SEM-REV Metocean design basis

O. Thilleul, Y. Perignon[1]

In collaboration with A. Bertholon, A. Blangy, M. Reynaud, L. Sigoigne

February 2022

[1]Contact: semrev@ec-nantes.fr

TABLE OF CONTENTS

DEFINITIONS

N.B: In this entire document the following statistics are used:

Bias:

$$\mathrm{Bias}(X,Y) = E[Y] - E[X]$$

Root Mean Square Error:

$$\mathrm{RMSE}(X,Y) = \sqrt{\frac{1}{N}\sum_i (Y_i - X_i)^2}$$

Scatter Index:

$$\mathrm{SCI}(X,Y) = \frac{\mathrm{RMSE}(X,Y)}{E[X]}$$

Standard Deviation:

$$\sigma[X] = \sqrt{E\left[(X_i - E[X])^2\right]}$$

Pearson's linear correlation coefficient:

$$\mathrm{Corr}(X,Y) = \frac{E[(X - E[X]) \cdot (Y - E[Y])]}{\sigma[X] \cdot \sigma[Y]}$$

EXECUTIVE SUMMARY

This document presents the metocean design basis of offshore test site « SEM-REV » operated by Centrale Nantes and dedicated to the test of floating wind turbines and wave energy converters. It is released in order to provide data for offshore operations and engineering in the French offshore area of South Brittany and Pays la Loire regions.

It presents a metocean analysis, based on a Measure-Correlate-Predict approach in a consolidated report which provides simultaneously design data for wind, waves, current, tides and marine growth on a French site. In particular, it uses data issued from more than 10 years of continuous campaigns performed since the creation of SEM-REV test site since 2009: 2 years of wind measurements, 10 years of wave measurements and 19 ADCP campaigns for current measurement.

The provided design data are operational statistics and long-term statistics such as values for return periods of 1, 5, 10, 25, 50 and 100 years and for various directional sectors. Additional information are also provided such as turbulence intensity, extreme direction change for wind. Scatter diagram, monthly distribution, beaking wave criteria… are provided for waves. Harmonic analysis of tidal measurements enable to hindcast and forecast water elevation on site. Deeper analysis of current on the water column is also provided. Marine growth thickness is evaluated on various components such as chains, nylon and dynamic cable. Additionally, other environmental conditions such as air density, normal and extreme air and sea temperature ranges are presented.

This report was appraised by Bureau Veritas Marine and Offshore which « certifi[es] that the metocean condition of the SEM-REV Test Site has been appraised according to the following international standards :

- IEC 61400-1:2019 Wind turbines – Part1 : Design requirements
- IEC 61400-3-1:2019 Design requirements for fixed offshore wind turbines
- IEC 61400-3-2:2019 Design requirements for floating offshore wind turbines

The following documents have been reviewed :

- SEM-REV Metocean design basis – rev 1.0 to rev 1.3

The metocean design basis of SEM-REV test site presented, and the associated Measure-Correlate-Predict based method has been found in compliance with the above standards […] »

INTRODUCTION

Centrale Nantes is actively involved in the development of marine renewable energies since several years, in partnership with industrial and academic partners.
Centrale Nantes started in 2007 to build an offshore test site, named SEM-REV, dedicated to test marine renewable energy devices in real conditions.

SEM-REV is located in Loire-Atlantique department, offices are based in the town of Le Croisic and the offshore site is beyond the western part of "Banc de Guérande" shoal. The distance between the offshore site and Le Croisic is approximately 20 km.

The test site is operational since 2015 and has onshore and offshore equipment enabling to test simultaneously several devices at full scale. As a test site, SEM-REV has administrative authorizations to host marine renewable energy devices for testing.

SEM-REV site is operated both by Centrale Nantes and CNRS through the research laboratory LHEEA (UMR CNRS 6598).

The test site comprises (Figure 1):

- An onshore base for research and maintenance located in Penn Avel park, in Le Croisic, belonging to « Conservatoire du Littoral » and managed by Le Croisic municipality (Figure 1A).
- An onshore electrical substation connected to Enedis national grid (Figure 1B).
- A sub-sea medium voltage export cable of 8 MW 20 kV enabling to transport electricity in alternating current between offshore test site and onshore electrical substation (Figure 1C). This cable is buried on its 23 km length and concrete mattresses are reinforcing the protection of two sections (Figure 1D).
- A subsea connection system mentioned as "connection hub", enabling to connect three devices simultaneously to the export cable.
- A public authorization to use maritime domain of approximately 1 km² delimits the offshore test site for marine renewable energy devices (Figure 1E).

Complementary information on SEM-REV site and its activities are regularly updated on the website https://sem-rev.ec-nantes.fr/

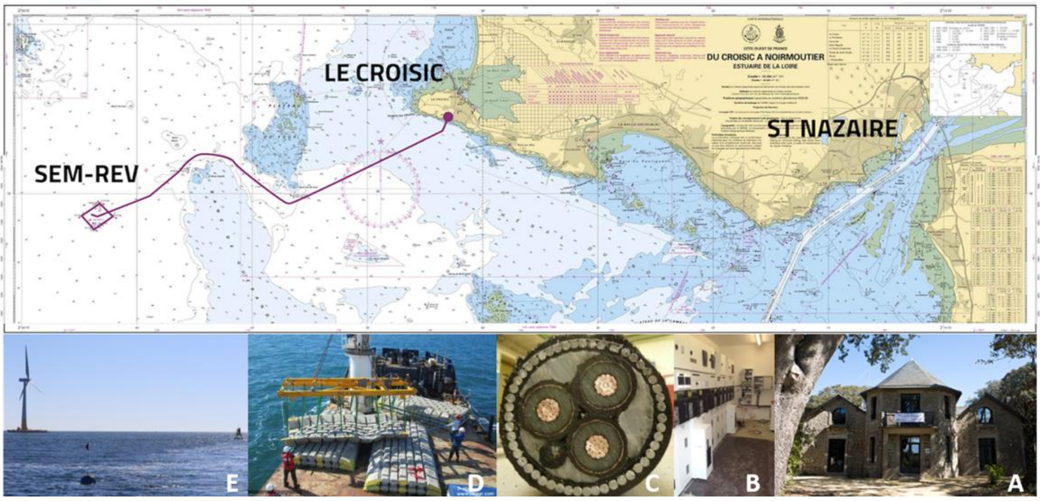


FIGURE 1: SEM-REV TEST SITE INFRASTRUCTURES

1. ENVIRONMENTAL CONDITIONS

1.1 SEM-REV TEST SITE LOCATION

SEM-REV test site is a zone of approximately 1 km² offshore of the town of Le Croisic, in Pays de la Loire, France. It is dedicated to the test of wind turbines, wave energy converters and technologies dedicated to renewable energy.

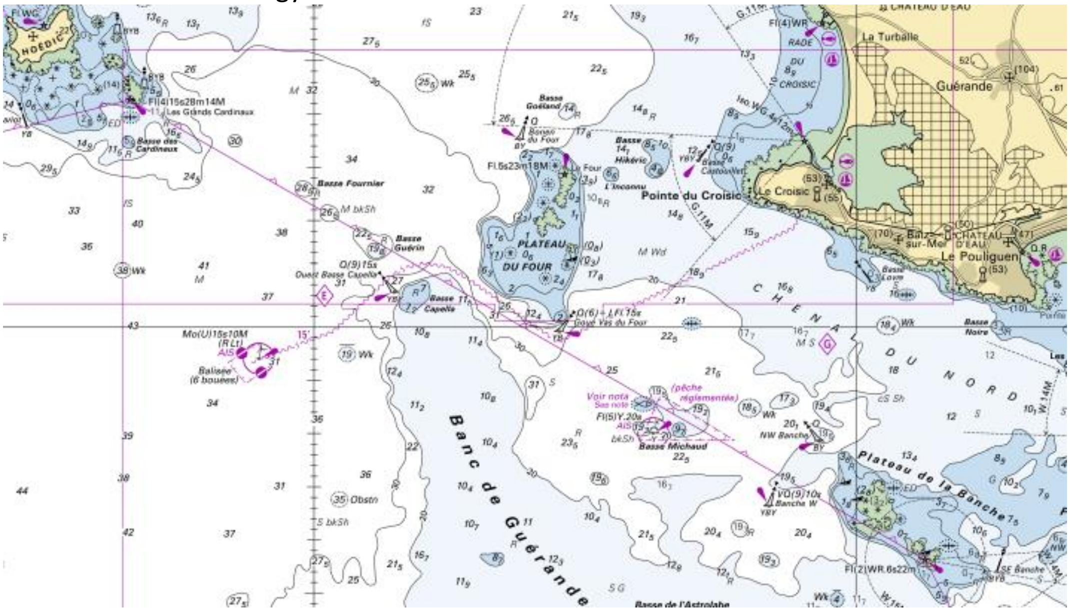


FIGURE 2: MARINE MAP OFFSHORE OF LE CROISIC. SEMREV TEST SITE IN PINK ZONE ON THE LEFT [16]

It is delimited by four special marks at the following coordinates in the WGS 84 coordinate system:

	North	East	South	West
Longitude (W)	2°46.58’	2°46.08’	2°46.88’	2°47.38’
Latitude (N)	47°14.7’	47°14.34’	47°13.94’	47°14.34’

TABLE 1 SPECIAL MARKS COORDINATES

1.2 BATHYMETRY

The bathymetry around SEM-REV test site is presented in the figure below.

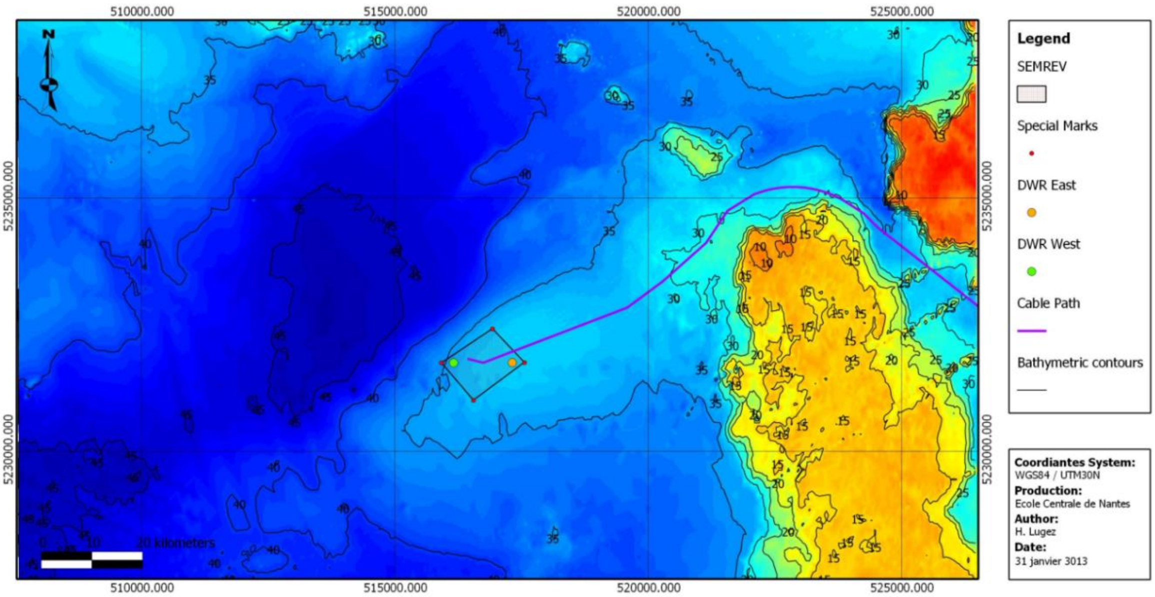


FIGURE 3 INTERPOLATION BASED ON THE LOCAL BATHYMETRIC DATA COLLECTED BY THE SHOM

The depths on SEMREV are included between 32.13m and 35.57m C.D., Chart Datum (Figure 4). These data are interpolated from measurements performed in 2008 and 2010 by Asterie.

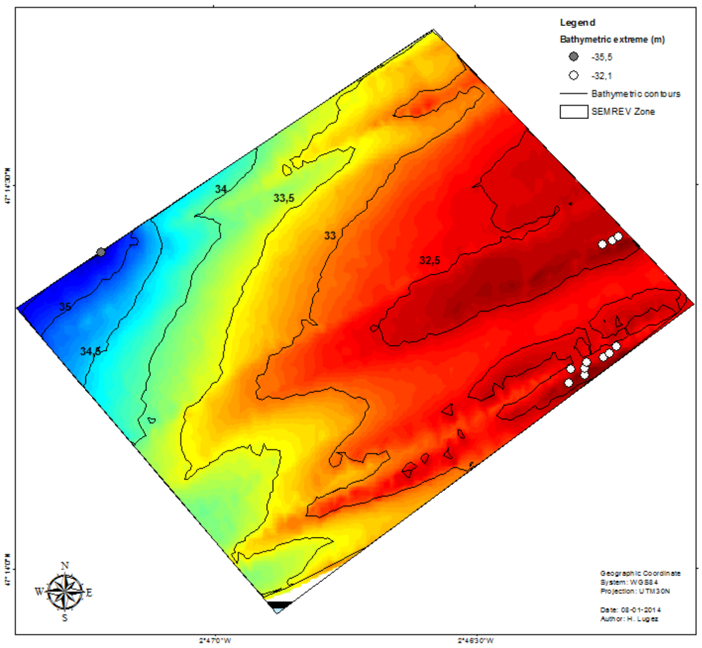


FIGURE 4 INTERPOLATION BASED ON THE LOCAL BATHYMETRIC DATA COLLECTED BY ASTERIE

The complete summary about measurement campaigns is available in Appendix 10.1 and 10.1.2.

The oceano-meteo conditions at the SEMREV test site (i.e. wind, waves, tides and currents) are presented in the following sections. The results are extracted from three different sources:

- In-situ measurements,
- Numerical model results, providing information in the longer term,
- Data provided by external institutes/organisations such as the SHOM, Ifremer, Météo-France…

Taking into account the possible lack of long term measurements, the environmental statistics are provided by numerical models, and validated with measurement when available.

Hence, for wind, waves and current, the following chapters are based on the same structure:

- Presentation of the long term data, the available measurements and the comparison between them
- Presentation of the statistics (operational & extremes) stemming from the previously validated data

2. WIND

2.1 MEASUREMENTS

2.1.1 SETUP

Measurements are performed on the Cardinaux lighthouse (yellow point on Figure 6) located 5.4 nm from SEM-REV site.
The technical details of the measurement campaign are presented below:

Date	Entity who performed measurements	Sensor	Height above mean sea level	Sampling frequency
06/2016-06/2018	ECN	3D sonic anenometer (3D Windmaster)	39 m	10 Hz

TABLE 2: WIND MEASUREMENTS CAMPAIGN DETAILS

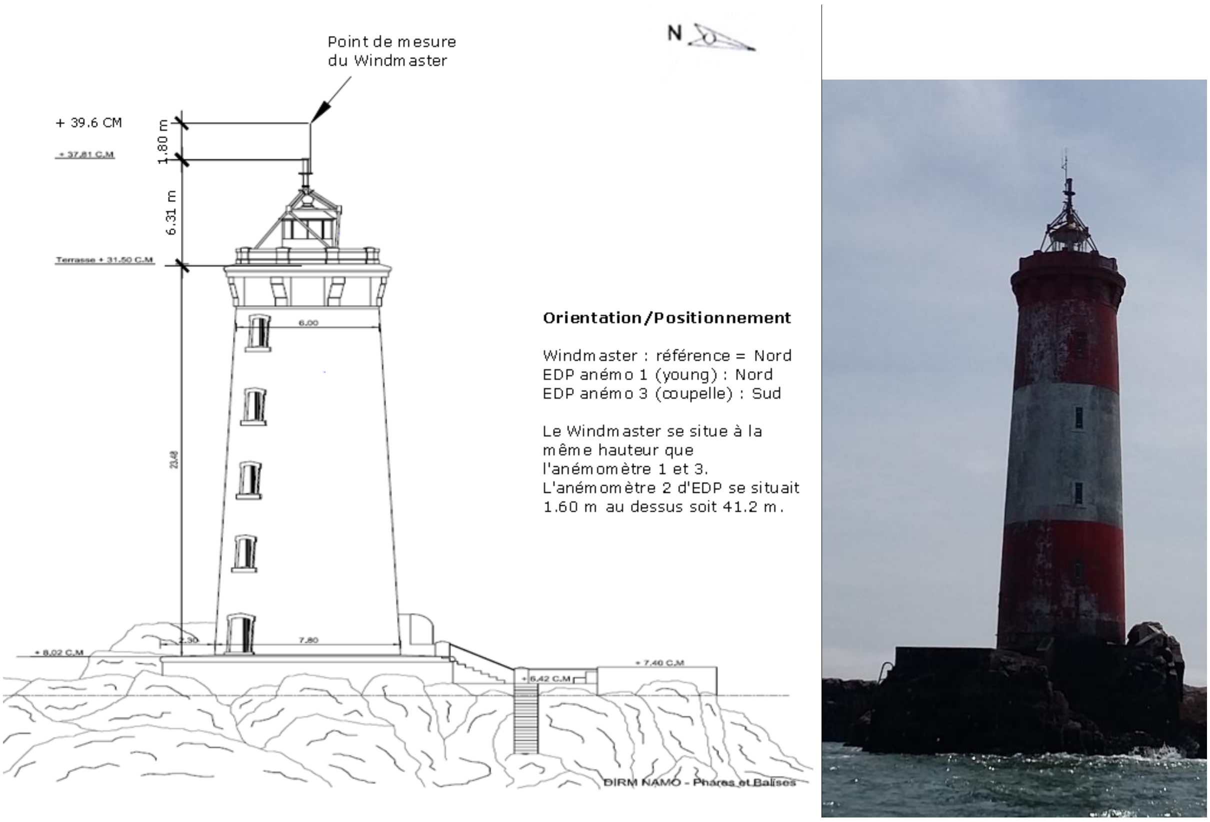


FIGURE 5: SKETCH AND PHOTO OF WINDMASTER LOCATION ON CARDINAUX LIGHTHOUSE

The measurement setup is not equivalent to a met mast but is the only data available until this date for model qualification. Complementary approaches such as joint lidar experiment including floating lidar will be deployed in the future for more accurate wind measurements on SEM-REV site.

2.1.2 ANEMOMETER CALIBRATION

The 3D windmaster anemometer used was set up by the manufacturer with the standard calibration, with an accuracy at 12 m/s of 1.5% RMS on wind speed and 2° in direction [51].

2.1.3 HEIGHT ABOVE MEAN SEA LEVEL FOR MEASUREMENTS

The available measurements were performed at 39 m above sea level (LAT), in the configuration which was possible on Cardinaux lighthouse. An extrapolation at other heights is proposed in section 2.7.

2.1.4 FLOW INCLINATION

2.1.4.1 ON CARDINAUX LIGHTHOUSE

The analysis of wind vertical component versus wind angle with a step of 10° on Cardinaux lighthouse, provides a value of 3.5° for all wind directions. It shows that the site is not subject to any topographic effect but the deviation can be attributed to the structure of the lighthouse itself.

2.1.4.2 ON SEM-REV SITE

SEM-REV site is located approximately 10 km offshore of the lighthouse and of all coasts. The results of vertical flow inclination obtained on Cardinaux lighthouse and mentioned in the previous section tends to consider SEM-REV site as an offshore site, under the definition provided in [5], i.e, with a 0° angle of vertical flow inclination.

2.1.5 QUALITY CHECKS

The measured raw data at 10 Hz is averaged to generate a database at 1 Hz. From this database, the measurements are filtered according to the following quality checks:

- If the horizontal wind speed magnitude < 0 m/s: values are removed
- If the horizontal wind speed magnitude > 50 m/s: values are removed
- If the horizontal wind speed acceleration > 4 m/s^2 : values are removed

This leads to remove 1 042 956 values out of 60 890 186 values, i.e 1.68 % of the database at 1Hz. The filtered database at 1 Hz is then used to generate average values over 10 minutes and 1 hour.

2.2 NUMERICAL MODEL

The wind field from the ERA5 reanalysis produced at ECMWF (European Centre for Medium-Range Weather Forecasts) is used to characterise the offshore wind climate. This database covers the period 1979-2019 (ERA5 hourly data on pressure levels from 1979 to present) [1].

The extracted data are:

- Wind speed velocity at 10 meters (U10)
- Wind speed velocity at 100 meters (U100)

The data from numerical model are extracted on the zone defined by blue points (grid of 0.25 x 0.25°).

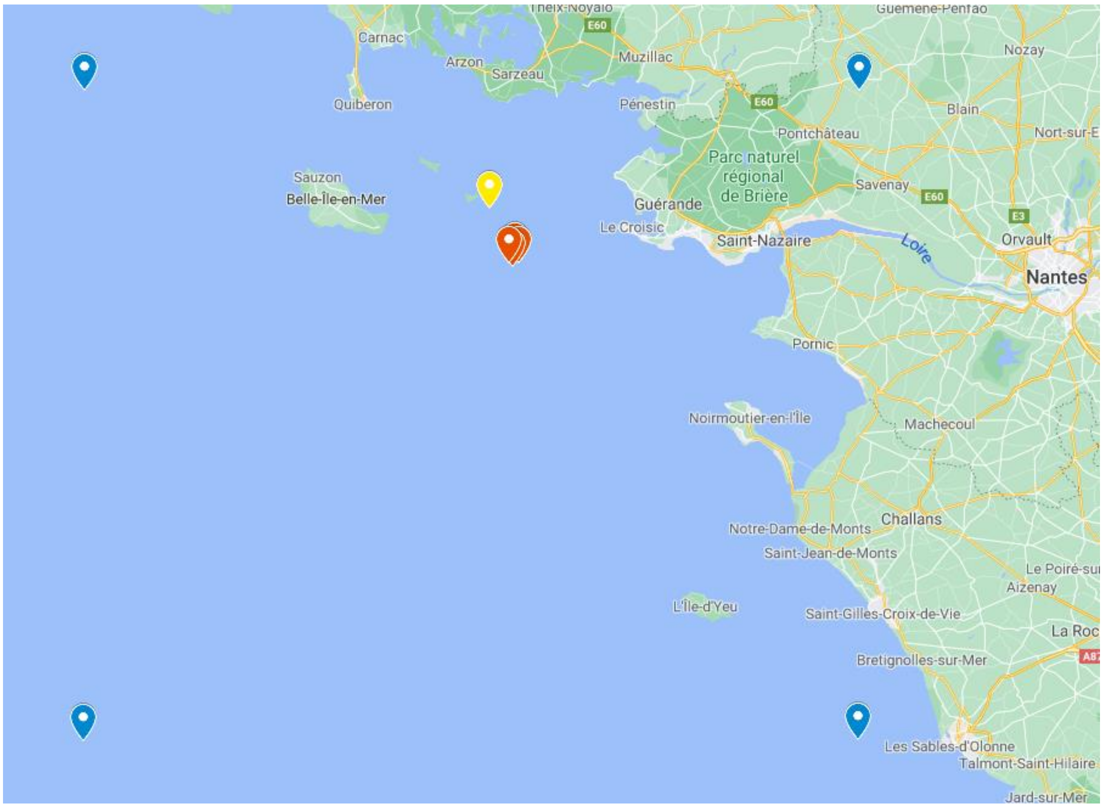


FIGURE 6: MAP OF ERA5 DATA EXTRACTED (BLUE), CARDINAUX LIGHTHOUSE LOCATION (YELLOW), SEM-REV SITE (RED)

2.3 CORRELATION (ON 1-H AVERAGE)

The correlation between the numerical model and the measurements performed at Cardinaux lighthouse is presented below. Since the numerical model provides data on an hourly basis, the correlation between measurements and the model is first performed on 1-H average.

2.3.1 WIND PROFILE

The wind speed can be extrapolated at a height z according to the power law ([4] section 6.3.1.2):

$$\boldsymbol{u(z) = U10\left(\frac{z}{10}\right)^{\alpha}} \quad \textbf{(1)}$$

IEC distinguishes normal wind conditions with α=0.14 and extreme wind conditions for which α=0.11.

According to [3], the computation of α from ERA5 model at each time step can also be computed a by :

$$\alpha(t) = \frac{\ln(\frac{U100}{U10})}{\ln(\frac{100}{10})} \quad (2)$$

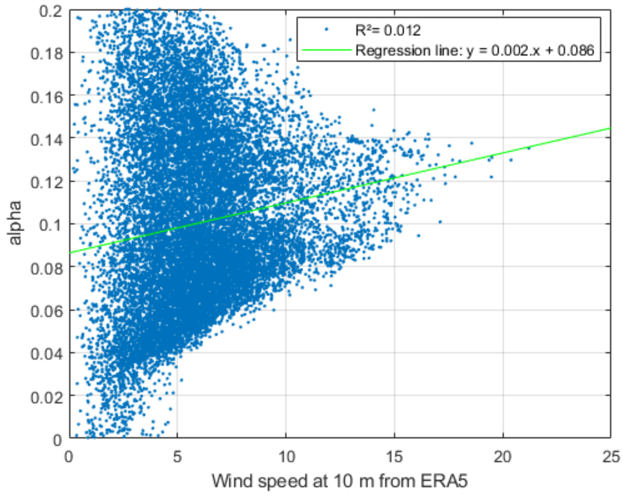


FIGURE 7: ALPHA FROM ERA5 U10 AND U100COMPUTATION (EQUATION [3]) BETWEEN 06/2016 AND 06/2018 (OMNIDIRECTIONAL)

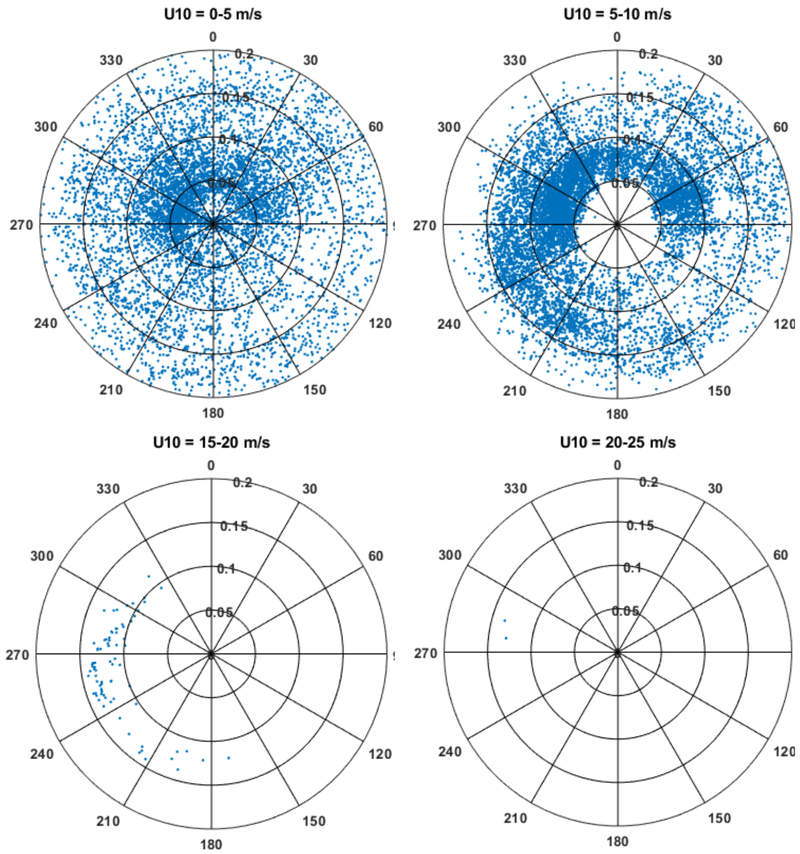


FIGURE 8: ALPHA (VALUE ALONG RADIUS) FROM ERA5 U10 AND U100COMPUTATION (EQUATION [3]) BETWEEN 06/2016 AND 06/2018 VS WIND DIRECTION FOR DIFFERENT RANGE OF WIND SPEED AT 10 METERS

2.3.2 RESULTS OF CORRELATION BETWEEN MODEL AND MEASUREMENTS

The results of the correlation between measurements of wind speed and direction at Cardinaux lighthouse and ERA5 model for the common available periods is presented below:

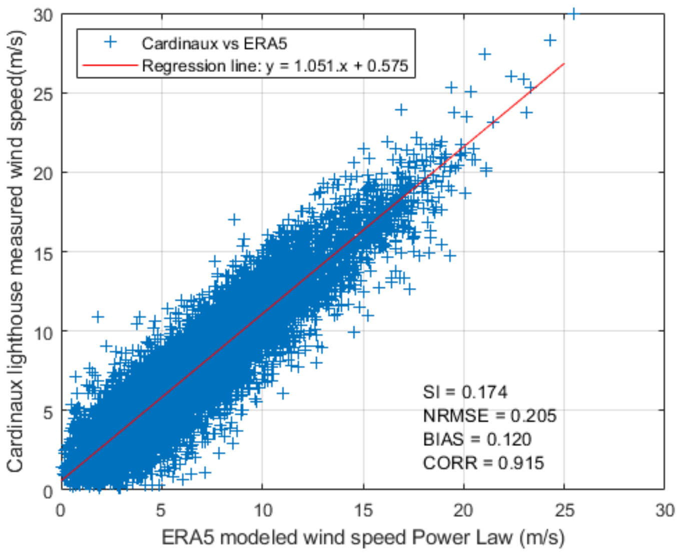


FIGURE 9 CARDINAUX LIGHTHOUSE WIND SPEED MEASUREMENTS VERSUS ERA5 MODELED WIND SPEED (1H-MEAN, OMNIDIRECTIONAL)

Standard metrics of errors (i.e. : bias, normalized root mean square error (NRMSE), scatter index (S.I.) and correlation (r)) are presented in Table 3 for Wind speed and direction at 39 m height.

	S.I	NRMSE	Bias	Correlation
Vmean (m/s)	0.174	0.205	0.120	0.915
Θmean (°)	0.350	0.351	-0.140	0.935

TABLE 3 VALIDATION CARRIED OUT WITH IN SITU-MEASUREMENTS (ERA5 / CARDINAUX LIGHTHOUSE)

The correlation of 91.5% between ERA5 model and omnidirectional wind measurements at Cardinaux lighthouse enables to consider ERA5 model as a sufficiently reliable model in the area. Hence, ERA5 model is used on SEM-REV to have a long-term dataset. For information, the wind speed correlation by directional sectors is presented in Appendix 10.4.

2.4 WIND TIMESERIES FROM ERA5 MODEL ON SEM-REV

The horizontal wind speed timeseries of ERA5 model dataset on SEM-REV at 10 m and 100 m are presented below. The annual mean wind speed is superimposed. The standard deviation of annual means is 0.18 for the wind speed at 10 meters and 0.23 at 100 meters.

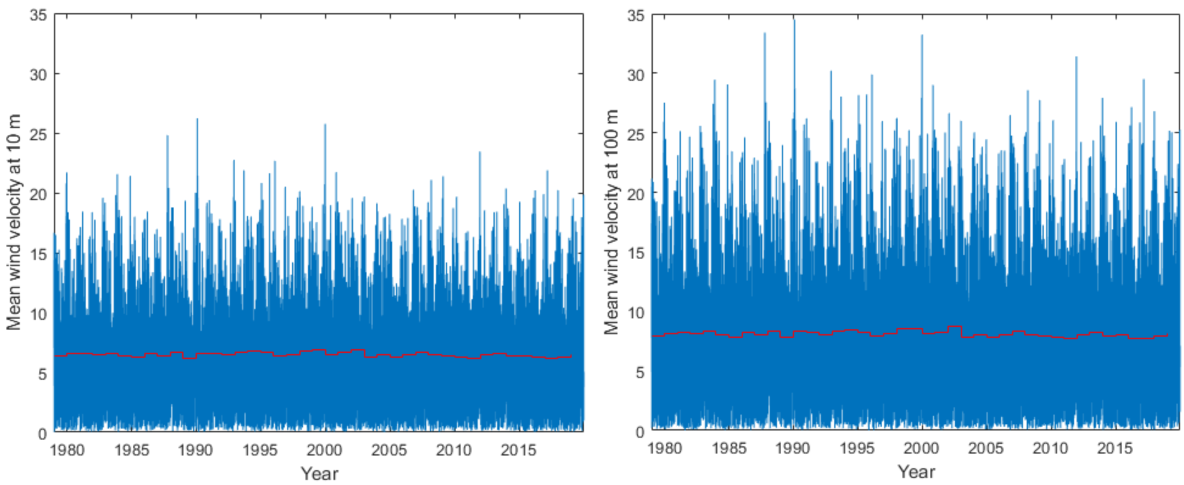


FIGURE 10: HORIZONTAL WIND SPEED FROM ERA5 ON SEM-REV AND MEAN ANNUAL VALUES (IN RED). LEFT: AT 10M, RIGHT: AT 100 M

2.5 STATISTICS OPERATIONAL (MEAN ON 1-HOUR FROM ERA5)

2.5.1 WIND 10 M ABOVE SEA LEVEL

Operational statistics are issued from ERA5 reanalysis at SEM-REV site. The figure below shows the wind velocity rose (m/s) discretised by 30º-wide angular sectors. The main direction of the wind is West and NE to a lesser extent. The mean velocity from measurements is 6.49 m/s (and 6.51 m/s from Weibull fit) with values essentially ranging from 2.5m/s to 14m/s (Figure 11). The strongest winds are coming from W (270°).

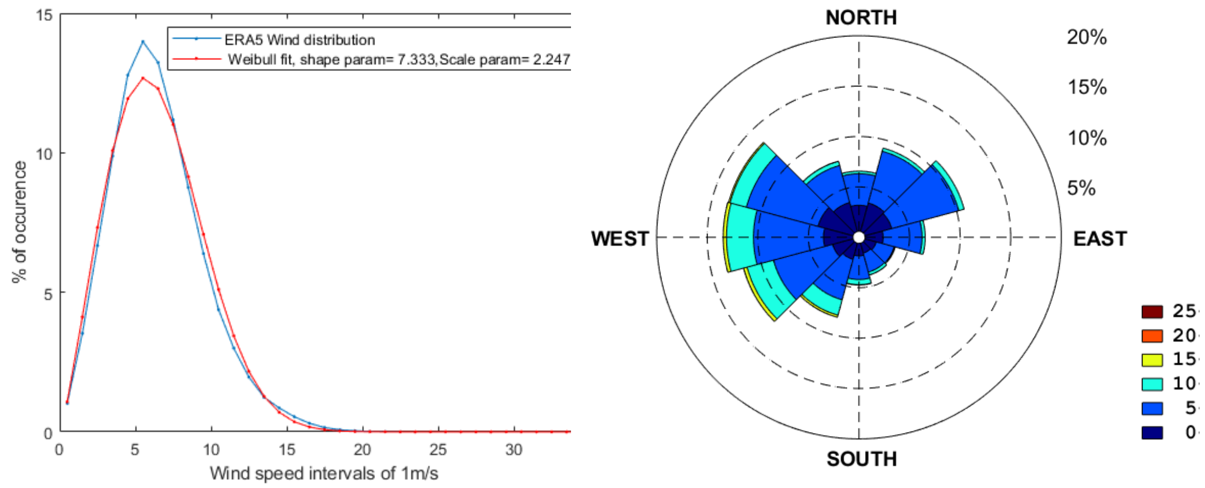


FIGURE 11: LEFT: ERA5 WIND DISTRIBUTION AND WEIBULL FIT PARAMETERS; RIGHT: WIND VELOCITY ROSE FOR WIND 1-HOUR AVERAGE WIND SPEED 10 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV. CONVENTION: “WIND IS COMING FROM”

Wind (m/s)	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	Omni
0 <= U < 2	0.44	0.40	0.37	0.32	0.30	0.29	0.33	0.36	0.39	0.44	0.45	0.45	**4.54**
2 <= U < 4	1.59	1.70	1.57	1.14	0.91	0.79	0.92	1.11	1.29	1.68	2.00	1.83	**16.55**
4 <= U < 6	2.20	3.04	3.21	1.93	1.13	1.04	1.17	1.65	2.19	3.01	3.69	2.49	**26.76**
6 <= U < 8	1.40	2.54	3.35	1.84	0.87	0.88	1.06	1.78	2.64	3.04	3.28	1.73	**24.41**
8 <= U < 10	0.67	1.15	1.70	0.99	0.39	0.55	0.71	1.51	2.24	2.25	2.10	0.88	**15.14**
10 <= U < 12	0.21	0.30	0.50	0.29	0.09	0.24	0.34	0.97	1.58	1.49	1.08	0.30	**7.38**
12 <= U < 14	0.04	0.04	0.05	0.03	0.01	0.06	0.14	0.48	0.86	0.91	0.47	0.11	**3.20**
14 <= U < 16	0.01	0.00	0.00	0.00	0.01	0.01	0.05	0.23	0.43	0.41	0.22	0.03	**1.40**
16 <= U < 18	0.00				0.00	0.00	0.01	0.10	0.15	0.14	0.05	0.01	**0.46**
18 <= U < 20	0.00					0.00	0.00	0.03	0.04	0.04	0.01	0.00	**0.11**
20 <= U < 22							0.00	0.01	0.01	0.01	0.00	0.00	**0.02**
22 <= U < 24								0.00	0.00	0.00	0.00		**0.00**
24 <= U < 26								0.00	0.00			0.00	**0.00**
26 <= U < 28										0.00			**0.00**
28 <= U < 30													
30 <= U													
Total (%)	**6.57**	**9.17**	**10.77**	**6.55**	**3.70**	**3.88**	**4.74**	**8.22**	**11.82**	**13.43**	**13.34**	**7.83**	**100.00**
Mean (m/s)	**5.33**	**5.73**	**6.14**	**5.91**	**5.27**	**5.86**	**6.20**	**7.37**	**7.81**	**7.43**	**6.67**	**5.59**	**6.49**
Max (m/s)	**18.91**	**14.66**	**15.02**	**14.38**	**16.66**	**18.23**	**20.74**	**24.81**	**24.40**	**26.22**	**22.66**	**25.75**	**26.22**

TABLE 4 : ANNUAL DIRECTION OF SAMPLE DISTRIBUTION (%) OF 1-HOUR AVERAGE WIND SPEED 10 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

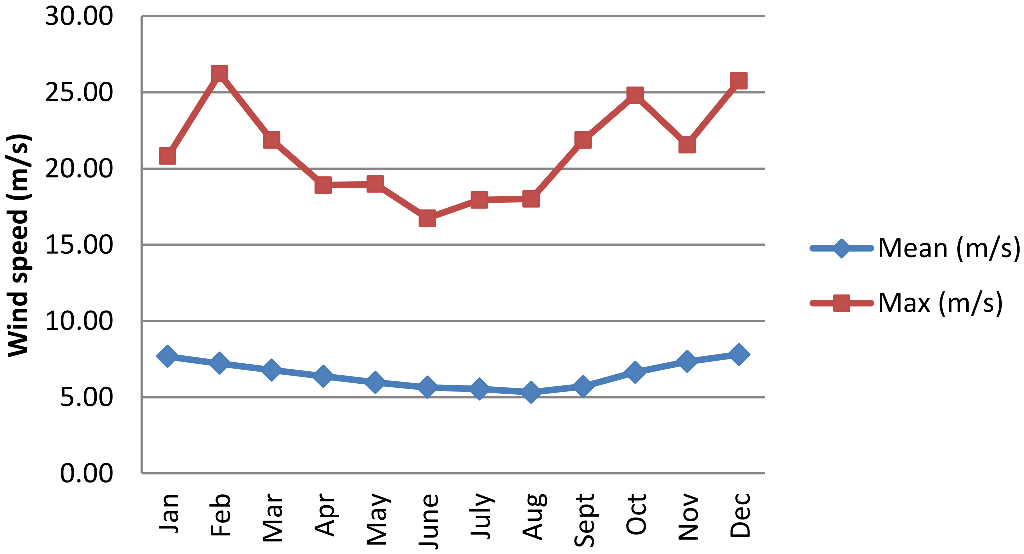


FIGURE 12: MONTHLY MEAN AND MAXIMUM 1-HOUR AVERAGE WIND SPEED 10 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

Wind (m/s)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
<2	0.26	0.28	0.38	0.38	0.46	0.45	0.39	0.50	0.56	0.39	0.25	0.24	**4.54**
2 <= U < 4	0.98	1.02	1.23	1.32	1.57	1.64	1.74	2.01	1.72	1.39	1.00	0.94	**16.55**
4 <= U < 6	1.67	1.69	2.01	2.21	2.47	2.74	3.03	2.99	2.44	2.12	1.76	1.63	**26.76**
6 <= U < 8	1.96	1.88	2.21	2.12	2.21	2.07	2.22	1.93	2.02	2.00	1.89	1.90	**24.41**
8 <= U < 10	1.62	1.46	1.39	1.35	1.16	0.91	0.83	0.78	0.96	1.38	1.64	1.65	**15.14**
10 <= U < 12	0.99	0.71	0.78	0.56	0.47	0.28	0.21	0.21	0.35	0.74	1.02	1.05	**7.38**
12 <= U < 14	0.53	0.38	0.32	0.18	0.12	0.09	0.06	0.06	0.12	0.32	0.45	0.58	**3.20**
14 <= U < 16	0.32	0.21	0.13	0.06	0.03	0.01	0.01	0.00	0.03	0.11	0.14	0.34	**1.40**
16 <= U < 18	0.12	0.09	0.03	0.02	0.01	0.00	0.00	0.00	0.01	0.03	0.04	0.11	**0.46**
18 <= U < 20	0.03	0.02	0.01	0.00	0.00			0.00	0.00	0.01	0.01	0.03	**0.11**
20 <= U < 22	0.00	0.00	0.00						0.00	0.00	0.00	0.01	**0.02**
22 <= U < 24		0.00								0.00		0.00	**0.00**
24 <= U < 26										0.00		0.00	**0.00**
26 <= U < 28		0.00											**0.00**
28 <= U < 30													
30 <= U													
Total (%)	**8.49**	**7.73**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**100.00**
Mean (m/s)	**7.67**	**7.22**	**6.78**	**6.36**	**5.96**	**5.64**	**5.54**	**5.32**	**5.70**	**6.63**	**7.34**	**7.81**	**6.49**
Max (m/s)	**20.82**	**26.22**	**21.87**	**18.92**	**18.97**	**16.74**	**17.93**	**18.00**	**21.87**	**24.81**	**21.56**	**25.75**	**26.22**

TABLE 5: MONTHLY DIRECTION OF SAMPLE DISTRIBUTION (%) OF 1-HOUR AVERAGE WIND SPEED 10 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

Sample distribution by month and by direction are available from the digital database.

2.5.2 WIND 100 M ABOVE SEA LEVEL

At 100 m, the mean velocity from measurements is 8.11 m/s (and it is the same value from Weibull fit).

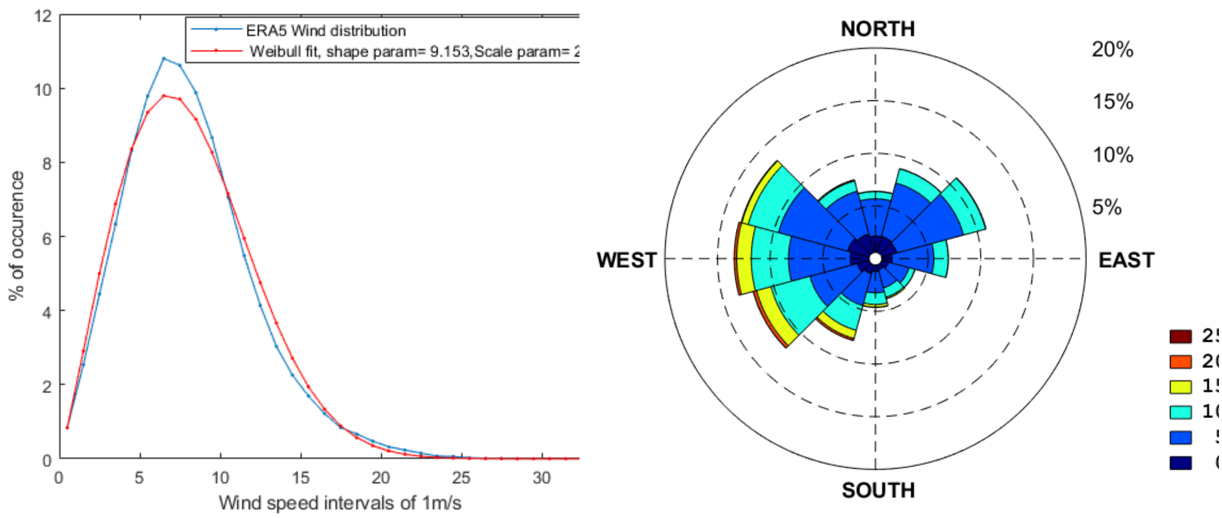


FIGURE 13: LEFT: ERA5 WIND DISTRIBUTION AND WEIBULL FIT PARAMETERS; RIGHT: WIND VELOCITY ROSE FOR WIND 1-HOUR AVERAGE WIND SPEED 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV. CONVENTION: "WIND IS COMING FROM"

Wind (m/s)	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	Omni
0 <= U < 2	0.32	0.29	0.26	0.25	0.24	0.22	0.24	0.27	0.28	0.32	0.34	0.34	**3.37**
2 <= U < 4	1.05	1.05	0.97	0.76	0.62	0.55	0.59	0.72	0.87	1.11	1.31	1.19	**10.77**
4 <= U < 6	1.70	1.94	1.97	1.29	0.85	0.69	0.79	1.07	1.43	2.06	2.43	1.88	**18.10**
6 <= U < 8	1.61	2.31	2.73	1.70	0.90	0.75	0.86	1.27	1.86	2.53	2.92	1.96	**21.41**
8 <= U < 10	1.01	1.85	2.73	1.55	0.68	0.66	0.76	1.28	1.99	2.23	2.54	1.27	**18.54**
10 <= U < 12	0.46	1.03	1.52	0.95	0.37	0.53	0.58	1.18	1.84	1.74	1.67	0.68	**12.54**
12 <= U < 14	0.17	0.32	0.56	0.35	0.17	0.30	0.40	0.91	1.45	1.29	0.99	0.27	**7.18**
14 <= U < 16	0.07	0.07	0.11	0.08	0.04	0.16	0.22	0.61	0.98	0.96	0.53	0.13	**3.95**
16 <= U < 18	0.01	0.01	0.02	0.01	0.01	0.06	0.10	0.35	0.61	0.58	0.27	0.05	**2.06**
18 <= U < 20	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.20	0.37	0.34	0.15	0.02	**1.15**
20 <= U < 22	0.00				0.00	0.01	0.03	0.12	0.21	0.15	0.05	0.00	**0.56**
22 <= U < 24	0.00					0.00	0.01	0.05	0.08	0.07	0.01	0.00	**0.23**
24 <= U < 26	0.00					0.00	0.00	0.03	0.04	0.02	0.00	0.00	**0.09**
26 <= U < 28	0.00						0.00	0.01	0.01	0.00	0.00	0.00	**0.02**
28 <= U < 30								0.00	0.00	0.00	0.00		**0.01**
30 <= U								0.00	0.00	0.00		0.00	**0.00**
Total (%)	**6.40**	**8.86**	**10.88**	**6.93**	**3.89**	**3.94**	**4.63**	**8.06**	**12.03**	**13.42**	**13.21**	**7.76**	**100.00**
Mean (m/s)	**6.40**	**7.06**	**7.62**	**7.38**	**6.67**	**7.61**	**8.03**	**9.48**	**9.96**	**9.22**	**8.15**	**6.75**	**8.11**
Max (m/s)	**26.01**	**18.91**	**19.04**	**18.09**	**21.28**	**25.06**	**27.93**	**33.42**	**33.24**	**34.52**	**29.89**	**32.82**	**34.52**

TABLE 6 : ANNUAL DIRECTION OF SAMPLE DISTRIBUTION (%) OF 1-HOUR AVERAGE WIND SPEED 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

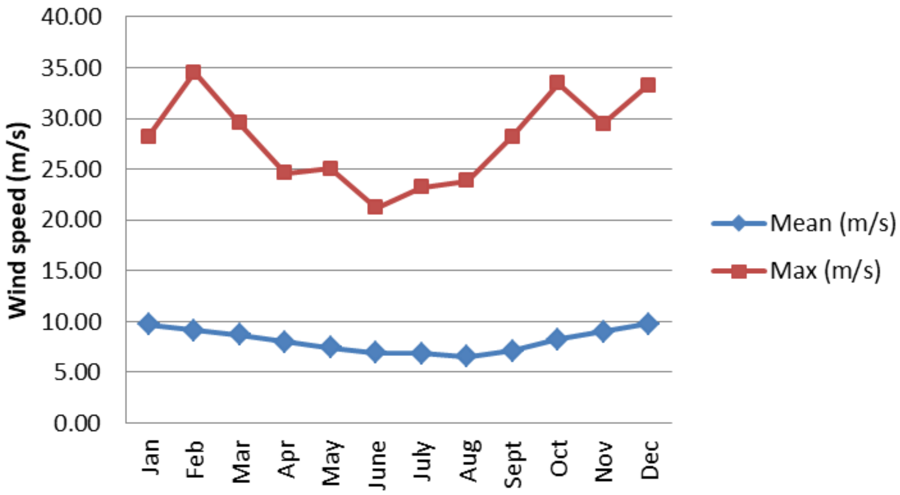


FIGURE 14: MONTHLY MEAN AND MAXIMUM 1-HOUR AVERAGE WIND SPEED 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

Wind (m/s)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
<2	0.20	0.20	0.26	0.26	0.36	0.34	0.31	0.39	0.40	0.27	0.19	0.18	**3.37**
2 <= U < 4	0.64	0.63	0.74	0.83	1.02	1.12	1.07	1.35	1.15	0.93	0.66	0.64	**10.77**
4 <= U < 6	1.09	1.09	1.24	1.42	1.66	1.82	2.02	2.15	1.78	1.49	1.25	1.11	**18.10**
6 <= U < 8	1.43	1.45	1.70	1.83	1.97	2.14	2.27	2.11	1.88	1.75	1.50	1.38	**21.41**
8 <= U < 10	1.50	1.45	1.67	1.65	1.69	1.49	1.68	1.44	1.50	1.53	1.45	1.49	**18.54**
10 <= U < 12	1.25	1.16	1.21	1.15	1.03	0.81	0.78	0.70	0.87	1.09	1.26	1.24	**12.54**
12 <= U < 14	0.90	0.71	0.81	0.59	0.47	0.32	0.24	0.23	0.37	0.71	0.91	0.90	**7.18**
14 <= U < 16	0.60	0.44	0.44	0.29	0.21	0.12	0.08	0.08	0.16	0.39	0.54	0.61	**3.95**
16 <= U < 18	0.38	0.28	0.23	0.10	0.05	0.04	0.03	0.03	0.07	0.18	0.26	0.43	**2.06**
18 <= U < 20	0.27	0.17	0.11	0.05	0.02	0.01	0.00	0.01	0.03	0.09	0.11	0.27	**1.15**
20 <= U < 22	0.14	0.09	0.05	0.02	0.01	0.00	0.00	0.00	0.01	0.03	0.05	0.14	**0.56**
22 <= U < 24	0.06	0.04	0.02	0.00	0.00		0.00	0.00	0.00	0.02	0.02	0.06	**0.23**
24 <= U < 26	0.03	0.01	0.01	0.00	0.00				0.00	0.01	0.01	0.02	**0.09**
26 <= U < 28	0.01	0.00	0.00						0.00	0.00	0.00	0.01	**0.02**
28 <= U < 30	0.00	0.00	0.00						0.00	0.00	0.00	0.00	**0.01**
30 <= U		0.00								0.00		0.00	**0.00**
Total (%)	**8.49**	**7.73**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**100.00**
Mean (m/s)	**9.70**	**9.14**	**8.69**	**7.98**	**7.39**	**6.93**	**6.85**	**6.54**	**7.08**	**8.22**	**9.02**	**9.76**	**8.11**
Max (m/s)	**28.17**	**34.52**	**29.51**	**24.58**	**25.04**	**21.19**	**23.19**	**23.81**	**28.22**	**33.42**	**29.45**	**33.24**	**34.52**

TABLE 7: MONTHLY DISTRIBUTION (%) OF 1-HOUR AVERAGE WIND SPEED 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEM-REV

2.6 LONG TERM WIND STATISTICS

The long term wind statistics is performed through the Peak Over Threshold method.
The method is based on the selection of samples whose reference value (Vm here) lies above a given threshold and for which a minimal time interval has to be verified. This ensures that several extreme values related to the same extreme event cannot contribute altogether to the statistical law. The threshold is determined for each directional sector through a sensitivity analysis.

2.6.1 MEAN ON 1-HOUR AT 10 M FROM ERA5

For the extreme events in the ERA5 1-hour dataset at 10 m, the threshold is set to 18 m/s. The correlation between the Pareto distribution and the modelled wind data is presented in the Figure below. The statistical fitted distribution shows an hourly mean wind speed of 26.37 m/s for a 50 years return period, when the maximum modelled wind velocity reached 26.22 m/s for this 41-years dataset.

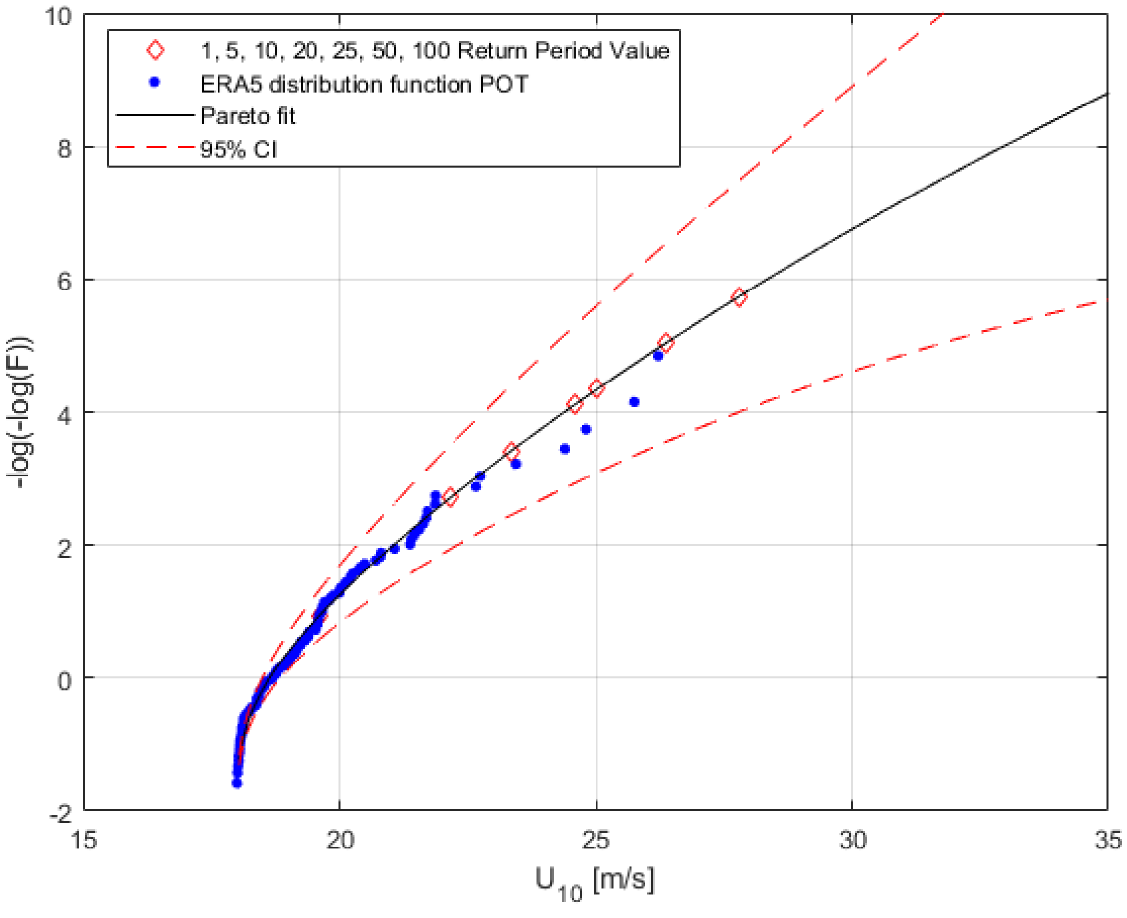


FIGURE 15 POT APPLIED TO 1H ERA5 DATA AT 10 M FOR A 18 M/S THRESHOLD. STATISTICAL DISTRIBUTION, PARETO FITTING, AND REPRESENTATIVE RETURN VALUES

From the previously presented POT long term extrapolation application, the return period of wind speed (for all directions) is presented below along with 95% confidence index (CI) interval.

Direction	*Proportion*	*Threshold*	*Vm max*	*Values (m/s) for return periods (years) and 95% CI Interval*					
(°)	*(%)*	*(m/s)*	*(m/s)*	*1*	*5*	*10*	*25*	*50*	*100*
All	**0.00**	**18**	**26.22**	**19.61**	**22.16**	**23.35**	**25.02**	**26.37**	**27.79**
				[19.33 19.83]	*[22.09 22.22]*	*[22.83 23.72]*	*[23.79 26.42]*	*[24.46 28.96]*	*[25.06 32.04]*

TABLE 8: RETURN PERIODS OF 1-H WIND SPEED FOR ALL DIRECTIONS ON SEM-REV AT 10 METERS

The return periods are also computed for directional sectors of 30° and presented below.

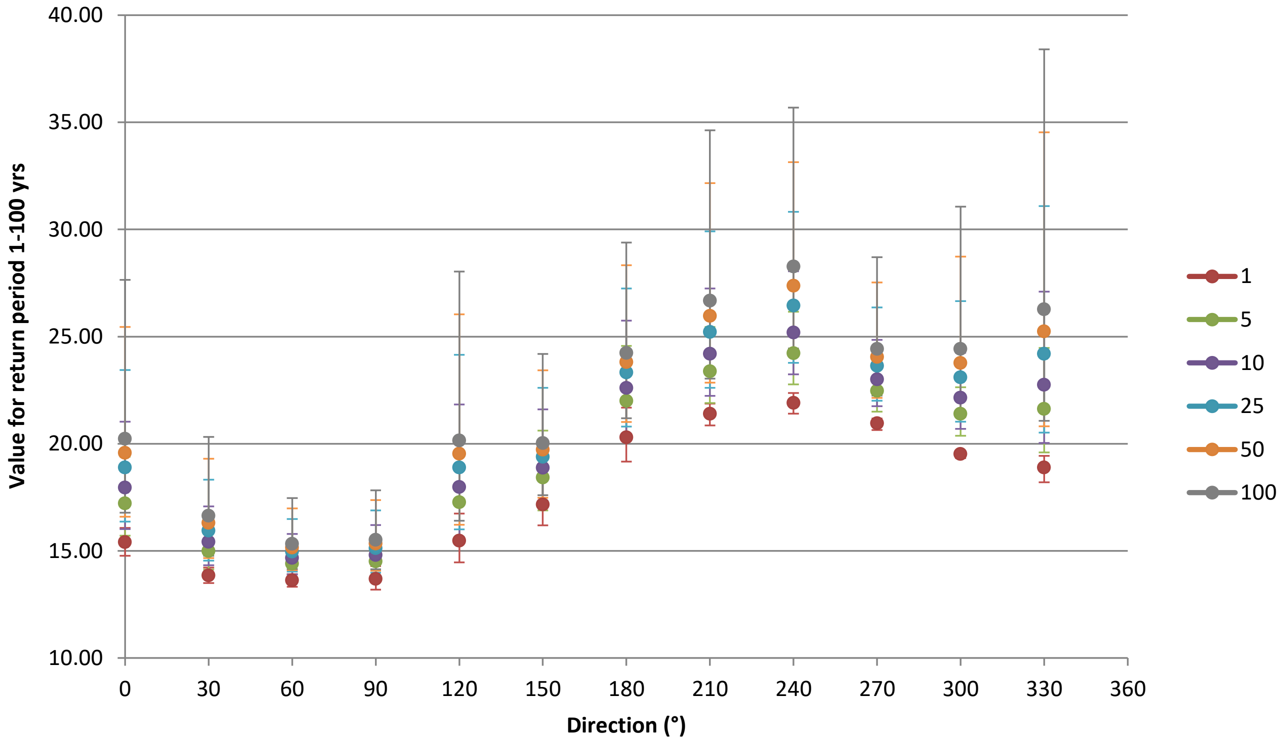


FIGURE 16: VALUES (M/S) (BY DIRECTIONAL SECTORS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS (POT) AND 95% CI INTERVALS (1H, 10 METERS)

Direction	*Proportion*	*Threshold*	*Vm max*	*Values (m/s) for return periods (years) and 95% CI Interval*					
(°)	*(%)*	*(m/s)*	*(m/s)*	*1*	*5*	*10*	*25*	*50*	*100*
0	6.57	10	18.91	15.40	17.21	17.95	18.89	19.57	20.23
				[14.77 16.07]	*[15.71 19.39]*	*[16.02 21.03]*	*[16.37 23.44]*	*[16.59 25.45]*	*[16.78 27.65]*
30	9.17	10	14.66	13.86	14.99	15.42	15.94	16.31	16.64
				[13.50 14.22]	*[14.13 16.18]*	*[14.33 17.08]*	*[14.54 18.32]*	*[14.66 19.30]*	*[14.77 20.32]*
60	10.77	10	15.02	13.62	14.40	14.67	14.97	15.16	15.32
				[13.33 13.92]	*[13.78 15.25]*	*[13.90 15.79]*	*[14.03 16.48]*	*[14.10 16.98]*	*[14.15 17.46]*
90	6.55	8.5	14.38	13.69	14.52	14.80	15.12	15.34	15.52
				[13.19 14.29]	*[13.67 15.66]*	*[13.82 16.21]*	*[13.98 16.89}*	*[14.07 17.37]*	*[14.14 17.82]*
120	3.70	8.5	16.66	15.48	17.27	17.98	18.89	19.54	20.16
				[14.46 16.74]	*[15.36 20.19]*	*[15.66 21.83]*	*[16.00 24.15]*	*[16.22 26.04]*	*[16.40 28.03]*
150	3.88	8.5	18.23	17.17	18.43	18.87	19.39	19.73	20.03
				[16.19 18.40]	*[16.89 20.61]*	*[17.11 21.50]*	*[17.34 22.61]*	*[17.48 23.42]*	*[17.60 24.19]*
180	4.74	10	20.74	20.30	21.99	22.61	23.32	23.80	24.24
				[19.17 21.69]	*[20.15 24.56]*	*[20.47 25.74]*	*[20.80 27.24]*	*[21.01 28.33]*	*[21.19 29.39]*
210	8.22	16	24.81	21.39	23.38	24.19	25.22	25.96	26.68
				[20.86 21.87]	*[21.90 25.45]*	*[22.24 27.25]*	*[22.61 29.91]*	*[22.85 32.16]*	*[23.04 34.63]*
240	11.82	16	24.40	21.90	24.23	25.19	26.44	27.37	28.27
				[21.40 22.37]	*[22.77 26.16]*	*[23.24 28.05]*	*[23.78 30.82]*	*[24.13 33.14]*	*[24.44 35.68]*
270	13.43	16	26.22	20.95	22.47	23.01	23.64	24.06	24.43
				[20.64 21.18]	*[21.50 23.72]*	*[21.75 24.85]*	*[22.00 26.36]*	*[22.14 27.52]*	*[22.25 28.70]*
300	13.34	15.5	22.66	19.52	21.40	22.15	23.09	23.77	24.42
				[19.33 19.52]	*[20.37 22.63]*	*[20.69 24.24]*	*[21.03 26.65]*	*[21.24 28.73]*	*[21.40 31.06]*
330	7.83	12	25.75	18.89	21.63	22.75	24.19	25.24	26.27
				[18.20 19.43]	*[19.59 24.47]*	*[20.04 27.10]*	*[20.52 31.09]*	*[20.82 34.53]*	*[21.07 38.41]*

TABLE 9 VALUES (M/S) (BY DIRECTIONAL SECTORS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS (POT) IN GREY AND 95% CI INTERVALS (1H, 10 METERS)

2.6.2 MEAN ON 1-HOUR AT 100 M FROM ERA5

For the extreme events in the ERA5 1-hour dataset at 100 m, the threshold is set to 24.5 m/s. The correlation between the Pareto distribution and the modelled wind data is presented in the Figure below. The statistical fitted distribution shows an hourly mean wind speed of 35.99 m/s for a 50 years return period, when the maximum modelled wind velocity reached 34.52 m/s for this 41-years dataset.

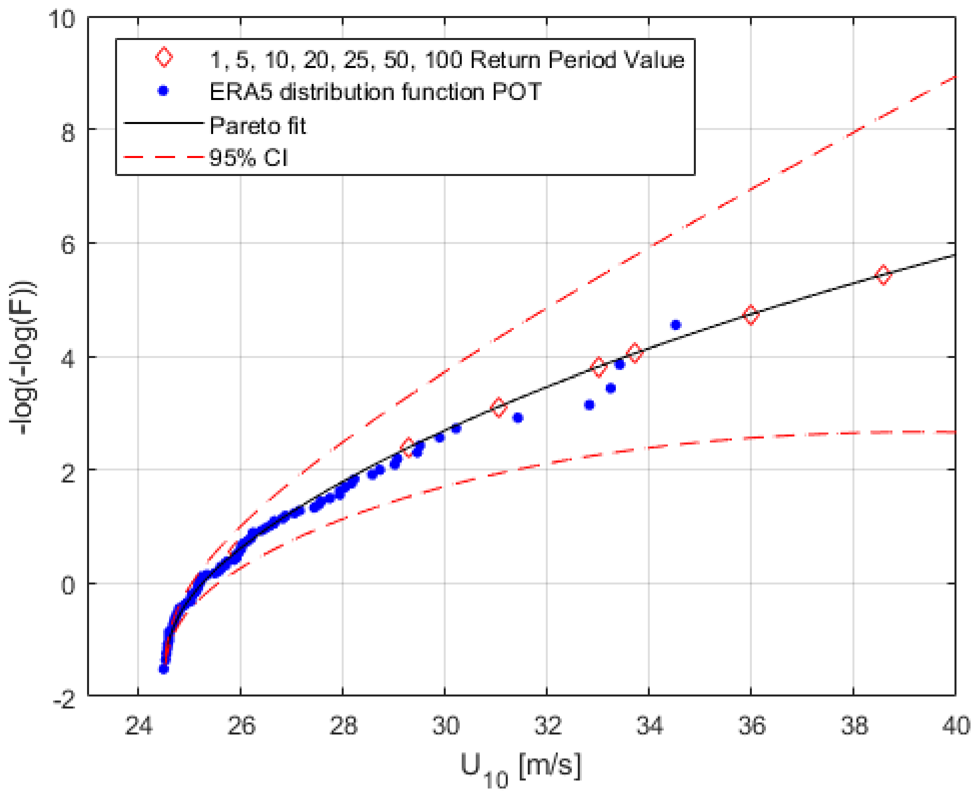


FIGURE 17: POT APPLIED TO 1H ERA5 DATA AT 100 M FOR A 24.5 M/S THRESHOLD. STATISTICAL DISTRIBUTION, PARETO FITTING, AND REPRESENTATIVE RETURN VALUES

From the previously presented POT long term extrapolation application, the return period of wind speed (for all directions) is presented below along with 95% confidence index (CI) interval.

Direction	*Proportion*	*Threshold*	*Vm max*	*Values (m/s) for return periods (years) and 95% CI Interval*					
(°)	*(%)*	*(m/s)*	*(m/s)*	*1*	*5*	*10*	*25*	*50*	*100*
All	**100.00**	**24.5**	**34.52**	**25.91**	**29.29**	**31.04**	**33.70**	**35.99**	**38.57**
				[25.57 26.19]	*[29.04 29.47]*	*[30.34 31.39]*	*[31.81 35.73]*	*[32.85 40.28]*	*[33.84 46.33]*

TABLE 10: RETURN PERIODS OF 1-H WIND SPEED FOR ALL DIRECTIONS ON SEM-REV AT 100 METERS

The return periods are also computed for directional sectors of 30° and presented below.

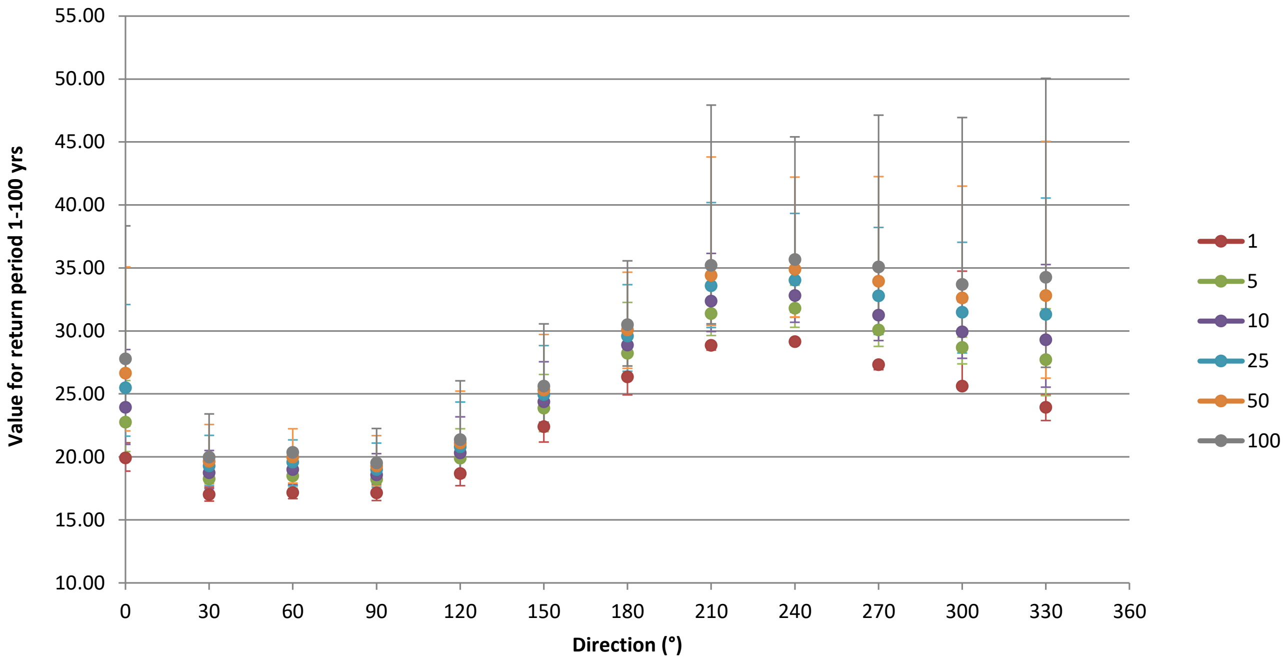


FIGURE 18: VALUES (M/S) (BY DIRECTIONAL SECTORS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS (POT) AND 95% CI INTERVALS (1H, 100 METERS)

Direction	*Proportion*	*Threshold*	*Vm max*	*Values (m/s) for return periods (years) and 95% CI Interval*					
(°)	*(%)*	*(m/s)*	*(m/s)*	**1**	**5**	**10**	**25**	**50**	**100**
0	6.40	11.4	26.01	**19.92**	**22.75**	**23.94**	**25.49**	**26.64**	**27.78**
				[18.87 21.13]	*[20.43 26.07]*	*[20.99 28.52]*	*[21.64 32.10]*	*[22.07 35.08]*	*[22.46 38.34]*
30	8.86	11.4	18.91	**17.02**	**18.27**	**18.74**	**19.28**	**19.65**	**19.99**
				[16.49 17.61]	*[17.24 19.68]*	*[17.48 20.55]*	*[17.73 21.70]*	*[17.89 22.56]*	*[18.02 23.41]*
60	10.88	11.4	19.03	**17.17**	**18.49**	**18.99**	**19.58**	**19.99**	**20.36**
				[16.68 17.73]	*[17.52 19.77]*	*[17.80 20.63]*	*[18.10 21.76]*	*[18.30 22.60]*	*[18.46 23.43]*
90	6.93	10.5	18.09	**17.15**	**18.21**	**18.57**	**19.00**	**19.27**	**19.52**
				[16.53 17.89]	*[17.18 19.59]*	*[17.38 20.26]*	*[17.59 21.10]*	*[17.71 21.69]*	*[17.82 22.25]*
120	3.88	10.5	21.28	**18.69**	**19.91**	**20.33**	**20.80**	**21.10**	**21.37**
				[17.72 19.92]	*[18.34 22.24]*	*[18.52 23.18]*	*[18.71 24.36]*	*[18.81 25.21]*	*[18.90 26.03]*
150	3.94	11.4	25.06	**22.40**	**23.87**	**24.37**	**24.94**	**25.31**	**25.63**
				[21.19 23.93]	*[22.00 26.54]*	*[22.24 27.56]*	*[22.49 28.83]*	*[22.64 29.72]*	*[22.76 30.57]*
180	4.63	11.4	27.93	**26.36**	**28.23**	**28.87**	**29.60**	**30.08**	**30.50**
				[24.92 28.13]	*[26.06 31.12]*	*[26.42 32.27]*	*[26.80 33.68]*	*[27.03 34.66]*	*[27.22 35.57]*
210	8.06	23	33.42	**28.85**	**31.39**	**32.37**	**33.58**	**34.42**	**35.21**
				[28.47 28.70]	*[29.64 33.54]*	*[29.96 36.15]*	*[30.27 40.20]*	*[30.44 43.80]*	*[30.57 47.94]*
240	12.03	23	33.24	**29.16**	**31.81**	**32.82**	**34.04**	**34.89**	**35.68**
				[28.87 29.08]	*[30.28 33.64]*	*[30.68 35.94]*	*[31.08 39.34]*	*[31.30 42.22]*	*[31.48 45.40]*
270	13.43	23	26.22	**27.33**	**30.08**	**31.25**	**32.79**	**33.95**	**35.09**
				[27.27 26.92]	*[28.77 31.34]*	*[29.23 33.93]*	*[29.71 38.21]*	*[30.00 42.25]*	*[30.23 47.14]*
300	13.21	21	29.89	**25.62**	**28.69**	**29.93**	**31.49**	**32.62**	**33.70**
				[25.75 34.75]	*[27.39 29.50]*	*[27.82 32.33]*	*[28.24 37.03]*	*[28.47 41.50]*	*[28.64 46.94]*
330	7.76	14	32.82	**23.94**	**27.73**	**29.30**	**31.32**	**32.81**	**34.26**
				[22.89 24.92]	*[24.87 31.77]*	*[25.53 35.28]*	*[26.26 40.54]*	*[26.72 45.05]*	*[27.12 50.06]*

TABLE 11 VALUES (M/S) (BY DIRECTIONAL SECTORS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS (POT) IN GREY AND 95% CI INTERVALS (1H, 100 METERS)

2.7 CORRELATION (ON 10-MIN AVERAGE, 39 M HEIGHT)

In a second step, the results of the correlation between measurements of wind speed and direction at Cardinaux lighthouse are performed on 10 min average. To do so, ERA5 model is extrapolated at 39 m height and 10 min according to formulation proposed in [7] section 2.3.2.11. where $U(T,z)$ is the mean wind speed U with averaging period T at height z above sea level:

$$\boldsymbol{U(T,z) = U_{10min,\ h} \cdot \left(1 + 0.137.\ln\left(\frac{z}{h}\right) - 0.047.\ln\left(\frac{T}{T_{10}}\right)\right)} \quad \textbf{(3)}$$

And $U_{10min,\ h}$ is the 10-minute mean wind speed at height *h.*
This reference comes from a version released in 2014 of the reference document, but provides a better fit with experiment than the Frøya wind profile, which generates a significant bias, especially for extreme wind speeds. Hence this formulation of extrapolation is retained.

Results of the correlation are presented below:

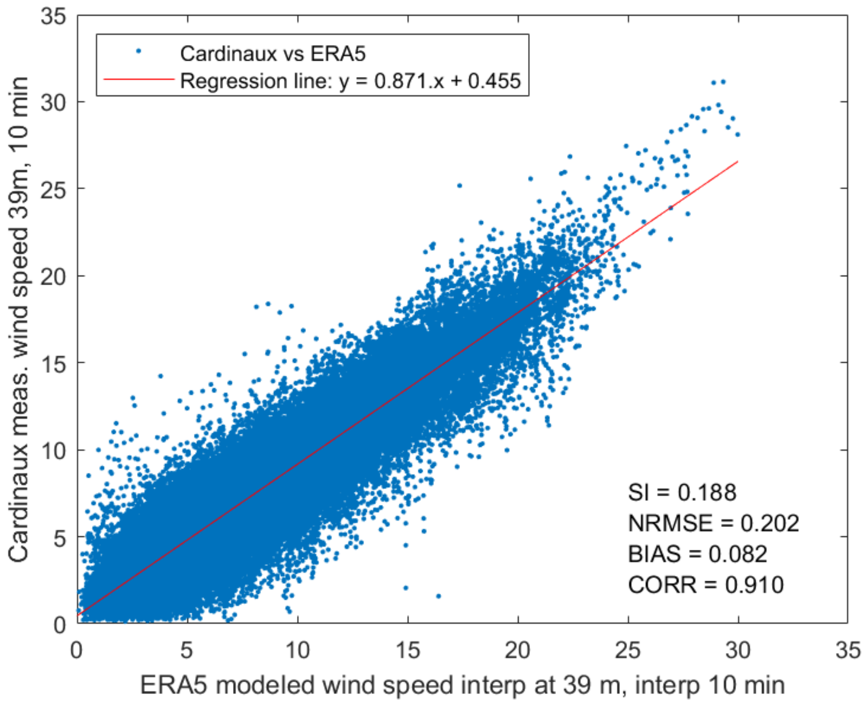


FIGURE 19 CARDINAUX LIGHTHOUSE WIND SPEED MEASUREMENTS VERSUS ERA5 MODELED WIND SPEED (10 MIN MEAN)

The standard metric errors: bias, normalized root mean square error (NRMSE), scatter index (S.I.) and correlation (r) are satisfactory to use the extrapolation for ERA5 model on 10 minutes.

2.8 STATISTICS OPERATIONAL (MEAN ON 10 MINUTES FROM ERA5 (EXTRAPOLATED), 100 M)

For means on 10 minutes and 100 meters, the mean velocity from measurements is 8.85 m/s (and it is the same value from Weibull fit).

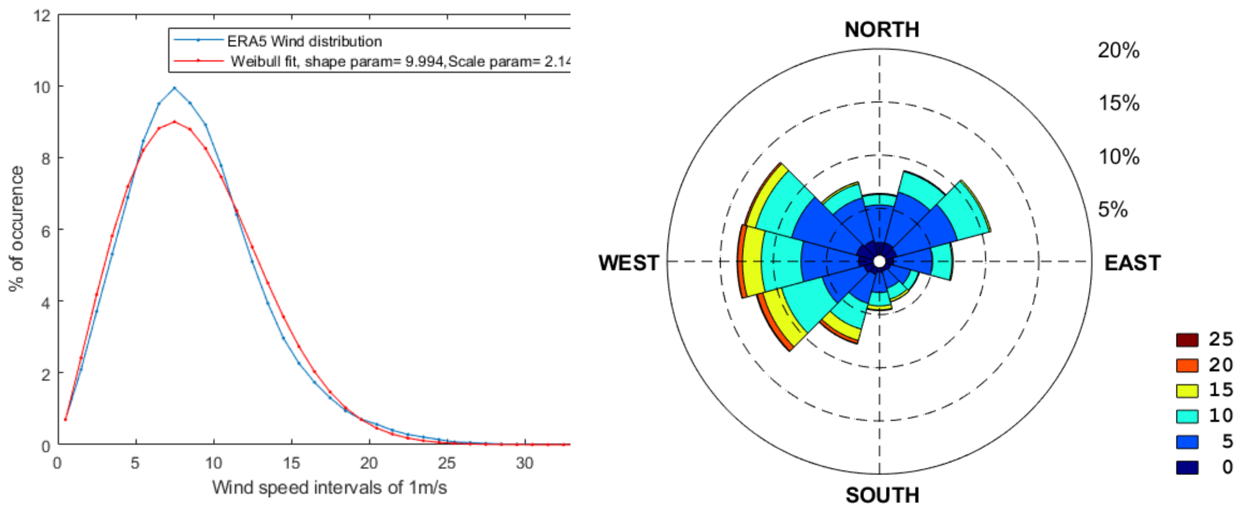


FIGURE 20: LEFT: WIND DISTRIBUTION AND WEIBULL FIT PARAMETERS; RIGHT: WIND VELOCITY ROSE FOR WIND SPEED EXTRAPOLATED AT 10-MIN AVERAGE AND AT 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEMREV. CONVENTION: "WIND IS COMING FROM"

Wind (m/s)	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	Omni
<2	0.27	0.23	0.22	0.20	0.20	0.19	0.20	0.23	0.23	0.27	0.28	0.28	2.80
2 <= U < 4	0.87	0.86	0.80	0.64	0.53	0.48	0.52	0.61	0.73	0.92	1.08	0.99	9.02
4 <= U < 6	1.45	1.62	1.59	1.07	0.77	0.62	0.70	0.94	1.21	1.73	2.02	1.63	15.34
6 <= U < 8	1.60	2.12	2.35	1.48	0.82	0.71	0.78	1.11	1.65	2.26	2.68	1.86	19.43
8 <= U < 10	1.12	1.91	2.64	1.54	0.72	0.61	0.74	1.20	1.76	2.21	2.53	1.43	18.43
10 <= U < 12	0.64	1.32	1.96	1.16	0.46	0.57	0.64	1.12	1.81	1.79	1.89	0.83	14.18
12 <= U < 14	0.28	0.58	0.95	0.58	0.25	0.38	0.44	1.00	1.52	1.42	1.23	0.42	9.04
14 <= U < 16	0.11	0.17	0.31	0.21	0.11	0.21	0.30	0.73	1.17	1.02	0.71	0.19	5.23
16 <= U < 18	0.04	0.04	0.06	0.04	0.02	0.13	0.17	0.47	0.80	0.82	0.39	0.08	3.05
18 <= U < 20	0.01	0.00	0.01	0.01	0.01	0.03	0.08	0.29	0.50	0.47	0.22	0.03	1.66
20 <= U < 22	0.00	0.00	0.00		0.00	0.01	0.04	0.17	0.33	0.28	0.12	0.01	0.97
22 <= U < 24	0.00				0.00	0.00	0.02	0.11	0.18	0.13	0.04	0.00	0.50
24 <= U < 26	0.00					0.00	0.00	0.05	0.08	0.07	0.01	0.00	0.22
26 <= U < 28	0.00					0.00	0.00	0.03	0.04	0.02	0.00	0.00	0.10
28 <= U < 30	0.00						0.00	0.01	0.01	0.00	0.00	0.00	0.03
30 <= U							0.00	0.00	0.01	0.00	0.00	0.00	0.01
Total (%)	6.40	8.86	10.88	6.93	3.89	3.94	4.63	8.06	12.03	13.42	13.21	7.76	100.00
Mean (m/s)	6.99	7.71	8.32	8.06	7.28	8.31	8.77	10.35	10.88	10.07	8.90	7.37	8.85
Max (m/s)	28.40	20.65	20.79	19.76	23.24	27.36	30.49	36.49	36.30	37.69	32.64	35.84	37.69

TABLE 12 : ANNUAL DIRECTION OF SAMPLE DISTRIBUTION (%) OF WIND SPEED EXTRAPOLATED AT 10-MIN AVERAGE AND AT 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEMREV

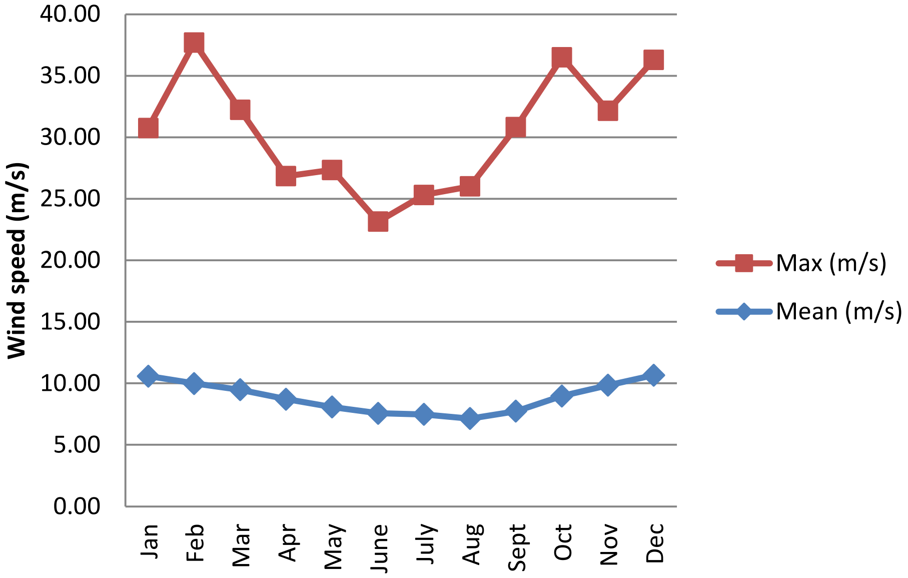


FIGURE 21: MONTHLY MEAN AND MAXIMUM OF WIND SPEED EXTRAPOLATED AT 10-MIN AVERAGE AND AT 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEMREV

Wind (m/s)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
<2	0.16	0.17	0.22	0.22	0.30	0.28	0.26	0.32	0.33	0.23	0.15	0.15	**2.80**
2 <= U < 4	0.53	0.53	0.62	0.70	0.88	0.93	0.88	1.12	1.00	0.77	0.54	0.53	**9.02**
4 <= U < 6	0.93	0.90	1.05	1.18	1.40	1.53	1.70	1.87	1.52	1.28	1.05	0.93	**15.34**
6 <= U < 8	1.24	1.28	1.45	1.63	1.75	2.02	2.14	2.05	1.75	1.57	1.33	1.23	**19.43**
8 <= U < 10	1.37	1.35	1.60	1.61	1.74	1.59	1.77	1.57	1.58	1.50	1.41	1.34	**18.43**
10 <= U < 12	1.30	1.21	1.34	1.29	1.23	1.05	1.08	0.93	1.04	1.20	1.24	1.25	**14.18**
12 <= U < 14	0.97	0.90	0.92	0.82	0.67	0.49	0.45	0.40	0.55	0.83	1.02	1.02	**9.04**
14 <= U < 16	0.73	0.50	0.61	0.41	0.33	0.20	0.14	0.14	0.24	0.52	0.70	0.71	**5.23**
16 <= U < 18	0.48	0.37	0.32	0.21	0.14	0.09	0.05	0.06	0.11	0.30	0.41	0.51	**3.05**
18 <= U < 20	0.32	0.23	0.18	0.07	0.03	0.03	0.02	0.02	0.05	0.14	0.20	0.36	**1.66**
20 <= U < 22	0.23	0.15	0.09	0.05	0.01	0.01	0.00	0.01	0.02	0.08	0.08	0.24	**0.97**
22 <= U < 24	0.12	0.08	0.05	0.02	0.01	0.00	0.00	0.00	0.01	0.03	0.05	0.13	**0.50**
24 <= U < 26	0.06	0.04	0.02	0.01	0.00		0.00	0.00	0.00	0.01	0.02	0.06	**0.22**
26 <= U < 28	0.03	0.01	0.01	0.00	0.00			0.00	0.00	0.01	0.01	0.02	**0.10**
28 <= U < 30	0.01	0.00	0.00						0.00	0.00	0.00	0.01	**0.03**
30 <= U	0.00	0.00	0.00						0.00	0.00	0.00	0.01	**0.01**
Total (%)	**8.49**	**7.73**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**100.00**
Mean (m/s)	**10.59**	**9.98**	**9.49**	**8.71**	**8.07**	**7.57**	**7.48**	**7.14**	**7.74**	**8.97**	**9.85**	**10.66**	**8.85**
Max (m/s)	**30.76**	**37.69**	**32.22**	**26.84**	**27.35**	**23.14**	**25.32**	**26.00**	**30.82**	**36.49**	**32.16**	**36.30**	**37.69**

TABLE 13: MONTHLY DISTRIBUTION (%) OF 10-MIN AVERAGE WIND SPEED EXTRAPOLATED AT 100 M ABOVE SEA LEVEL FOR THE PERIOD 1979-2019 ON SEMREV

2.9 LONG-TERM WIND STATISTICS (MEAN ON 10-MIN AT 100 M FROM ERA5)

The long term wind statistics is performed through the Peak Over Threshold method.

A threshold set to 26.5 m/s allows the selection of the extreme events in the ERA5 dataset at 100 m extrapolated at 10-min for application of the POT method. The correlation between the Pareto distribution and the modelled wind data is presented in the Figure below. The statistical fitted distribution shows a 10-min mean wind speed of 38.78 m/s for a 50 years return period, when the maximum modelled wind velocity reached 37.69 m/s for this 41-years dataset.

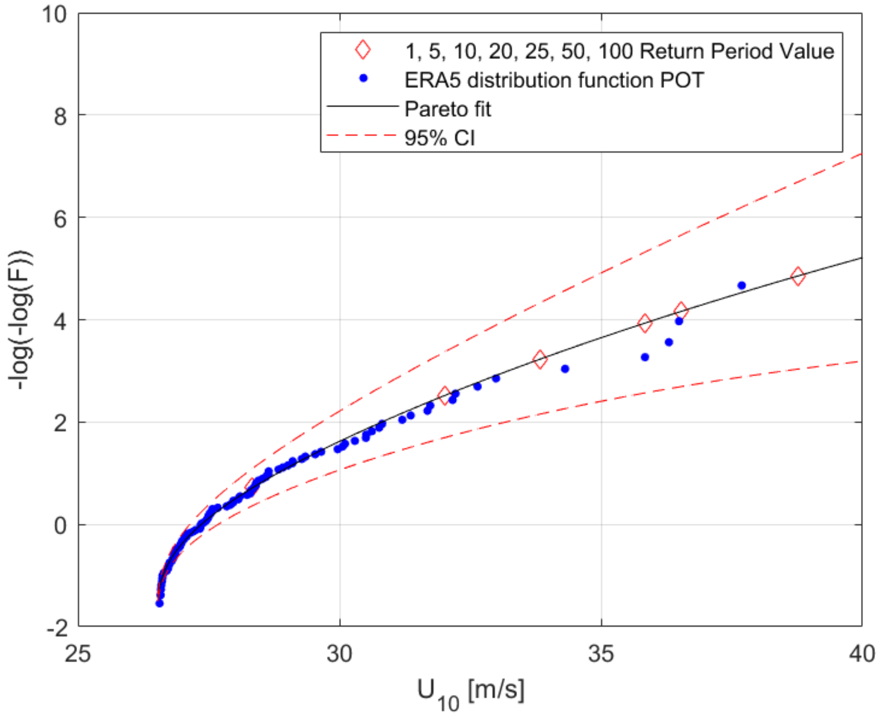


FIGURE 22: FIGURE 23 POT APPLIED TO ERA5 AT 100M, 10MIN (EXTRAPOLATION) FOR A 26.5M/S THRESHOLD. STATISTICAL DISTRIBUTION, PARETO FITTING, AND REPRESENTATIVE RETURN VALUES

Direction	*Proportion*	*Threshold*	*Vm max*	*Values (m/s) for return periods (years) and 95% CI Interval*					
(°)	**(%)**	**(m/s)**	**(m/s)**	**1**	**5**	**10**	**25**	**50**	**100**
All	**100.00**	**26.5**	**37.69**	**28.34**	**32.01**	**33.85**	**36.53**	**38.78**	**41.23**

TABLE 14: RETURN PERIODS OF 10-MIN WIND SPEED FOR ALL DIRECTIONS ON SEM-REV AT 100 METERS

2.10 NORMAL WIND PROFILE (NWP)

The normal wind profile is defined in section 2.3.1 from model data provided by ERA5.

2.11 NORMAL TURBULENCE INTENSITY (NTM)

The measurements performed at Cardinaux lighthouse at 39 m height are used to calculate the turbulence intensity in the vicinity of SEM-REV site. The lighthouse is located offshore, there is no major obstacle in its immediate vicinity but Belle Ile island is located 18 km west of the lighthouse and could be a source of disturbance on atmospheric properties.

As specified in section 2.1, the sampling frequency of measurements is 10 Hz. Mean values of 1 Hz are then de-trended over 10 minutes time intervals and used to compute the mean wind speed and standard deviation calculated over ten minutes.

The figure below presents the standard deviation σ versus mean wind speed.

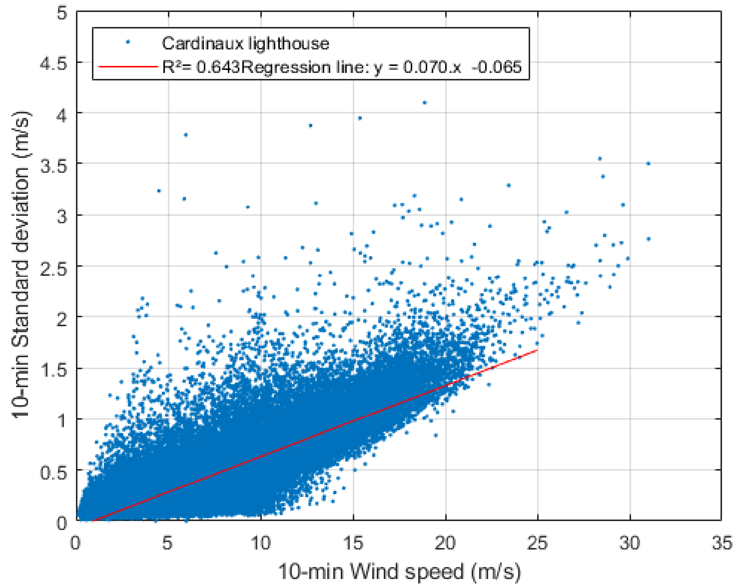


FIGURE 24: STANDARD DEVIATION OF WIND SPEED AT 1 HZ AND 39 M HEIGHT

The turbulence intensity is calculated by:

$$TI = \frac{\sigma}{U_{10min}} \quad (4)$$

Results are compared to turbulence intensity for the normal turbulence model in standards (DNVGL [8] section 2.3.2). Figure 25 shows that the turbulence level on Cardinaux lighthouse is low as it is very close to offshore classe C defined in [8].

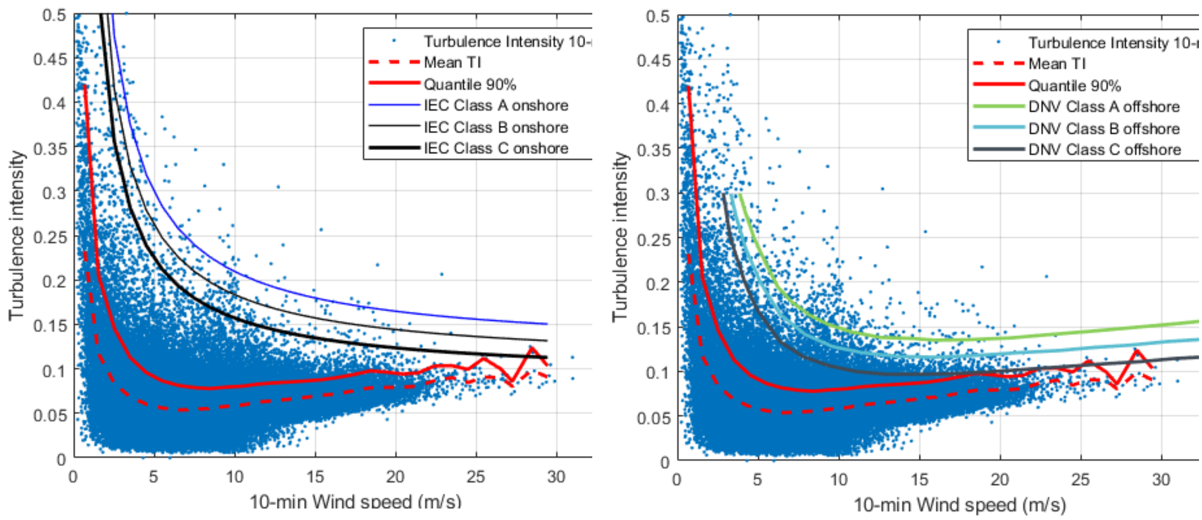


FIGURE 25 : STANDARD DEVIATION VERSUS MEAN WIND SPEED (LEFT) AND TURBULENCE INTENSITY VERSUS MEAN WIND SPEED ON 10 MINUTES (RIGHT) AND COMPARISON TO STANDARDS

Mean U_10min (m/s)	Mean TI	Quantile 90%
0.70	0.232	0.420
1.55	0.117	0.206
2.53	0.083	0.146
3.52	0.068	0.113
4.52	0.060	0.096
5.51	0.056	0.086
6.50	0.054	0.081
7.50	0.054	0.079
8.48	0.056	0.078
9.48	0.058	0.079
10.48	0.059	0.080
11.48	0.063	0.083
12.47	0.064	0.084
13.48	0.066	0.085
14.48	0.068	0.086
15.48	0.070	0.088
16.48	0.072	0.090
17.49	0.076	0.094
18.45	0.079	0.098
19.46	0.079	0.096
20.45	0.079	0.094
21.42	0.081	0.095
22.44	0.087	0.103
23.51	0.090	0.104
24.52	0.085	0.099
25.49	0.091	0.112
26.56	0.090	0.100
27.27	0.080	0.086
28.49	0.099	0.124
29.46	0.091	0.103

TABLE 15: VALUES OF TURBULENCE INTENSITY VERSUS MEAN WIND SPEED ON 10 MINUTES

For information as specified in [5] section 6.4.3, the wind speed standard deviation of the standard deviation value is 0.324.

2.12 EXTREME WIND PROFILE (EWP)

There is no measurements of wind profile at Cardinaux lighthouse, and the single point measurements does not enable to determine an extreme wind profile.

2.13 EXTREME OPERATING GUST (EOG)

The highest wind gust recorded at Cardinaux lighthouse between 06/2016 and 06/2018 is occurring on 6th of March 2017 bteween 8:16:35 and 8:16:55. The measurements are extrapolated at a predefined hub height of 100 m using the extreme wind profile power law with alpha = 0.14.

For this event, the extreme operating gust model proposed in IEC [4] section 6.3.2.2 is computed and compared to the measured extreme event.

Parameters used in IEC model are presented in Table 16 and comparison is presented on Figure 26.

Param	Description	Value used
H	Hub height	100 m
Iref	Expected value of turbulence intensity at 15 m/s	0.1 (corresponding to offshore class C in [8]) and 0.12 (corresponding to offshore class B in [8])
D	Rotor diameter in example	80 m
Λ_1	Turbulence scale parameter	42 m (ref [4] section 6.3)
Vref	Reference wind speed average over 10 min with a recurrence period of 50 years	38.78 m/s (see Table 14)
Vgust	Largest gust magnitude with an expected recurrence period of 50 years. Computed from [4] section 3.2.2.2	8.43 m/s (for Iref=0.1) and 10.12 for (Iref =0.12)
T	Duration of wind gust. Chosen to fit with the event.	20 s

TABLE 16: PARAMETERS USED TO COMPUTE EXTREME OPERATING GUST ACCORDING TO IEC [4]

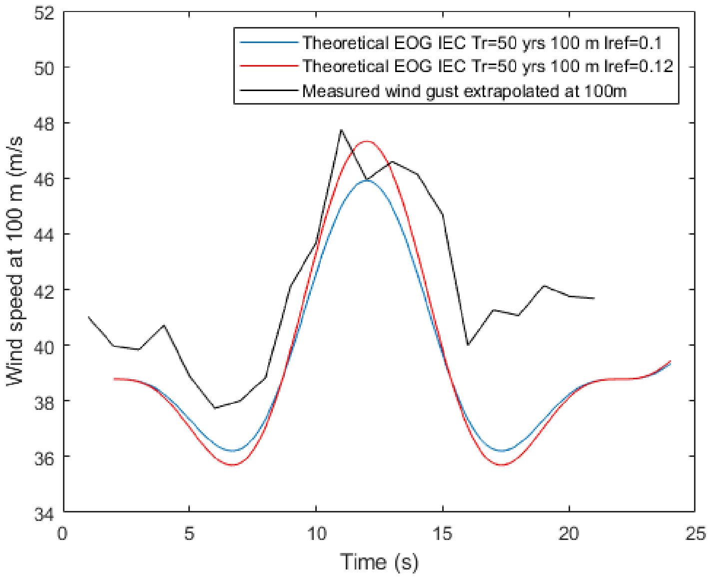


FIGURE 26: WIND EXTREME OPERATING GUST (IEC AND EVENT OF 03/06/2017 8:16:35 MEASURED AT CARDINAUX LIGHTHOUSE)

It should be noted that largest gust magnitude calculated with an expected recurrence period of 50 years from IEC formulation is comparable to the highest event recorded on a period of only 2 years.

2.14 EXTREME DIRECTION CHANGE (EDC)

The extreme direction change magnitude θ_e, is calculated according to IEC [4].
Figure 27 (left) shows the extreme direction change magnitude (absolute value) versus wind speed at hub for both measurements at Cardinaux lighthouse (in the period 2016-2018 as described in 2.1) and for IEC formulation. It shows that IEC formulation is adapted to the site considered.
On The right figure shows the transient extreme direction change following IEC formulation applied using parameters described in Table 16, with a period T representing the duration of the extreme direction change, with T=6 s. The example of transient direction change is given for a velocity at hub of 25 m/s.

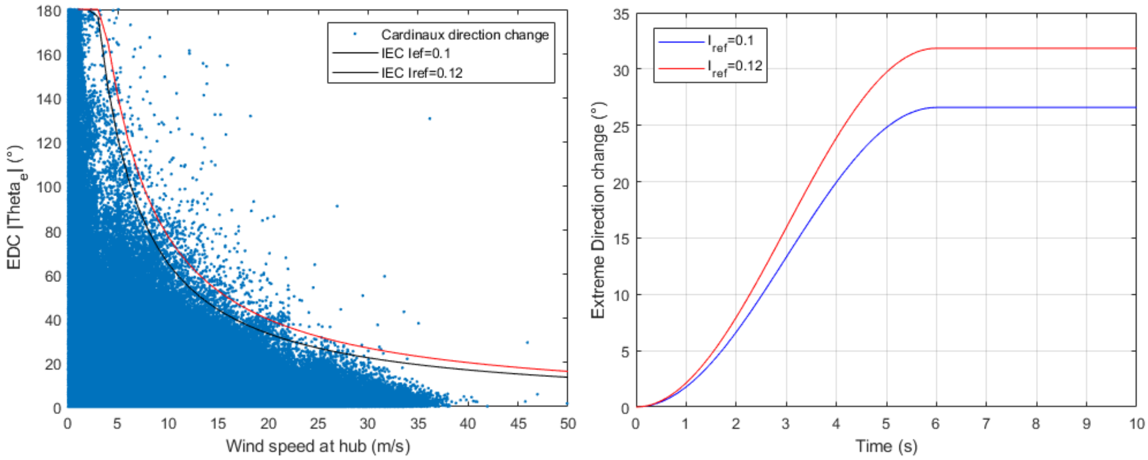


FIGURE 27: LEFT: EXTREME DIRECTION CHANGE MAGNITUDE FOR PARAMETERS IN TABLE 16. RIGHT: TRANSIENT DIRECTION CHANGE FOR V_{HUB}=25 M/S

3. WAVES

3.1 MEASUREMENT

Wave conditions are measured on SEM-REV sites almost continuously since 2009. Waves are measured with two independent, identical, directional Datawell MkIII Waverider buoys. They are deployed, operated and recovered by ECN. They are both located on SEM-REV site and are named “SEM-REV East buoy” and “SEM-REV West buoy”. Practically, they are distant of 1 km. For the correlation of measurements with HOMERE model, the data from West buoy are used.

	East	***West***
Device	DWR-MkIII Datawell	DWR-MkIII Datawell
Location (average)	47°14.30’N, 02°46.30’W	47°14.36’N, 02°47.15’W
Local depth	34,5m	32,5m
Sampling Frequency	1.28Hz	1.28Hz
Measurement Frequency	2/hour	2/hour

N.B. : A third buoy located outside SEMREV is also operated by CEREMA in the frame of Candhis network, S-W of Belle-Ile-en-mer Island (coordinates 47°17.10’N, 03°17.08’O) and at roughly 62.5m water depth.

TABLE 17 CHARACTERISTICS OF THE INSTRUMENTATION USED FOR WAVE MEASUREMENTS ON SEMREV

3.2 NUMERICAL MODEL

A sea-states hindcast database identified as HOMERE [38] covering the Channel and Bay of Biscay over a 26 years period from 1994 to 2019 has been built by Ifremer, running an up-to-date configuration of the Wave-Watch III_ (WW3 version 4.11) wave model on a refined unstructured grid.

The parameterisation of wave generation and dissipation used in this configuration has been developed in the framework of the IOWAGA (Integrated Ocean Waves for Geophysical and other Applications) project and is employed by the PREVIMER operational forecast model demonstrator. The wave model is forced by the wind field from the NCEP-CFSR reanalysis ***[26]***. The selected locations from HOMERE outputs locations inside SEM-REV test site are: HOMERE_NGUG-v3_sem-e_.dat (2° 46.26’ W – 47° 14,34) & HOMERE_NGUG-v3_sem-o_.dat (2° 47.16’ W – 47° 14,34)

3.3 CORRELATION

A comparison between HOMERE database and in-situ measurements was performed for the Period 2010-2019 ***[38]***. The West buoy located on SEM-REV site is identified as “Plateau du Four” Buoy in the Cetmef CANDHIS. It is compared to the HOMERE West output.

The significant wave height correlation between measurements and the hourly hindcast data is presented on Figure 28. The standard metric errors: bias, normalized root mean square error (NRMSE), scatter index (S.I.) and correlation (r) are presented in Table 18 for significant wave height, peak period, and wave direction at peak period.

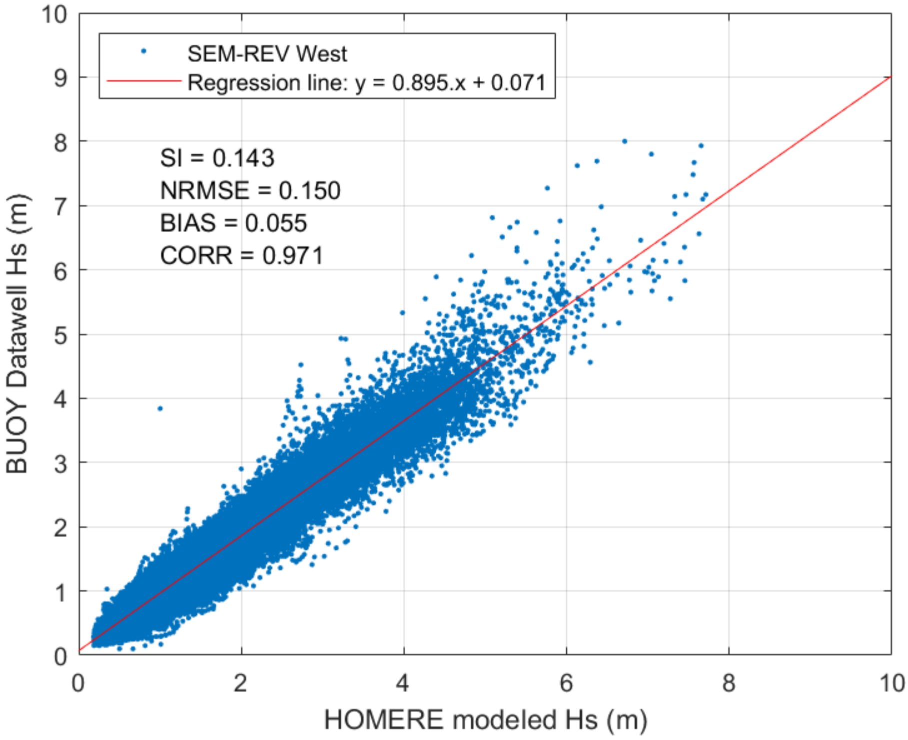


FIGURE 28: LINEAR REGRESSION OF HS FROM DATAWELL BUOY MEASUREMENTS AND HOMERE MODEL

	S.I	NRMSE	Bias	Correlation
Hs (m)	0.143	0.150	0.055	0.940
Tp (s)	0.271	0.285	0.094	0.616
Θpeak (rad)	0.199	0.205	0.048	0.454

TABLE 18: CORRELATION AND ERROR STATISTICS BETWEEN DATAWELL BUOY MEASUREMENTS AND HOMERE MODEL

Statistics and plots (comparisons in terms of Hs) show a good overall agreement with the observations. A correlation coefficient equal to 97% for waves indicates the numerical model is satisfactory. The bias is also relatively low for the various validation points and the scatter index and the NRMSE confirm the good agreement. The prediction chain developed in ***[38]*** accounts for a proper physical evolution of wave in the SEMREV coastal region and provides a good time resolution (equal to 1 hour in the case of HOMERE database).

However, underestimations of the large wave heights are noticeable, which appears to be characteristic for the CFSR winds (forcing of the wave model). HOMERE database slightly underestimates peaks of significant wave height as shown on Figure 28, where the tail of correlation distribution is higher for measurements than for HOMERE model. The selection of the upper boundary of the confidence interval is expected to compensate the difference between the modelled and measured data.

3.4 STATISTICS OPERATIONNAL

Operational statistics are issued from HOMERE reanalysis. The Figure below shows the annual wave height rose (%) distributed in angular sectors of 15º. More 90% of the sea states in SEMREV are characterized by a mean direction included in the intervals 240° +/- 7.5° and 270° +/- 7.5° = [236.25°-277.5°]. The highest waves are coming from the WSW sector.

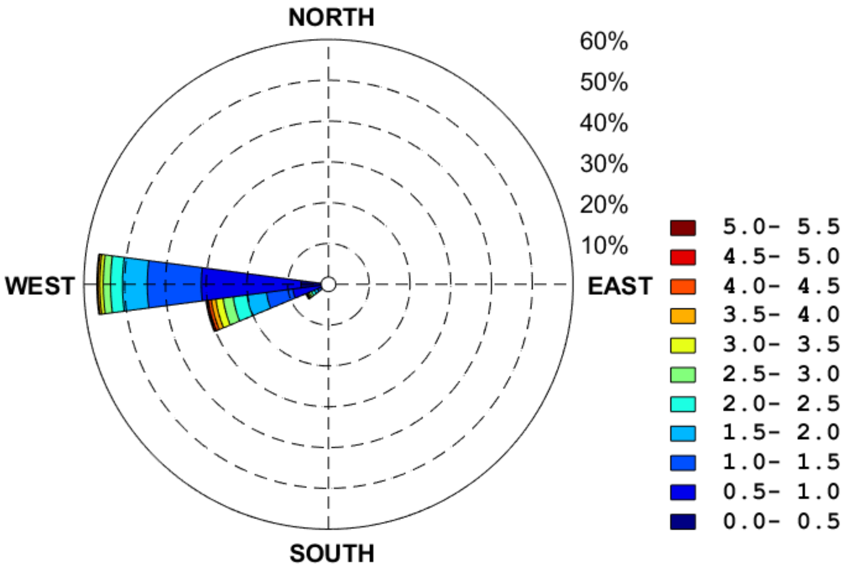


FIGURE 29 SIGNIFICANT WAVE HEIGHT ROSE DISTRIBUTION (HOMERE_NGUG-V3_SEM-O_, 1994-2019). CONVENTION: "WAVES ARE COMING FROM"

Waves Hs (m)	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°	Omni
0 <= Hs < 0.5	0.02	0.03	0.09	0.11	0.07	0.02	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.10	0.53	1.65	6.74	0.06	0.00	0.00	0.01	0.01	**9.50**
0.5 <= Hs < 1	0.08	0.13	0.33	0.38	0.31	0.16	0.14	0.09	0.04	0.02	0.02	0.08	0.28	0.13	0.08	0.28	1.41	7.18	24.47	0.07	0.01	0.01	0.02	0.04	**35.77**
1 <= Hs < 1.5	0.02	0.02	0.05	0.05	0.05	0.05	0.03	0.04	0.03	0.01	0.01	0.05	0.40	0.23	0.15	0.25	1.01	6.50	13.25	0.05	0.01	0.00	0.01	0.01	**22.28**
1.5 <= Hs < 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.22	0.23	0.11	0.15	0.80	4.82	6.09	0.01	0.00	0.00	0.00	0.00	**12.47**
2 <= Hs < 2.5				0.00	0.00							0.00	0.11	0.15	0.08	0.15	0.80	3.42	2.92	0.00			0.00		**7.64**
2.5 <= Hs < 3												0.00	0.03	0.07	0.06	0.09	0.57	2.50	1.79	0.00					**5.11**
3 <= Hs < 3.5													0.01	0.04	0.03	0.05	0.37	1.79	0.83						**3.12**
3.5 <= Hs < 4													0.00	0.02	0.02	0.03	0.25	1.13	0.47						**1.91**
4 <= Hs < 4.5														0.01	0.01	0.02	0.17	0.72	0.19						**1.12**
4.5 <= Hs < 5														0.00	0.01	0.01	0.09	0.40	0.06						**0.56**
Hs > 5														0.00	0.00	0.00	0.07	0.41	0.03						**0.52**
Total (%)	**0.12**	**0.18**	**0.47**	**0.55**	**0.43**	**0.23**	**0.19**	**0.14**	**0.07**	**0.04**	**0.03**	**0.15**	**1.06**	**0.87**	**0.55**	**1.13**	**6.07**	**30.53**	**56.84**	**0.19**	**0.03**	**0.02**	**0.04**	**0.06**	**100.00**
Mean (m)	**0.75**	**0.73**	**0.71**	**0.69**	**0.72**	**0.78**	**0.78**	**0.85**	**0.91**	**0.97**	**0.84**	**0.98**	**1.38**	**1.77**	**1.88**	**1.60**	**1.80**	**1.78**	**1.13**	**0.81**	**1.04**	**0.87**	**0.85**	**0.82**	**1.38**
Max (m)	**1.50**	**1.59**	**1.58**	**2.10**	**2.00**	**1.64**	**1.65**	**1.62**	**1.63**	**1.86**	**1.82**	**2.51**	**3.68**	**5.08**	**6.90**	**7.94**	**8.48**	**7.76**	**6.61**	**2.95**	**1.86**	**1.82**	**2.25**	**1.96**	**8.48**

TABLE 19 : ANNUAL DIRECTION OF SAMPLE DISTRIBUTION (%) OF SIGNIFICANT WAVE HEIGHT FOR THE PERIOD 1994-2019 ON SEM-REV

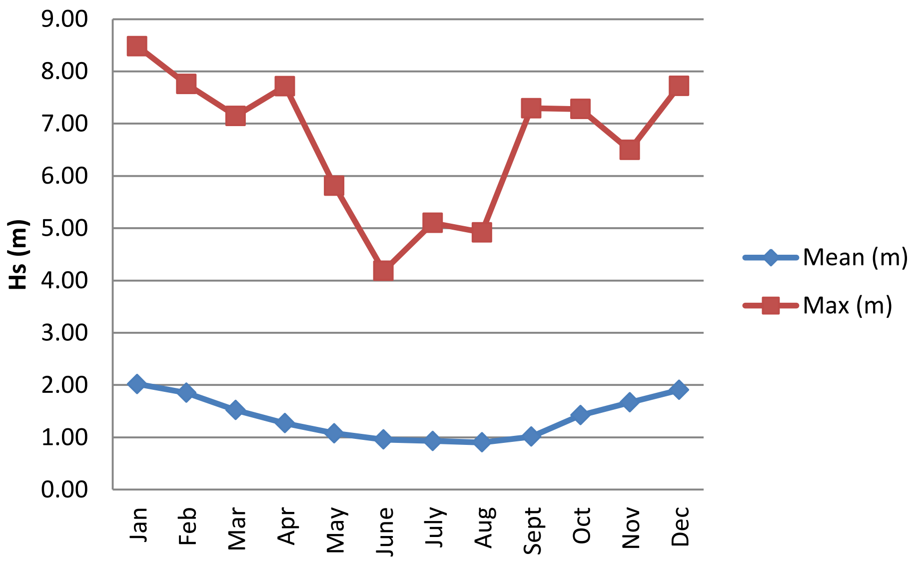


FIGURE 30 MONTHLY MEAN AND MAXIMUM SIGNIFICANT WAVE HEIGHT FROM HOMERE FOR THE PERIOD 1994-2019 ON SEM-REV

Waves Hs (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0 <= Hs < 0.5	0.16	0.24	0.42	0.80	0.91	1.31	1.28	1.50	1.59	0.58	0.48	0.22	**9.50**
0.5 <= Hs < 1	1.47	1.64	2.42	3.09	4.00	4.07	4.33	4.47	3.60	2.82	2.01	1.83	**35.77**
1 <= Hs < 1.5	1.96	1.83	2.24	1.93	1.92	1.71	1.90	1.51	1.53	2.09	1.84	1.83	**22.28**
1.5 <= Hs < 2	1.36	1.20	1.30	1.13	0.90	0.62	0.63	0.60	0.77	1.21	1.35	1.41	**12.47**
2 <= Hs < 2.5	1.15	0.90	0.86	0.62	0.44	0.31	0.22	0.22	0.35	0.79	0.90	0.89	**7.64**
2.5 <= Hs < 3	0.76	0.71	0.61	0.32	0.19	0.13	0.08	0.11	0.22	0.47	0.72	0.78	**5.11**
3 <= Hs < 3.5	0.55	0.51	0.31	0.16	0.07	0.05	0.03	0.06	0.09	0.23	0.45	0.61	**3.12**
3.5 <= Hs < 4	0.45	0.32	0.17	0.09	0.03	0.01	0.01	0.01	0.04	0.14	0.23	0.42	**1.91**
4 <= Hs < 4.5	0.30	0.20	0.08	0.04	0.01	0.00	0.01	0.01	0.01	0.08	0.14	0.24	**1.12**
4.5 <= Hs < 5	0.16	0.10	0.04	0.02	0.01		0.00	0.00	0.01	0.05	0.06	0.11	**0.56**
Hs > 5	0.17	0.09	0.03	0.02	0.01		0.00		0.01	0.03	0.04	0.12	**0.52**
Total (%)	**8.49**	**7.73**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**8.49**	**8.21**	**8.49**	**8.21**	**8.49**	**100.00**
Mean (m)	**2.02**	**1.85**	**1.52**	**1.27**	**1.08**	**0.96**	**0.93**	**0.90**	**1.01**	**1.42**	**1.67**	**1.91**	**1.38**
Max (m)	**8.48**	**7.76**	**7.15**	**7.72**	**5.81**	**4.18**	**5.10**	**4.92**	**7.29**	**7.28**	**6.50**	**7.72**	**8.48**

TABLE 20: MONTHLY DISTRIBUTION (%) OF SIGNIFICANT WAVE HEIGHT FOR THE PERIOD 1994-2019 ON SEM-REV

The scatter diagram obtained from HOMERE hindcast database is presented on Table 21.

Hs (m) / Tp (s)	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-16	16-18	18-20	20-22	22-24	24-26	TOTAL (%)
0 - 0.5 m	0.43	0.05	0.04	0.08	0.11	1.55	1.73	1.90	1.42	0.90	0.59	0.32	0.19	0.12	0.06	0.01	0.00	0.00	**9.50**
0.5 - 1 m	0.42	1.77	0.63	0.95	0.57	3.47	4.69	5.68	5.83	4.57	3.22	1.86	1.07	0.68	0.25	0.08	0.02	0.01	**35.77**
1 - 1.5 m	0.00	0.27	0.67	1.31	0.83	2.13	1.84	2.39	2.90	2.94	2.60	2.10	1.23	0.73	0.27	0.06	0.02	0.00	**22.28**
1.5 - 2 m	0.00	0.00	0.04	0.64	0.63	1.67	1.13	1.23	1.17	1.30	1.59	1.39	0.90	0.55	0.19	0.04	0.00	0.00	**12.47**
2 - 2.5 m	0.00	0.00	0.00	0.07	0.37	1.29	0.77	0.78	0.74	0.70	0.87	0.85	0.67	0.36	0.14	0.02	0.00	0.00	**7.64**
2.5 - 3 m	0.00	0.00	0.00	0.00	0.04	0.72	0.51	0.54	0.58	0.53	0.53	0.57	0.57	0.36	0.15	0.01	0.00	0.00	**5.11**
3 - 3.5 m	0.00	0.00	0.00	0.00	0.00	0.24	0.33	0.40	0.39	0.39	0.34	0.31	0.34	0.26	0.10	0.03	0.00	0.00	**3.12**
3.5 - 4 m	0.00	0.00	0.00	0.00	0.00	0.04	0.16	0.26	0.24	0.27	0.23	0.19	0.21	0.19	0.09	0.02	0.00	0.00	**1.91**
4 - 4.5 m	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.14	0.18	0.18	0.17	0.12	0.13	0.09	0.07	0.00	0.00	0.00	**1.12**
4.5 - 5 m	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.10	0.11	0.10	0.07	0.05	0.04	0.04	0.01	0.00	0.00	**0.56**
> 5 m	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.08	0.11	0.12	0.06	0.05	0.04	0.01	0.00	0.00	**0.52**
TOTAL (%)	**0.84**	**2.10**	**1.38**	**3.06**	**2.54**	**11.12**	**11.21**	**13.36**	**13.58**	**11.95**	**10.33**	**7.90**	**5.43**	**3.42**	**1.41**	**0.29**	**0.06**	**0.01**	**100.00**

TABLE 21 HM0 / TP SCATTER DIAGRAM (INCLUDING ALL DIRECTIONS) IN % (HOMERE _SEM-W_1994-2019)

3.5 LONG-TERM WAVE STATISTICS

The long term wave statistics is performed through the Peak Over Threshold method.
The method is based on the selection of samples whose reference value (Hs here) lies above a given threshold and for which a minimal time interval has to be verified. This ensures that several extreme values related to the same extreme event cannot contribute altogether to the statistical law.

A threshold set to 5.2 m allows the selection of the extreme events in the HOMERE dataset for the POT method application. The correlation between the Pareto distribution and the modelled wave data is presented in the Figure below. The statistical fitted distribution shows an hourly significant wave height of 8.59 m for a 25 years return period, when the maximum modelled wave height reached 8.48 m for this 26-years dataset.

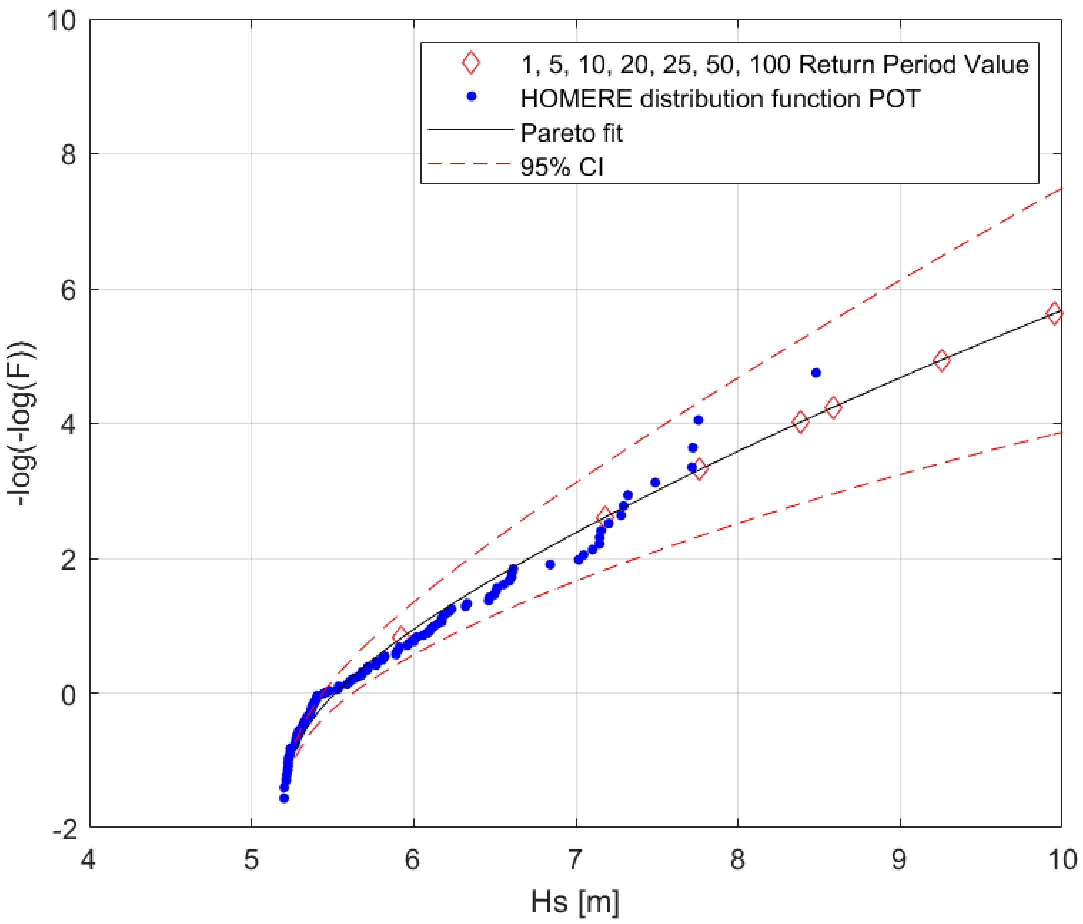


FIGURE 31 POT APPLIED TO HS VALUES (FROM HOMERE DATABASE) FOR A 5.2 M THRESHOLD. STATISTICAL DISTRIBUTION, PARETO FITTING, 95% CONFIDENCE INTERVAL AND REPRESENTATIVE RETURN VALUES. ALL DIRECTIONS INCLUDED

<table>
<tr><th>Direction</th><th>Proportion</th><th>Threshold</th><th>Hs max</th><th colspan="12">Values (m) for return periods (years) and 95% CI Interval</th></tr>
<tr><th>(°)</th><th>(%)</th><th>(m)</th><th>(m)</th><th colspan="2">1</th><th colspan="2">5</th><th colspan="2">10</th><th colspan="2">25</th><th colspan="2">50</th><th colspan="2">100</th></tr>
<tr><td rowspan="2">All</td><td rowspan="2">100.00</td><td rowspan="2">5.2</td><td rowspan="2">8.48</td><td colspan="2">5.93</td><td colspan="2">7.18</td><td colspan="2">7.76</td><td colspan="2">8.59</td><td colspan="2">9.25</td><td colspan="2">9.95</td></tr>
<tr><td>6.03</td><td>5.78</td><td>7.12</td><td>7.12</td><td>7.52</td><td>7.91</td><td>8.00</td><td>9.24</td><td>8.32</td><td>10.51</td><td>8.61</td><td>12.05</td></tr>
</table>

TABLE 22: RETURN PERIODS OF HS FOR ALL DIRECTIONS ON SEM-REV

The estimation of the threshold remains a crucial question to address. It is presently determined using the mean residual life plot and mean excess relatively to the threshold, as implemented in the WAFO toolbox ***[39]***:
The choice of the threshold is made when a break in the slope is observed. Convergence around this threshold value is performed in order to select a threshold which represents the best compromise to be conservative on the return values and for which the Pareto law fits the best the HOMERE distribution dataset.

From the previously presented POT long term extrapolation application, the following table has been obtained for directional sectors of 15°:

Direction	Proportion	Threshold	Hs max	Values (m) for return periods (years) and 95% CI Interval											
(°)	(%)	(m)	(m)	1		5		10		25		50		100	
0	0.12	0.4	1.50	**1.69**		**1.72**		**1.73**		**1.74**		**1.74**		**1.74**	
				1.5	*2.64*	*1.5*	*2.99*	*1.50*	*3.12*	*1.50*	*3.30*	*1.50*	*3.43*	*1.50*	*3.55*
15	0.18	0.6	1.59	**1.56**		**1.59**		**1.60**		**1.61**		**1.61**		**1.62**	
				1.24	*2.06*	*1.24*	*2.37*	*1.24*	*2.49*	*1.24*	*2.65*	*1.24*	*2.77*	*1.24*	*2.89*
30	0.47	0.6	1.58	**1.54**		**1.60**		**1.61**		**1.63**		**1.64**		**1.64**	
				1.25	*1.81*	*1.26*	*2.03*	*1.27*	*2.11*	*1.27*	*2.22*	*1.27*	*2.30*	*1.27*	*2.37*
45	0.55	0.6	2.10	**1.86**		**2.02**		**2.08**		**2.16**		**2.21**		**2.25**	
				1.45	*2.33*	*1.49*	*2.89*	*1.50*	*3.15*	*1.52*	*3.51*	*1.52*	*3.80*	*1.53*	*4.10*
60	0.43	0.8	2.00	**1.66**		**1.73**		**1.75**		**1.77**		**1.79**		**1.80**	
				1.14	*1.82*	*1.15*	*2.22*	*1.15*	*2.40*	*1.16*	*2.65*	*1.16*	*2.85*	*1.16*	*3.05*
75	0.23	0.7	1.64	**1.80**		**1.88**		**1.90**		**1.93**		**1.95**		**1.96**	
				1.3	*2.3*	*1.31*	*2.78*	*1.32*	*2.99*	*1.32*	*3.29*	*1.32*	*3.52*	*1.32*	*3.76*
90	0.19	0.6	1.65	**1.71**		**1.75**		**1.76**		**1.77**		**1.78**		**1.79**	
				1.35	*2.22*	*1.35*	*2.52*	*1.35*	*2.64*	*1.35*	*2.79*	*1.35*	*2.91*	*1.36*	*3.01*
105	0.14	0.6	1.62	**1.54**		**1.55**		**1.56**		**1.56**		**1.56**		**1.56**	
				1.67	*2.33*	*1.67*	*2.46*	*1.68*	*2.51*	*1.68*	*2.57*	*1.68*	*2.61*	*1.68*	*2.64*
120	0.07	0.6	1.63	**1.65**		**1.66**		**1.66**		**1.66**		**1.67**		**1.67**	
				1.75	*2.68*	*1.75*	*2.89*	*1.75*	*2.97*	*1.75*	*3.06*	*1.75*	*3.13*	*1.75*	*3.19*
135	0.04	0.6	1.86	**2.19**		**2.24**		**2.25**		**2.27**		**2.28**		**2.28**	
				1.98	*4.71*	*1.98*	*6.06*	*1.98*	*6.73*	*1.98*	*7.71*	*1.98*	*8.53*	*1.98*	*9.42*
150	0.03	0.5	1.82	**1.83**		**1.83**		**1.83**		**1.83**		**1.83**		**1.83**	
				1.97	*3.55*	*1.97*	*3.94*	*1.97*	*4.1*	*1.97*	*4.3*	*1.97*	*4.44*	*1.97*	*4.58*
165	0.15	0.9	2.51	**2.36**		**2.41**		**1.43**		**2.44**		**2.45**		**2.46**	
				1.99	*3.38*	*1.99*	*3.92*	*1.99*	*4.15*	*1.99*	*4.46*	*1.99*	*4.69*	*1.99*	*4.92*
180	1.06	1	3.68	**3.82**		**3.97**		**4.02**		**4.07**		**4.10**		**4.12**	
				3.29	*4.39*	*3.35*	*4.81*	*3.36*	*4.97*	*3.37*	*5.15*	*3.38*	*5.28*	*3.38*	*5.39*
195	0.87	1.5	5.08	**5.27**		**5.54**		**5.62**		**5.71**		**5.77**		**5.81**	
				4.6	*6.36*	*4.69*	*7.15*	*4.71*	*7.46*	*4.73*	*7.85*	*4.74*	*8.12*	*4.75*	*8.38*
210	0.55	1.6	6.90	**6.02**		**6.36**		**6.47**		**6.60**		**6.68**		**6.75**	
				5.04	*7.40*	*5.14*	*8.45*	*5.17*	*8.88*	*5.20*	*9.42*	*5.22*	*9.82*	*5.23*	*10.20*
225	1.13	2.9	7.94	**6.69**		**7.27**		**7.49**		**7.74**		**7.91**		**8.07**	
				5.44	*7.69*	*5.61*	*9.51*	*5.66*	*10.37*	*5.71*	*11.58*	*5.74*	*12.55*	*5.76*	*13.57*
240	6.07	5	8.48	**6.99**		**7.65**		**7.90**		**8.19**		**8.40**		**8.59**	
				5.73	*6.10*	*5.96*	*7.70*	*6.02*	*8.58*	*6.08*	*9.94*	*6.11*	*11.16*	*6.13*	*12.57*
255	30.53	5	7.76	**7.10**		**8.24**		**8.71**		**9.31**		**9.75**		**10.19**	
				6.05	*6.07*	*6.74*	*7.79*	*6.97*	*8.69*	*7.22*	*10.1*	*7.37*	*11.2*	*7.5*	*12.6*
270	56.84	5	6.61	**5.17**		**6.09**		**6.49**		**7.02**		**7.42**		**7.83**	
				4.21	*4.07*	*4.85*	*5.28*	*5.07*	*5.95*	*5.32*	*7.01*	*5.48*	*7.96*	*5.62*	*9.07*
285	0.19	0.4	2.95	**2.70**		**2.82**		**2.86**		**2.90**		**2.93**		**2.95**	
				2.73	*4.57*	*2.75*	*5.27*	*2.75*	*5.57*	*2.76*	*5.95*	*2.76*	*6.24*	*2.76*	*6.53*
300	0.03	0.4	1.86	**1.75**		**1.75**		**1.75**		**1.75**		**1.75**		**1.75**	
				2.17	*3.56*	*2.17*	*3.82*	*2.17*	*3.92*	*2.17*	*4.04*	*2.17*	*4.12*	*2.17*	*4.19*

315	0.02	0.4	1.82	**1.70**		**1.70**		**1.70**		**1.70**		**1.70**		**1.70**	
				1.46	*3.68*	*1.46*	*4.6*	*1.46*	*5.02*	*1.46*	*5.62*	*1.46*	*6.1*	*1.46*	*6.61*
330	0.04	0.4	2.25	**1.94**		**1.98**		**1.98**		**1.99**		**2.00**		**2.00**	
				1.48	*4.05*	*1.48*	*5.17*	*1.48*	*5.71*	*1.48*	*6.47*	*1.48*	*7.1*	*1.48*	*7.77*
345	0.06	0.4	1.96	**2.05**		**2.10**		**2.12**		**2.13**		**2.14**		**2.14**	
				1.58	*3.72*	*1.59*	*4.53*	*1.59*	*4.9*	*1.59*	*5.4*	*1.59*	*5.8*	*1.59*	*6.21*

TABLE 23 HS (BY DIRECTIONAL SECTORS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS (POT) FROM HOMERE (1994-2019). MAIN DIRECTIONS OF PROBABILTY OF OCCURENCE ARE HIGHLIGHTEN IN BLUE

Once the extrapolation adequately fits the modelled data for the significant wave height, the necessity for assessing the other characteristic spectral parameters arises. A relation between the most energetic sea states and parameters such as $T_{p,R5}$ or Hmax is then proposed based on in-situ measurements (spectral estimate of the 1 hour length signals measured by DWR East from august 2010 to December 2011, including in particular “Joachim” storm).

3.6 SIGNIFICANT WAVE HEIGHT-PEAK PERIOD DISTRIBUTION

3.6.1 RELATION BETWEEN HS AND TP FOR HS > 4 M

It is assumed that the extreme conditions follow the same trend existing between parameters, at least for the highest values of the main parameter. Hence, the correlation between Hs and Tp is presented on Figure 32 for in-situ measurements (2009-2020) on both buoys (SEM-REV East and West).
The relation between the significant wave height (Hs) and the peak period (T_p) for the most energetic sea states (Hs > 4m) is obtained by the least square method :

$$T_P = 4.56.HS^{1/2} + 1.92 \quad [S] \tag{5}$$

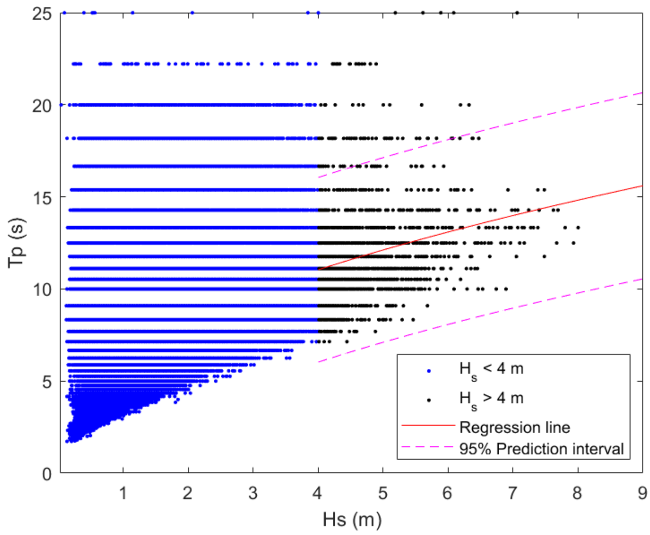


FIGURE 32 HS – TP JOINT DISTRIBUTION AND REGRESSION LINE FOR HS>4M VALUES

3.7 SPECTRUM SHAPE: RELATION BETWEEN HS AND GAMMA

Determining an empirical relationship between the peak enhancement factor of a JONSWAP spectrum and the significant wave height for extreme sea conditions, requires adjustments of the formula for every spectral density measured. Then, the significant height, the peak period and the peak factor will vary in order to obtain a satisfactory spectral adjustment.

The results are obtained for in-situ measurements (2009-2020) on both buoys (SEM-REV East and West). Broad banded spectra are discarded (i.e. the peak factor is below the acceptable JONSWAP limit of 0.85) and the narrowest spectra (gamma >7) are also discarded.

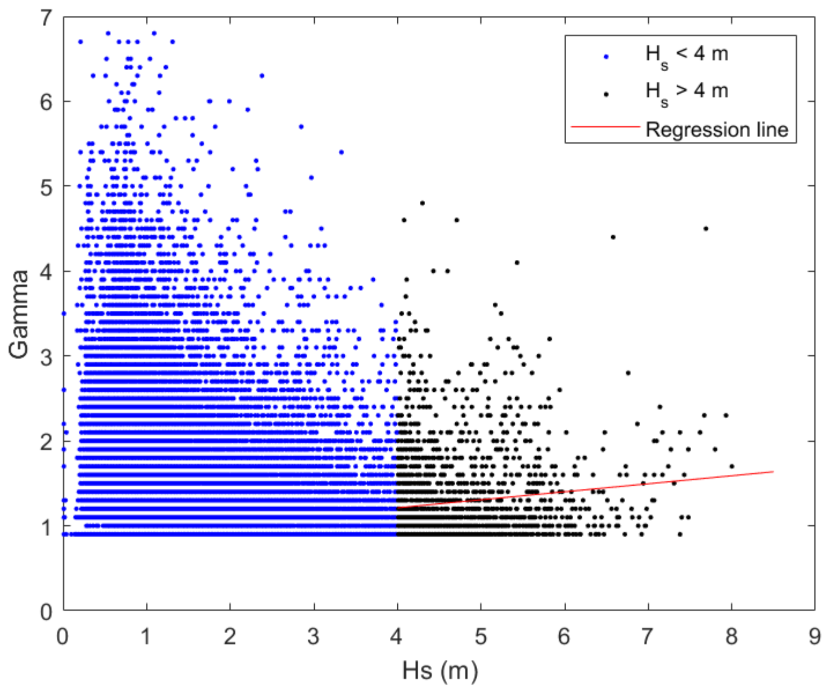


FIGURE 33 PEAK ENHANCEMENT FACTOR γ (HIGH AND LOW FREQUENCY) OBTAINED WITH SINGLE MODE ADJUSTMENT AND A DEVIATION INFERIOR TO 30%

According to the previous results, the identification of a relationship between the peak factor and the significant wave height is relevant when H_{m0}>4m. The regression line equation is:

$$\gamma = 0.0944.H_{m0} + 0.8345 \quad (6)$$

Twin peak spectra are frequently observed (wind sea and swell). Nonetheless, in extreme conditions (for instance when H_{m0} > 5m), the spectrum is often characterised by a strong wind sea and therefore presents only one mode (spectrum with just one peak). An additional analysis of sea state composition is available in section 4.4.

Examples of observed twin peak spectra are presented below. Other examples of events selected by highest Hs are presented in appendix 10.5.

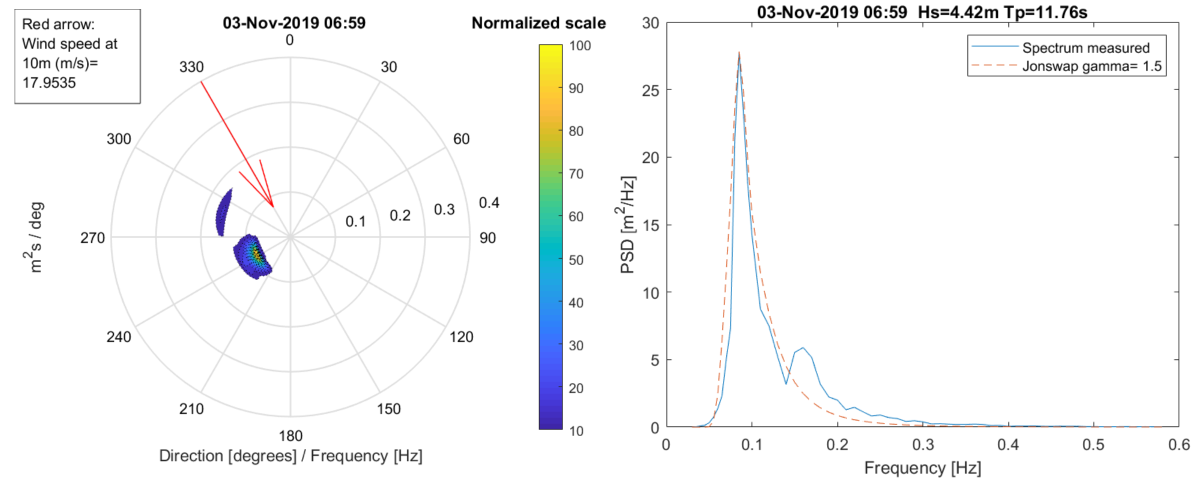


FIGURE 34: SPECTRUM WITH TWO PEAKS FOR HS > 4 M

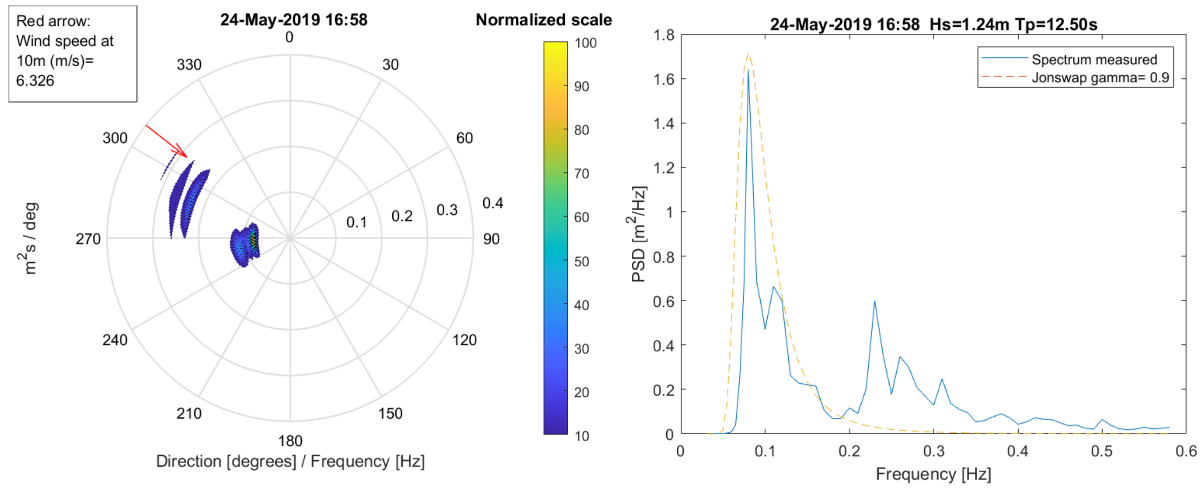


FIGURE 35: SPECTRUM WITH TWO PEAKS FOR HS AROUND 1 M. CONVENTION: “WAVES AND WIND ARE COMING FROM”

3.8 RELATION BETWEEN HS AND HMAX

A relation is proposed between the significant wave height (wave-by-wave analysis $H_{1/3}$) and the maximum wave height for the most energetic sea states:

$$HMAX = 1.511 * H_{1/3} + 0.422 \quad [M] \qquad (7)$$

This formula is obtained by a linear regression based of the Hs > 4m values.
For information the relation between $H_{1/3}$ and Hmax for all significant wave heights is:

$$HMAX = 1.600 * H_{1/3} + 0.059 \quad [M] \qquad (8)$$

Figure 36 presents the correlation between Hmax and $H_{1/3}$ for in-situ measurements (2009-2020) on both buoys (SEM-REV East and West) and regression line for Hs >4m.

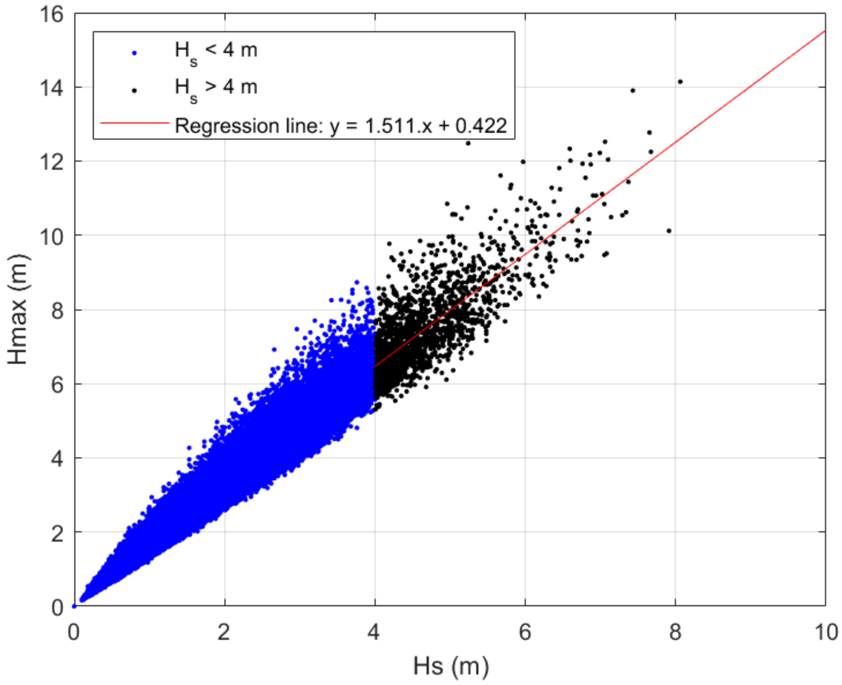


FIGURE 36 CORRELATION BETWEEN H_{MAX} AND H_S AND LINEAR REGRESSION FOR H_S>4 M

3.9 BREAKING WAVES

To estimate the possibility of wave breaking, three configurations of waves are studied. The first one is based on the significant wave height for a return period of 50 years. It then uses the Hs-Hmax correlation in section 3.8 and the Hs-Tp correlation in section 3.6.1. The two other configurations studied are based on the highest wave (Hmax) measured on site since 2010 during Joachim storm in 2011. Two periods corresponding to interval observed on the timeseries are studied.

These parameters, are then used to evaluate the risk of breaking waves on site regarding wave theory reproduced in IEC 61400-3 Appendix C and as reported in Appendix 10.7. It shows that these maximum conditions are still below the theoretical wave breaking limit.

Hs	**Hmax**	**T / Tp**	**Breaking wave limit**
9.75 m (T_R=50 yrs at 255°)	15.15 m (Hs-Hmax correlation)	16 s (Hs-Tp correlation)	Below
-	14 m (Joachim storm)	12 s	Below
-	14 m	9 s	Below

TABLE 24: WAVE CONFIGURATIONS STUDIED TO EVALUATE RISK OF BREAKING WAVES

4. WIND-WAVE

The wind and wave data correlation is computed from

- HOMERE model data for waves (see section 3.2)
- ERA5 model data for wind (see section 2.2)

Both model data used are located at SEM-REV site.

4.1 WIND SPEED AND WAVE HEIGHT

The scatter points presented on Figure 37 do not show a significant correlation between significant wave height and 1-hour mean wind speed 10 m above the sea level. This can be explained by the fact that SEM-REV site is open to North Atlantic Ocean and related swell and not only subject to Wind Sea.

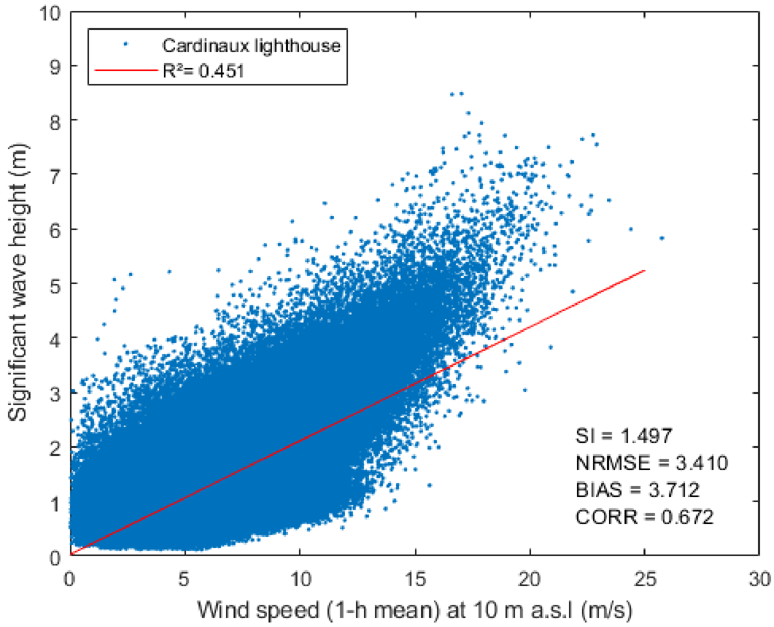


FIGURE 37: SIGNIFICANT WAVE HEIGHT VERSUS 1-HOUR MEAN WIND SPEED AT 10 M ABOVE SEA LEVEL (1994-2020)

U (m/s) / Hs (m)	0 - 0.5 m	0.5 - 1 m	1 - 1.5 m	1.5 - 2 m	2 - 2.5 m	2.5 - 3 m	3 - 3.5 m	3.5 - 4 m	4 - 4.5 m	4.5 - 5 m	5 - 5.5 m	5.5 - 6 m	6 - 6.5 m	6.5 - 7 m	7 - 7.5 m	7.5 - 8 m	8 - 8.5 m	TOTAL (%)
0 - 2 m/s	0.79	2.30	0.96	0.32	0.09	0.02	0.01	0.00	0.00		0.00							4.49
2 - 4 m/s	3.14	8.03	3.55	1.24	0.40	0.14	0.04	0.01		0.00	0.00							16.56
4 - 6 m/s	4.02	12.34	6.34	2.58	0.96	0.46	0.13	0.03	0.00		0.00							26.87
6 - 8 m/s	1.50	9.42	6.76	3.67	1.70	0.86	0.37	0.10	0.03	0.01	0.00							24.40
8 - 10 m/s	0.05	3.24	3.67	3.39	2.48	1.39	0.63	0.26	0.07	0.01	0.00	0.00	0.00					15.21
10 - 12 m/s	0.00	0.42	0.92	1.16	1.64	1.48	0.95	0.52	0.22	0.05	0.02	0.00	0.00					7.38
12 - 14 m/s		0.01	0.08	0.10	0.35	0.65	0.79	0.62	0.39	0.15	0.04	0.01	0.00	0.00				3.19
14 - 16 m/s			0.00	0.01	0.02	0.09	0.19	0.33	0.33	0.21	0.10	0.04	0.02	0.00	0.00			1.34
16 - 18 m/s				0.00		0.01	0.02	0.04	0.08	0.11	0.09	0.05	0.01	0.01	0.00	0.00	0.00	0.42
18 - 20 m/s							0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00		0.11
20 - 22 m/s								0.00		0.00	0.00	0.00	0.01	0.00	0.00			0.02
22 - 24 m/s												0.00	0.00	0.00		0.00		0.00
24 - 26 m/s												0.00						0.00
26 - 28 m/s																		
28 - 30 m/s																		
> 30																		
TOTAL (%)	9.50	35.77	22.28	12.47	7.64	5.11	3.12	1.91	1.12	0.56	0.28	0.13	0.06	0.03	0.02	0.00	0.00	100.00
Mean Wind speed (m/s)	4.33	5.25	6.06	7.01	8.28	9.30	10.52	11.80	13.09	14.37	15.25	16.28	17.49	18.17	18.48	19.43	16.99	6.49
Max Wind speed (m/s)	10.38	13.73	15.64	16.03	15.89	18.00	19.80	20.91	19.55	21.87	21.09	25.75	22.66	23.45	21.83	22.92	17.33	25.75

TABLE 25: SCATTER TABLE OF SIGNIFICANT WAVE HEIGHT VERSUS 1-HOUR MEAN WIND SPEED AT 10 M ABOVE SEA LEVEL

4.2 WIND SPEED AND PEAK PERIOD

The scatter points presented on Figure 38 do not show any correlation between wave peak period and and 1-hour mean wind speed 10 m above the sea level.

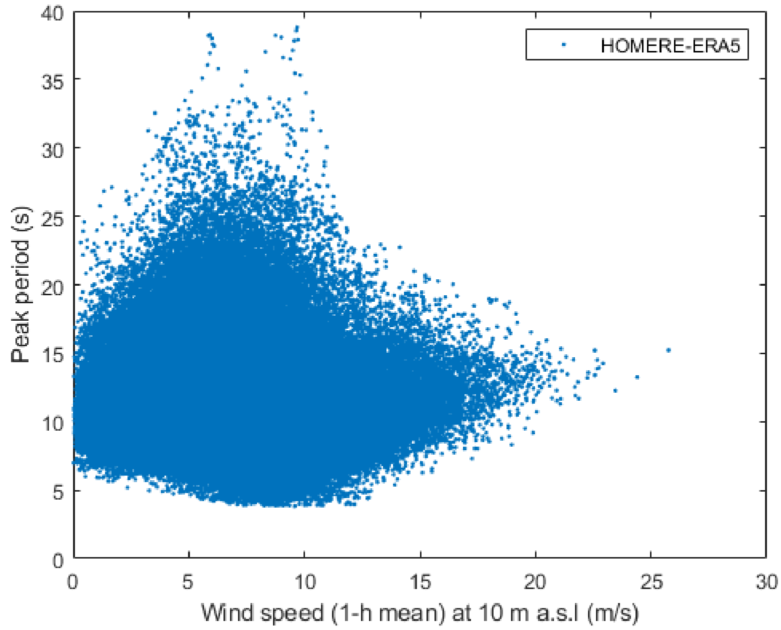


FIGURE 38: PEAK PERIOD VERSUS 1-HOUR MEAN WIND SPEED AT 10 M ABOVE SEA LEVEL (1994-2020)

4.3 WIND DIRECTION AND WAVE DIRECTION

The scatter points presented on Figure 39 higher density points for swell generated offshore of North Atlantic and coming from West (255-270°). Other peak period directions may be related to wind sea (in the case where Wind sea energy is higher than swell because the analysis does not consider wave system partitioning).

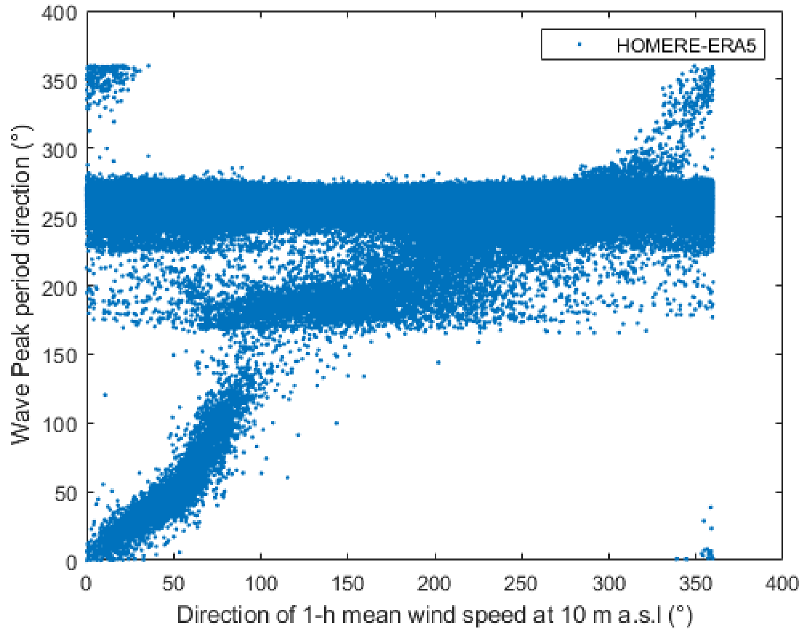


FIGURE 39: WAVE PEAK PERIOD DIRECTION VERSUS 1-HOUR MEAN WIND SPEED DIRECTION AT 10 M ABOVE SEA LEVEL (1994-2020)

4.4 ANALYSIS OF SEA STATE COMPOSITION

The coastal properties of the test site, located in intermediate to shallow waters and at a short distance from the coast over a wide variety of directions, greatly influence the nature of sea states occurring on site. The analysis conducted on the sea state composition in terms of wave system reveals that over a 3 m H_{m0} threshold, all the observed sea states are composed of only one single system [47]. More over, no clear trend emerges from system decomposition regarding wind seas and swell. Swell systems are notably harder to track in those coastal locations, as different deep water offshore swell systems tend to align all together along their propation path.
It is thus emphasized that specific sensitivities of devices to be hosted on site should be considered with regards to the full spectro-directional sea state data that have been gathered from in situ observation as well as numerical modelling.

Hm0 threshold :	**> 0.5 m**	**> 1m**	**> 3m**
Nb of wave systems = 1	63.7 %	85.8 %	100 %
Nb of wave systems = 2	33.3 %	13.9 %	0
Nb of wave systems > 2	3.0 %	0.3 %	0
Nb of sea states (h)	7219	3672	172

TABLE 26: SEA STATES SYSTEM COMPOSITION IN SEM-REV IN 2011 ACCORDING TO [47] FOR GIVEN H_{M0} THRESHOLDS

5. VARIATIONS OF WATER LEVEL

5.1 WATER LEVEL PROVIDED BY SHOM IN NEAREST HARBOUR

The “Great Maritime Harbour of Nantes – Saint-Nazaire” is equipped with a tidal gauge that belongs to the National numerical tidal gauge network RONIM (*Réseau d'Observation du Niveau de la Mer*) [31], managed by the SHOM. This radar telemeter is installed at the south entrance of Saint-Nazaire harbour since January 2007.

Water level mainly evolves according to astronomical tide and to barometric variations. Mean spring and neap tides are characterised by a tidal coefficient of 95 and 45 respectively. Exceptional tides are characterized by a tidal coefficient of 120. The lowest tides are characterized by a coefficient of 45. Tidal data is available from the SHOM tide atlas [28].

The SHOM provided information regarding the characteristic levels which covers the marine altimetry references ([29] yearly updated), including:

- Characteristics tide levels
- The ratings of the « Chart Datum » in the geographic, altimetric and planimetric reference systems.
- The depths on SEMREV are included between 32.13m and 35.57m C.D., Chart Datum (cf section 1.1).

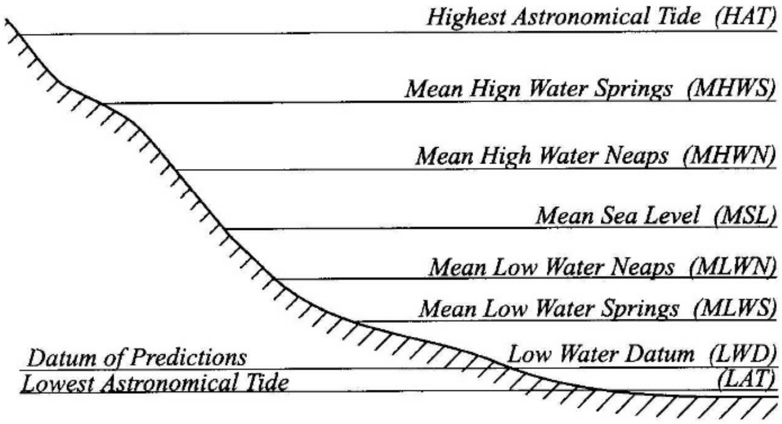


FIGURE 40: SCHEME OF WATER LEVEL DEFINITION AND ACRONYMS

The following table provides the water level (Chart Datum) determined by the SHOM for “Le Croisic” harbour: (0.00 m CD = -2.86 m IGN69).

<table>
<tr><td colspan="5">Le Croisic (47.18ºN, 2.31ºO)</td></tr>
<tr><td>HAT</td><td>6.13</td><td></td><td></td><td rowspan="7">6.16</td></tr>
<tr><td>MHWS</td><td>5.40</td><td></td><td rowspan="5">4.70</td></tr>
<tr><td>MHWN</td><td>4.25</td><td rowspan="3">2.25</td></tr>
<tr><td>MSL</td><td>3.30</td></tr>
<tr><td>MLWN</td><td>2.00</td></tr>
<tr><td>MLWS</td><td>0.70</td><td></td></tr>
<tr><td>LAT</td><td>-0.03</td><td></td><td></td></tr>
</table>

TABLE 27 WATER LEVELS AND TIDAL RANGES [M] AGAINST C.D IN LE CROISIC. SOURCE: SHOM 2017

5.2 HARMONIC ANALYSIS OF WATER LEVEL ON SEM-REV SITE

The longest continuous ADCP campaign performed on SEM-REV is selected to perform the harmonic analysis of water level. The campaign is N°17 from 06th of July to 16th of December 2015. From the water elevation measured by the ADCP, a harmonic analysis if performed [46]. Main components, amplitude and phases are presented on Figure 41. Coefficients of harmonic analysis are presented in appendix 10.6 in Table 45. They can be used for the predictive model of tide on SEM-REV site. Each harmonic component is described by a symbol (for example M2 for the main component) which refers to the physical origin of the component (in this example M2: mean lunar component). Details of the symbols can be find in [48].

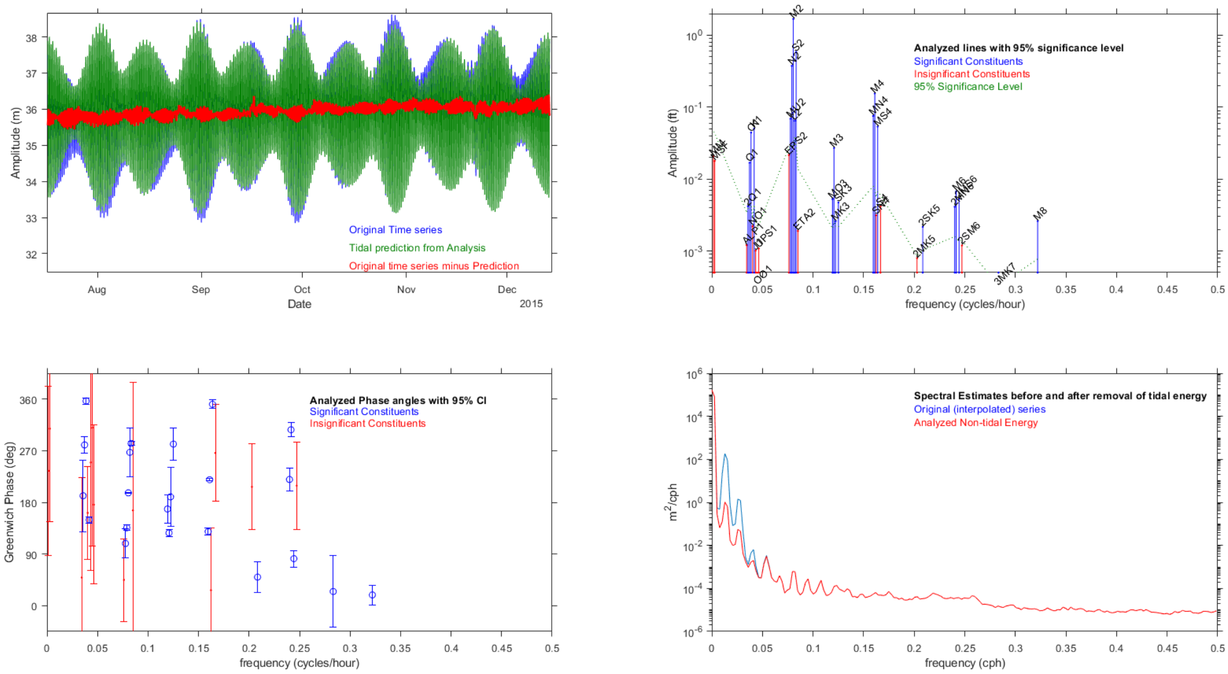


FIGURE 41: HARMONIC ANALYSIS OF WATER ELEVATION ON SEM-REV DURING CAMPAIGN N°17 (07-12/2015)

5.3 SURGE

Atmospheric conditions (wind and pressure) may cause the water level to be higher than predicted by astronomical tides. A study carried out by Météo-France [30] provides assessments of the extreme surge values all over the French coast (English Channel & Atlantic). This study is mainly used to anticipate the floods on the coasts open to Atlantic Ocean conditions.

As a first step and to remain conservative, the maximal surge level estimated for the harbour of Le Croisic must be considered on SEMREV (1.5m-1.7m). The extreme values in terms of water level for Le Croisic harbour can also be used to characterize SEMREV test.

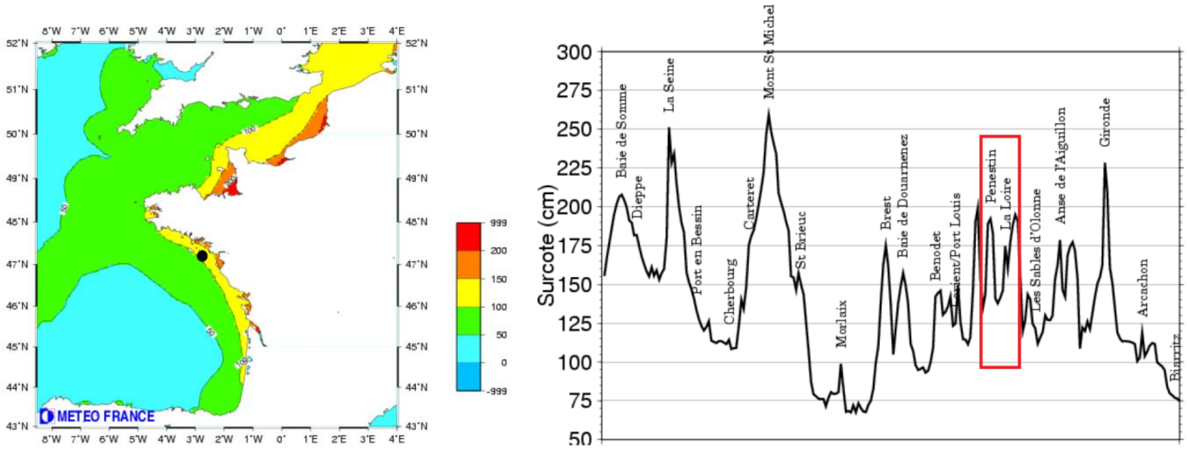


FIGURE 42 MAXIMAL SURGE ESTIMATED ON THE FRENCH COASTLINE; SEMREV (SOURCE : MÉTÉO-FRANCE)

5.4 SEA LEVEL RISE

The effect of global warming on sea level rise is expected to be 0.29 – 1.10 m by the year 2100 [45]. Global mean sea level from tides gauges and observation increased from 3.6 mm/year over the period 2006-2015.

6. CURRENT

6.1 MODEL

Water levels, surges and currents have been computed using the MARS 2D (Model for Applications at Regional Scale) hydrodynamic model, based on the shallow water equations and developed at IFREMER. This model is actually composed of seven embedded models with different refinements (rank 0, rank 1 and ranks 2). The rank 2 model represents the entire south Brittany region (PREVIMER_L1-MARS2D-SUDBZH250) [33].

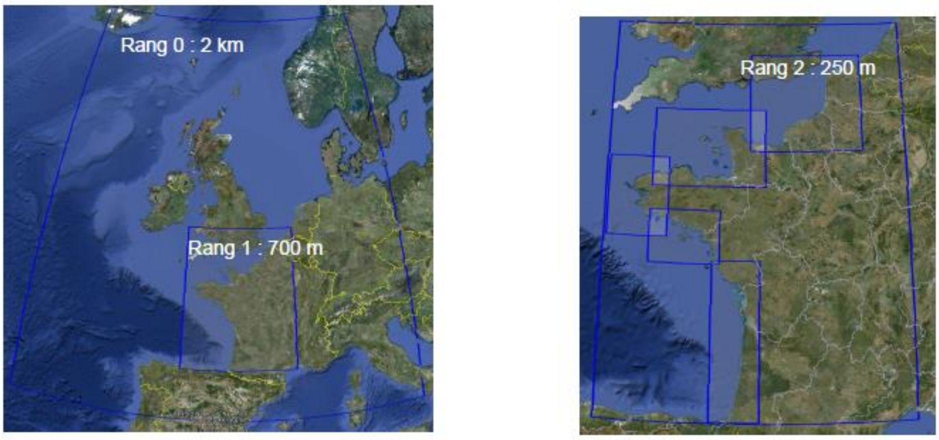


FIGURE 43: MARS2D EMBEDDED RANKS IN THE MODEL [33]

Last improvements enabled the introduction of elaborated sea surface drag parameterization and high resolution meteorological forcing. For the implementation of tides and tidal currents, the rank 0 model is forced by the sea surface height from the FES (2004) global tidal model from the LEGOS, with 14 tidal components. The rank 1 is embedded in rank 0 and is then forced by the tides (level and currents) from rank 0. The rank 2 models are forced by the tide from the cstFRANCE tidal model with 115 tidal components, provided by SHOM. The rank 2 models are also forced by surges computed from rank 0 and rank 1. This methodology allows an accurate evaluation of water levels and tidal currents at rank 2.

Météo-France data are used for the meteorological forcing which induce effects on both levels and currents. Rank 0 and rank 1 models are forced using data from the 0.5° ARPEGE meteorological model, with a six hours time step. Starting in November 2011, ARPEGE data is available with higher resolution (0.1° and 1 hour time step). Rank 2 models are forced with the data from the 0.025° AROME meteorological model, with a 1 h time step. The wind parameterisation is based on Charnock formulation with Charnock coefficient from WaveWatchIII.

The hindcast was produced over 8 years and it consists in 15 minutes water levels, surges and currents data (not atlases of harmonic components). The tidal constituents and water levels are provided on a 250m resolution model grid. The parameters available from the PREVIMER_L1-MARS2D-SUDBZH250 hindcast data are listed below:

- Time
- Sea surface height above sea level
- Barotropic sea water x velocity
- Barotropic sea water y velocity
- Anomalies of the parameters previous parameters…

The main output used from MARS2D model output is then the barotropic velocity, i.e the mean velocity on the water column and the barotropic direction of current.

Current data may also be provided by tidal atlases n°558-UAJ & 559-UAJ from the SHOM [34]. The surface tidal velocity is given for several tidal coefficients at a reference harbour.

6.2 MEASUREMENT

6.2.1 ADCP

On the SEMREV test site, currents are measured using independent, Teledyne RDI 'Workhorse Sentinel' broad-band (600kHz) Acoustic Doppler Current Profilers (ADCPs) [35]) that can be deployed on the seabed depending on the project needs. They are deployed, operated and recovered by ECN. The current velocity estimates are obtained from the Doppler-shifted acoustic echoes received by the four-beam, upward-looking Janus head of each ADCP.
A summary of the measurements campaigns details is presented below:

Date	Entity who performed measurements	Sensor	Mean depth	Time between 2 samples
19 campaigns of 2-3 months between 12/2010 – 03/2021	ECN	Teledyne RDI 'Workhorse Sentinel'	34 - 37.7 m	10 min (30 min for 2 campaigns)

TABLE 28: CHARACTERISTICS OF CURRENT MEASUREMENT CAMPAIGNS

From these campaigns, the following averaged profiles are provided with a spatial distribution of 1m:

- Current velocity magnitude
- Current direction
- Current velocity standard deviation

6.2.2 MEAN CURRENT PROFILE

The 19 campaigns of measurements are concatenated to constitute a discontinuous dataset of 3 years. The mean and maximum velocity is computed at each height above sea bottom and presented on the figure below.

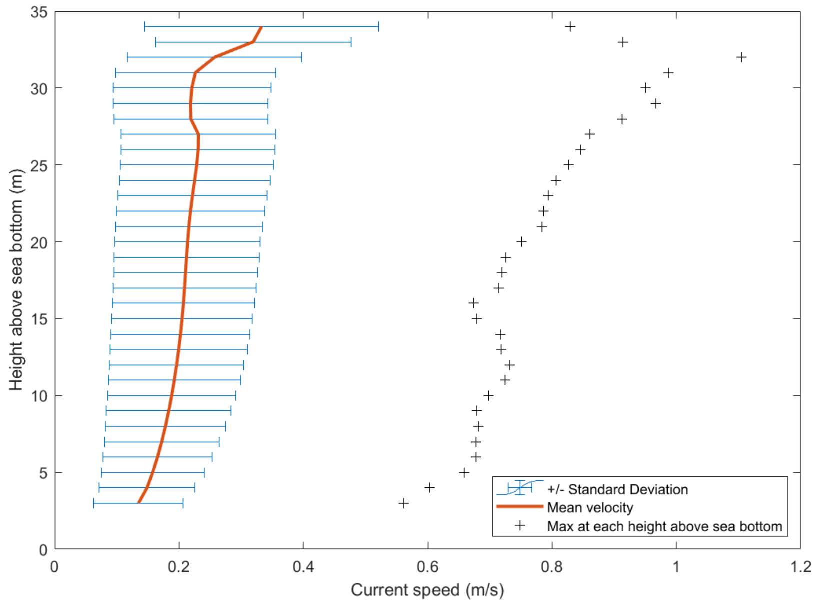


FIGURE 44 : MEAN VELOCITY PROFILES & STATISTICS OVER 30 METERS FROM THE BOTTOM (CAMPAIGN N°5)

The measurement campaign dataset is also analysed for various steps of mean current profile on the water column (for a mean velocity of 0 to 0.54 m/s with steps of 0.1 m/s) and for extreme values above 0.54 m/s. The analysis enables to provide mean current profiles on the water column, as presented on Figure 45 and Table 29. These profiles are provided for a height until 33 m above sea bottom, i.e on the nearest location to the sea surface for which measurements are possible. For profiles corresponding to Umean=0.52 m/s and 0.6 m/s the profiles are plotted until 33 m height but it is for indicative purpose because there are respectively less than 10 values above 31 m and 28 m. The profiles show that classical logarithmic profiles are not relevant to model current on SEM-REV site, especially for the lowest and highest mean current.

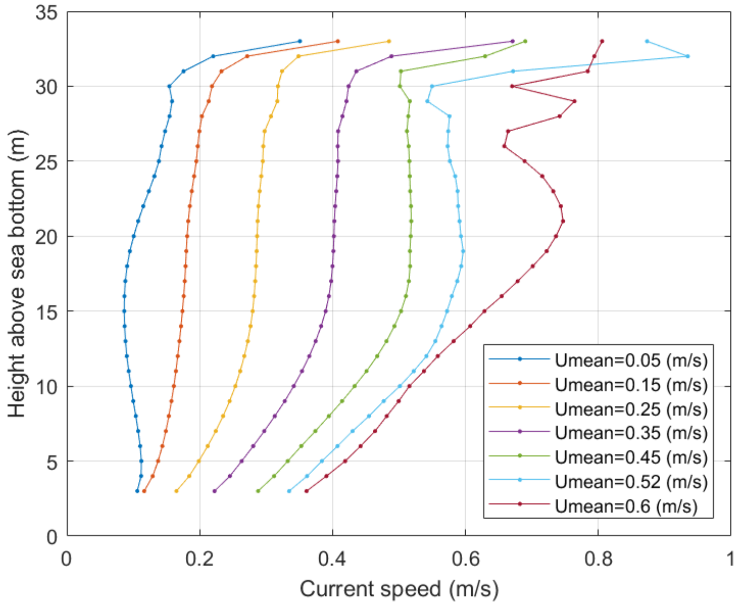


FIGURE 45: MEAN CURRENT PROFILES ON THE WATER COLUMNS FOR VARYING MEAN VELOCITY ON THE WATER COLUMNS

Height above sea bottom (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
U_{mean}=0.05 m/s	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.11
U_{mean}=0.15 m/s	0.12	0.13	0.14	0.14	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.12
U_{mean}=0.25 m/s	0.17	0.18	0.20	0.21	0.22	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.28	0.28	0.28	0.17
U_{mean}=0.35 m/s	0.22	0.25	0.26	0.28	0.30	0.31	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.39	0.40	0.22
U_{mean}=0.45 m/s	0.29	0.31	0.33	0.35	0.37	0.39	0.41	0.43	0.45	0.47	0.48	0.49	0.50	0.51	0.51	0.29
U_{mean}=0.52 m/s	0.33	0.36	0.38	0.41	0.43	0.45	0.48	0.50	0.52	0.54	0.55	0.56	0.57	0.58	0.59	0.33
U_{mean}=0.6 m/s	0.36	0.39	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.61	0.63	0.65	0.68	0.36

Height above sea bottom (m)	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
U_{mean}=0.05 m/s	0.09	0.10	0.11	0.12	0.12	0.13	0.14	0.14	0.15	0.15	0.16	0.15	0.18	0.22	0.35
U_{mean}=0.15 m/s	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.20	0.20	0.20	0.21	0.22	0.23	0.27	0.41
U_{mean}=0.25 m/s	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.30	0.30	0.31	0.32	0.32	0.32	0.35	0.48
U_{mean}=0.35 m/s	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.44	0.49	0.67
U_{mean}=0.45 m/s	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.51	0.51	0.51	0.52	0.50	0.50	0.63	0.69
U_{mean}=0.52 m/s	0.60	0.59	0.59	0.59	0.59	0.58	0.58	0.57	0.57	0.58	0.54	0.55	0.67	0.93	0.87
U_{mean}=0.6 m/s	0.72	0.74	0.75	0.74	0.73	0.72	0.69	0.66	0.66	0.74	0.76	0.67	0.78	0.79	0.81

TABLE 29: DIMENSIONAL MEAN CURRENT PROFILES ON THE WATER COLUMN

6.2.3 CURRENT VELOCITY NEAR SEA SURFACE

In order to evaluate current speed at sea surface, Figure 46 shows the correlation between the velocities measured at the last reliable cell near the surface versus the mean current speed on the water column. The last reliable cell is between 2.25 and 4 m below the sea surface depending on the campaign considered. It shows that even for low mean current speed (<0.2 m/s), the near surface current can reach approximately 1.2 m/s.

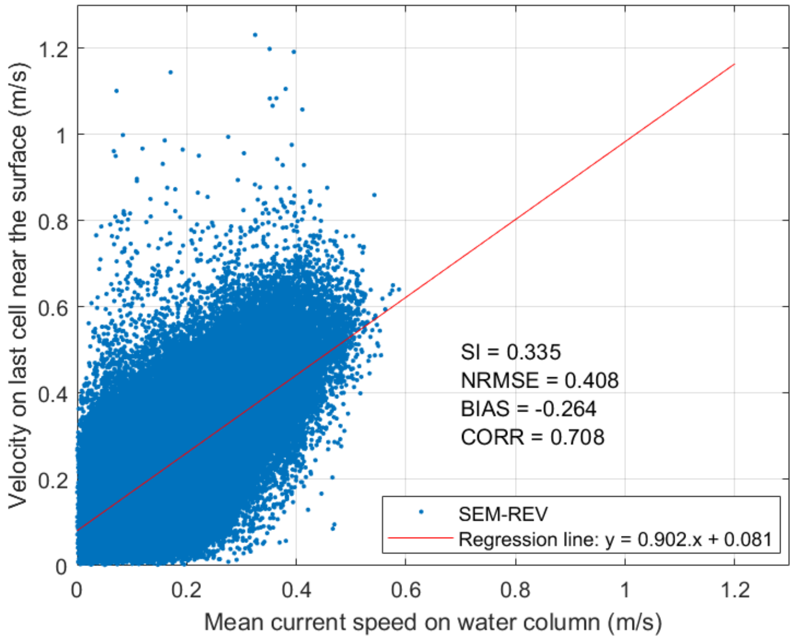


FIGURE 46: CORRELATION OF VELOCITY ON THE LAST RELIABLE CELL NEAR THE SURFACE VERSUS MEAN CURRENT SPEED ON WATER COLUMN

6.2.4 CURRENT DIRECTION NEAR SEA SURFACE

The current profile in direction is barotropic for most of the conditions. The correlation between the current direction at the last reliable cell near the surface versus mean current direction on water column (for mean velocities above 0.1 m/s and 0.3 m/s) is presented on Figure 47. It shows a global correlation between current direction in surface and the mean direction, although some exceptions occur, especially for lower mean current speeds.

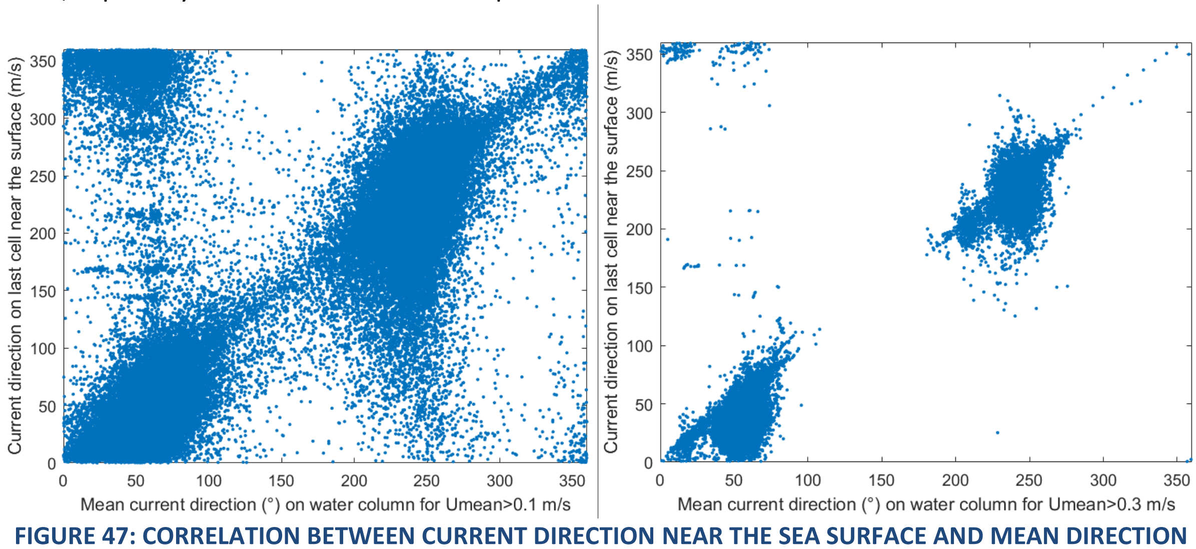


FIGURE 47: CORRELATION BETWEEN CURRENT DIRECTION NEAR THE SEA SURFACE AND MEAN DIRECTION ON WATER COLUMN FOR U_{MEAN}>0.1 M/S (LEFT) AND U_{MEAN}>0.3 M/S (RIGHT). CONVENTION: "CURRENT IS GOING TO".

For increasing mean velocities on the water column, the correlation between current direction near the surface and mean current direction is clearer.

6.2.5 EXAMPLES OF SINGLE EVENTS OF CURRENT VELOCITY PROFILES AND DIRECTION

It is noted that beyond the mean profiles, local maximum can occur. Table 30 presents the profiles corresponding to several maximum of velocities at 3 m to 30 m above the sea bottom. The corresponding date and tidal coefficients are also indicated. It is noted that the maximum velocity measured at each depth often occurs on sheared current profile until 20 m above sea level.
Figure 48 to Figure 50 focuses on some velocity profiles for which a maxima is observed, along with corresponding direction profile, tidal coefficients and time for which the maximum is observed in the tidal cycle. As expected, the observed maxima are occurring at intermediate tides and for high coefficients.

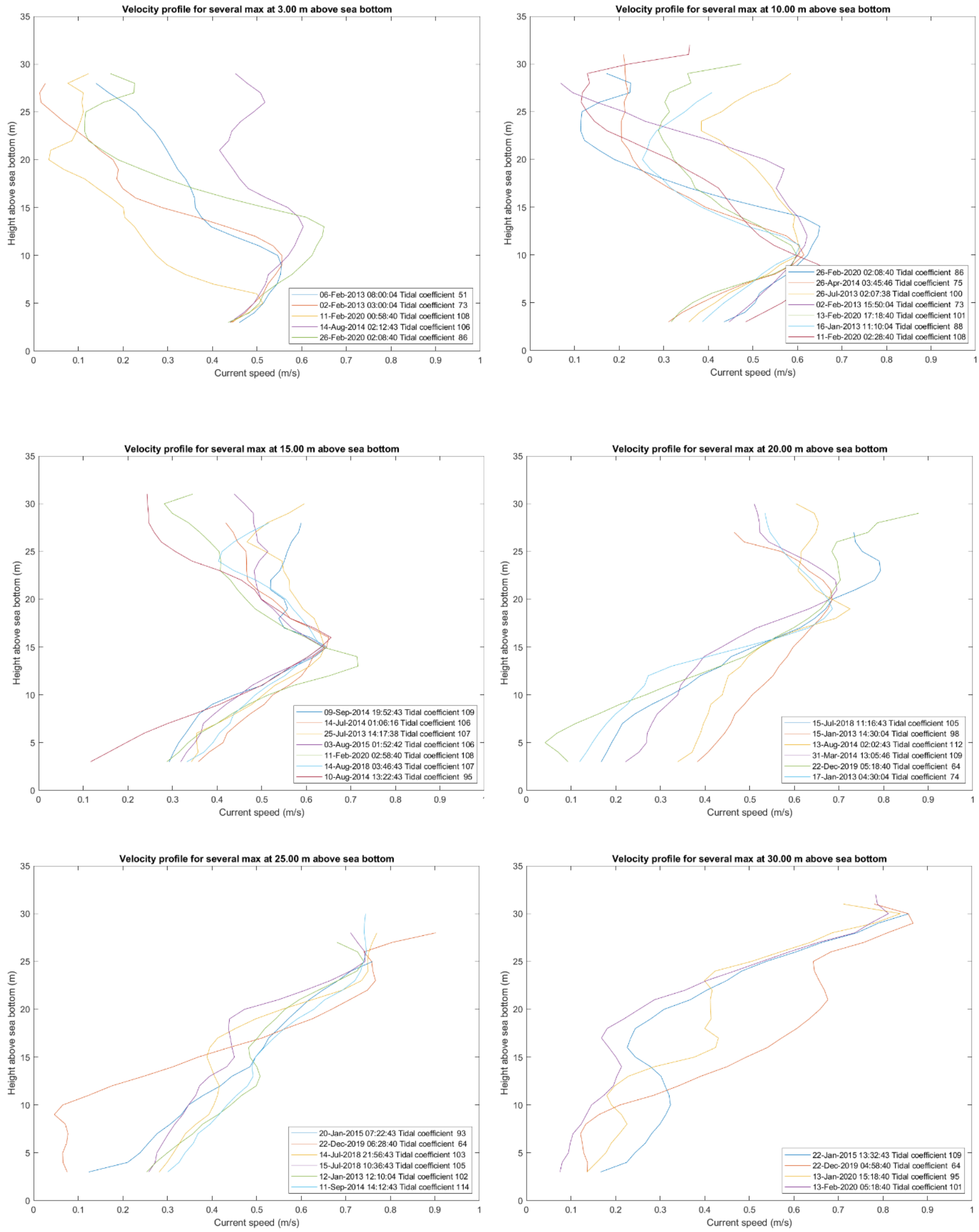


TABLE 30: VELOCITY PROFILES CORRESPONDING TO SEVERAL MAXIMUM OF VELOCITIES AT 3 M TO 30 M ABOVE THE SEA BOTTOM

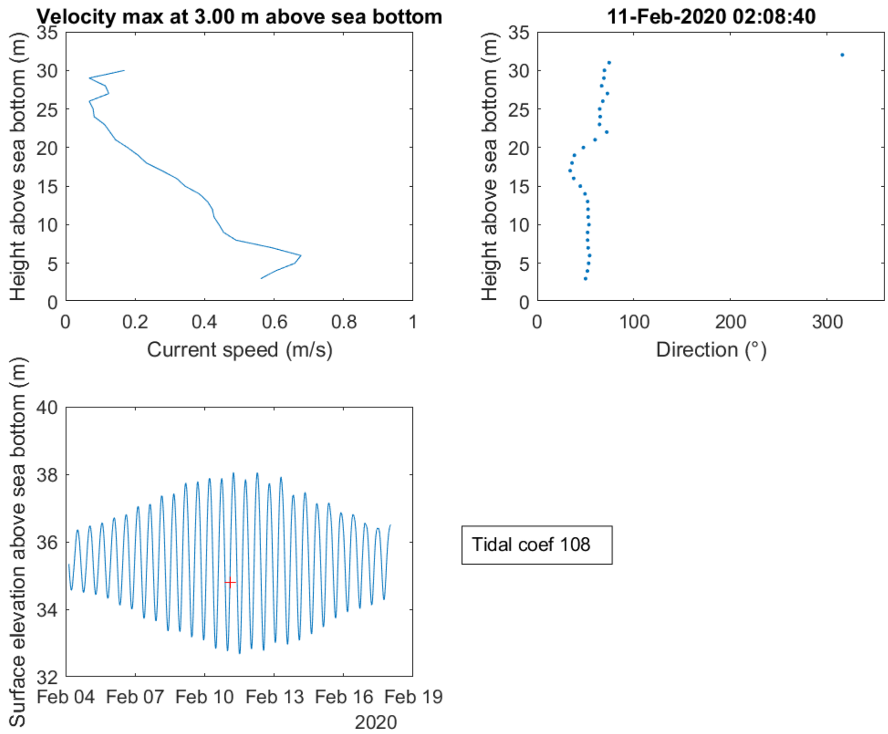


FIGURE 48: EXAMPLE OF VELOCITY PROFILE AND DIRECTION CORRESPONDING TO A MAXIMUM OF VELOCITY MEASURED AT 3 M ABOVE SEA BOTTOM. THE TIDAL COEFFICIENT AND TIME WHERE THE MAX IS OBSERVED IN TIDAL CYCLE IS ALSO INDICATED (RED CROSS)

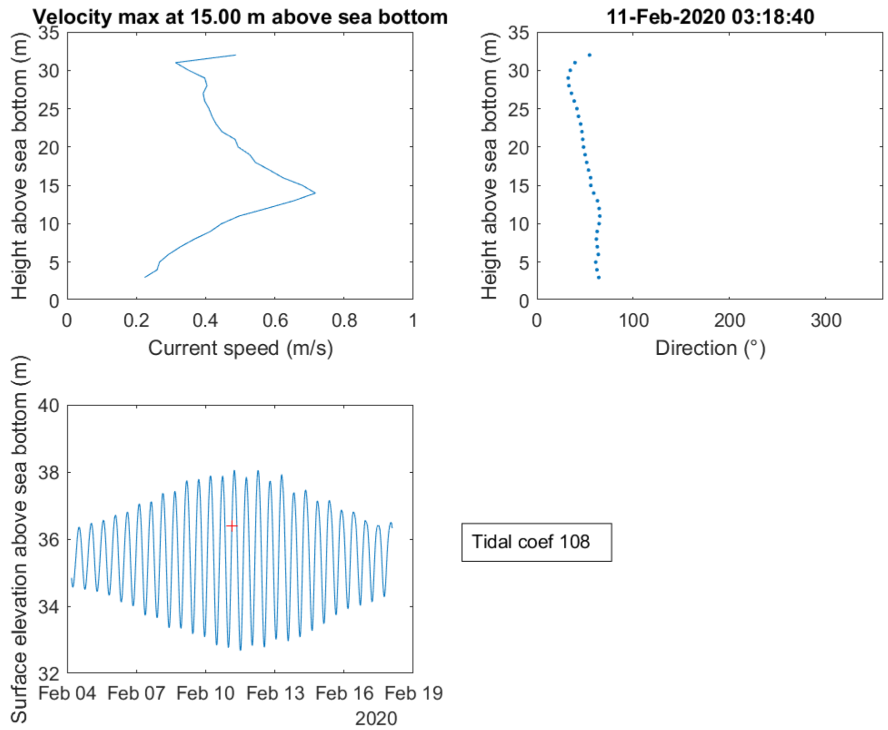


FIGURE 49: EXAMPLE OF VELOCITY PROFILE AND DIRECTION CORRESPONDING TO A MAXIMUM OF VELOCITY MEASURED AT 15 M ABOVE SEA BOTTOM. THE TIDAL COEFFICIENT AND TIME WHERE THE MAX IS OBSERVED IN TIDAL CYCLE IS ALSO INDICATED (RED CROSS)

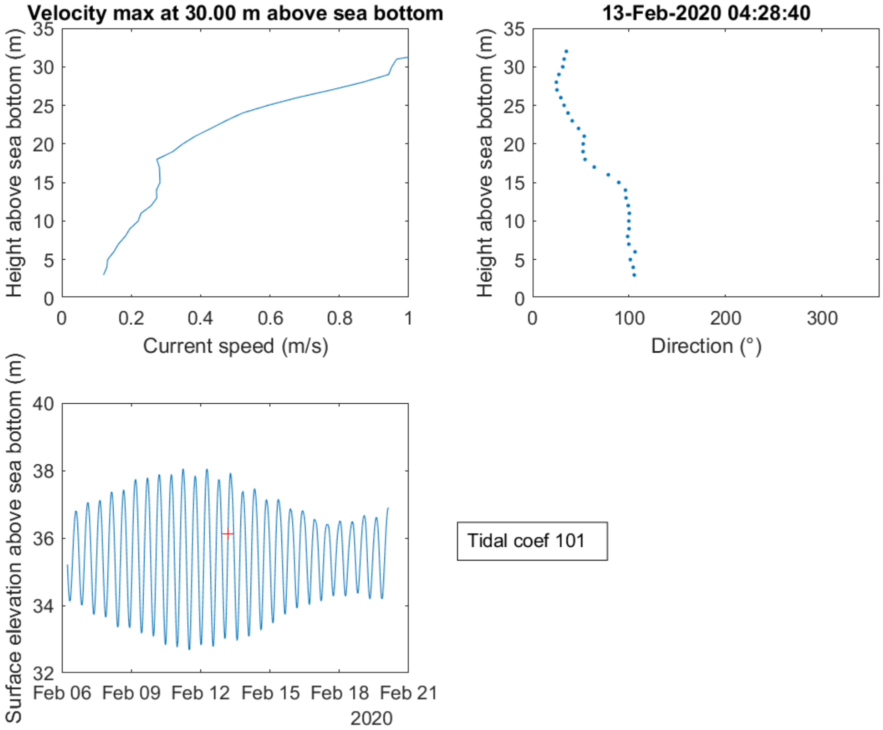


FIGURE 50: EXAMPLE OF VELOCITY PROFILE AND DIRECTION CORRESPONDING TO A MAXIMUM OF VELOCITY MEASURED AT 30 M ABOVE SEA BOTTOM. THE TIDAL COEFFICIENT AND TIME WHERE THE MAX IS OBSERVED IN TIDAL CYCLE IS ALSO INDICATED (RED CROSS)

6.3 CORRELATION

In order to compare the measurements with the outputs of the Previmer model (barotropic), the measured values for each 10 minutes period shall be averaged over the entire water column. The selected calculation methods consists in averaging the velocity vectors (barycentre). Applying this method avoids loosing physical meaning, induced for instance in the case of a “basic” averaging of the velocity modules where different directions are added together.
Table 31 summarises the main mathematical estimators characterising this comparison for 7 measurement campaigns between 2010 and 2014.

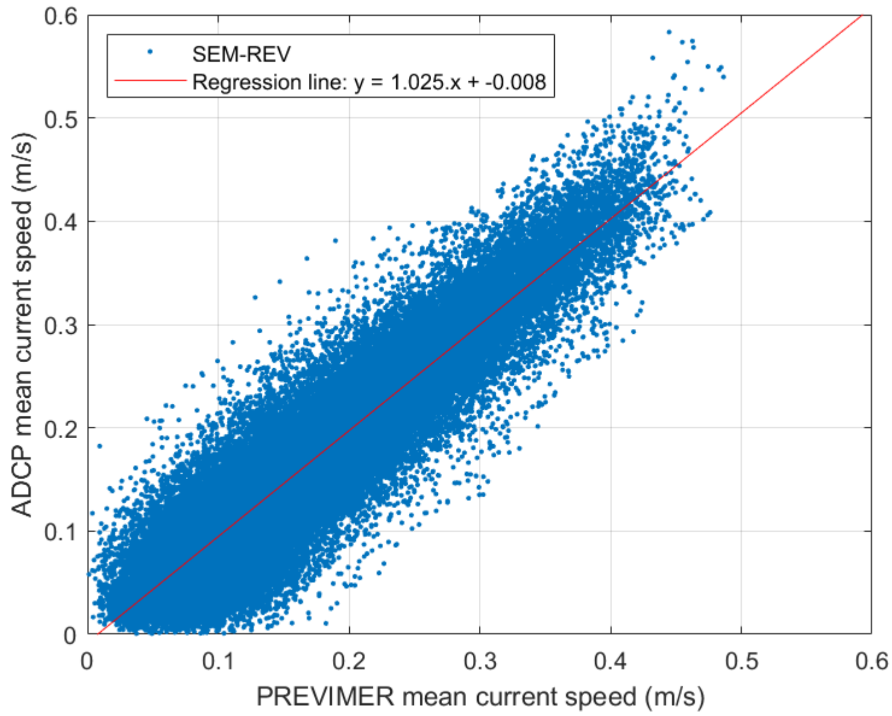


FIGURE 51: LINEAR REGRESSION BETWEEN ADCP MEASUREMENTS (7 CAMPAIGNS FROM 2010 TO 2014) AND PREVIMER ESTIMATES

	S.I	NRMSE	Bias	Correlation
U mean (m)	0.194	0.195	0.019	0.920
Θ mean (°)	0.311	0.315	-0.057	0.825

TABLE 31: CORRELATION AND ERROR STATISTICS BETWEEN ADCP MEASUREMENTS AND PREVIMER MODEL

6.4 OPERATIONNAL STATISTICS

The statistics are issued from both measurements and a numerical model Model (MARS 2D (Model for Applications at Regional Scale) hydrodynamic model, based on the shallow water equations and developed at IFREMER. The model was validated and compared to measurements.

Figure 52 shows the mean current velocity distribution (m/s) discretised by 15º-wide angular sectors. The main direction of the current is SW and NE to a lesser extent. The tidal streams could be considered as barotropic if the directions of the different layers are close to each other. Site measurements showed that the directions can be almost at the opposite through the water column. However the opposite direction is generally negligible, in terms of velocity amplitude and compared to the main direction when considering the S-W & N-E directional sectors. The velocities range essentially from 0m/s to 0.4m/s. The strongest currents are coming from S-W (225°-240°).

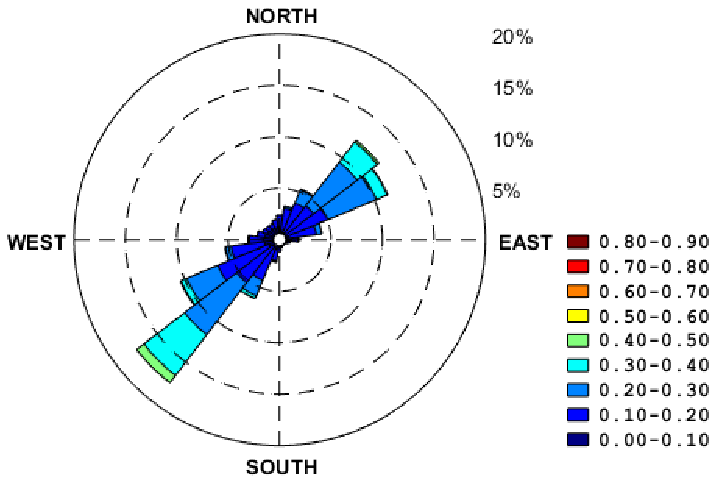


FIGURE 52: CURRENT VELOCITY (BAROTROPIC) DISTRIBUTION (PREVIMER, 2006-2013). CONVENTION: “CURRENT IS COMING FROM”

Scatter table is presented in Table 32 and profiles issued from measurements analysis presented in section 6.2.2 can be associated to this table.

Current U (m/s)	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°	Omni
0 <= U < 0.1	1.12	0.92	0.72	0.61	0.62	0.88	0.89	0.74	0.64	0.58	0.59	0.65	0.78	0.88	0.93	0.84	1.13	1.48	1.53	1.43	1.31	1.27	1.23	1.24	**23.02**
0.1 <= U < 0.2	1.24	2.17	3.15	3.53	4.45	2.71	0.87	0.28	0.12	0.07	0.08	0.13	0.36	1.19	3.34	4.40	5.38	3.27	1.41	0.76	0.50	0.44	0.48	0.72	**41.03**
0.2 <= U < 0.3	0.05	0.19	1.36	5.35	5.10	0.54	0.07	0.01	0.01	0.00	0.00	0.01	0.03	0.13	1.63	6.39	3.27	0.54	0.13	0.04	0.01	0.01	0.01	0.02	**24.91**
0.3 <= U < 0.4	0.00	0.00	0.11	2.47	1.14	0.02	0.01					0.00	0.00	0.02	0.31	4.99	0.60	0.07	0.01						**9.76**
0.4 <= U < 0.5		0.00	0.01	0.22	0.05	0.00								0.00	0.02	0.89	0.08	0.00							**1.27**
0.5 <= U < 0.6			0.00		0.00											0.01	0.00								**0.01**
0.6 <= U < 0.7																									
0.7 <= U < 0.8																									
0.8 <= U < 0.9																									
0.9 <= U < 1																									
Total (%)	**2.40**	**3.29**	**5.34**	**12.18**	**11.37**	**4.15**	**1.85**	**1.03**	**0.77**	**0.65**	**0.67**	**0.79**	**1.17**	**2.22**	**6.23**	**17.52**	**10.46**	**5.37**	**3.09**	**2.23**	**1.82**	**1.72**	**1.72**	**1.98**	**100.00**
Mean (m/s)	0.11	0.13	0.17	0.23	0.21	0.14	0.11	0.08	0.07	0.07	0.07	0.07	0.09	0.12	0.17	0.25	0.18	0.13	0.11	0.09	0.09	0.08	0.09	0.09	**0.18**
Max (m/s)	**0.31**	**0.42**	**0.50**	**0.50**	**0.50**	**0.40**	**0.36**	**0.30**	**0.30**	**0.26**	**0.26**	**0.30**	**0.39**	**0.40**	**0.47**	**0.56**	**0.57**	**0.46**	**0.38**	**0.29**	**0.25**	**0.24**	**0.23**	**0.27**	**0.57**

TABLE 32: ANNUAL DIRECTION OF SAMPLE DISTRIBUTION (%) OF MEAN CURRENT VELOCITY ON THE WATER COLUMN (PREVIMER, 2006-2013)

6.5 LONG TERM STATISTICS

The correlation of the Pareto distribution to the Previmer hindcast data is presented in Figure 53. (POT extrapolation with threshold set to 0.46 m/s).The statistical fitted distribution predicts for instance a 15-minutes mean current velocity of 0.55 m/s for a 10 years return period and 0.60 m/s for a 50 years return period, when the empirical maximum current velocity reached 0.49 m/s for this 8-year Previmer dataset and 0.58 m/s for the 24 campaigns of measurements, equivalent to 3.2 years of continuous measurements.

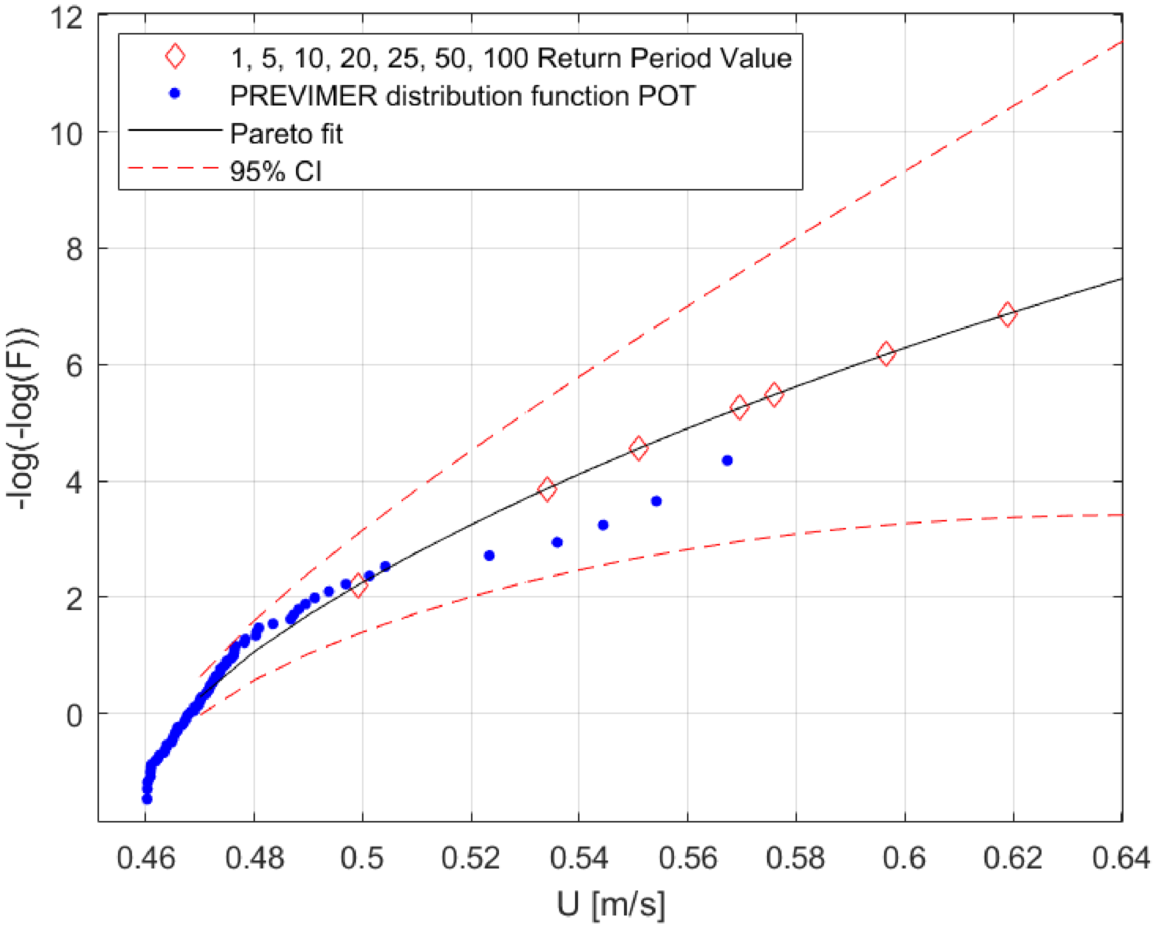


FIGURE 53 POT APPLIED TO VELOCITY VALUES (PREVIMER) FOR A 0.54M/S THRESHOLD. STATISTICAL DISTRIBUTION, PARETO FITTING, 95% CONFIDENCE INTERVAL AND REPRESENTATIVE RETURN VALUES. ALL DIRECTIONS INCLUDED

Values corresponding to return periods are presented in Table 33 and profiles issued from measurements analysis presented in section 6.2.2 can be associated to this table.

	Direction	*Proportion*	*Threshold*	*Vm max*	*Return periods (years)*					
	(°)	(%)	(m/s)	(m/s)	1	5	10	25	50	100
Total	All	100	0.46	0.58	0.50	0.53	0.55	0.58	0.60	0.62

TABLE 33 VMEAN (15-MINUTES, ALL DIRECTIONS) FOR THE RETURN PERIODS 1, 5, 10, 25, 50, 100 YEARS

7. MARINE GROWTH

7.1 MEASUREMENTS

The methodology to evaluate marine growth thickness is based on experimental measurements performed on

- SEM-REV mooring lines at full scale after 21 months of immersion
- SEM-REV dynamic cable at full scale after 21 months of exploitation
- Mooring lines of special marks which delimits SEM-REV test site

Date	Duration of immersion	Entity who performed measurements	Location	Structure analysed	Way of inspection
2018-2020	21 months	ECN	SEM-REV site	Dynamic electrical cable (Ø $110\ mm$) Chains Nylon rope	ROV survey (visual inspection)
2017-2019	3 times 1 year of immersion	ECN	SEM-REV site	Chains: mooring lines of special marks (buoys with keel)	Visual inspection, samples, measurements

TABLE 34: MARINE GROWTH MEASUREMENTS CAMPAIGN DETAILS

7.1.1 DESCRIPTION OF CHAINS (FULL SCALE)

The parts in chains of three mooring lines at full scale and in various directions are analysed.
There are two parts of chains:

- Between 3 and 15 m depth
- Between 30 and 36 m depth (and on the sea bottom), connected to anchors

7.1.2 DESCRIPTION OF NYLON ROPE

As for chains, the nylon section of three mooring lines at full scale and in various directions are analysed.

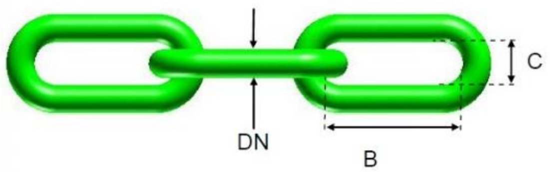
- Between 3 and 30 m depth

7.1.3 DESCRIPTION OF DYNAMIC CABLE

The dynamic electrical cable is 110 mm diameter and is going from sea surface to sea bottom.

7.1.4 DESCRIPTION OF MOORING LINES OF SPECIAL MARKS

Several sections of chains are used for the mooring lines of special marks. Chains are DN30 and DN35 defined by:



Chain type	DN30	DN35
DN	30 mm	35 mm
B	150 mm	175 mm
C	45 mm	52.5 mm

FIGURE 54: DESCRIPTION OF CHAINS USED ON SPECIAL MARKS MOORING.

Attention is raised on the fact that mooring lines of special marks are cleaned every year for maintenance. Hence, no data are available on more than two consecutive years.

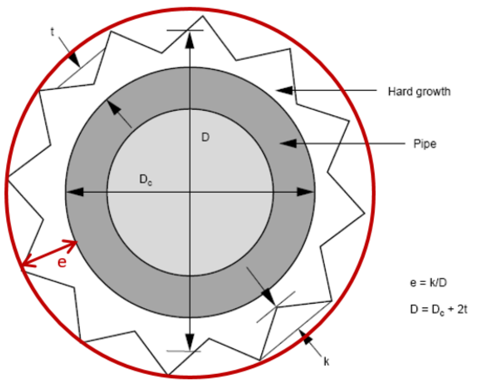
7.2 RECOMMENDED PRACTICES

For reference and as presented in Table 35, Norsok [9] provides references to consider marine growth in North Atlantic and provides data on roughness, wheight of marine growth and density.

Depth (m)	Thickness (mm)	Roughness (mm)	Weight in air (kg/m^2)	Weight in water (kg/m^2)	Density (t/m^3)
Between + 2 m and -40 m	100	20	133	30	1.33
Below -40	50	20	66	15	1.33

TABLE 35: RECOMMANDED PRACTICE FOR MARINE GROWTH (DNV-RP-C205. STANDARD API SPECIFICATION 17E. STANDARD NORSOK N-003).

The various parameters are illustrated below from API [11], the marine growth thickness as measured on SEM-REV is “e” and refers to a maximum:



Name	Description
Dc	Pipe diameter
t	Marine growth thickness (average)
e	Maximum marine growth thickness (SEM-REV measurements)
k	Roughness
D	Effective diameter (taking into account marine growth D=Dc+2.t

FIGURE 55 : DESCRIPTION OF PARAMETERS RELATIVE TO MARINE GROWTH THICKNESS IN STRUCTURE DESIGN [11]

These values are used to be compared to SEMREV results as presented below for weight and density of marine growth on special marks measurements. The values proposed by standards for weight and density are conservative and representative of SEM-REV site.

Thickness of marine growth is detailed in section 7.4 for the structures presented in section 7.1.

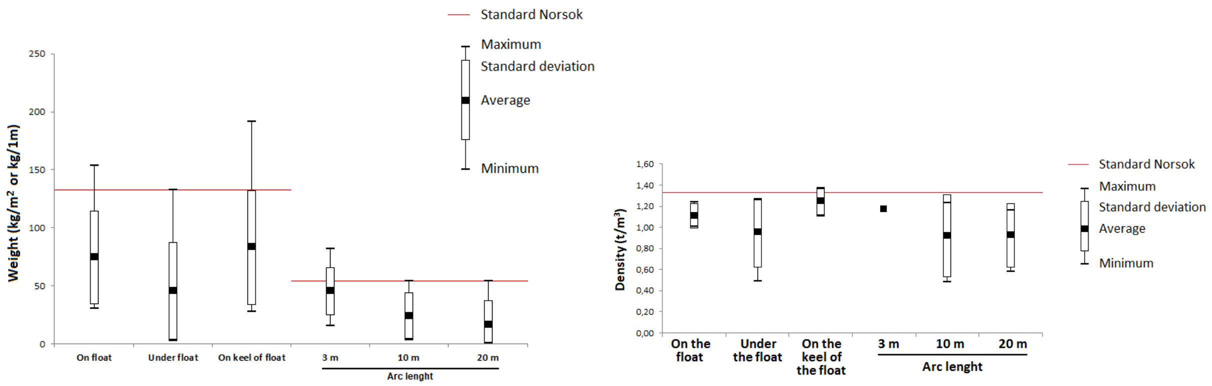


FIGURE 56: LEFT: WEIGHT OF MARINE GROWTH IN AIR (ON THE FLOAT AND ALONG THE MOORING LINE (ARC LENGTH)), RIGHT: DENSITY OF MARINE GROWTH ON SPECIAL MARKS OF MOORING CHAINS

7.3 SPECIES

On the analysis, marine growth was splitted in two classes:

- Soft biofouling corresponds the following species and biological groups: Hydrozoans (Hydrozoa), Actiniarian (sea anemones), Alcyoniidae (soft corals) and Tunicates.
- Hard biofouling corresponds the following species and biological groups: mussels (Mytilus edulis), cirripede (barnacles) and annelids tubeworms.

7.4 MARINE GROWTH THICKNESS

7.4.1 MARINE GROWTH THICKNESS ON CHAINS (FULL SCALE)

On chains, the maximum thickness of marine growth are averaged every 3 meters. The maximum is equal to 150 mm with a surface coverage rate varying from 59 to 100%.
The marine growth thickness as defined in standards Norsok [9] is displayed as a blue line.

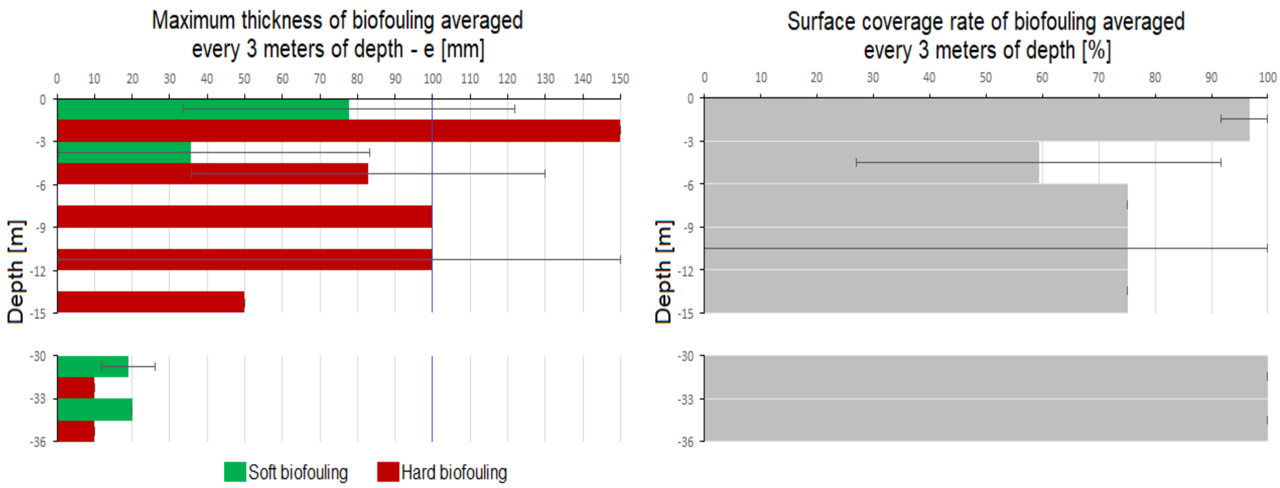


FIGURE 57: MARINE GROWTH MAXIMUM THICKNESS ON CHAINS (FULL SCALE). BLUE LINE: NORSOK STANDARD, ERROR BARS: STANDARD DEVIATION

7.4.2 MARINE GROWTH THICKNESS ON NYLON (FULL SCALE)

On nylon, the maximum thickness of marine growth, averaged every 3 meters, is 80 mm with surface coverage rate varying from 34 to 63%.

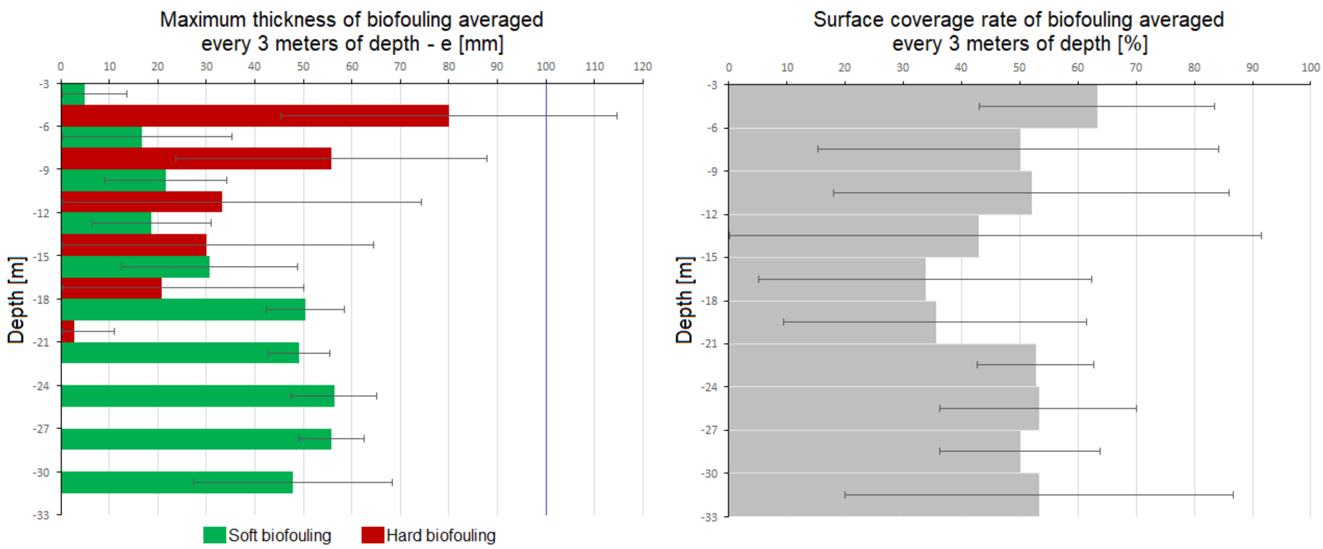


FIGURE 58: MARINE GROWTH MAXIMUM THICKNESS ON NYLON (FULL SCALE). BLUE LINE: NORSOK STANDARD, ERROR BARS: STANDARD DEVIATION

7.4.3 MARINE GROWTH ON DYNAMIC CABLE (FULL SCALE)

On the dynamic electrical cable, the maximum thickness of marine growth, averaged every 3 meters, is 110 mm with surface coverage rate varying from 16 to 100 %.

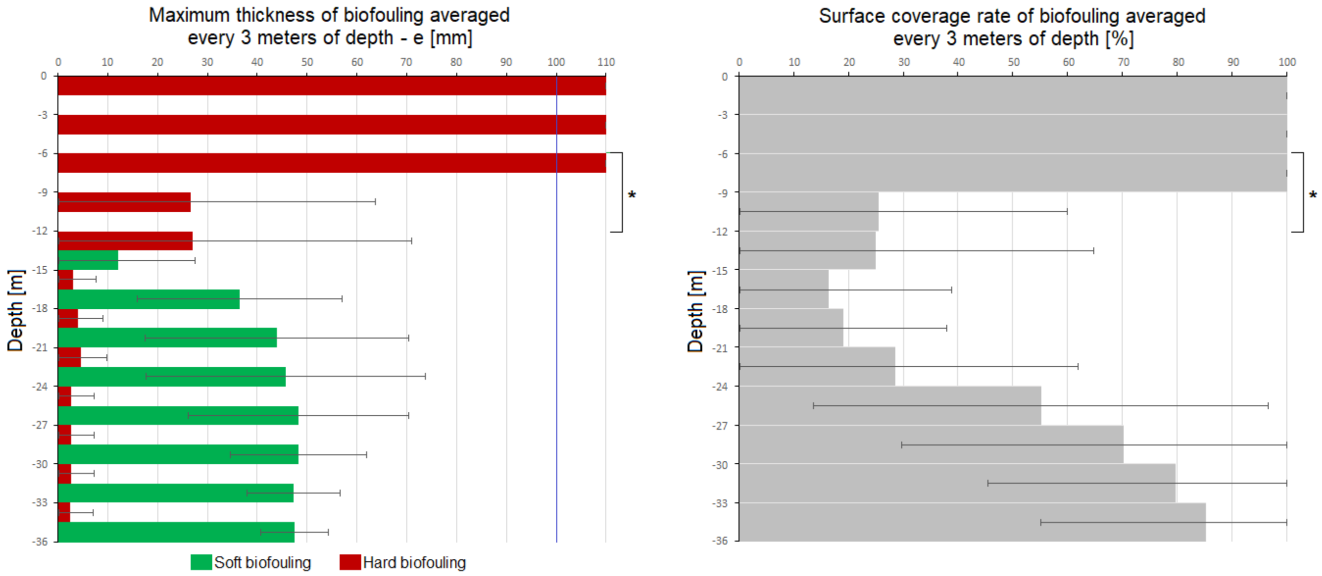


FIGURE 59: MARINE GROWTH MAXIMUM THICKNESS ON DYNAMIC CABLE (FULL SCALE). BLUE LINE: NORSOK STANDARD, ERROR BARS: STANDARD DEVIATION

7.4.4 MARINE GROWTH THICKNESS ON CHAINS OF MOORING LINES OF SPECIAL MARKS (SMALL SCALE)

On chains of mooring lines of special marks, the average maximum thickness of marine growth is 130 mm between 1 and 2 m depth.

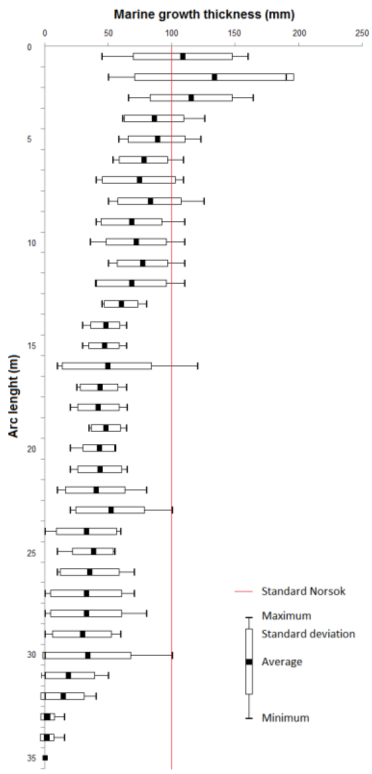


FIGURE 60: MARINE GROWTH THICKNESS ON MOORING LINES OF SPECIAL MARKS (SMALL SCALE). RED LINE: NORSOK STANDARD, ERROR BARS: STANDARD DEVIATION, MAX AND MIN

8. OTHER ENVIRONMENTAL CONDITIONS

8.1 NORMAL AND EXTREME AIR TEMPERATURE RANGES

The air temperature measured during wind measurement campaign at Cardinaux lighthouse (2016-2018) is presented below. The minimum recorded during this period is -5°C and the maximum is 29.6 °C. The correlation with ERA5 modeled temperature is also presented below. It shows a good correlation but deviation are observed for highest and lowest temperature with an underestimation of the model for absolute extreme values.

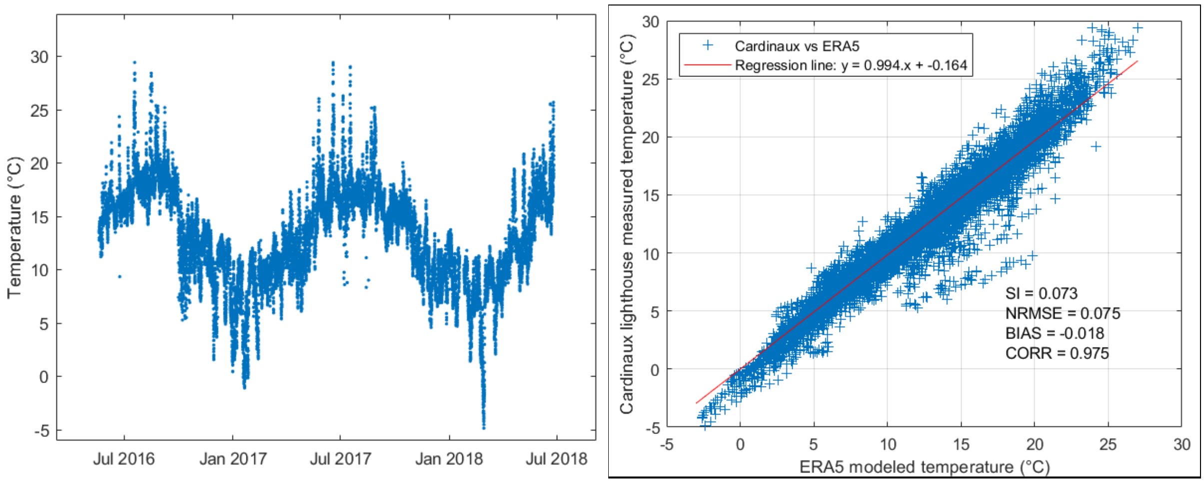


FIGURE 61: LEFT: AIR TEMPERATURE MEASUREMENTS DURING WIND MEASUREMENTS CAMPAIGN AT CARDINAUX LIGHTHOUSE (2016-2018). RIGHT: CORRELATION WITH ERA5 MODEL

Temperature modelled by ERA5 on SEMREV site between 1979 and 2019 is presented on the figure below.

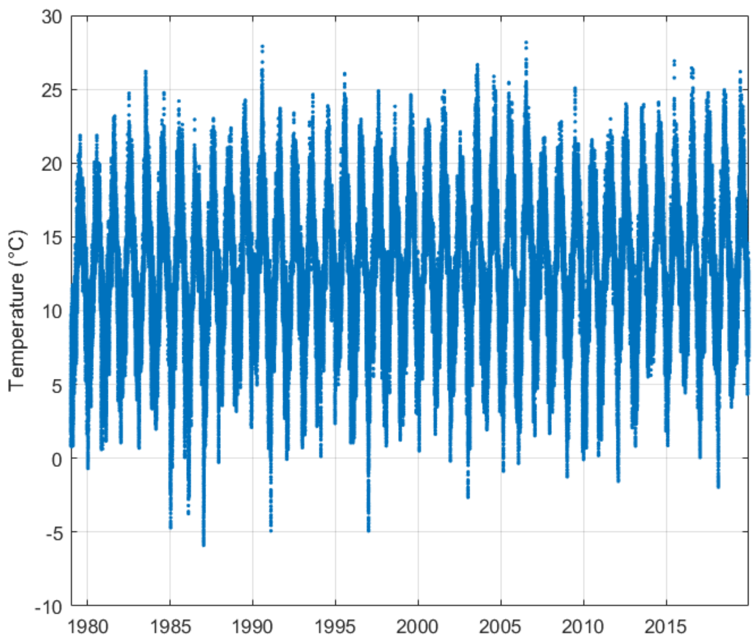


FIGURE 62: TEMPERATURE MODELLED BY ERA5 ON SEMREV (1979-2019)

	Maximum modelled (°C) (1979-2019)	Mean Temp (°C)	Min modelled (°C) (1979-2019)
SEM-REV (44)	28.2	12.9	-5.9

TABLE 36: MEAN, MIN AND MAX TEMPERATURE MODELLED ON SEM-REV BY ERA5

Statistical data are also available on longer terms from Meteo France onshore [49] in Belle Ile (56) and Saint-Nazaire (44) and are summarized below:

	Maximum recorded (°C) (01/07/1957-02/05/2021)	Max Temp (Mean in °C)	Mean Temp (Mean in °C)	Min Temp (Mean in °C)	Min recorded (°C) (01/07/1957-02/05/2021)
Belle Ile (56)	34.8	15.2	12.7	10.2	-10
St Nazaire (44)	38.4	16.6	12.4	8.1	-13.6

TABLE 37: YEARLY STATISTICS OF TEMPERATURE AND MAX AND MIN RECORDED

	Tx>=30°C	Tx>=25°C	Tx<=0°C	Tn<=0°C	Tn<=-5°C	Tn<=-10°C
Belle Ile (56)	0.9	10.7	0.4	7.0	0.4	0
St Nazaire (44)	8.5	39.2	1.3	32.2	3.8	0.3

TABLE 38: MEAN NUMBER OF DAYS WITH TN : MINIMAL TEMPERATURE AND TX: MAXIMAL TEMPERATURE ABOVE OR BELOW GIVEN CRITERIA

8.2 AIR DENSITY

The air density value should be considered as specified by [4] section 6.4.2, i.e Air density=1.225 kg.m^{-3} in normal environmental conditions with ambient temperature range of -10°C to +40°C.
For information, the air density on site can be calculated by:

$$\boldsymbol{Density} = \frac{\boldsymbol{P}}{\boldsymbol{R.T}} \tag{9}$$

With P: atmospherical pressure 101325 Pa
R: gas constant = 287 J/(kg.K)
T : Temperature in Kelvin

Based on 41 years database of ERA5 temperature and mean sea level pressure, the air density is computed from equation 9. The mean density is presented in the table below for all months and wind speed intervals. Minimum and maximum (single) values computed by months (over 41 years) or by wind speed intervals are also provided.

Wind (m/s)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean	Min	Max
<2	1.274	1.272	1.264	1.247	1.232	1.224	1.217	1.216	1.223	1.234	1.251	1.268	1.239	1.175	1.333
2 <= U < 4	1.276	1.272	1.263	1.247	1.234	1.226	1.218	1.217	1.224	1.234	1.251	1.270	1.239	1.174	1.337
4 <= U < 6	1.273	1.272	1.262	1.247	1.235	1.227	1.219	1.218	1.225	1.234	1.251	1.268	1.240	1.173	1.338
6 <= U < 8	1.270	1.270	1.260	1.248	1.236	1.227	1.219	1.218	1.224	1.233	1.248	1.264	1.240	1.176	1.332
8 <= U < 10	1.267	1.267	1.257	1.247	1.236	1.225	1.218	1.216	1.223	1.230	1.245	1.261	1.241	1.173	1.328
10 <= U < 12	1.261	1.261	1.252	1.244	1.234	1.223	1.216	1.214	1.219	1.227	1.243	1.256	1.240	1.178	1.331
12 <= U < 14	1.252	1.253	1.247	1.240	1.232	1.222	1.214	1.210	1.215	1.221	1.238	1.247	1.238	1.168	1.324
14 <= U < 16	1.246	1.246	1.242	1.236	1.228	1.222	1.211	1.207	1.210	1.216	1.229	1.239	1.234	1.178	1.326
16 <= U < 18	1.239	1.239	1.238	1.234	1.225	1.223	1.209	1.203	1.206	1.213	1.224	1.234	1.231	1.175	1.313
18 <= U < 20	1.235	1.236	1.233	1.232	1.220	1.216	1.206	1.199	1.200	1.211	1.219	1.230	1.229	1.180	1.313
20 <= U < 22	1.230	1.232	1.230	1.224	1.214	1.214	1.207	1.198	1.194	1.209	1.215	1.224	1.225	1.177	1.272
22 <= U < 24	1.226	1.227	1.227	1.222	1.212		1.209	1.195	1.193	1.198	1.211	1.221	1.221	1.172	1.252
24 <= U < 26	1.223	1.221	1.223	1.217	1.211				1.188	1.192	1.210	1.216	1.216	1.171	1.248
26 <= U < 28	1.223	1.225	1.224						1.182	1.194	1.210	1.215	1.212	1.172	1.243
28 <= U < 30	1.217	1.217	1.221						1.183	1.196	1.203	1.200	1.206	1.180	1.238
30 <= U		1.225								1.175		1.202	1.201	1.171	1.238
													All years		
Mean	1.262	1.263	1.255	1.245	1.235	1.226	1.218	1.217	1.222	1.229	1.243	1.256	1.239		
Min	1.196	1.186	1.200	1.202	1.195	1.173	1.168	1.177	1.177	1.171	1.180	1.175	1.168		
Max	1.338	1.331	1.311	1.293	1.279	1.265	1.249	1.253	1.263	1.291	1.310	1.322	1.338		

TABLE 39: MEAN AIR DENSITY VERSUS MONTHS AND WIND SPEED INTERVALS (WIND SPEED VALUES PROVIDED ON 1H AT 100 M)

8.3 HUMIDITY

The humidity measured during wind measurement campaign at Cardinaux lighthouse (2016-2018) is presented below. No filter is applied, which can explain when some data equals to zero (may be related to sensor availability) and are not continuous. The measured values are between 10 and 100%.

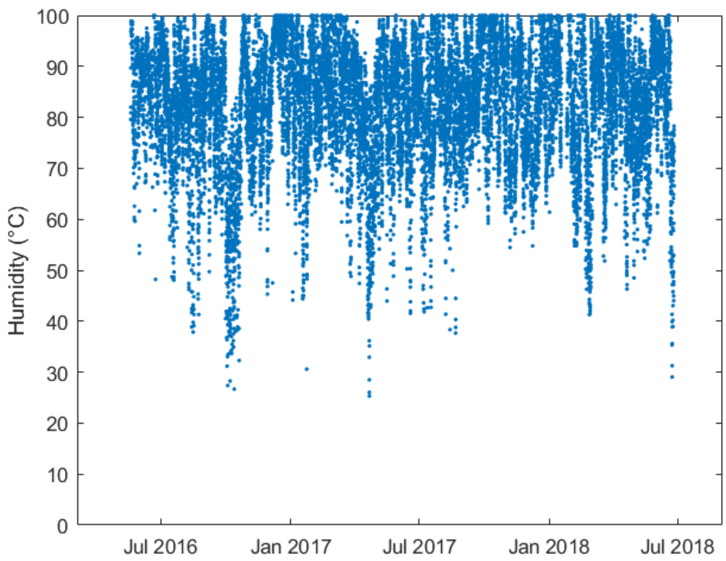


FIGURE 63: HUMIDITY MEASURED ON CARDINAUX LIGHTHOUSE (2016-2018)

8.4 NORMAL AND EXTREME SEA TEMPERATURE RANGES

Sea temperature measurements are available in Surval database maintained by Ifremer [50]. The results from the point 069-P-075 – Basse Michaud (coordinates 47.2292 -2.5833) during the period 2016-2021 show a temperature between 7 and 21°C in surface (0-1m) and between 8 and 18°C near the sea bottom (0-1m from the sea bottom).

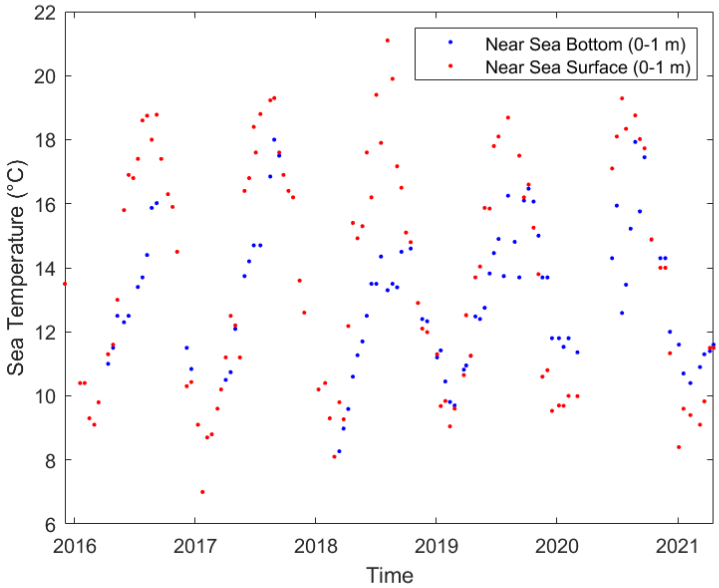


FIGURE 64: SEA TEMPERATURE NEAR THE SURFACE AND THE SEA BOTTOM (2016-2021) FROM SURVAL DATABASE

8.5 SEA ICE

The sea temperature presented in the previous section is between 7 °C and 21°C. It shows that there is no risk of sea ice formation on SEM-REV site.

8.6 SALINITY

Reference [8] proposes to use a value of water salinity of 3.5% which is coherent with measurements available in Surval database (see section 8.4).

8.7 WATER DENSITY

Reference [8] proposes to use a value of water density of 1025 kg/m^3.

10. APPENDIX

10.1 APPENDIX BATHYMETRY

10.1.1 BATHYMETRY TILES

The ETOPO1 Global Relief Model provides a 1 minute resolution bathymetric grid surrounding the SEMREV (available from the National Oceanic and Atmospheric Administration website, NOAA [15]).

The bathymetric information of the region may also be recovered from the maritime chart n°7395 issued by the French "Service Hydrographic de la Marine" (SHOM) [16]. The bathymetric data stemming from different campaigns (integrated into the SHOM's database [17]) provided roughly 200 measurement points over the SEMREV (depths included between 31.85m & 34.6m, Chart Datum). This data may be interpolated to produce, for instance, a 50m regular grid (Figure 65) used in wave propagation models.

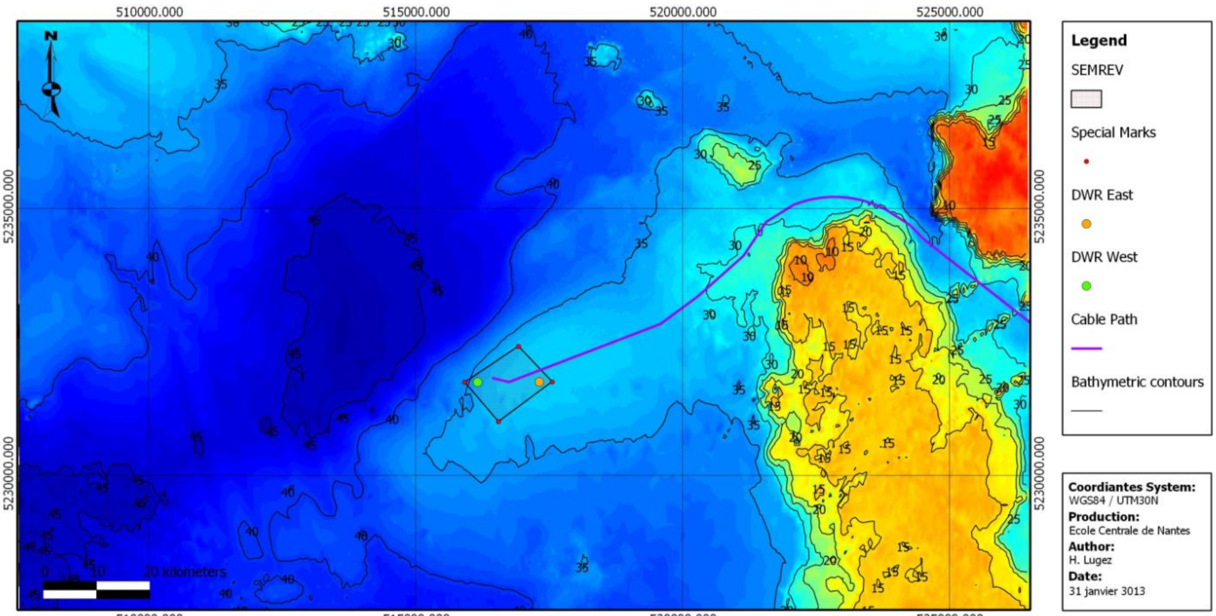


FIGURE 65 INTERPOLATION BASED ON THE LOCAL BATHYMETRIC DATA COLLECTED BY THE SHOM

10.1.2 SINGLE BEAM SURVEY (2010)

A two stages geophysical campaign was carried out by ASTERIE research department in the scope of the export cable layout study [18]. The first measurements occurred in 2008, whereas the second phase took place in October 2010. The RGF93 geodesic system was used for this study (with its IAG GRS 1980 associated ellipsoid) and the geographic coordinates have been projected with the NTF Lambert 1 Nord projection. A possible better suited projection for SEMREV Test Site would have been the NTF Lambert 2 Centered. Indeed it was used as a reference for the DGPS point and for the RTK GPS positioning system (Real time Kinematic leading to a centimetric precision). To take into account the errors produced by the swell and tide, the centimetric Magellan Proflex 500 GPS system have been used. The depth measurements (position and movement corrected) have been synchronized within the sounder (single beam echosounder Hydrotrac, Odom) before being logged by the HYPACK acquisition software.

The measurement of depth depends on the speed of sound in the water and therefore on the pressure, salinity and temperature. The information about the establishment of velocity profiles during the single beam survey is not available and the accuracy of the bathymetry achieved during this survey is questionable. The 3783 measurements obtained over the SEMREV (depths included between 32.13m and 35.57m C.D., Chart Datum) are plotted on Figure 66.

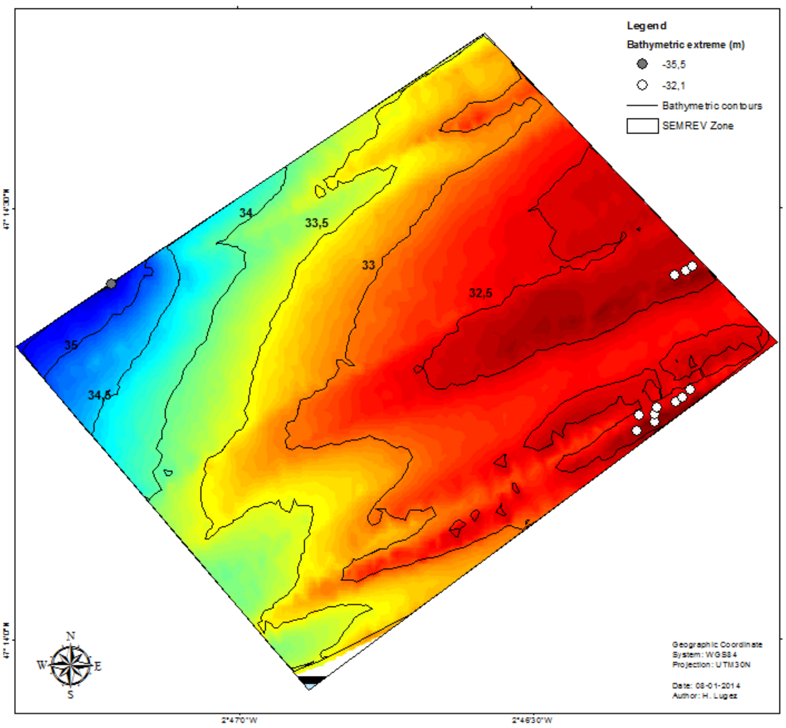


FIGURE 66 INTERPOLATION BASED ON THE LOCAL BATHYMETRIC DATA COLLECTED BY ASTERIE

10.2 GEOPHYSICS

A geophysical campaign was conducted by ASTERIE in October 2010. The campaign allowed identifying the nature and structure of sediments on the site. To determinate the sub-surface soil/rock and identify the seabed layers boundary (characterized by a discontinuity in the acoustic wave reflection), an ENERGOS 100 has been used (SIG France) coupled to a Sparker (electrode system as a seismic source) and a Streamer (composed by 6 hydrophones as seismic receiver). The prior knowledge of certain physical properties and the identification of the reflection allowed the determination of the sedimentary thickness. The system presents the following characteristics:

- Penetration: about 40m;
- Vertical resolution: about 0.5 m; Horizontal resolution: 40 to 60 cm;
- Frequency: 300 to 3000 Hz; Sample rate: 250 ms;

The thickness of unconsolidated sediments has been calculated by subtracting the depth of the top of the crystalline basement (R2) to the depth of the water/sediment (or rock) interface reflector (R1, corresponding to the seabed). The digitalization of the differences between the two reflectors (R1 and R2) is used to represent the sediment thickness present on site.

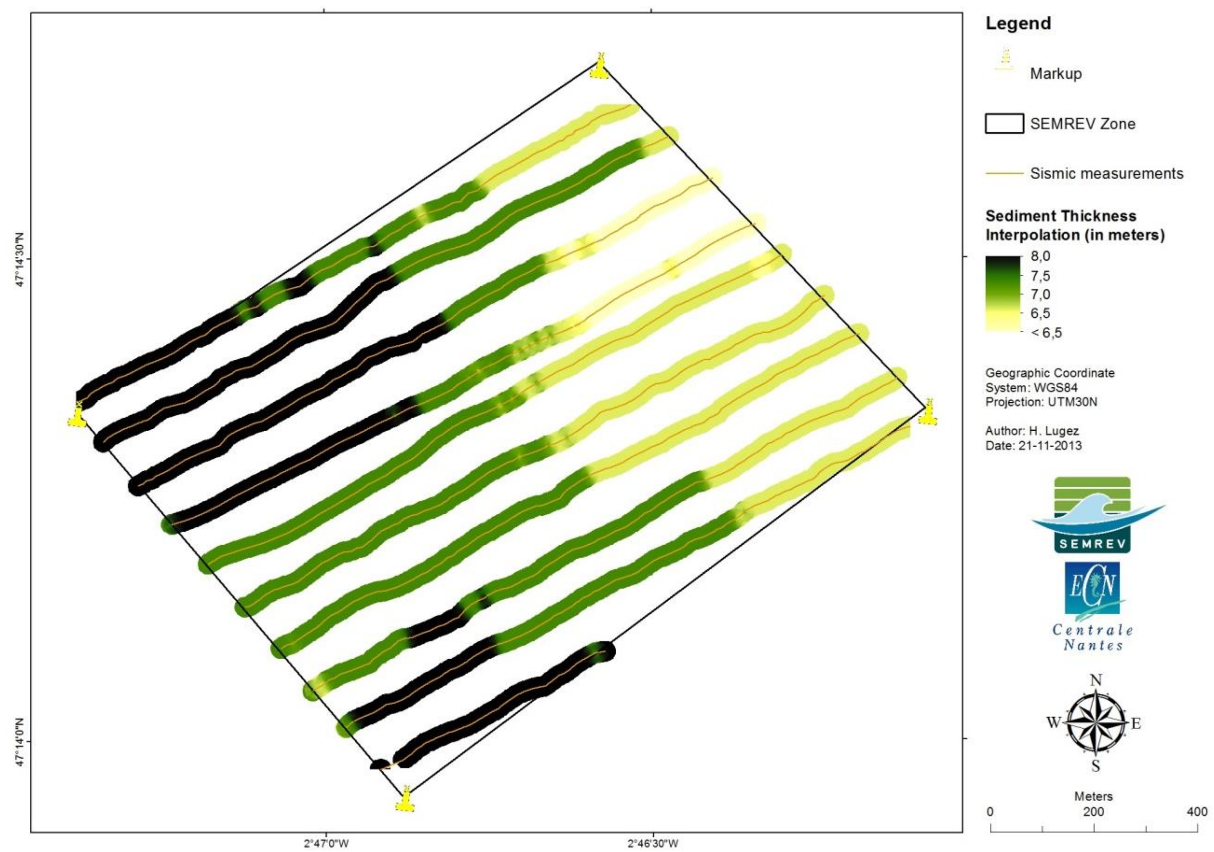


FIGURE 67: SEDIMENT THICKNESS ON THE SEMREV TEST SITE

A sedimentary layer of at least 5 m is scattered over the entire area. This sedimentary layer rests on a rocky layer flush in the east of the area and identified as a crystalline rock. The dataset available is not sufficient to interpret this substrate much further.

The available sparker data do not allow determining the thin stratigraphy of this sand layer. Due to the length of the sparker signature, a potential risk is the existence of local subsurface induration that cannot be identified. The superficial layer thickness is relatively homogeneous but the internal acoustic facies of this layer is not uniform (however little ambiguity exists) and there are some local stratifications (however rarely continuous). These variations of the acoustic facies certainly reflect a change in the composition of the surface sediment layer.

The limited number of profiles on the area prevents any improvement of the map thickness accuracy and isograds extrapolation. Surficial sediment layer matches the available coring data: fine to medium sand with a medium to coarse shelly sand at a depth of 5m. At coring point, the core analysis shows no interface.

10.3 GEOTECHNICS

10.3.1 VIBRO CORE SAMPLE

A geotechnical campaign was realized (IN VIVO, February 2012) including a detailed soil survey. It has led to 11 3m-Cone Penetration Tests (CPT) ***[20]*** and to one 6m Vibro Core Sample (CBT) ***[21]***.

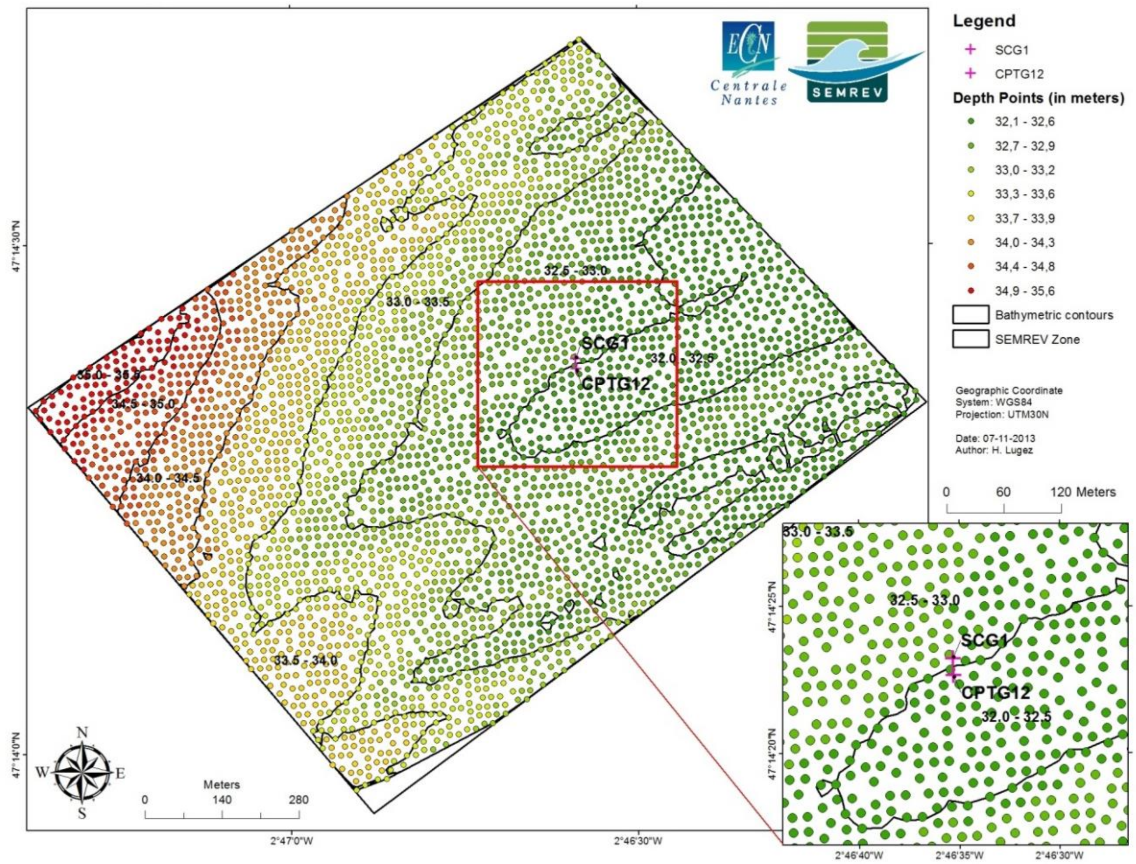


FIGURE 68 CORE SAMPLES LOCALISATION CPT/SCG ON SEMREV

The x, y, and z measurements precision varies between 0.2 and 0.3m (accuracy of the ship positioning system was 20 cm in the X,Y plane, water depth lecture was performed with a 0.1 m estimated accuracy echo-sounder, tide lecture on the tidal gauge (electronic acquisition) with a 0.2m estimated accuracy). Elevations point surveys are referring to Chart Datum and to St-Nazaire port.

The main characteristics of the Vibro Core Drill carried out at the centre of the site are presented in Table 40 and Figure 69.

Spatial coordinates UTM 30N		Sea-bed level	Reference level for sample	Date
X(m)	Y(m)	Z(CM)	(CM)	

516917.43	5231835.91	-32.98	-38.98	18/01/2012

TABLE 40 VIBRO CORE DRILL CARACTÉRISTICS AT SEMREV CENTRE

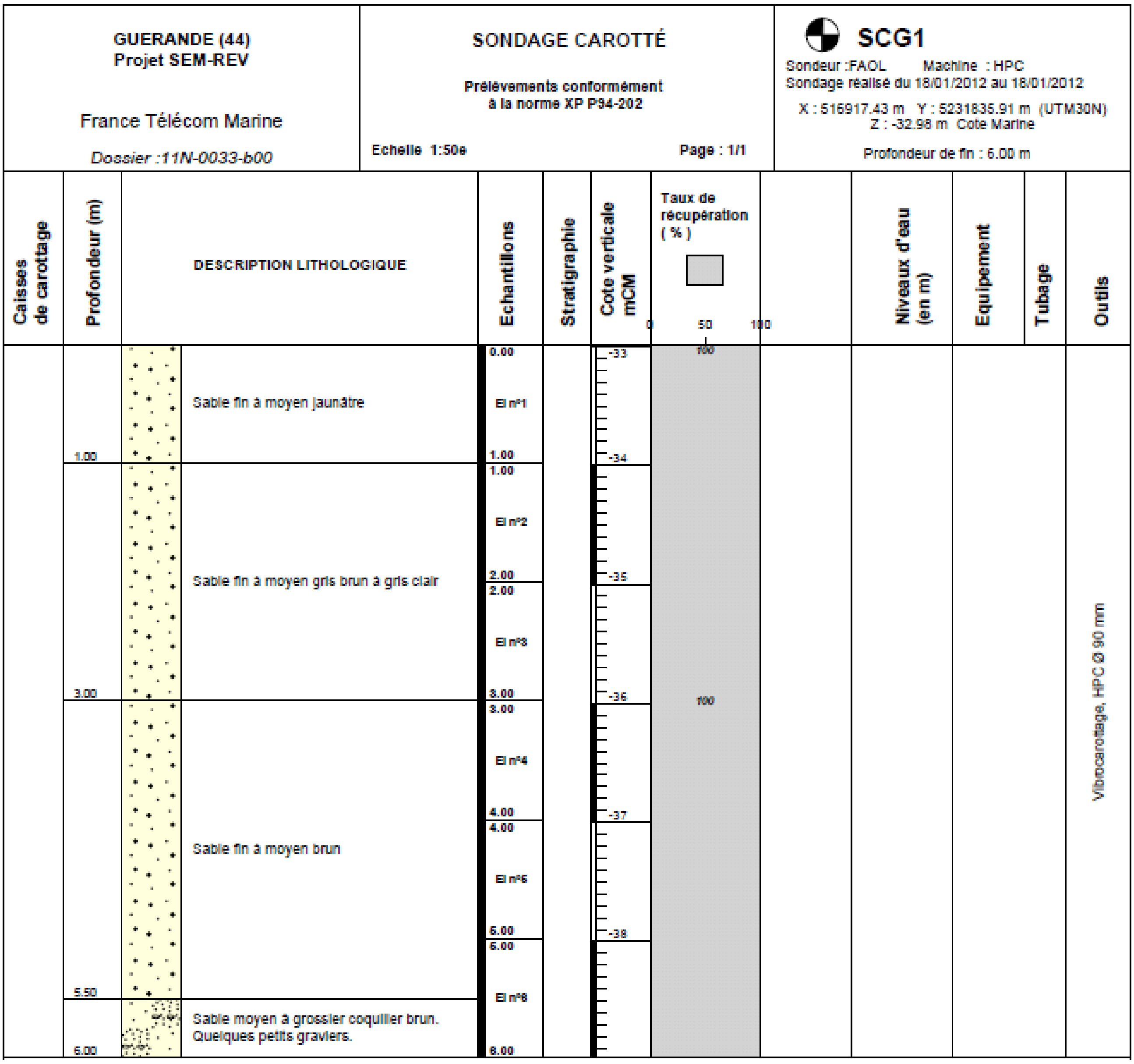


FIGURE 69 VIBRO CORE DRILL AT THE CENTRE OF THE SEMREV TEST SITE

10.3.2 CONE PENETRATION TEST

The water depths of the 3 bathymetric surveys closest to the core drilling (-32.98 m CD), range from -32,48m to -32,41m (items listed below). Whereas the depths of the 3 bathymetric surveys closest to the CPT (-30.95 m CD) vary from -32,62m to -32,48m. The difference in term of bathymetry is close to 1.5m between the two different campaigns. Both point separated from each other by 18m have a height difference of 2m.

TABLE 41 A) CPTG12 DEPTH = -30.95M CD

516914,42	5231823,93	32,48
516913,34	5231839,89	32,62
516929,84	5231833	32,52

B) SCG1 DEPTH = -32.98 M CD

516914,42	5231823,93	32,48
516907,53	5231807,43	32,44
516923,49	5231808,52	32,41

The main characteristics of the CPT ***[20]***, carried out at the centre of the site, are presented in Table 42 and Figure 70.

Sample number	Spatial coordinates UTM 30N		Sea-bed level	Depth reached
	X(m)	Y(m)	Z(CM)	m
CPTG12	516917.91	5231817.88	-30.95	4.08

TABLE 42 CPT CHARACTERISTICS AT THE CENTER OF SEMREV

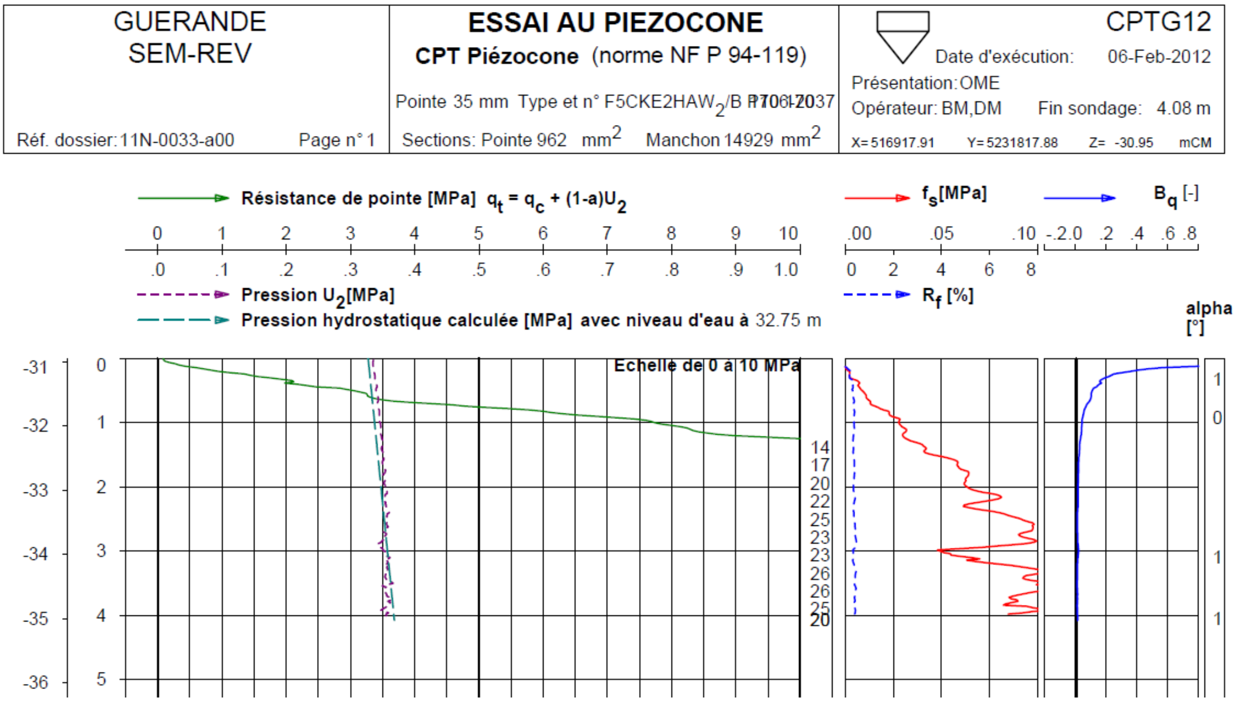


FIGURE 70 CONE PENETRATION TEST AT THE CENTRE OF THE SEMREV TEST SITE

10.3.3 LABORATORY RESULTS

Based on this geotechnical campaign, laboratory tests were performed on the samples in order to better characterize the sedimentary layers ***[22]***. The tests can be classified in two categories:

10.3.3.1 SOILS IDENTIFICATION:

- Granulometry

Particle Size Analysis example at 5.5m (Figure 71);

- Water contents (nature and consolidation of the sediments)

W=20,3% from 1 to 2m, W=20,7% from 3 to 4m, W=20,1% from 5 to 6m

- Density (γd, allows assessing the relative density)

ρ_{min} = 1358 kg/m^3 and ρ_{max} = 1594 kg/m^3 from 1 to 2m; ρ_{min} = 1317 kg/m^3 and ρ_{max} = 1558 kg/m^3 from 3 to 4m; ρ_{min} = 1395 kg/m^3 and ρ_{max} = 1642 kg/m^3 from 5 to 6m;

- Teneur en Carbonate de Calcium (CaCO3)

C_{ca} = 7% from 1 to 2m, C_{ca} = 9% from 3 to 4m, C_{ca} = 8% from 5 to 6m (%$CaCO_3$ < 10 %: non-calcareous)

- Methylene blue (indicates the clay contents in the sand).

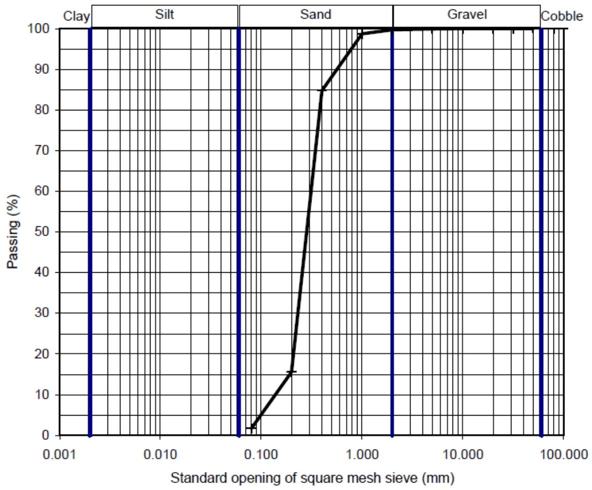
VBS = 0,05g at 1,5m, W = 0,05g at 3,5m, W = 0,15g at 5,5m (for 100g of sediment)

NF P 94-056

Project Informations		*Sample Informations*			
Project n° :	11N-0033c00	**Sampling type :**	BH	**Borehole n° :**	SCG1
Project :	GUERANDE - 44	**Sampling number :**	-	**Depth :**	5.50m
	Projet SEM-REV	**Conservation mode :**	EI	**Date :**	02/05/2012
		Identification number :	12P0116	**Dmax (mm) :**	10
	-	**Reception date :**	24/01/2012	**Tamis Dc :**	- (mm)
Client :	-	**Description :**	Sand fine to medium grey		

Results of sieving NF P 94-056

Sieve diameter mm	Passing % on 0/D	Passing % on 0/50mm
100		
80		
50		
31.5		
20		
10	100.0	100.0
5	99.9	99.9
2	99.7	99.7
1	98.7	98.7
0.400	84.8	84.8
0.200	15.6	15.6
0.080	1.7	1.7



Method of drying soils : ☑ *drying 105 °C* ☐ *drying 50 °C*

FIGURE 71 PARTICLE SIZE ANALYSIS AT 5.5M AT THE CENTRE OF SEMREV

10.3.3.2 MECHANICAL CHARACTERISTICS:

- Cone penetration resistance with a penetrometer (for dense sands)
- Drained triaxial trial (friction angle)
- Undrained triaxial test (cohesion).

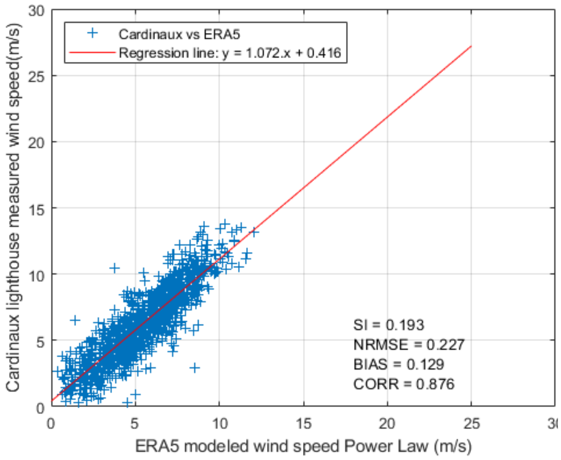
TEST TUBE N°	INITIAL CARACTERISTICS						
	H	ϕ	W	γ	γd	e	Sr
	mm	mm	%	kN/m^3	kN/m^3		%
1	70	35	24.1	19.61	15.81	0.71	92
2	70	35	24.6	19.51	15.66	0.72	92
3	70	35	23.5	19.60	15.86	0.70	91
4							
5							
6							

TEST TUBE N°	CARACTERISTICS AFTER CONSOLIDATION AND AT THE END OF THE TEST												
	γ s	Final W	ΔH_s	ΔV_s	Initial Volume	Saturation W	γ h	γ d	e	T100	σ'3c	Back Pressure	B
	kN/m3	%	cm	cm3	cm3	%	kN/m3	kN/m3		min	kPa	kPa	%
1	27.0	25.3	0.01	0.4	67.3	25.9	20.01	15.89	0.70	-	48	798	100
2	27.0	25.3	0.01	0.4	67.3	26.5	19.91	15.74	0.72	-	146	811	100
3	27.0	24.5	0.01	0.4	67.3	25.7	20.04	15.95	0.69	1.0	330	788	100
4													
5													
6													

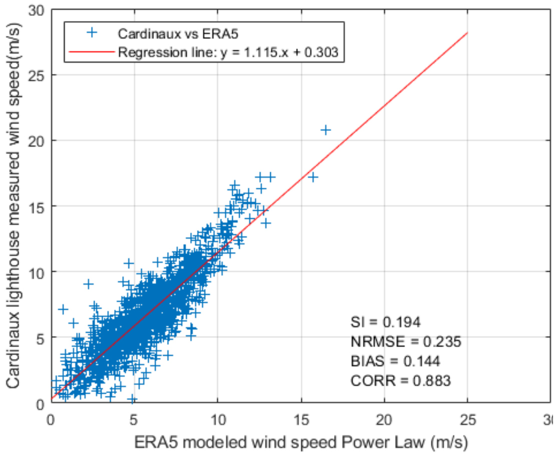
TEST TUBE N°	CRITERION 1 (σ1 - σ3)MAX				Rate
	(σ1-σ3)	U	T	Af	
	kPa	kPa	%	%	mm/mn
1	258.56	0.00	4.07	0.00	0.0085
2	629.71	0.00	3.71	0.00	0.0085
3	1166.49	0.00	4.69	0.00	0.0085
4					
5					
6					

FIGURE 72 DRAINED TRIAXIAL TRIAL RESULTS AT 5.5M AT THE CENTRE OF SEMREV

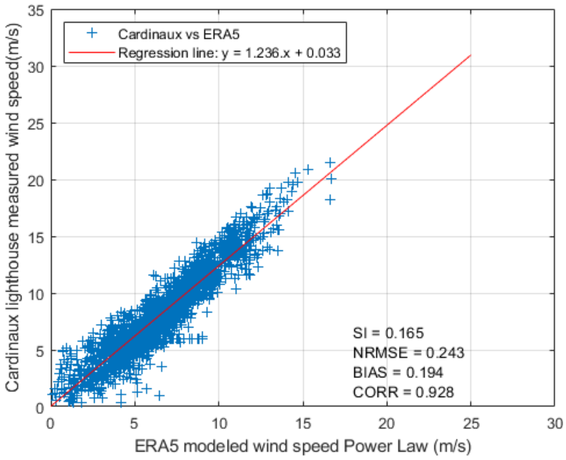
10.4 CORRELATION OF WIND SPEED (CARDINAUX MEASURES VS ERA5) BY DIRECTIONAL SECTORS



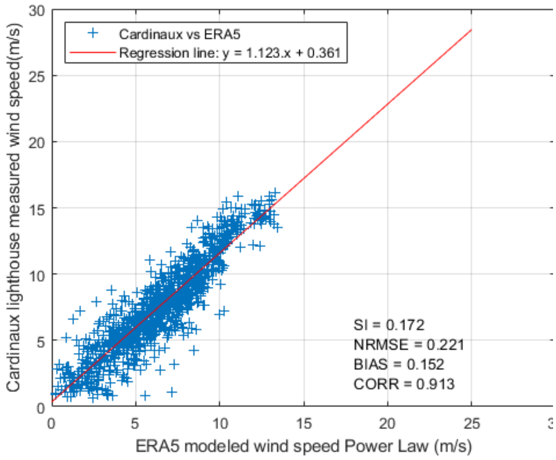
0° (North)



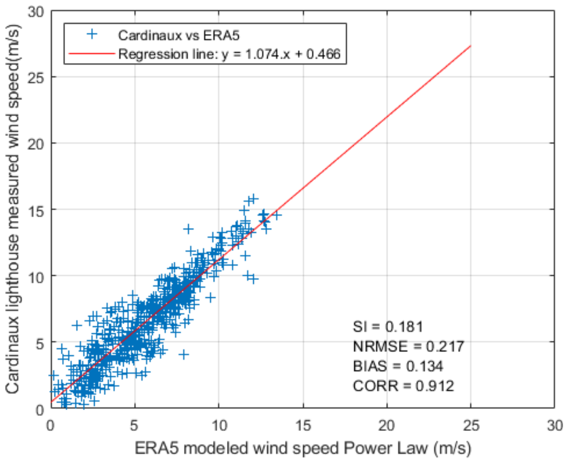
30°



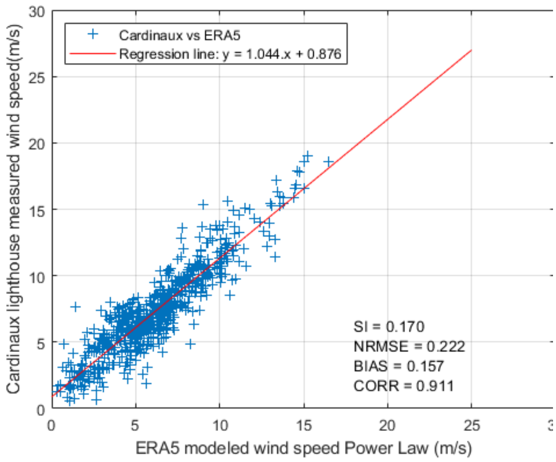
60°



90° (East)

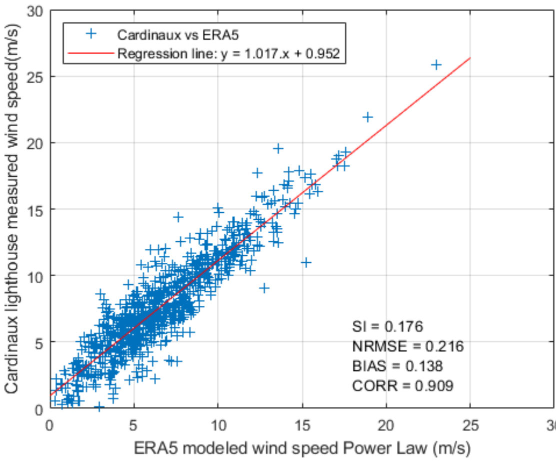


120°

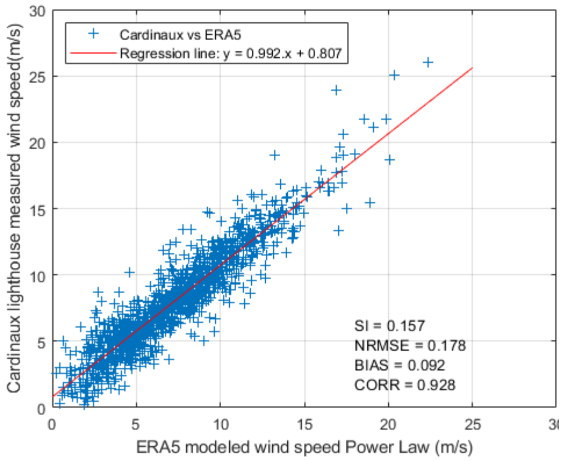


150°

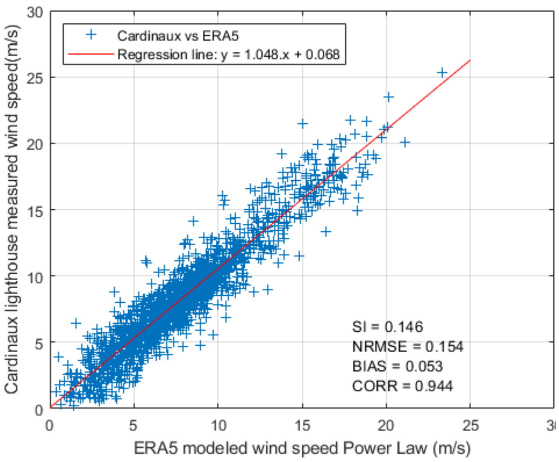
TABLE 43: CORRELATION OF WIND SPEED (CARDINAUX MEASURES VS ERA5) BY DIRECTIONAL SECTORS (0-150°)



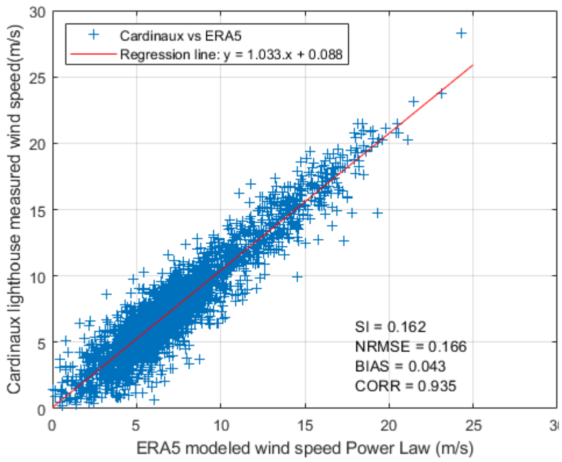
180° (South)



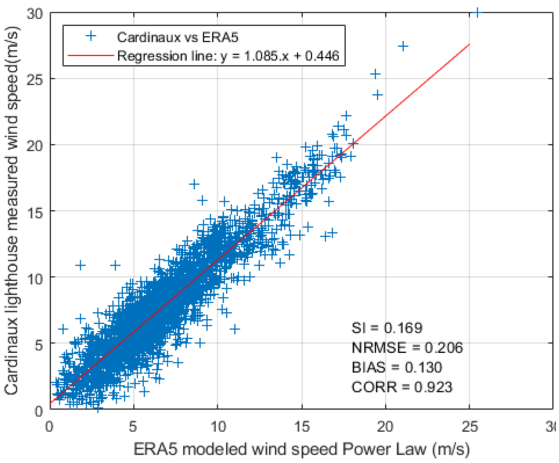
210°



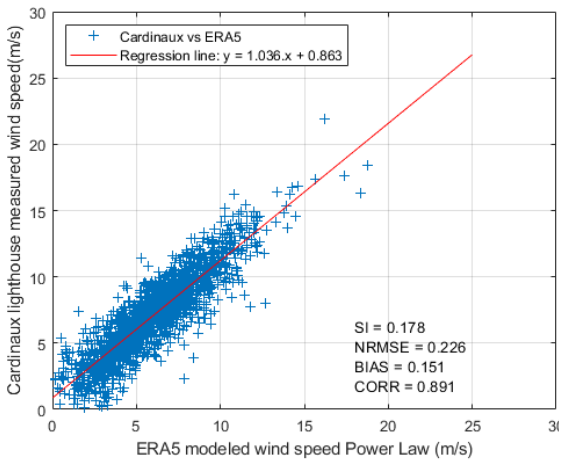
240°



270° (West)



300°



330°

TABLE 44: CORRELATION OF WIND SPEED (CARDINAUX MEASURES VS ERA5) BY DIRECTIONAL SECTORS (180-330°)

10.5 SELECTED EVENTS OF EXTREME WAVES

The events corresponding to extreme Hs are analysed in this appendix.

10.5.1 EXTREME EVENT: JOACHIM STORM, HIGHEST HS RECORDED IN SITU DURING THE PERIOD 2009-2020

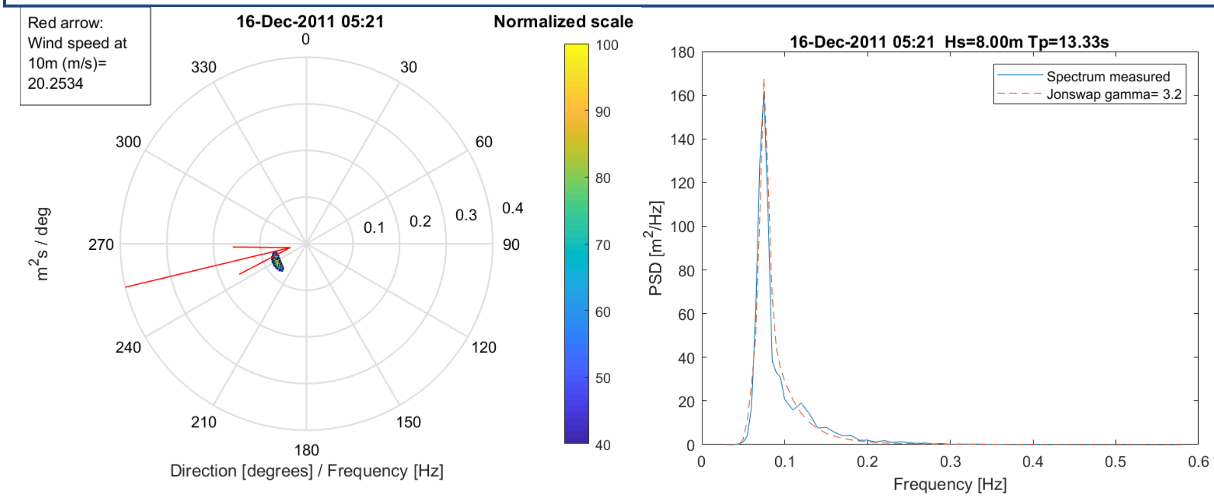


FIGURE 73: DIRECTIONAL SPECTRA AND OMNIDIRECTIONAL SPECTRA DURING JOACHIM EVENT FROM 05:21 AND FOR 30 MIN DURING WHICH THE HIGHEST HS IS MEASURED

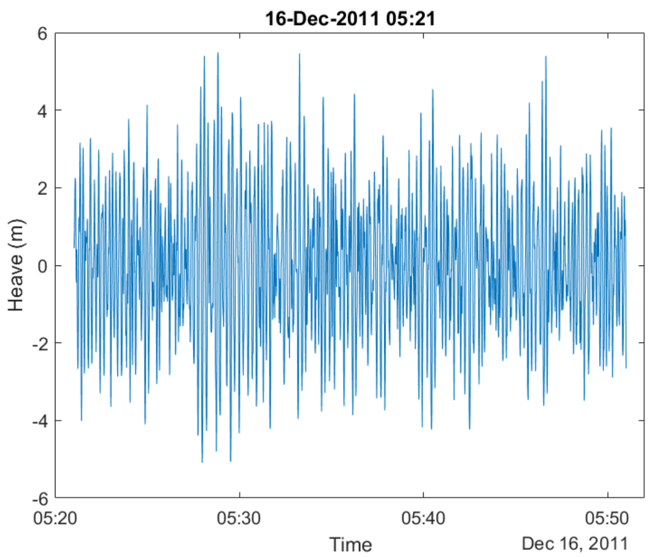
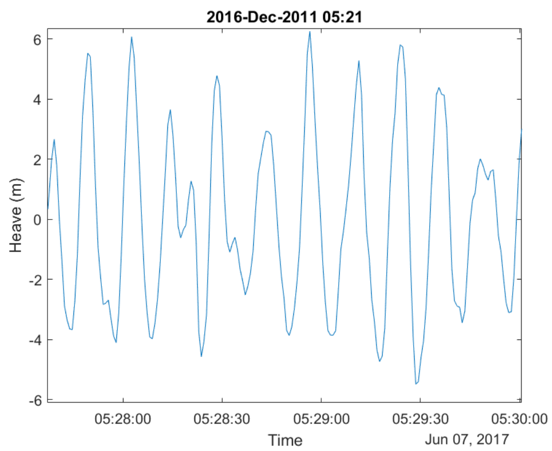


FIGURE 74: TIMESERIE OF WAVE ELEVEATION DURING JOACHIM EVENT

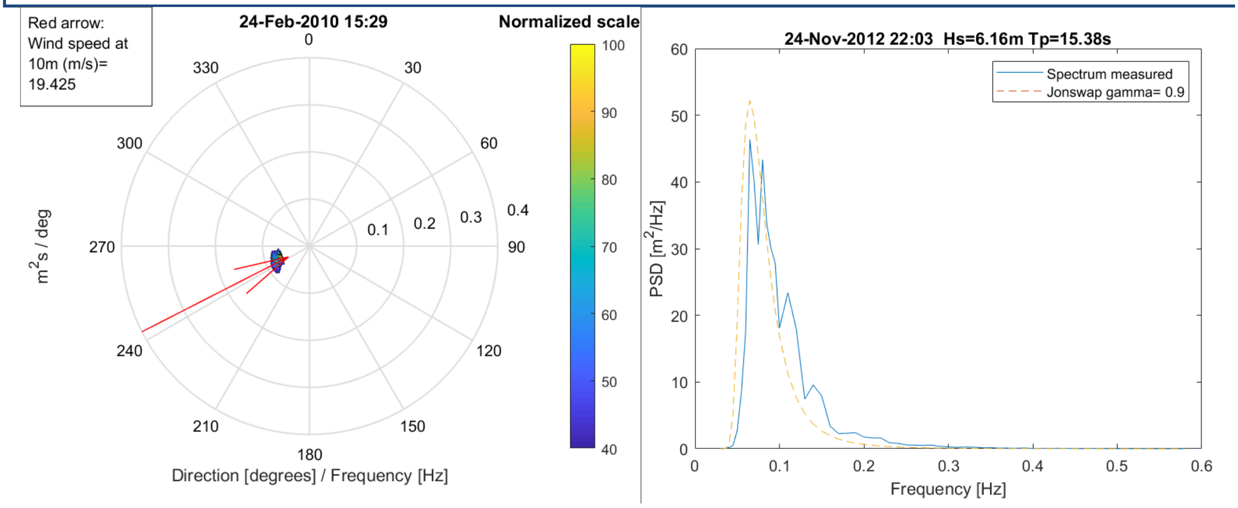


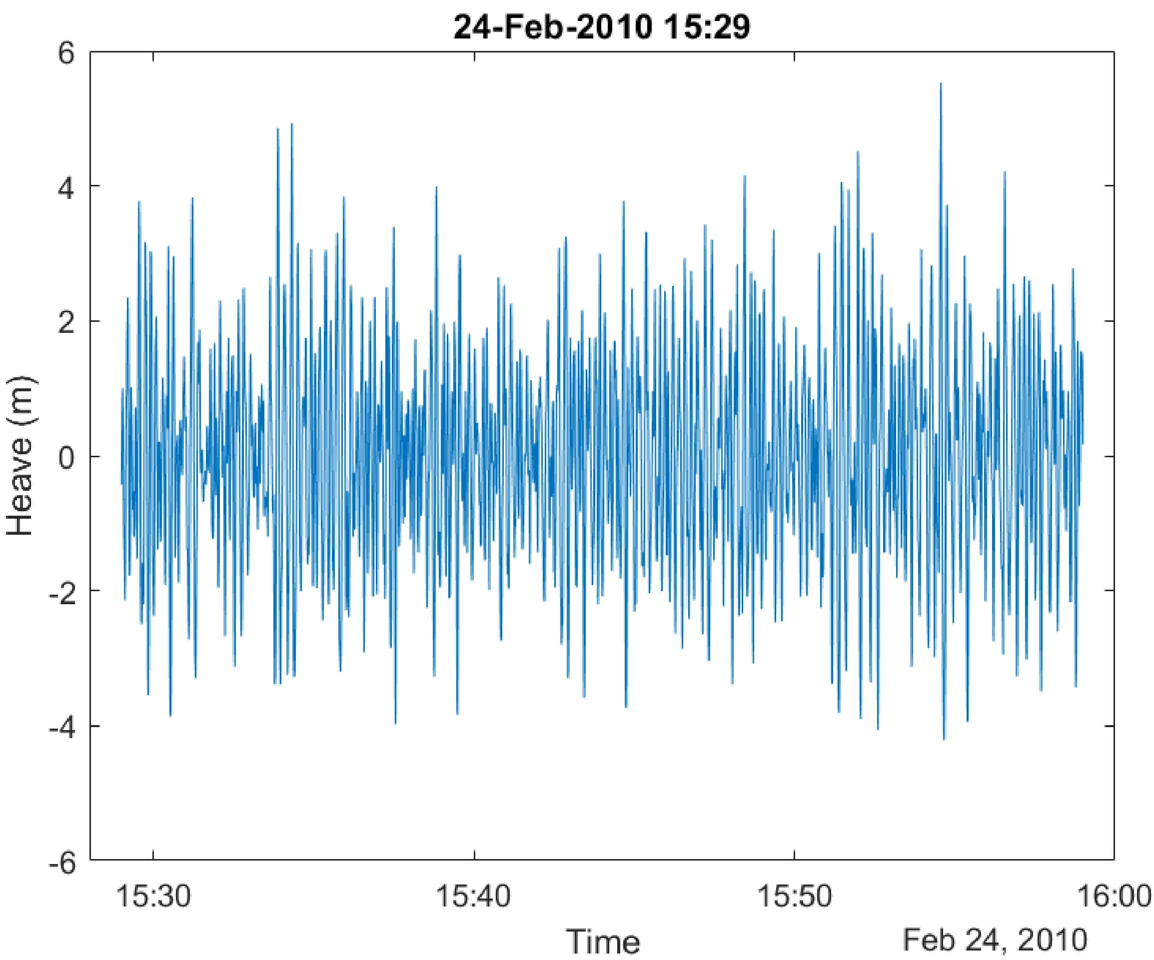
Time	Crest	Trough
05:28:44	2.91 m	
05:28:50		-3.87 m
05:28:56	6.26 m	
05:29:02		-3.86 m
05:29:11	5.28 m	
05:29:17		- 4.74 m
05:29:23	5.81 m	
05:29:28		-5.49 m
05:29:35	4.39 m	
05:29:42		-3.45 m

FIGURE 75: ZOOM ON TIMESERIE WAVE ELEVATION DURING JOACHIM EVENT AND MAXIMUM WAVE HEIGHT (CREST AND TROUGH VALUES)

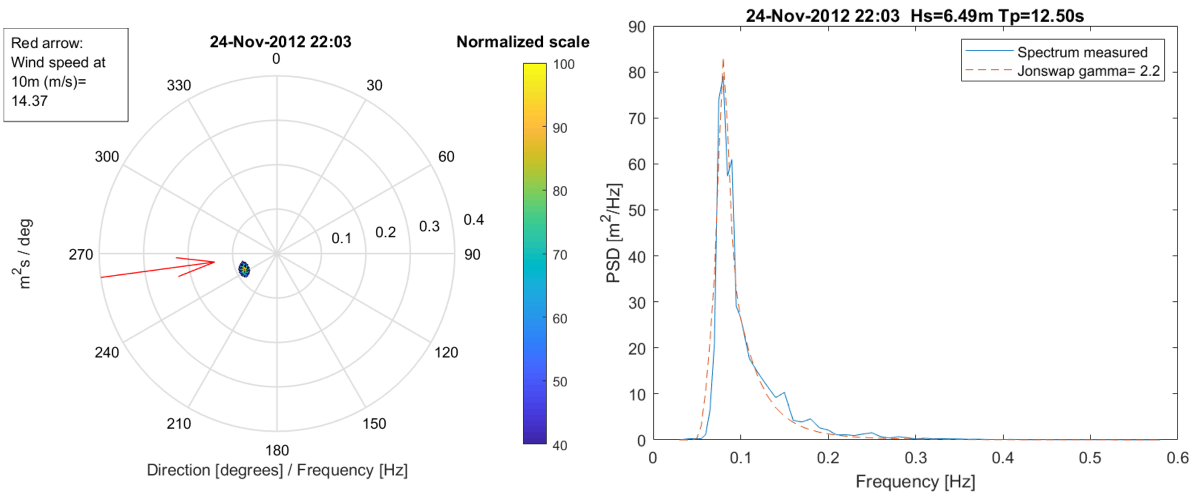
At 05:29:23, the crest is 5.81 m and the following through at 05:29:28 is -5.49 m leading to a maximum wave height (crest to through) of 11.30 m measured.

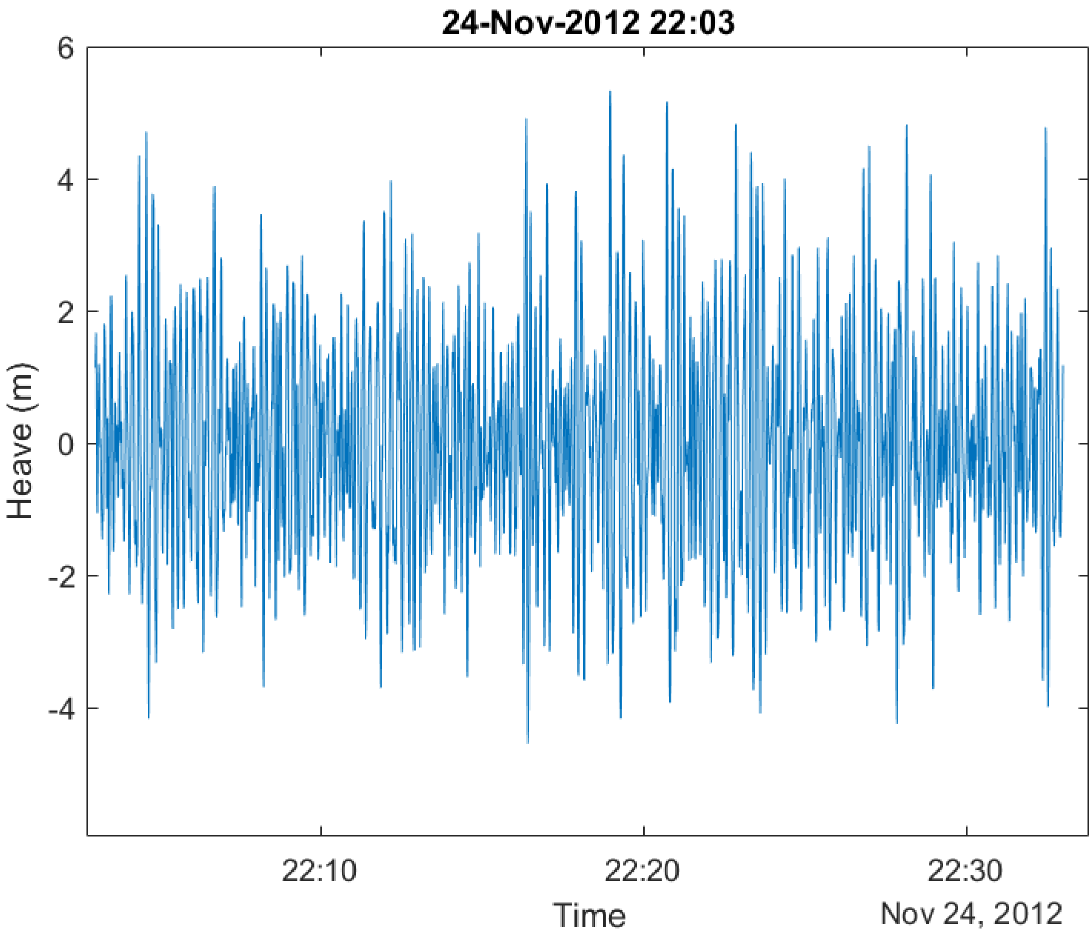
10.5.2 24/02/2010



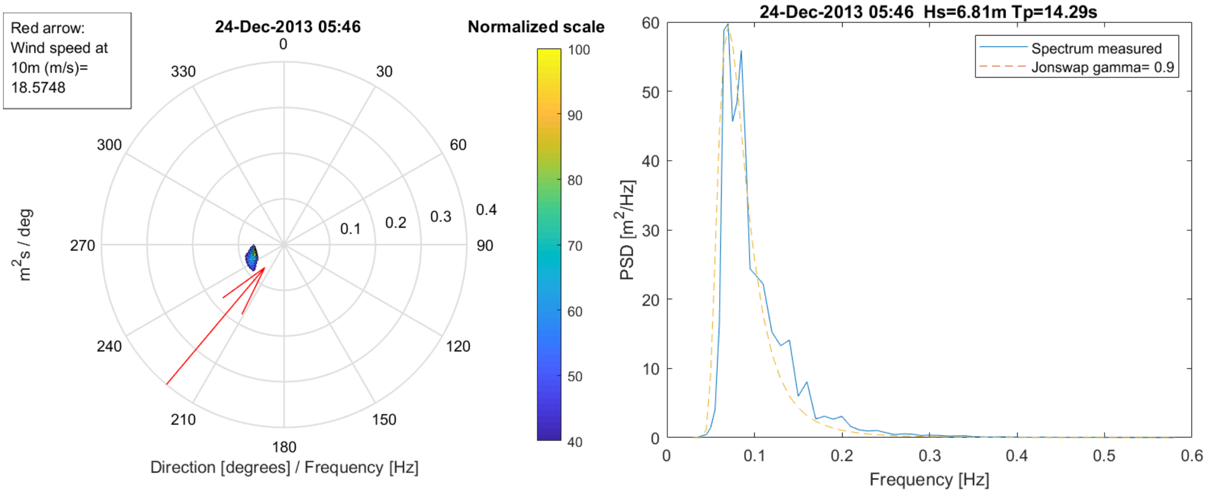


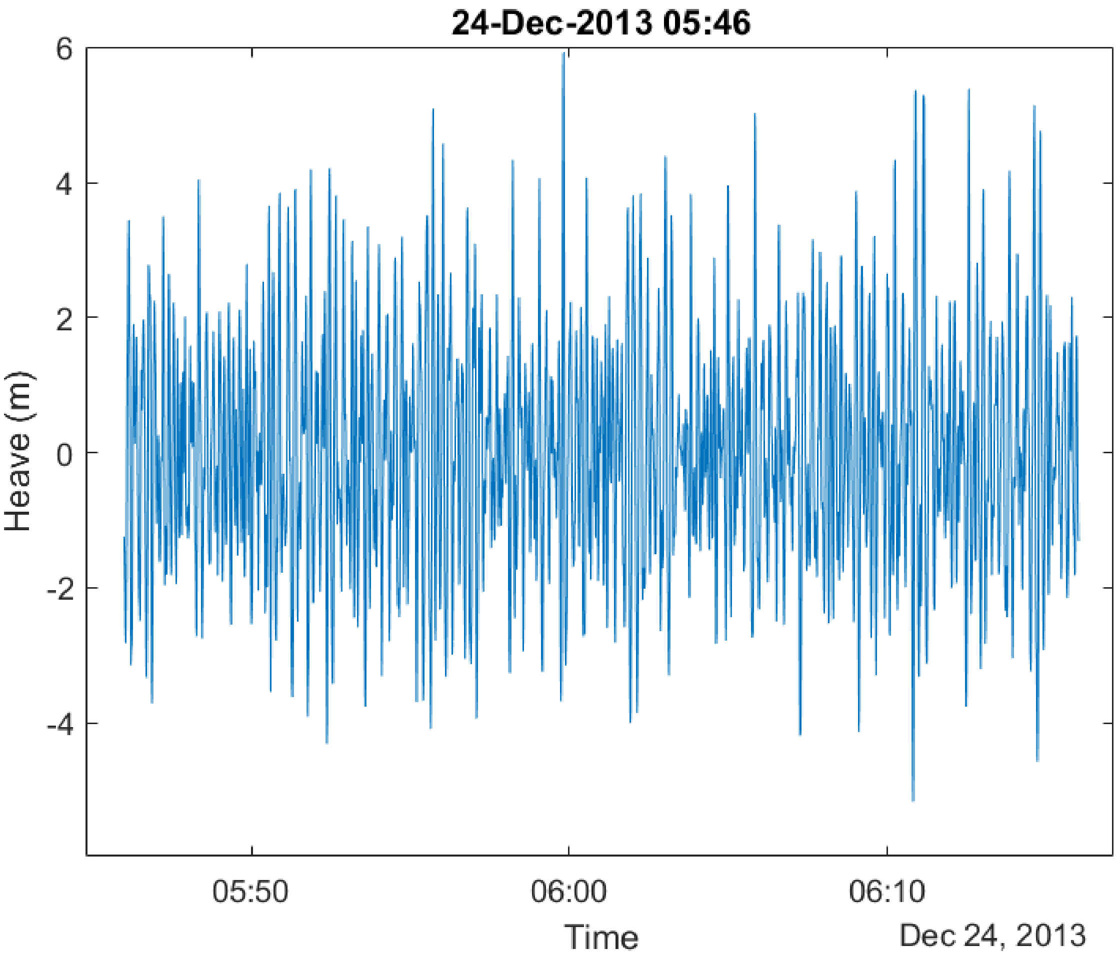
10.5.3 24/11/2012





10.5.4 24/12/2013





10.6 HARMONIC ANALYSIS OF WATER LEVEL ON SEM-REV: COEFFICIENTS

Tide	Frequency	Amplitude	Amp_error	Phase	Pha_error
MM	0.0015122	0.0208	0.046	234.91	147.75
MSF	0.0028219	0.0178	0.043	308.49	162.1
ALP1	0.0343966	0.0012	0.003	48.86	173.88
2Q1	0.0357064	0.0042	0.004	191.5	62.31
*Q1	0.0372185	0.0169	0.004	280.1	14.4
*O1	0.0387307	0.0443	0.004	356.72	5.29
NO1	0.0402686	0.0022	0.003	161.57	80.77
*K1	0.0417807	0.0504	0.004	149.34	5.41
J1	0.0432929	0.001	0.003	249.64	187.95
OO1	0.0448308	0.0003	0.002	310.09	206.51
UPS1	0.046343	0.0011	0.002	176.03	138.7
EPS2	0.0761773	0.0216	0.028	44.79	72.04
*MU2	0.0776895	0.0691	0.028	108.27	25.58
*N2	0.0789992	0.3752	0.03	135.65	4.63
*M2	0.0805114	1.6841	0.028	196.58	0.99
*L2	0.0820236	0.0645	0.039	267.23	42.2
*S2	0.0833333	0.5849	0.029	282.64	3
ETA2	0.0850736	0.0019	0.014	166	223.19
*MO3	0.1192421	0.0053	0.002	168.43	24.34
*M3	0.1207671	0.027	0.003	126.75	6.18
MK3	0.1222921	0.0026	0.002	189.6	51.16
*SK3	0.1251141	0.0047	0.002	281.55	27.89
*MN4	0.1595106	0.0755	0.008	128.92	5.9
*M4	0.1610228	0.1547	0.007	219.47	2.34
SN4	0.1623326	0.0031	0.006	27	109.09
*MS4	0.1638447	0.0536	0.007	351.01	7.59
S4	0.1666667	0.0041	0.006	266.21	84.21
2MK5	0.2028035	0.0008	0.001	206.94	74.64
*2SK5	0.2084474	0.0022	0.001	49.65	26.44
*2MN6	0.2400221	0.0041	0.002	219.89	20.24
*M6	0.2415342	0.0067	0.001	306.53	12.26
*2MS6	0.2443561	0.0053	0.001	81.85	14.43
2SM6	0.2471781	0.0012	0.001	209.03	76.58
3MK7	0.2833149	0.0003	0	24.58	62.47
*M8	0.3220456	0.0026	0.001	18.6	16.97

TABLE 45: COEFFICIENTS OF HARMONIC ANALYSIS OF WATER LEVEL ON SEM-REV (*: SIGNIFICANT CONSTITUENTS)

10.7 BREAKING WAVES

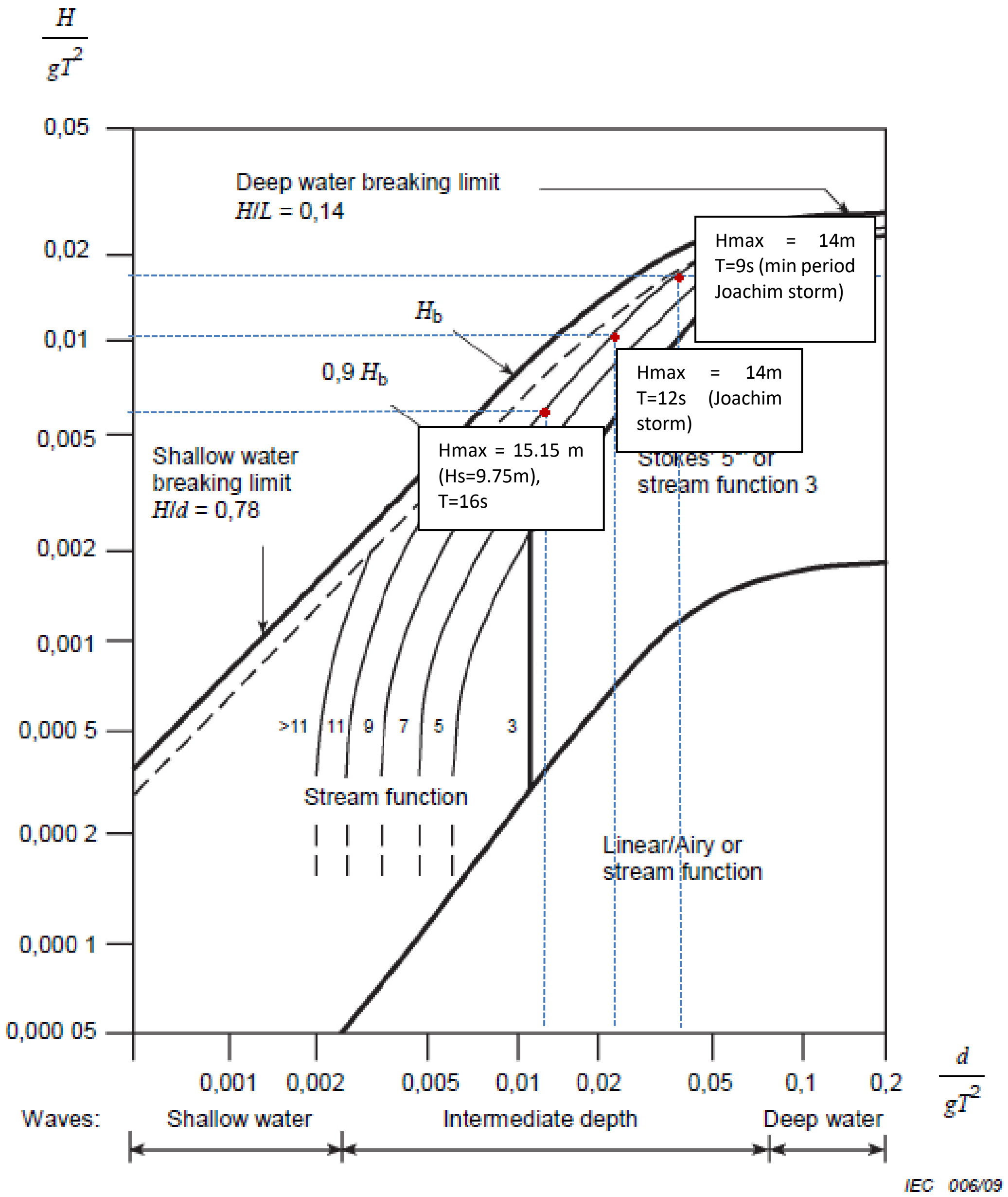


Figure C.1 – Regular wave theory selection diagram

REFERENCES

[1] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2018): ERA5 hourly data on pressure levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 02-04/10/2020), 10.24381/cds.bd0915c6

[2] DNVGL-ST-0126, 2018-07, Support structures for wind turbines

[3] Gualtieri G., Renewable energy vol 43, p 183-200, 2012, « Methods to extrapolate wind resource to the turbine hub height based on power law: a 1-h wind speed vs Weibull distribution extrapolation comparison"

[4] IEC 61400-1:2019 Wind turbines – Part1: Design requirements

[5] IEC 61400-3-1:2019 Design requirements for fixed offshore wind turbines

[6] IEC 61400-3-2:2019 Design requirements for floating offshore wind turbines

[7] DNVGL-RP-C205, 2019-11, amended 2020-12. "Environmental conditions and environmental loads"

[8] DNVGL-ST-0437, 2016-11 "Loads and site conditions for wind turbines"

[9] NORSOK N-003 (Norsok Standard, 2007)

[10] API Specification 17E (API 2017)

[11] API-RP-2A-WSD, 2014, Recommended practice for planning, designing and constructing fixed offshore platforms

[12] G02-SP-ENV-G-6012_Site_metocean_data_collection_specification_Rev_C1

[13] G02-SP-GEO-6513-00_Site_geophysical_geotechnical_scope_definition Rev C3

[14] GD049058 R5.1 Necessary data to perform a Site Assessment Study

[15] NOAA (National Oceanic and Atmospheric Administration) Bathymetric database ETOPO1 http://www.ngdc.noaa.gov/mgg/global/global.html

[16] Maritime chart n°7395 from the French "Service Hydrographic de la Marine" (SHOM)

[17] http//www.shom.fr/les-produits/bases-de-donnees-numeriques/bathymetrie/dalles-bathymetriques

[18] Astérie Final Report, 78pp, October 2010. "Geophysical Measurements Campaign – SEMREV Cable Layout Study"

[19] In Vivo Final Report Version A, 85pp, November 2012. "Geophysical Measurements Campaign – SEMREV Cable Layout Study"

[20] In Vivo Folder N°11N-0033-a00, 18pp, February 2012. "Static Penetrometer trials - Report presenting the results"

[21] In Vivo Folder N°11N-0033-b00, 6pp, January 2012. "Nautical collection of soil samples - Report presenting the results"

[22] Fugro Report of the geotechnical trials performed in laboratory, February 2012 (CD - SCG1 1.5m (12P0112), CD - SCG1 3.5m (12P0114), CD - SCG1 5.5m (12P0116), GRA_SCG1, SCG1 – Samples Photos, VBS_SCG1, WC_SCG1)

[23] Creocean Folder N°1-09134-R, 438pp, April 2010. "Construction of the marine infrastructures of SEMREV test site – Authorisation application dossier"

[24] Atelier de l'Ile Landscape Report, 63pp, June 2012. "Offshore Wind Turbine Project – SEMREV Landscape Aspects"

[25] Creocean Folder N° Dossier 1-12008-R, 289pp, January 2013. "Authorisation application dossier for SEMREV extension to Floating Wind Turbine"

[26] American Meteorological Society, Vol. 91, pp. 1015-1057, Issue 8, August 2010. "The NCEP Climate Forecast System Reanalysis" http://cfs.ncep.noaa.gov/cfsr/

[27] Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters, Cambridge University Press.

[28] REFMAR (Reference network for tidal observations): http://refmar.shom.fr/

[29] SHOM, 126 pp, 2020. "Marine Altimetry References, Harbours from mainland France and overseas – Rates of the Hydrographical Reference and characteristic tidal levels" https://diffusion.shom.fr/pro/references-atimetriques-maritimes-ram.html

[30] Météo-France Final Report, 10pp (+ Annexe 1, 73pp), 2001. "Hazard mapping of surge risk area on the English Channel and Atlantic Ocean coastlines"

[31] RONIM (Sea Level Observation Network): http://www.shom.fr/les-activites/activites-scientifiques/maree-et-courants/marees/reseau-dobservation/

[32] X. Bertin et al. Ocean Modelling, vol. 42, pp. 16-30, 2012. "Importance of wave age and resonance in storm surges: The case Xynthia, Bay of Biscay"

[33] PREVIMER, ODE/DYNECO/PHYSED/2013-05 version 1.0, June 2013. 2D hydrodynamic model Validation at English Channel and Atlantic Ocean coastlines: http://www.previmer.org/content/download/7384/39384/file/2013_06_05_rap_valid_modeles_PREVIMER_L1-MARS2D.pdf

[34] SHOM tidal atlas n°558-UAJ (South Coast of Brittany) and n°559-UAJ (West Coast of Pays-de-la Loire)

[35] Documentation ADCP Teledyne RDI: http://www.rdinstruments.com/datasheets/wh_sentinel.pdf

[36] Boudiere Edwige, Maisondieu Christophe, Ardhuin Fabrice, Accensi Mickael, Pineau-Guillou Lucia, Lepesqueur Jeremy (2013). A suitable metocean hindcast database for the design of Marine energy converters. International Journal of Marine Energy, 3-4, e40-e52. Publisher's official version : http://dx.doi.org/10.1016/j.ijome.2013.11.010 , Open Access version : http://archimer.ifremer.fr/doc/00164/27524/

[37] Documentation Datawell Directional Wave Rider: http://download.datawell.nl/documentation/datawell_brochure_dwr-mk3_b-09-04.pdf

[38] Ifremer, HOMERE Public Note Version 1, January 2014. "(HOMERE database User Guide – HOMERE database description over the English Channel –Biscay Bay Area (NGUG-v3)"

[39] WAFO Toolbox (Wave Analysis for Fatigue and Oceanography) http://www.maths.lth.se/matstat/wafo/

[40] NF EN 1991-1-3/NA May 2007 Eurocode 1 – Actions on structure – Part 1-3 : General Actions – Snow loads. National Annex to NF EN 1991-1-3 :2004

[41] NF EN 1991-1-5/NA February 2008 Eurocode 1 – Actions on structure – Parti 1-5 : General Actions – Thermic Actions. National Annex to NF EN 1991-1-5 :2004

[42] G02-SP-ELE-4506-B2_Dynamic_Umbilical_Specification

[43] API Specification 17E, Fourth Edition, Jan, 2010 "Specification for Subsea Umbilicals" / ISO 13628-5:2009 — Design and operation of subsea production systems — Part 5: Subsea umbilicals

[44] Environmental impact assessment study on SEM-REV 2017

[45] IPCC, 2019: Technical Summary [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, E. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.- O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

[46] R. Pawlowicz, B. Beardsley, and S. Lentz, "Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE", Computers and Geosciences 28 (2002), 929-937.

[47] Saulnier J.B, Le Crom I. « Peakedness of wave systems observed on the french wave energy test site (SEM-REV) using a spectral partitioning algorithm, OMAE2013-11470

[48] B.Simon, "La marée océanique côtière", ISBN 978-2-903581-32-9

[49] Meteo France Fiches climatologiques de Belle Ile Le Talut (56) et Saint-Nazaire – Montoire 44), statistiques 1981-2010 et records https://donneespubliques.meteofrance.fr/

[50] Ifremer, Base Surval: accès aux données d'environnement marin et littoral. https://wwz.ifremer.fr/surval/Donnees/Cartographie-Inventaire-des-reseaux-d-observation-et-de-surveillance-du-littoral#/map

[51] Gill windmaster user manuel, issue 15 November 2019