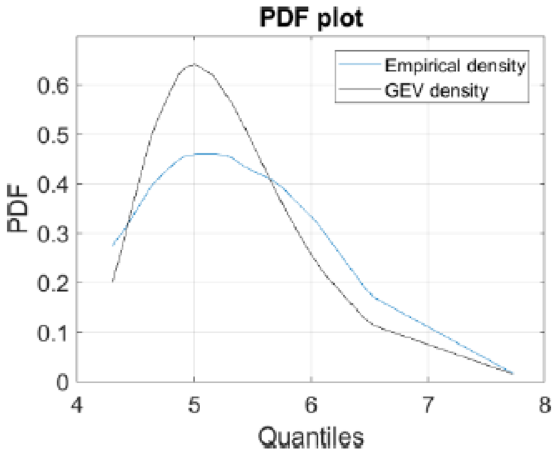
A.2.5 Directional sector: 75°-105°

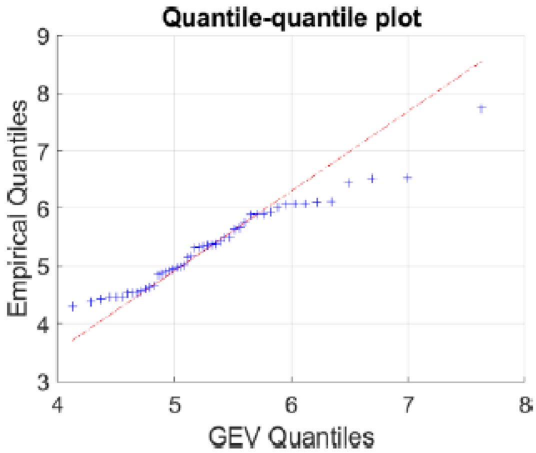


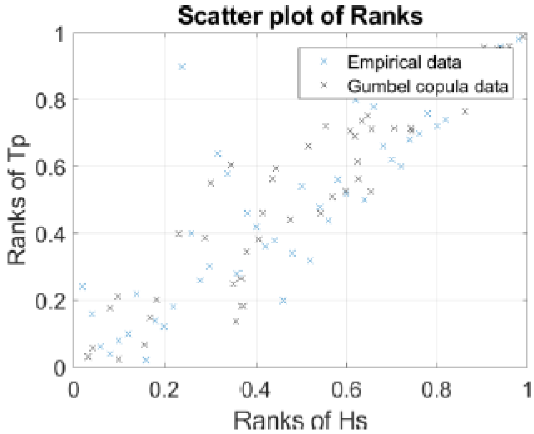
A.2.6 **Directional sector**: 105°-135°



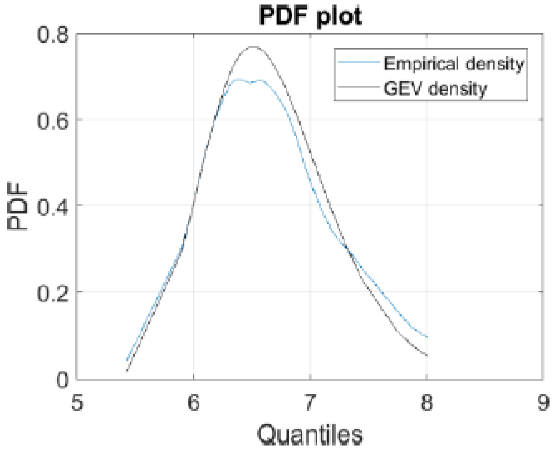
A.2.7 **Directional sector**: 135°-165°

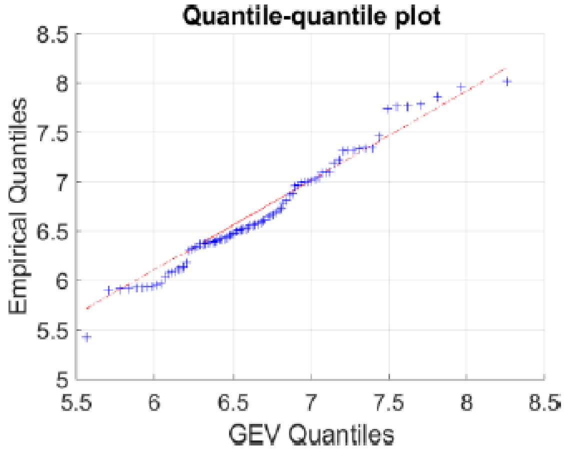


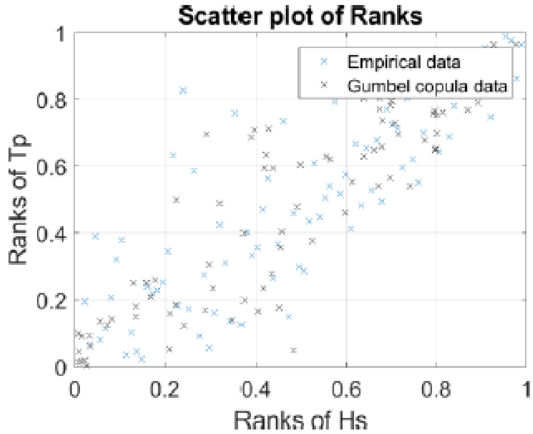




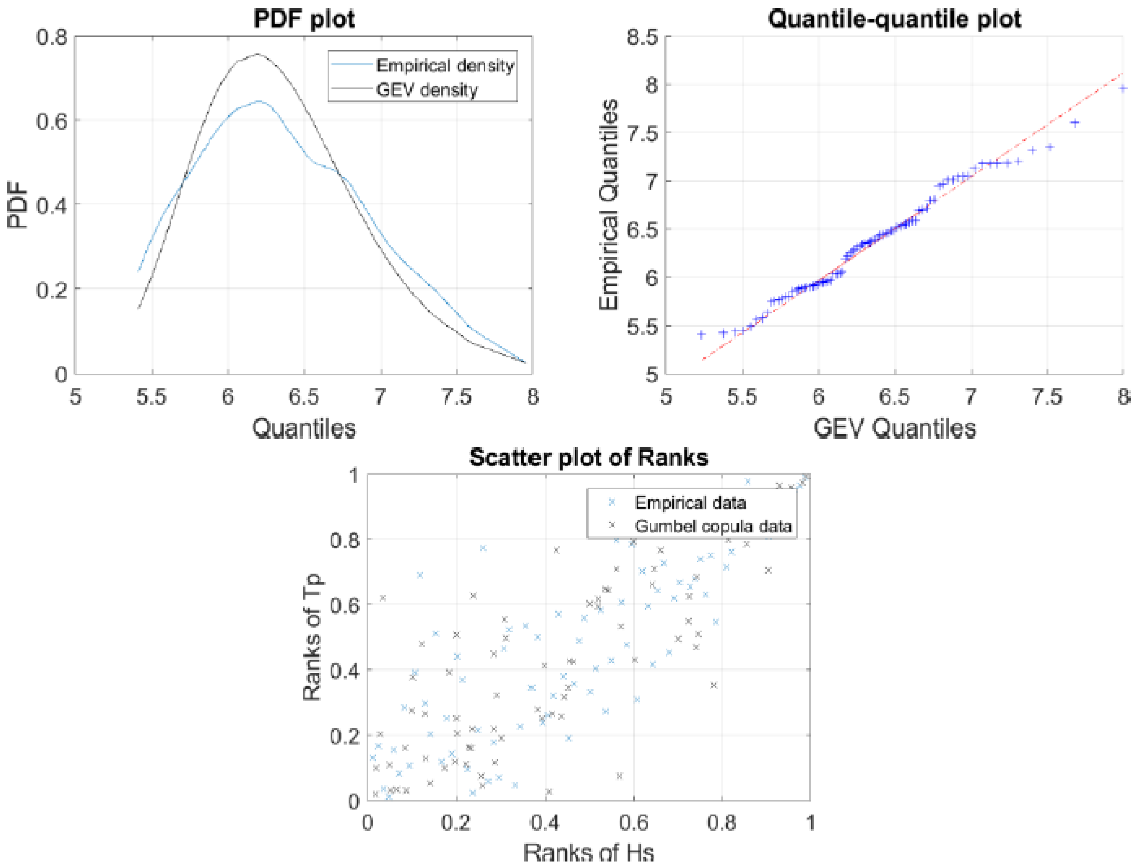
A.2.8 **Directional sector**: 165°-195°



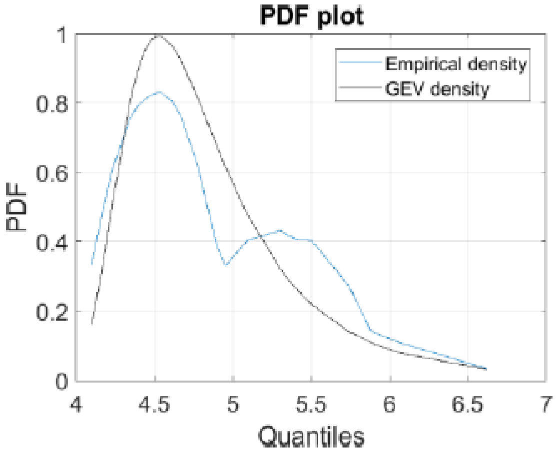


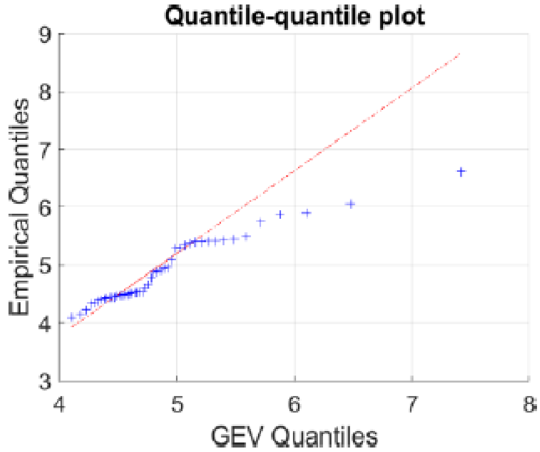


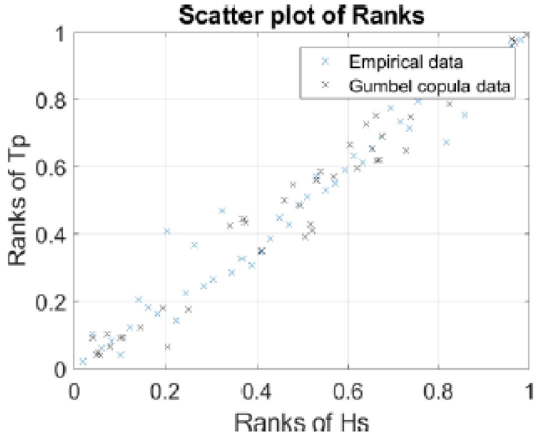
A.2.9 **Directional sector**: 195°-225°



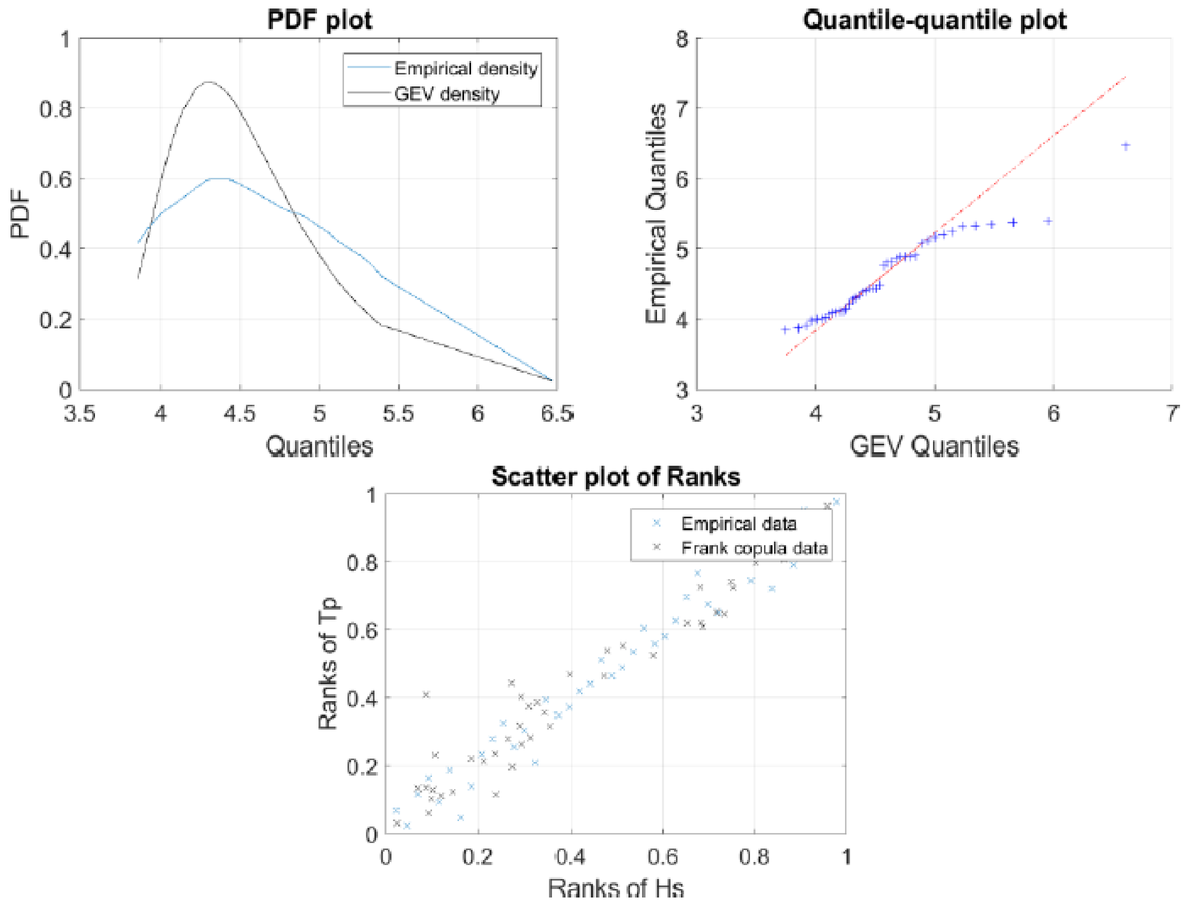
A.2.10 **Directional sector**: 255°-285°



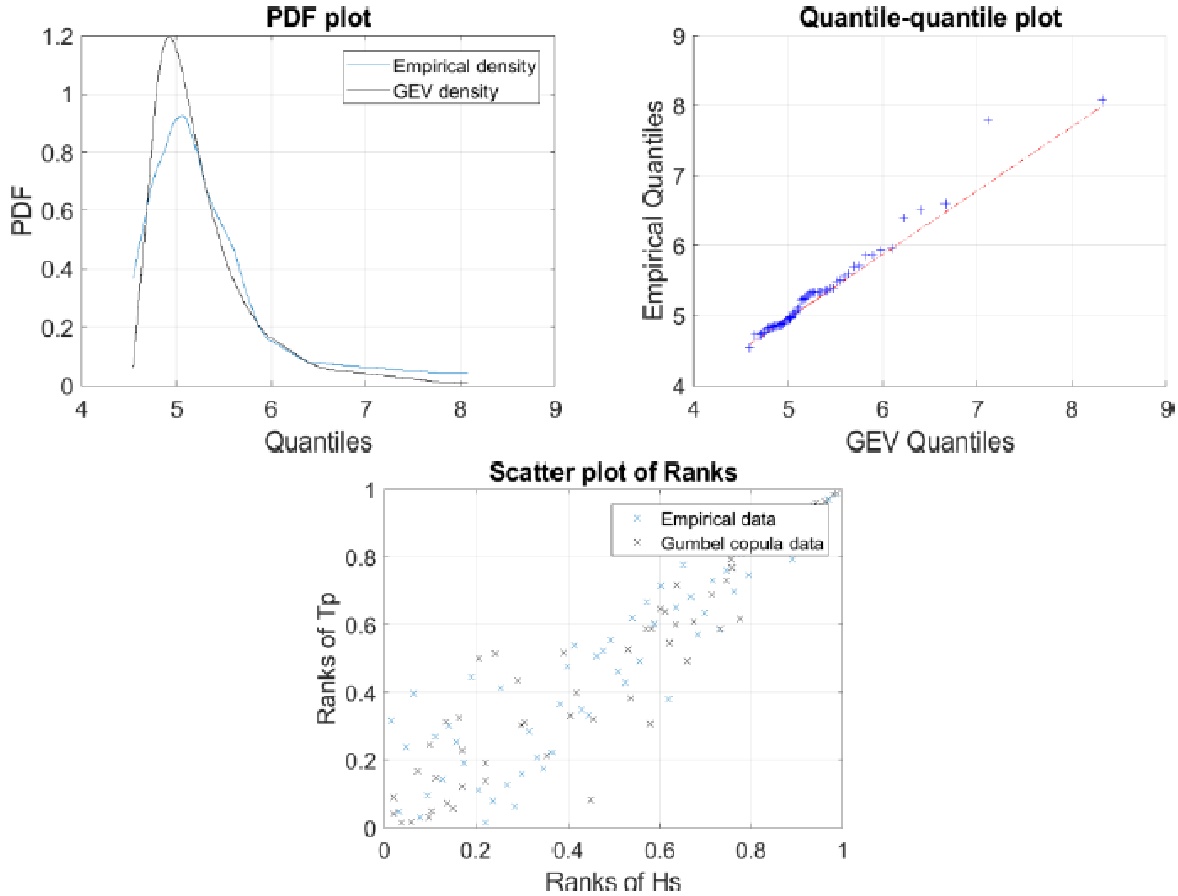




A.2.11 Directional sector: 285°-315°

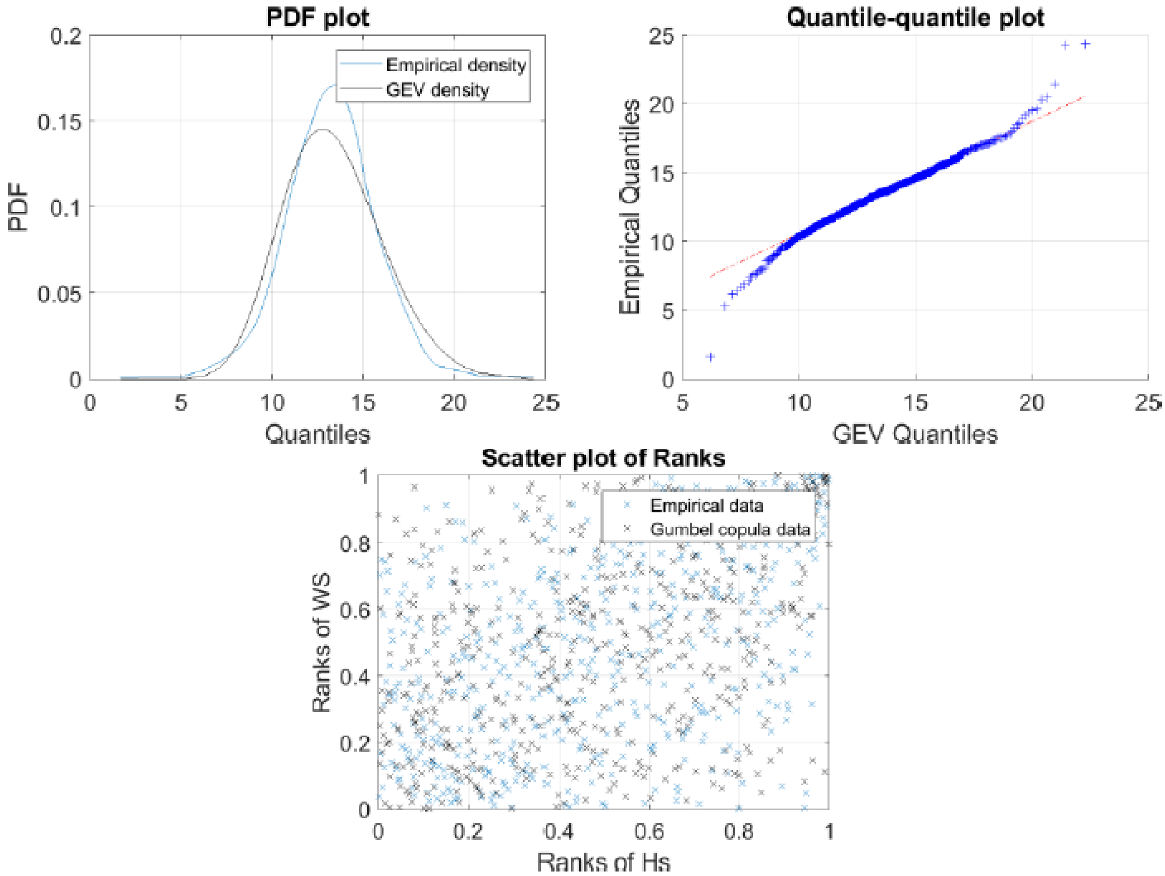


A.2.12 Directional sector: 315°-345°

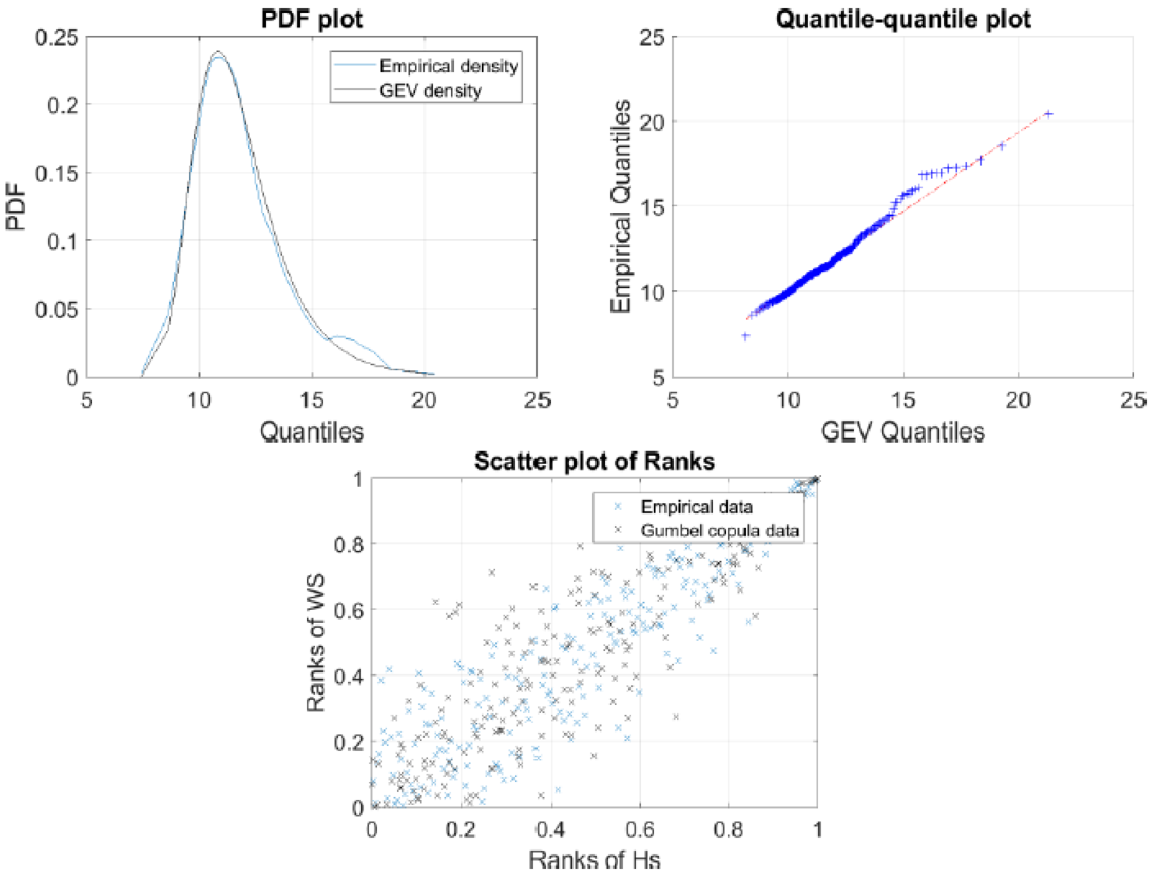


A.3 Associated variable (WS)

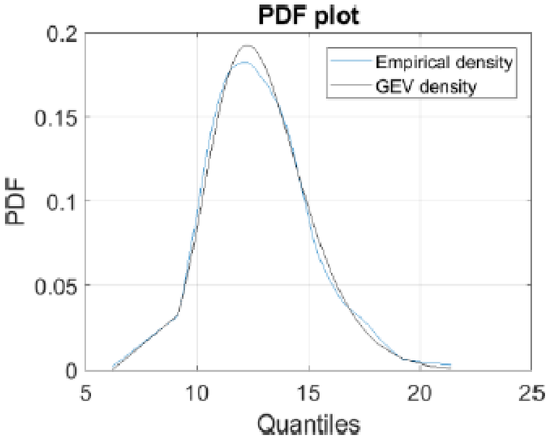
A.3.1 Directional sector: 0°-360°

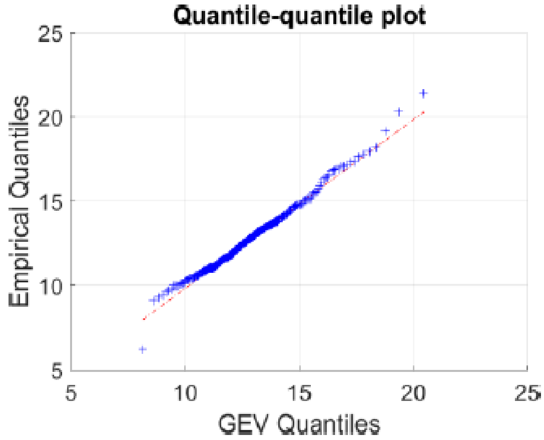


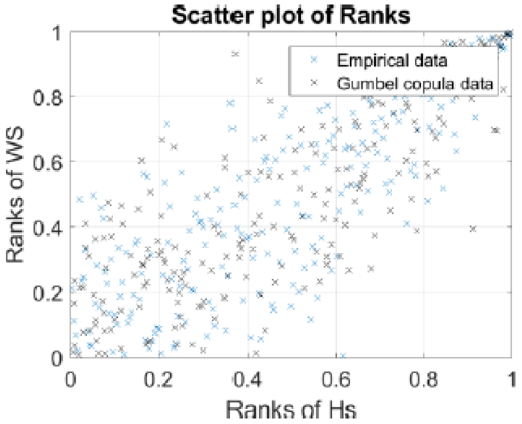
A.3.2 **Directional sector**: 345°-15°



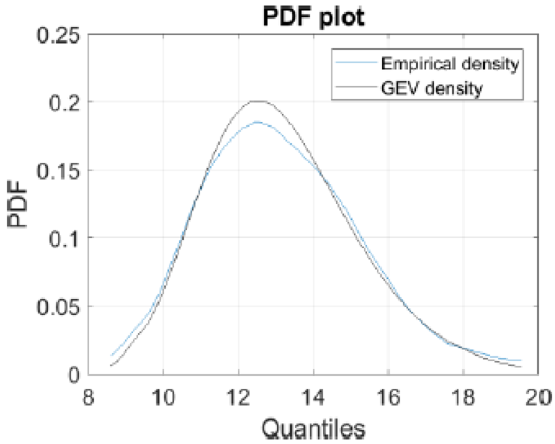
A.3.3 **Directional sector**: 15°-45°

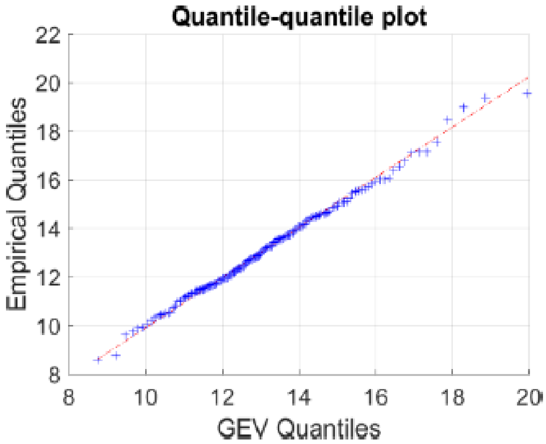


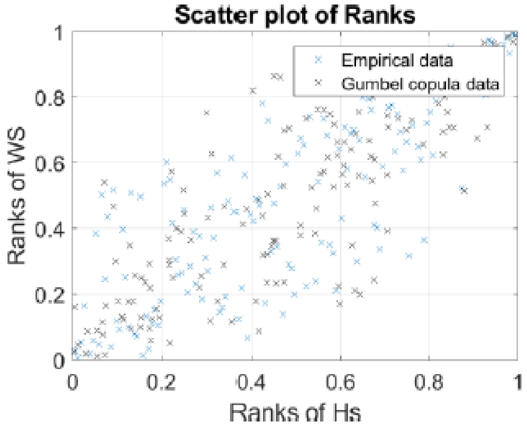




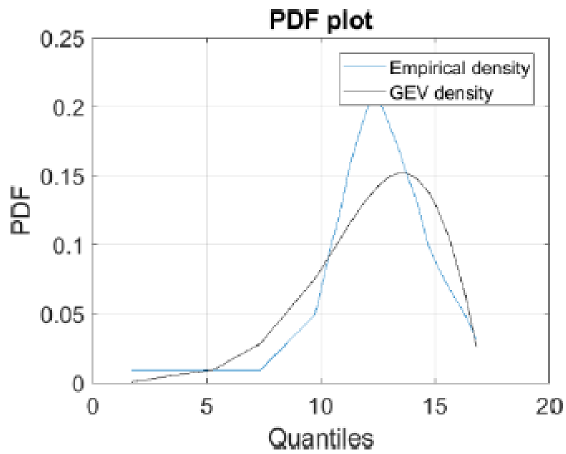
A.3.4 **Directional sector**: 45°-75°

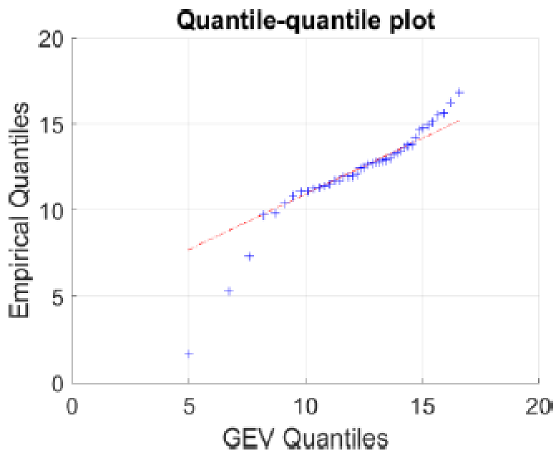


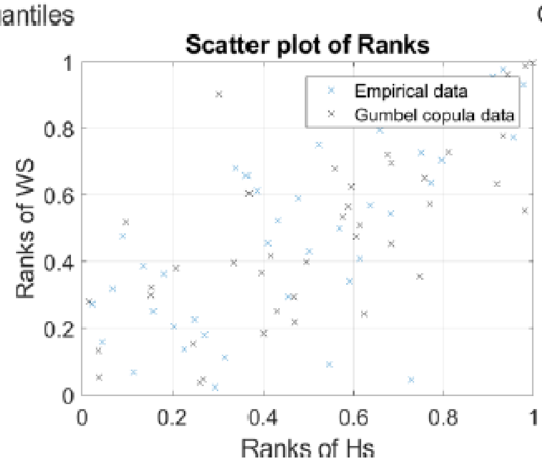




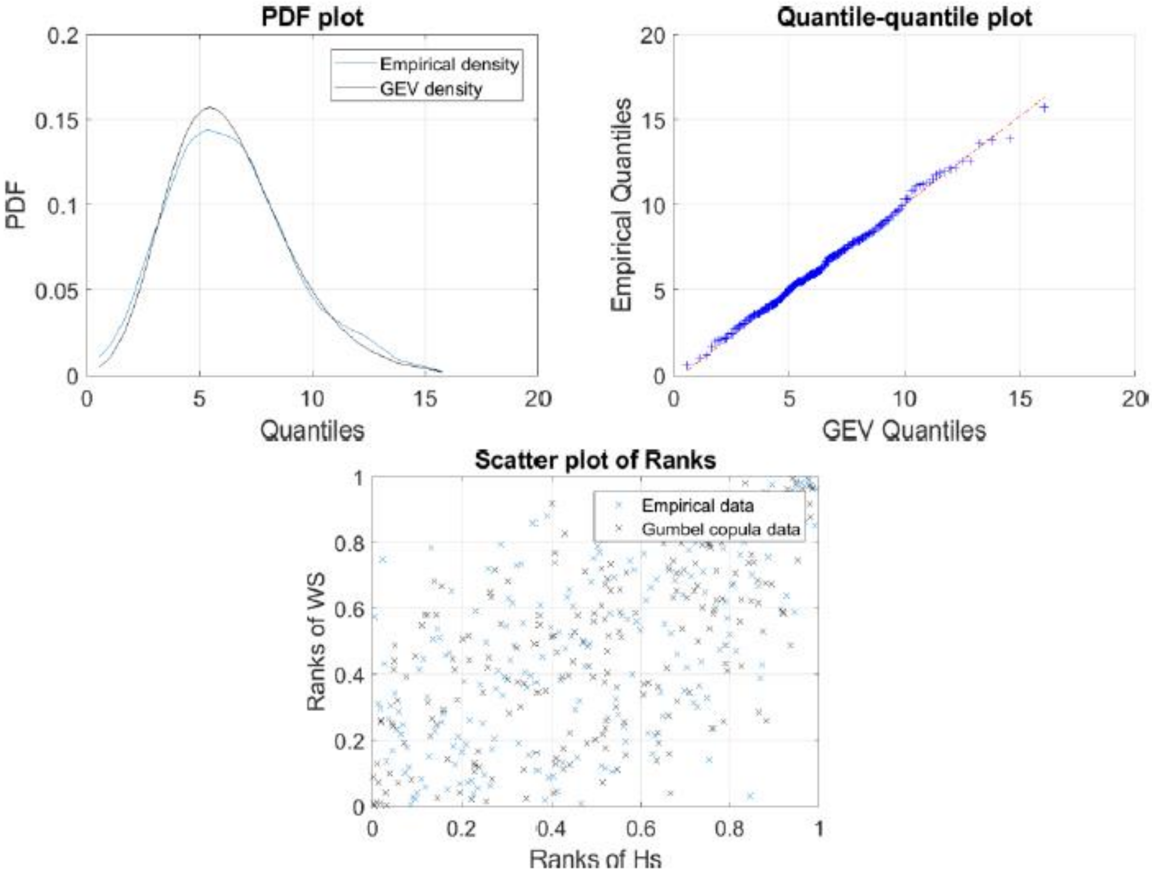
A.3.5 **Directional sector**: 75°-105°



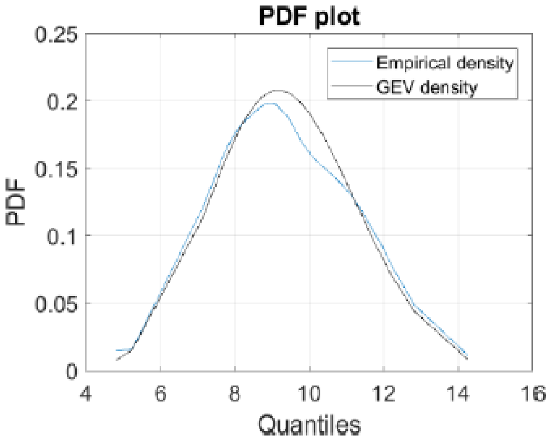


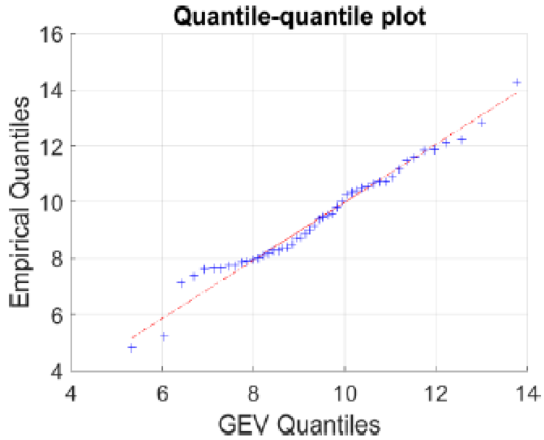


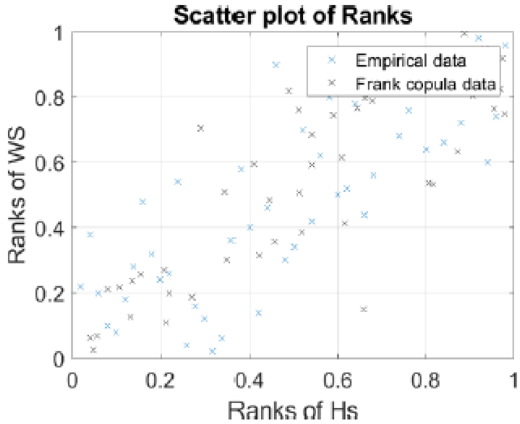
A.3.6 Directional sector: 105°-135°



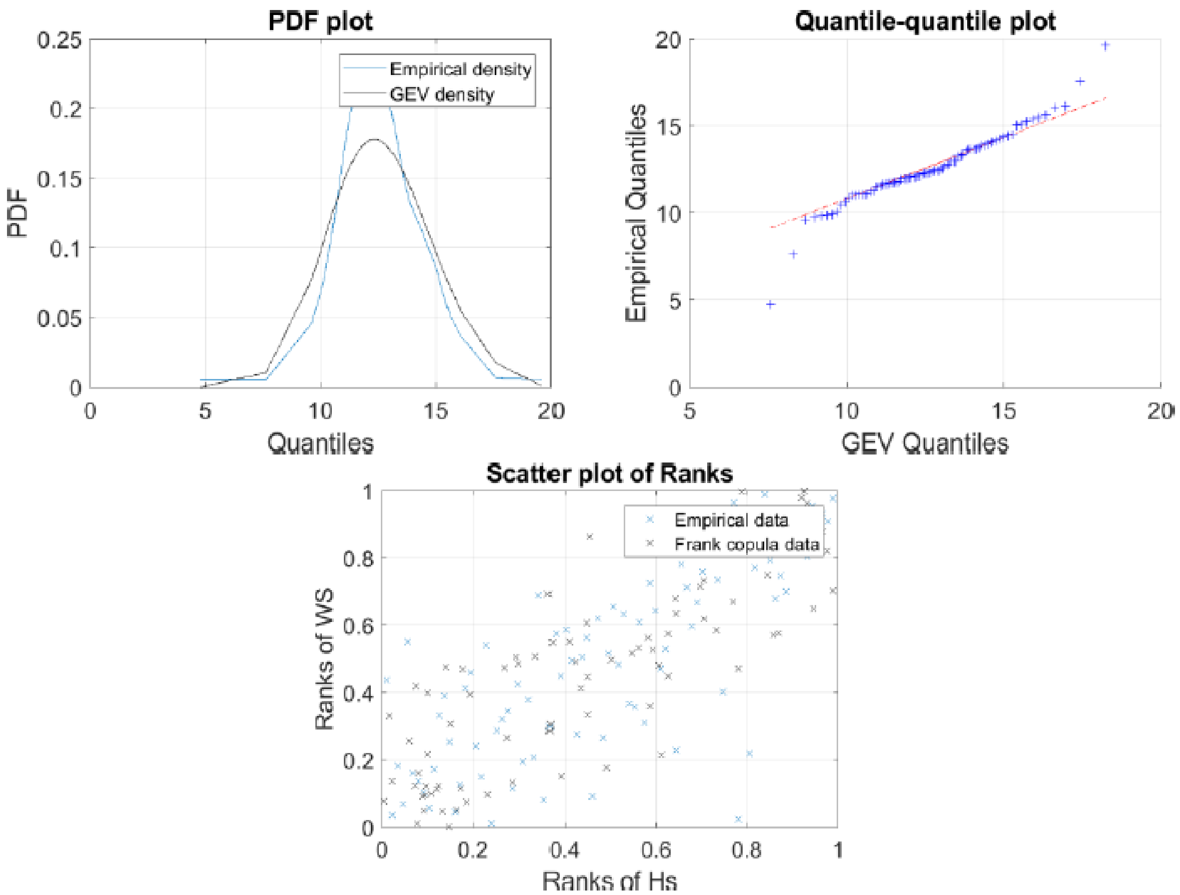
A.3.7 Directional sector: 135°-165°



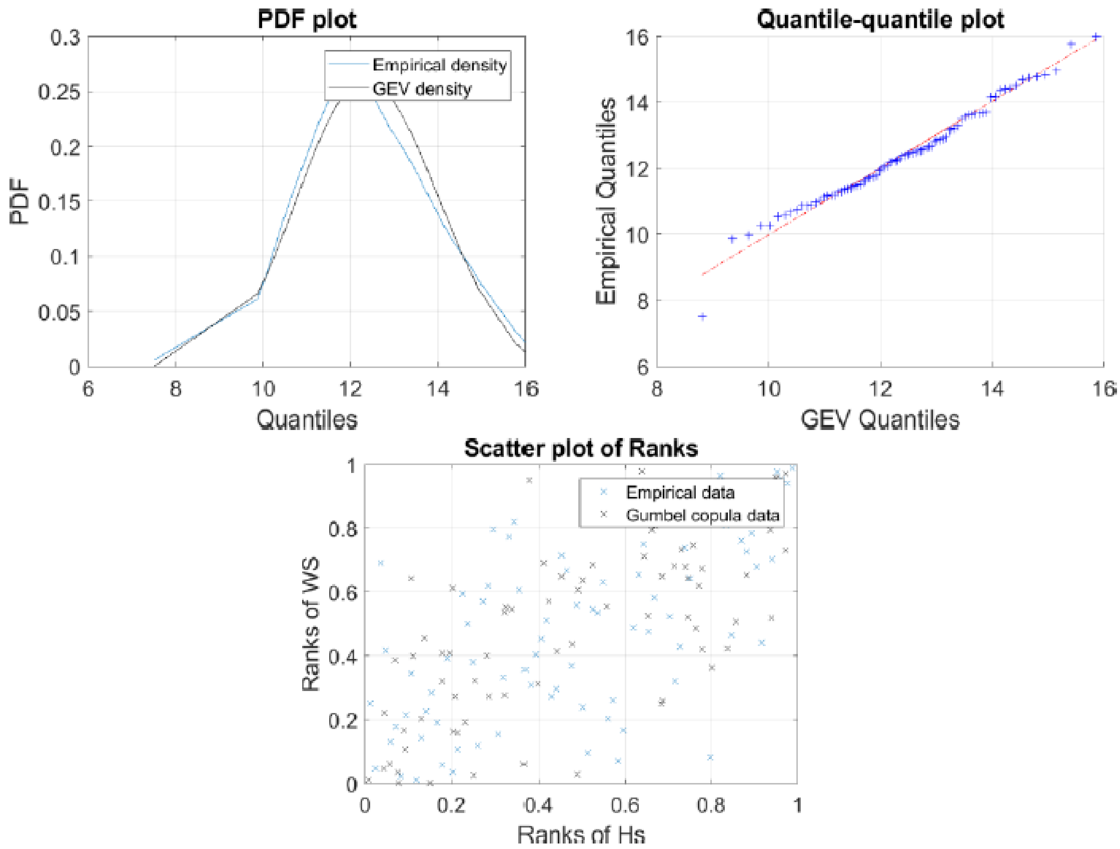




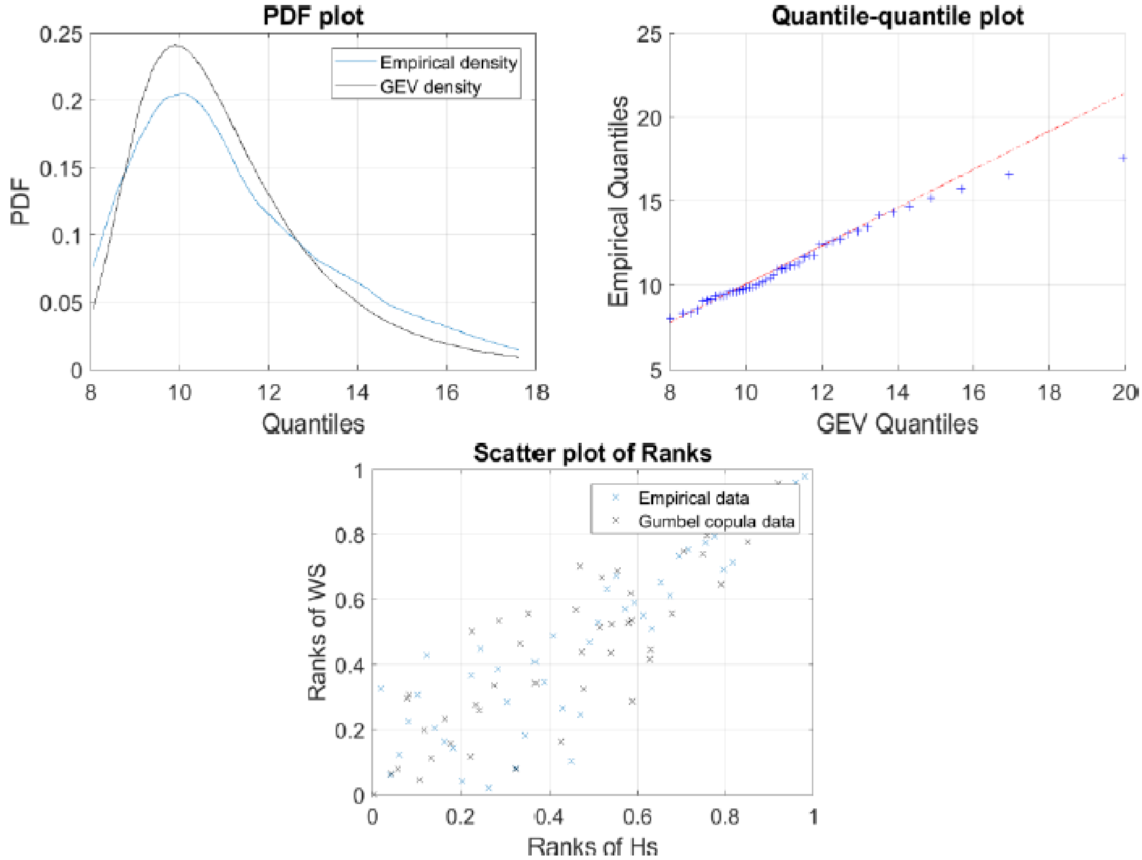
A.3.8 Directional sector: 165°-195°



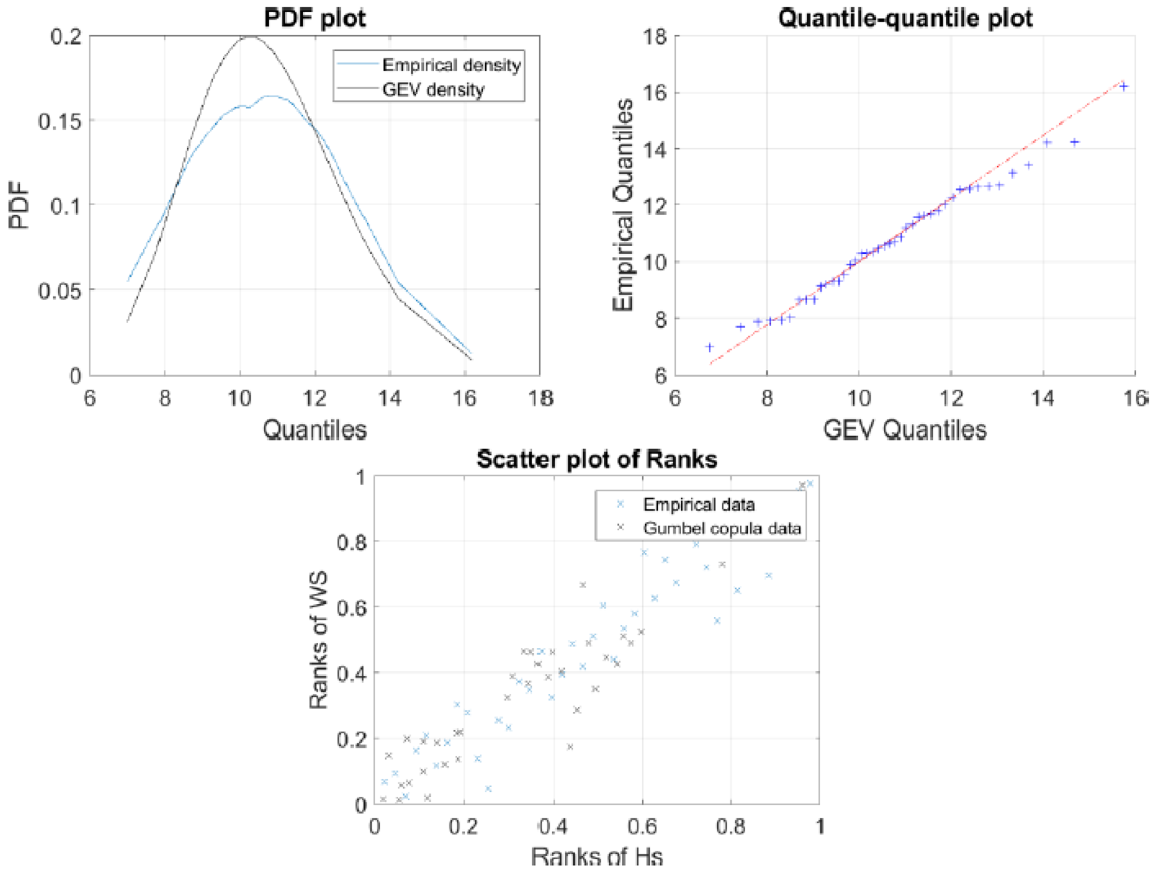
A.3.9 Directional sector: 195°-225°



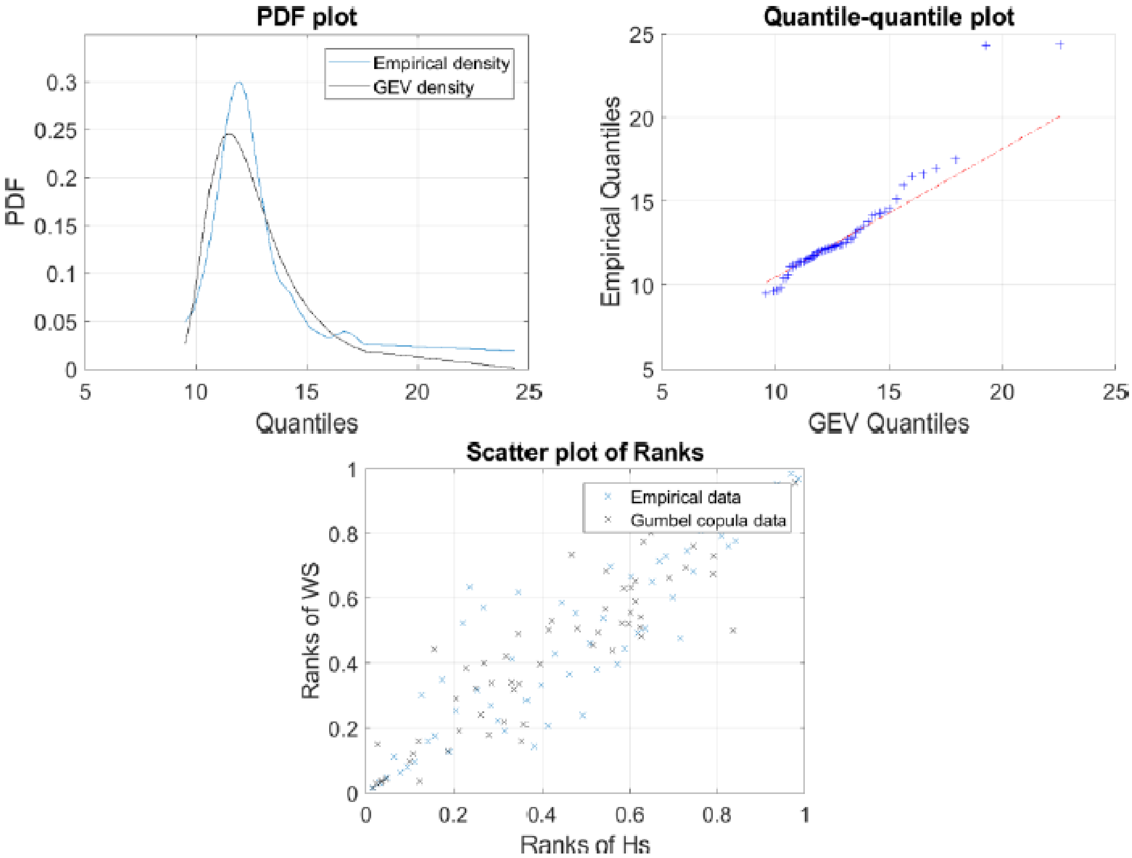
A.3.10 **Directional sector**: 255°-285°



A.3.11 **Directional sector**: 285°-315°



A.3.12 **Directional sector**: 315°-345°



ANNEX 10.3 – OUTPUT LOCATIONS UTM35N

Location / X Coordinates [UTM35E] / Y-Coordinates [UTM35N]

ANEXA 10.3 – LOCAȚII DE IEȘIRE UTM35N

Locație	Coordonate-X [UTM35E]	Coordonate-Y [UTM35N]
Loc01	632089	4902262
Loc02	634209.8	4907246
Loc03	633283.9	4907622
Loc04	632358	4907998
Loc05	631432.1	4908374
Loc06	634079.2	4906908
Loc07	633141	4907252
Loc08	632202.7	4907596
Loc09	631264.5	4907940
Loc10	633960.4	4906566
Loc11	633010.8	4906878
Loc12	632061.3	4907189
Loc13	631111.8	4907501
Loc14	633853.3	4906220
Loc15	632893.7	4906499
Loc16	631934	4906777
Loc17	630974.3	4907056
Loc18	633758.3	4905870
Loc19	632789.6	4906116
Loc20	631820.9	4906362
Loc21	630852.2	4906607
Loc22	633675.2	4905518
Loc23	632698.7	4905730
Loc24	631722.2	4905942
Loc25	630745.6	4906154
Loc26	633604.4	4905162
Loc27	632621.2	4905341
Loc28	631637.9	4905519
Loc29	630654.6	4905698
Loc30	633545.8	4904805
Loc31	632557	4904949
Loc32	631568.2	4905094
Loc33	630579.4	4905239
Loc34	633499.5	4904446
Loc35	632506.3	4904556
Loc36	631513.2	4904667
Loc37	630520	4904777
Loc38	633465.6	4904085
Loc39	632469.2	4904161
Loc40	631472.8	4904238
Loc41	630476.4	4904314
Loc42	633444.1	4903723
Loc43	632445.7	4903765
Loc44	631447.3	4903807
Loc45	630448.8	4903850
Loc46	633435.1	4903361
Loc47	632435.8	4903369
Loc48	631436.5	4903377
Loc49	630437.2	4903384
Loc50	633438.5	4902999
Loc51	632439.5	4902972
Loc52	631440.5	4902946
Loc53	630441.6	4902919
Loc54	633454.3	4902637
Loc55	632456.9	4902576
Loc56	631459.4	4902515
Loc57	630461.9	4902454
Loc58	633482.6	4902276
Loc59	632487.8	4902181
Loc60	631493	4902085
Loc61	630498.2	4901990
Loc62	633523.3	4901916
Loc63	632532.3	4901786
Loc64	631541.4	4901657
Loc65	630550.4	4901528
Loc66	633576.3	4901557
Loc67	632590.3	4901394
Loc68	631604.4	4901231
Loc69	630618.5	4901068
Loc70	633641.5	4901201
Loc71	632661.8	4901004
Loc72	631682.1	4900807
Loc73	630702.4	4900610
Loc74	633719	4900847
Loc75	632746.6	4900617
Loc76	631774.3	4900386
Loc77	630801.9	4900156
Loc78	633808.6	4900496
Loc79	632844.7	4900232
Loc80	631880.9	4899968
Loc81	630917	4899705
Loc82	633910.2	4900148
Loc83	632956	4899852
Loc84	632001.7	4899555

Loc85	631047.5	4899258
Loc86	634023.7	4899804
Loc87	633080.2	4899475
Loc88	632136.7	4899146
Loc89	631193.3	4898816
Loc90	630661.8	4898853
Loc91	630643.3	4898902
Loc92	630626.7	4898949
Loc93	630607.2	4898995
Loc94	630585.8	4899041
Loc95	630564.8	4899087
Loc96	630543.5	4899134
Loc97	630498.4	4899111
Loc98	630452.6	4899090
Loc99	630473.8	4899044
Loc100	630492.7	4898997
Loc101	630510.7	4898951
Loc102	630528.3	4898903
Loc103	630541.3	4898855
Loc104	630554.4	4898806
Loc105	630569.4	4898758
Loc106	630618.4	4898773
Loc107	630672.9	4898802
Loc108	630328.6	4898589
Loc109	630374.8	4898608
Loc110	630419.4	4898632
Loc111	630464	4898655
Loc112	630508.1	4898678
Loc113	630553.9	4898700
Loc114	630691	4898762
Loc115	630830.5	4898819
Loc116	630753.7	4898599
Loc117	630729.7	4898643
Loc118	630684.1	4898622
Loc119	630637.1	4898602
Loc120	630657.2	4898556
Loc121	630675.4	4898510
Loc122	630776	4898552
Loc123	630355.9	4898537
Loc124	630400	4898562
Loc125	630444.6	4898586
Loc126	630488.5	4898611
Loc127	630532	4898638
Loc128	630577.7	4898659

Loc129	630659.1	4898701
Loc130	630450.7	4898870
Loc131	630407.9	4898852
Loc132	630362.1	4898829
Loc133	630314	4898808
Loc134	630273.4	4898788
Loc135	630620.2	4898525
Loc136	630579.9	4898496
Loc137	630539.5	4898468
Loc138	630502.3	4898439
Loc139	630460.9	4898410

Krasovsky/Stereo 70:

Location / X Coordinates [Stereo70 E] / Y-Coordinates [Stereo70 N]

Krasovsky/Stereo 70:

Location	X-Coordinate [Stereo70 E]	Y-Coordinate [Stereo70 N]
Loc01	791911.0	313468.8
Loc02	793907.5	318507.9
Loc03	792971.9	318860.9
Loc04	792036.2	319213.9
Loc05	791100.6	319566.8
Loc06	793785.4	318166.6
Loc07	792838.2	318487.2
Loc08	791891.0	318807.8
Loc09	790943.8	319128.4
Loc10	793675.1	317821.2
Loc11	792717.4	318109.1
Loc12	791759.8	318397.0
Loc13	790802.1	318684.9
Loc14	793576.7	317472.3
Loc15	792609.7	317727.1
Loc16	791642.7	317982.0
Loc17	790675.7	318236.8
Loc18	793490.4	317120.2
Loc19	792515.2	317341.7
Loc20	791540.0	317563.1
Loc21	790564.8	317784.6
Loc22	793416.2	316765.4
Loc23	792434.0	316953.2
Loc24	791451.8	317141.0
Loc25	790469.5	317328.8
Loc26	793354.2	316408.2
Loc27	792366.2	316562.1
Loc28	791378.1	316716.1
Loc29	790390.0	316870.0
Loc30	793304.6	316049.1
Loc31	792311.8	316169.0
Loc32	791319.0	316288.9
Loc33	790326.2	316408.8
Loc34	793267.3	315688.5
Loc35	792271.0	315774.2
Loc36	791274.7	315859.9
Loc37	790278.3	315945.7
Loc38	793242.5	315326.8
Loc39	792243.8	315378.3
Loc40	791245.1	315429.7
Loc41	790246.4	315481.2
Loc42	793230.0	314964.5
Loc43	792230.2	314981.6
Loc44	791230.3	314998.7
Loc45	790230.4	315015.8
Loc46	793230.1	314602.0
Loc47	792230.2	314584.7
Loc48	791230.3	314567.5
Loc49	790230.5	314550.2
Loc50	793242.6	314239.7
Loc51	792243.9	314188.1
Loc52	791245.2	314136.5
Loc53	790246.5	314084.9
Loc54	793267.5	313878.0
Loc55	792271.2	313792.1
Loc56	791274.9	313706.2
Loc57	790278.5	313620.4
Loc58	793304.8	313517.4
Loc59	792312.0	313397.3
Loc60	791319.3	313277.3
Loc61	790326.5	313157.2
Loc62	793354.5	313158.3
Loc63	792366.5	313004.2
Loc64	791378.4	312850.1
Loc65	790390.3	312696.0
Loc66	793416.5	312801.1
Loc67	792434.4	312613.2
Loc68	791452.2	312425.2
Loc69	790470.0	312237.3
Loc70	793490.8	312446.3
Loc71	792515.6	312224.7
Loc72	791540.5	312003.1
Loc73	790565.3	311781.5
Loc74	793577.2	312094.2
Loc75	792610.2	311839.2
Loc76	791643.3	311584.3
Loc77	790676.3	311329.3
Loc78	793675.6	311745.3
Loc79	792718.0	311457.3
Loc80	791760.4	311169.2
Loc81	790802.7	310881.2
Loc82	793786.0	311400.0
Loc83	792838.8	311079.2

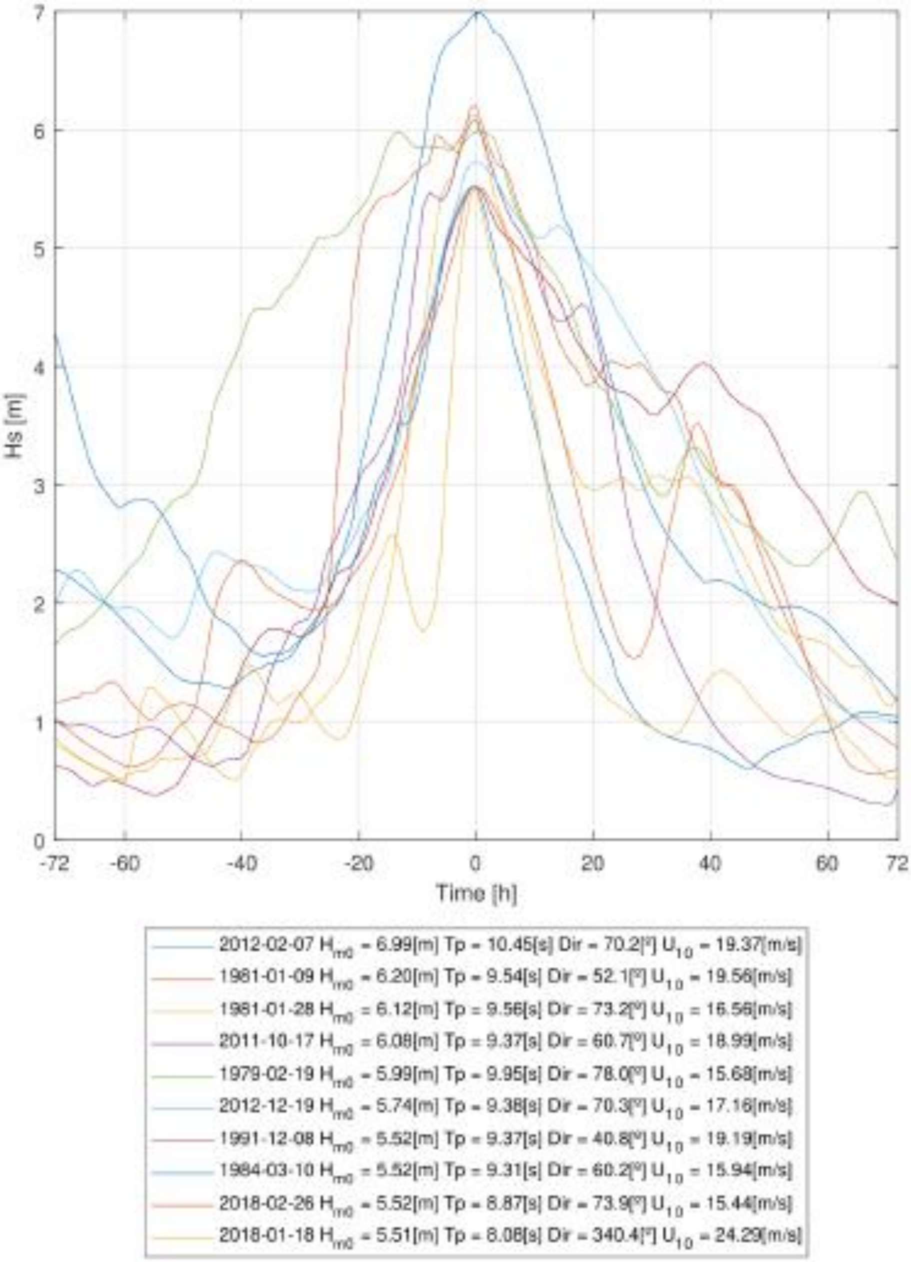
Loc84	791891.7	310758.5
Loc85	790944.5	310437.7
Loc86	793908.2	311058.6
Loc87	792972.6	310705.5
Loc88	792037.0	310352.4
Loc89	791101.4	309999.3
Loc90	790568.8	310022.6
Loc91	790549.1	310071.0
Loc92	790531.3	310118.2
Loc93	790510.6	310163.9
Loc94	790488.1	310209.2
Loc95	790465.9	310254.9
Loc96	790443.5	310300.7
Loc97	790398.9	310276.5
Loc98	790353.6	310254.2
Loc99	790376.0	310209.2
Loc100	790396.1	310163.1
Loc101	790415.2	310116.6
Loc102	790434.0	310069.9
Loc103	790448.2	310021.7
Loc104	790462.5	309973.5
Loc105	790478.8	309925.3
Loc106	790527.4	309941.8
Loc107	790581.2	309972.2
Loc108	790242.1	309750.0
Loc109	790287.8	309770.6
Loc110	790331.8	309795.9
Loc111	790375.9	309819.4
Loc112	790419.4	309843.9
Loc113	790464.7	309866.7
Loc114	790600.3	309932.9
Loc115	790738.5	309993.4
Loc116	790667.1	309770.9
Loc117	790642.0	309814.8
Loc118	790596.9	309792.4
Loc119	790550.4	309771.5
Loc120	790571.7	309725.9
Loc121	790591.1	309679.7
Loc122	790690.6	309724.6
Loc123	790270.7	309699.5
Loc124	790314.2	309724.7
Loc125	790358.2	309750.2
Loc126	790401.5	309776.7
Loc127	790444.4	309804.1

Loc128	790489.5	309827.1
Loc129	790570.0	309870.8
Loc130	790357.2	310034.1
Loc131	790314.9	310015.7
Loc132	790269.6	309991.1
Loc133	790222.0	309969.5
Loc134	790181.9	309948.2
Loc135	790535.4	309694.0
Loc136	790495.8	309663.7
Loc137	790456.1	309634.9
Loc138	790419.7	309604.7
Loc139	790379.0	309574.4

ANNEX 10.4 - CHECKING THE SHAPE OF THE STORM

Storm projection, 10 highest peaks, +/- 72h around peak moment

Offshore	
Coordinate:	*44°N 29.5°E*
Depth:	*69m*
Samples:	*357576 samples (1979.01.16-2019.10.31)*
Dir. Sector	*Omni*



- input time series: [illegible]
- m-file: [illegible]
- print date: [illegible]

ANNEX 10.5 – MODEL PERFORMANCE

The spatial chart for conditions 9 and 10 is shown in Figure 10.1. A complete list of the final design conditions is shown in Table 6-2. The offshore data location 44.0°N 29.5°E (UTM35 700438m E 4874911m Y) is represented by the blue/green cross. The wave height at the offshore location matches the boundary conditions, showing that the wave height remains constant along the model boundary. This justifies the performance of the model.

The figures confirm that the imbrication and convergence of the wave pattern is good.

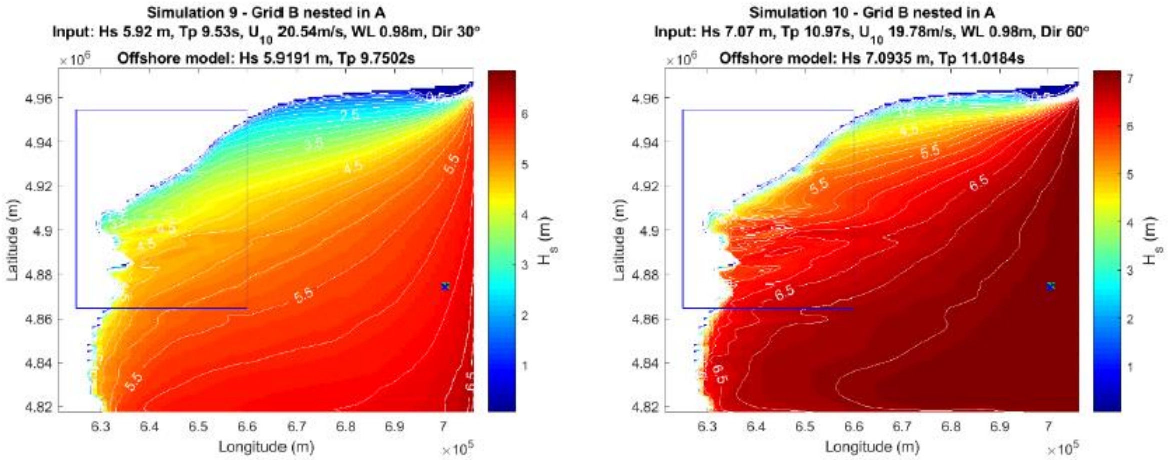


Figure 10.1: Spatial chart of wave height for condition 9 (left) and condition 10 (right)

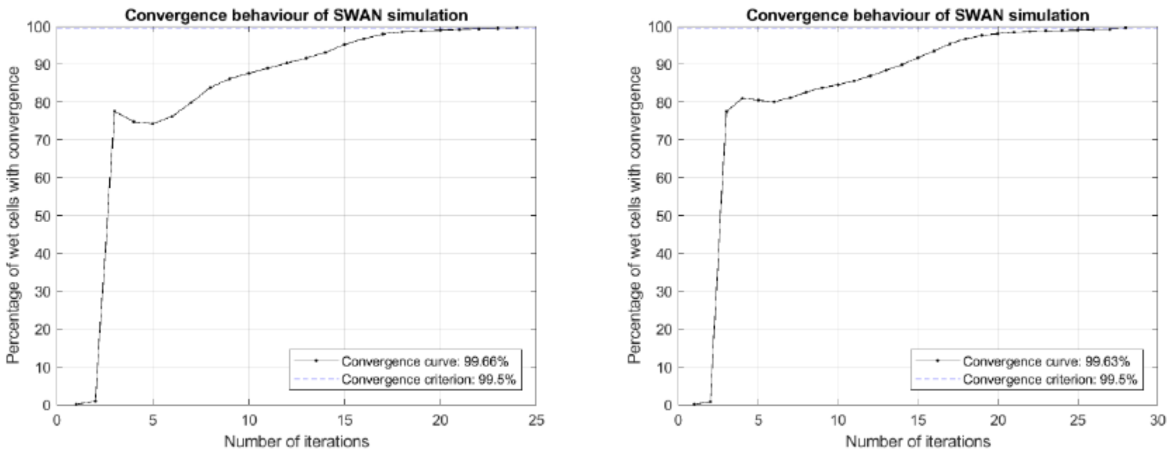


Figure 10.2: Model convergence behaviour of SWAN simulation 9 (left) and 10 (right) for the grid.