

# Coastal protection of the Romanian nearshore throughout hybrid wave and offshore wind farms

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**Abstract.** The objective of the present work is to estimate the influence of several hybrid wind and wave farm configurations on the wave conditions reported in the vicinity of the Saint George coastal area, in the Romanian nearshore of the Black Sea. Based on the wave data coming from a climatological database (ERA20C) and also on in situ measurements, it was possible to identify the most relevant wave patterns, which will be further considered for assessment. The numerical simulations were carried out with the SWAN (Simulating Waves Nearshore) wave model, which may provide a comprehensive picture of the wave transformation in the presence of the marine farms. Although the impact of the wind farm is not visible from the spatial maps, from the analysis of the values corresponding to the reference points, it was noticed that a maximum variation of 2% may occur for several wave parameters.

## 1 Introduction

Romania is defined by numerous opportunities in terms of the renewable energy sources, from which it can be mentioned the hydropower and wind energy. With a generated capacity of 1894 MWh (reported to 2015), the hydropower sector has a share of 26% from the total electricity production, from which a significant percentage is obtained throughout one of the largest project from Europe (the Iron Gate I power station) [1]. As for the wind energy (reported to 2014), it was estimated that almost 75 of the wind farms operates in Romania, most of the projects being implemented in the Dobrogea Plateau (78 %), which is an geographical area located close to the Black Sea [2].

There is a close connection between wind and waves, and during the recent years it was highlighted that the western part of the Black Sea seems to be defined by consistent marine conditions which can be extracted efficiently throughout wind and wave farms, or eventually throughout hybrid wind-wave projects [3-5]. In the case of the Romanian nearshore, the combination between the wave action and the reduced sediment flux due to the presence of the dams on the Danube River has accentuated the local coastal erosion [6]. In order to tackle this issue, a possible solution will be to consider the use of some Wave Energy Converter (WECs) which may be deployed in a wave farm capable to attenuate the wave power which is propagated throughout the surf area. Similar approaches were proposed for some other coastal environments, such as in the case of the Portuguese nearshore or for the western sector of the Mediterranean Sea [7-9]. If we consider the progress reported by the wave industry and the attractiveness of the wave power, it is expected that in the near future this source of energy

will become more competitive, being possible to develop wave farms in enclosed basins (such as the Black Sea) defined by less energetic conditions than the ones reported in the ocean environments. Nevertheless, if we discuss about the western part of the Black Sea it is more feasible to consider that an offshore wind farm has better chances to be developed first, being possible in this way to support the development of a pilot wave project.

In this context, the objective of the present work will be simulate the coastal impact of different hybrid wind and wave farm configuration on a target area located in the vicinity of the Danube Delta, which is a protected area included in the UNESCO heritage.

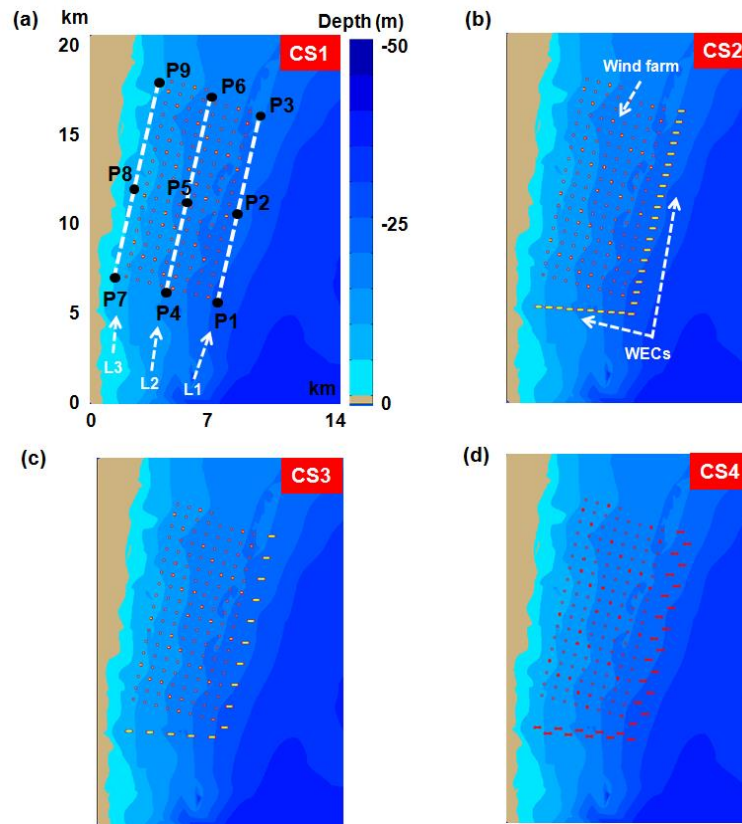
## 2 Methods and materials

The target area considered for simulation is located on the western part of the Black Sea, more precisely close to the Saint George sector (Romania) which is in the vicinity of the Danube Delta. Figure 1 illustrates the computational domain considered for simulation, and also the proposed case studies (denoted with CS). The numerical simulations will be carried out by using the SWAN (Simulating Waves Nearshore) wave model which is considered to be a third-generation model capable to provide a realistic estimation of the wave parameters from the coastal environments [10, 11]. In the background is presented the bathymetry, where a maximum depth of 50 m may be observed in the offshore region. The computational domain is rectangular, being defined by a length of 14 km in the X-direction, while a 20 km is reported along the Y-axis. In Figure 1a, is presented the offshore wind farm considered for investigation which includes 140 wind turbines, similar to the Greater Gabbard project from UK which is one of the

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largest wind farm from this area. The total area covered by the farm is around 147 km<sup>2</sup>, while the distance between the piles was set to 650 m, similar to the original

project configuration [12]. More details regarding the SWAN setup and the computational domain may be found in Table 1.



**Figure 1.** The computational domain considered for the SWAN simulations (Saint George coastal area). In the background, the bathymetry is represented while in the foreground the references lines/points are indicated, as also the selected case studies, where: a) CS1; b) CS2; c) CS3; d) CS4.

**Table 1.** Characteristics of the SWAN computational domain and description of the physical processes activated.

Computational domain setup		Input/process	
Coordinates: Cartesians	No points in Y-direction: 406	Waves: X	Interactions: Quad; Triads
$\Delta x$ (m): 50	No of frequencies: 34	Wind: X	Whitecapp.: X
$\Delta y$ (m): 50	No of directions: 35	Current: X	Refraction, Diffraction: X
$\Delta \theta$ (°): 5	Mode: Stationary	Gen:	Nearshore processes:
No points in X-direction: 355		Westh.	Friction; Breaking; Set up

The designed offshore wind farm will represent the base, around which will be developed several case studies which include wave converters, as it can be observed from Figure 1b where a single line of WECs was added. For the current work was considered useful to use the technical characteristics of the Wave Dragon device, which is one of the largest system on the market being defined by a total length of 300 m [13]. For this case, the distance between the devices was considered equal to the length of this device, respectively 300 m. For the case study CS3, a similar setup was considered, the difference is that in this case the space between the WECs is double (600 m), which means that a much smaller number of

devices were considered (15 WECs). The last case study, denoted with CS3, is based on the CS2 scenario, with the mention that in this case a second line of WECs was added in front of the existing devices. All the WECs are located in front of the wind farm in order to provide a sheltering area for the wind turbines and for the beach area.

More details regarding these case studies are presented in Table 2, where are also mentioned the absorption property of the wind and wave devices, which were included in the SWAN simulation as obstacles [13, 14].

**Table 2.** Description of the case studies considered for investigation in the SWAN simulations.

Case studies		Absorption scenarios	
CS1	Offshore wind farm – 140 piles; Distance between piles – 650 m.		
CS2	Wind farm+WECs deployed on a single line; Distance between the systems – 300 m (the total length of a Wave Dragon).	Turbine piles	WECs
CS3	Wind farm+WECs deployed on a single line; Distance between the systems – 600 m (double the length of a Wave Dragon).	TRANS=0.72	TRANS=0.68
CS4	Wind farm+WECs deployed on two lines; Distance between the systems – 600 m.	REFL=0.2	REFL=0.2

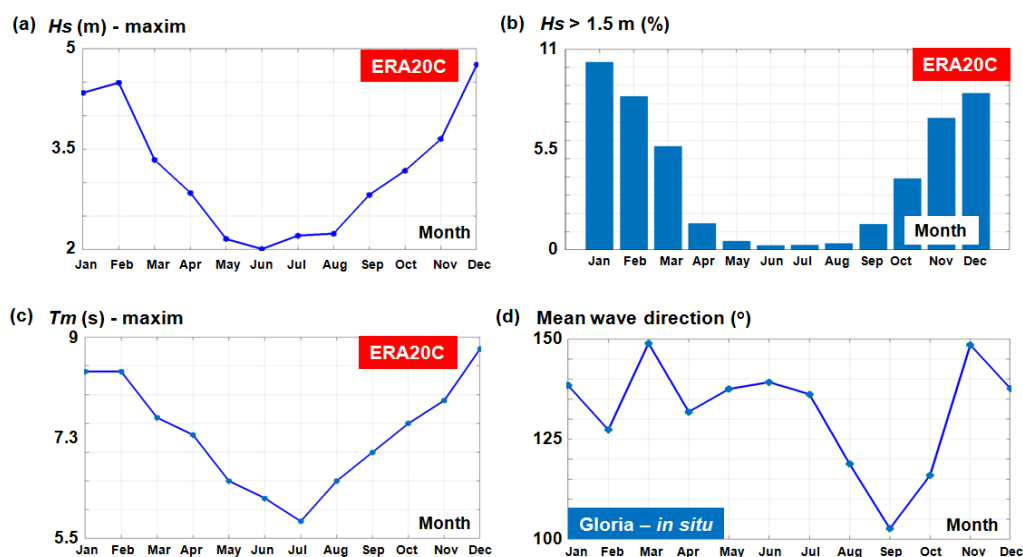
In addition to the case studies configuration, another important step is related to the correct assessment of the wave conditions from the targeted area in order to initiate the SWAN model. Two datasets will be considered for investigation, from which the first one is related to the ERA20C database which is a reanalysis product component of the European Reanalysis of Global Climate Observations project [15]. This data cover the interval from January 1900 to December 2010, while for this study the time series of the significant wave height ( $H_s$ ) and the wave period ( $T_m$ ) were processed for the entire interval (111 years of data) considering a references point located in the vicinity of the target area ( $45^\circ\text{N}/30^\circ\text{E}$ ). As for the wave direction, were considered the in situ measurements registered at the Gloria drilling platform ( $44^\circ31'\text{N}/29^\circ34'\text{E}$ ), covering the interval from January 2003 to December 2009.

Figure 2 illustrates the monthly distribution of the wave parameters from the vicinity of the Saint George sector, a particular attention being given to the extreme values which are more relevant for the coastal stability. In terms of the  $H_s$  parameter, we can easily identify the differences between the summer and winter time (October-March), where the last one reveal more

energetic values. A maximum of 4.76 m may expect in December, compared to the summer values which during the interval May-August does not exceed 2.3 m. Other important winter months are January and February, during which the  $H_s$  heights of 4.34 m and 4.49 m may be reached. In Figure 2b is presented the distribution of the waves higher than 1.5 m limit, which is considered to be a representative threshold for the maritime activities being linked to the operational limit of the workboats [16].

In this case the best results are reported during the summer time when a maximum of 1.45% may occur in April, while on opposite side we found January and December with 10.3% and 8.6%, respectively. The wave period varies between 5.8 s and 8.8 s, while in terms of the wave direction an average value of  $137.6^\circ$  (south-east) may be considered representative for the entire year, with the mention that during September may be encountered waves associated with the  $102.7^\circ$  value.

From the analysis of these values was considered interesting to run the SWAN simulation with a sea state associated to the following wave parameters:  $H_s$  – 4.76 m;  $T_m$  – 8.8 s;  $Dir$  –  $137.6^\circ$ .



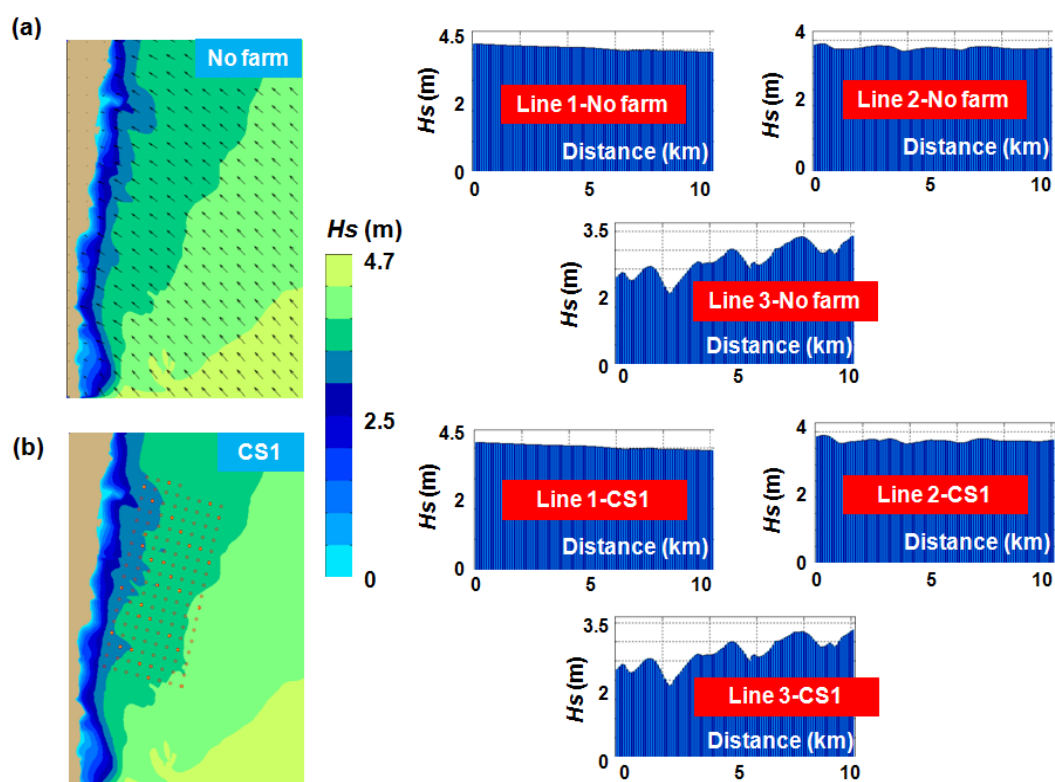
**Figure 2.** Monthly wave statistics in the vicinity of the target area (Saint George) as resulting from processing the ERA20C database and the Gloria in situ measurements, where: a)  $H_s$  parameter – maximum values; b)  $H_s$  parameter – percentage exceeding 1.5 m; c)  $T_m$  parameter – maximum values; d) Wave direction – average values.

### 3 Results

Figure 3 illustrates the spatial distribution of the  $H_s$  values in the absence of the farm and for the case study CS1 (wind farm), where was also included the evolution of this parameter along the considered reference lines. In Figure 3a was also included the wave vectors in order to notice the direction of the waves (south-east) used in the simulations, but in the next figures this field will be removed in order highlight more clearly the influence of the wind and wave devices. Several wave fields occur in the target area, their variation being related to the orientation of the water depth isolines being indicated

that in the vicinity of the coastline a wave field of 2.5 m may be encountered. From the distribution of the  $H_s$  heights along the reference lines can be observed the transition of the waves from the offshore area to the shallow water (line 3) where the dissipative effects become more important. The impact of the wind farm seems to be minimal, being noticed no variation in the spatial distribution or along the selected lines.

A complete description of the wave parameters is presented in Table 3 (no farm situation), where with the  $V_{bot}$  (m/s) is indicated the bottom velocity, where a zero value represent a truly deep water [17].



**Figure 3.** Evaluation in the geographical space of the wave distribution, where: a) No farm; b) CS1 – offshore wind farm similar to the Greater Gabbard project (140 turbines).

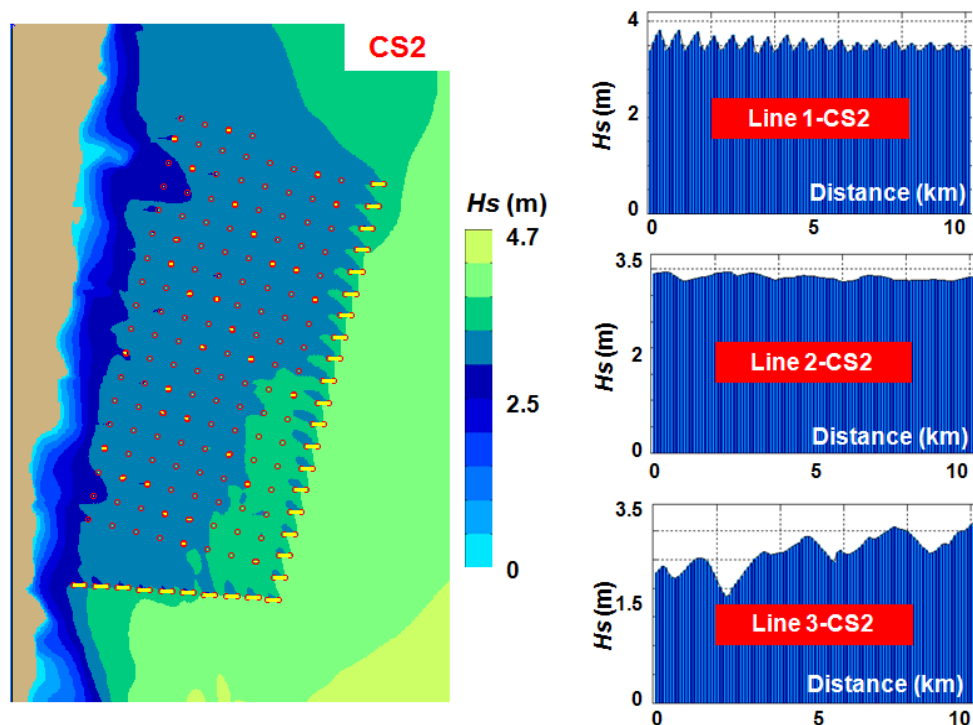
**Table 3.** The values of the wave parameters corresponding to the references points P1-P9. No wind or wave farm was considered for this evaluation, which is representative for the following sea state:  $H_s$  – 4.76 m;  $T_m$  – 8.8 s;  $Dir$  – 137.6°.

Parameter	Reference points								
	P1	P2	P3	P4	P5	P6	P7	P8	P9
Depth (m)	26.06	22.4	19.8	15.3	17.3	16.85	4.814	7.153	8.601
$H_s$ (m)	4.194	4.069	3.932	3.867	3.763	3.772	2.295	2.948	3.374
$T_m$ (s)	7.661	7.734	7.721	7.748	7.765	7.775	8.222	8.076	7.97
$Dir$ (°)	134.7	131.2	129.3	126.4	126.4	128	108.9	112	117
$V_{bot}$ (m/s)	0.6265	0.7365	0.8144	1.04	0.9	0.9257	1.475	1.464	1.467

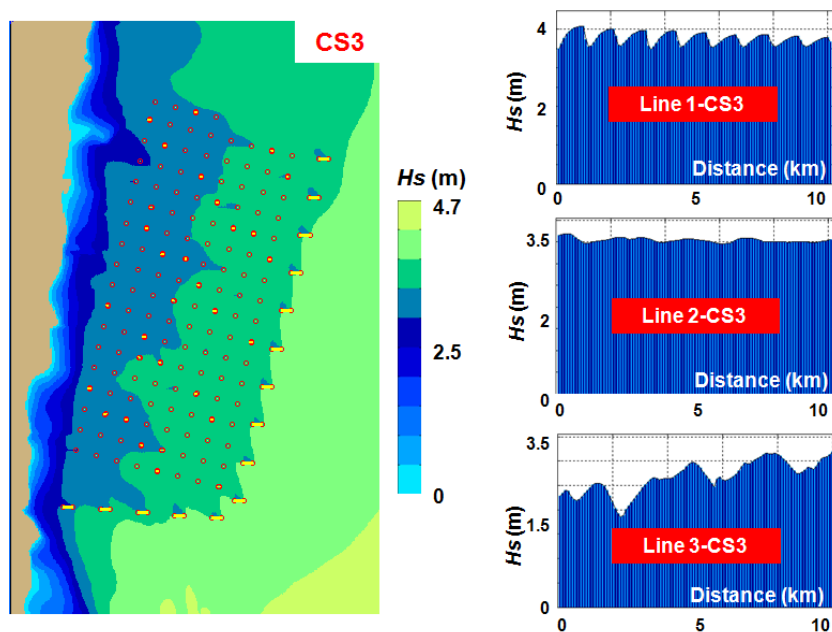
Figure 4 presents the evolution of the wave fields in the presence of the CS2 scenario. The influence of the WECs is visible throughout the entire wind farm, more important variations being reported along the reference line 1, which is located between the wind and wave farm. Also it seems that on a local scale, the wind turbines seem to generate small shadow areas, aspect which was not noticed in the previous distribution. The  $H_s$  values reported in the center of the wind farm (line 2) seems to decrease with almost 0.5 m, this variation being constant along this line. For the area located between the wind

farm and coastline, it seems that no important variation will occur.

By increasing the spaces between the WECs, the shadow effect of the WECs will significantly decrease, as it can be observed from Figure 5 (CS3 study case). Nevertheless the influence of the wave farm is still visible in the lower part of the wind park (facing the coastline), being also observed along the reference line 1.



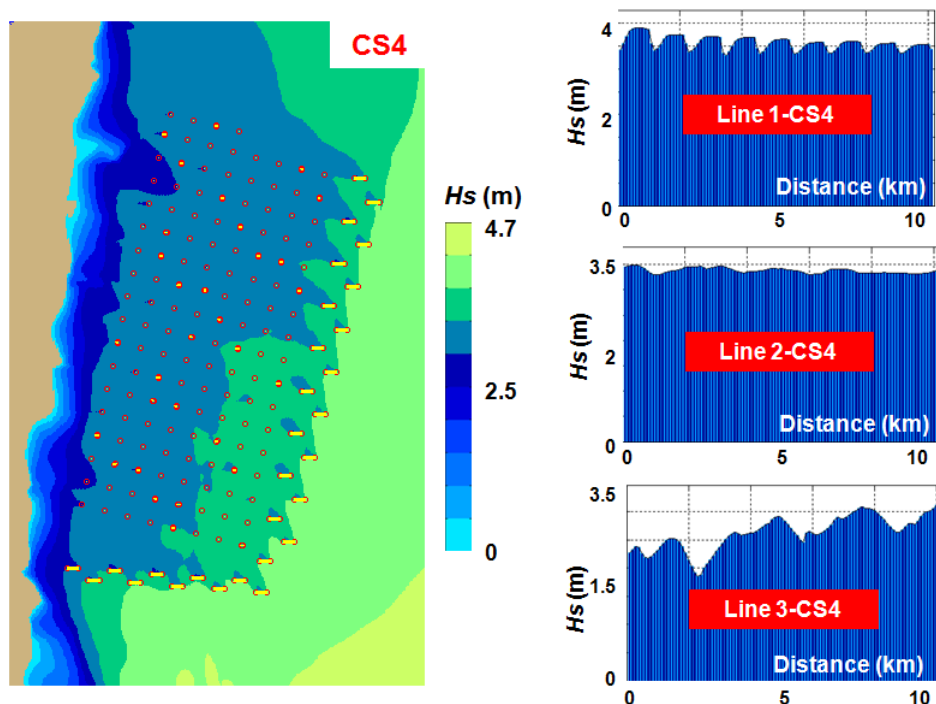
**Figure 4.** Evaluation in geographical space of the significant wave heights considering CS2 scenario.



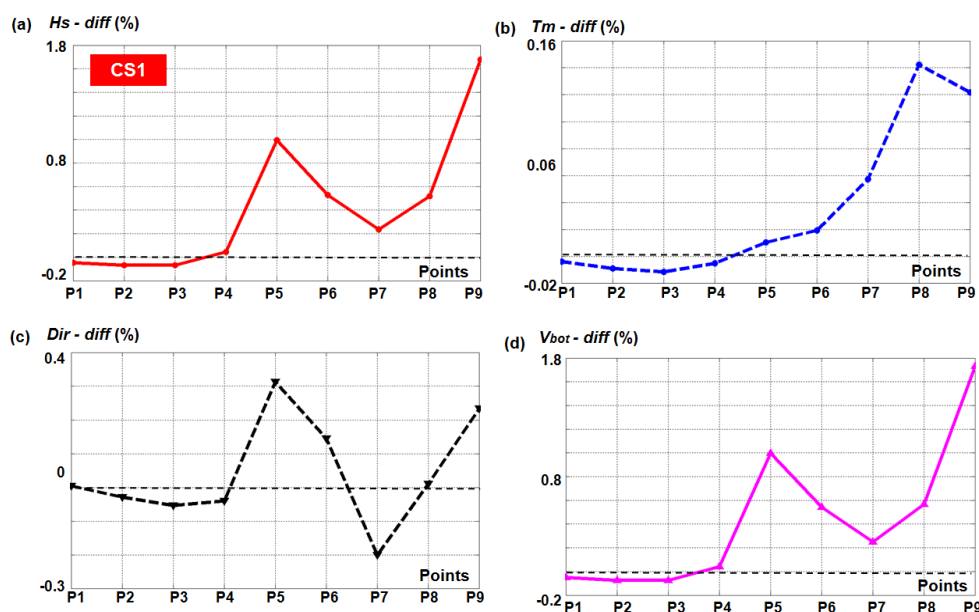
**Figure 5.** Evaluation in the geographical space of the significant wave heights considering the CS3 scenario.

A similar distribution is presented in Figure 6 for the CS4 case study, where two lines of WECs were taken into account. On a first evaluation it seems that the spatial impact of this configuration is similar to the one reported for CS2, however from the analysis of the line 1 profile we can noticed that the crest of the waves are trimmed which highlight the presence of the second line of WECs. For this case, the  $H_s$  values reported along the line 2 are located below the 3.5 m limit.

It is difficult to quantify the influence of the wind and wave farm by using only the spatial maps and references lines, so as a next step the information provided by the reference points P1-P9 will be evaluated in details. Figures 7, 8, 9 and 10 highlight an analysis, where the differences reported between the no farm situation and the case studies were indicated in percentages. A positive value reveal an attenuation of the wave parameter, while a negative sign reveal a reverse trend.

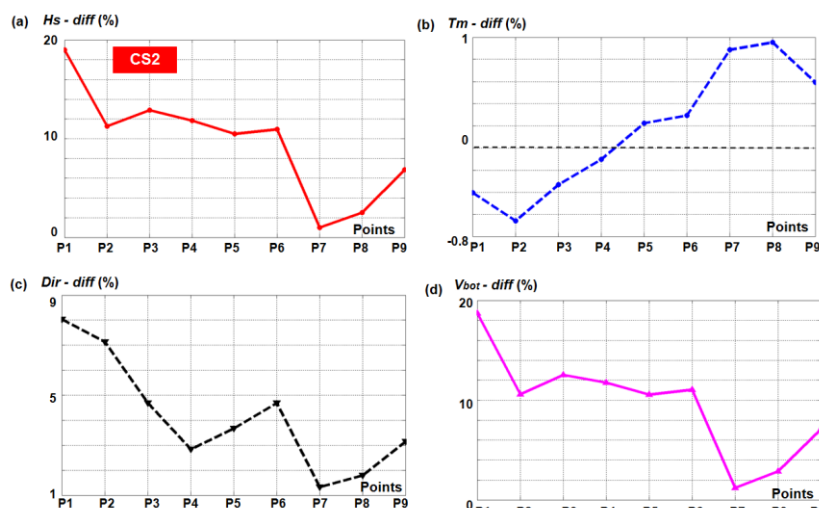


**Figure 6.** Evaluation in geographical space of the significant wave heights considering CS4 scenario.

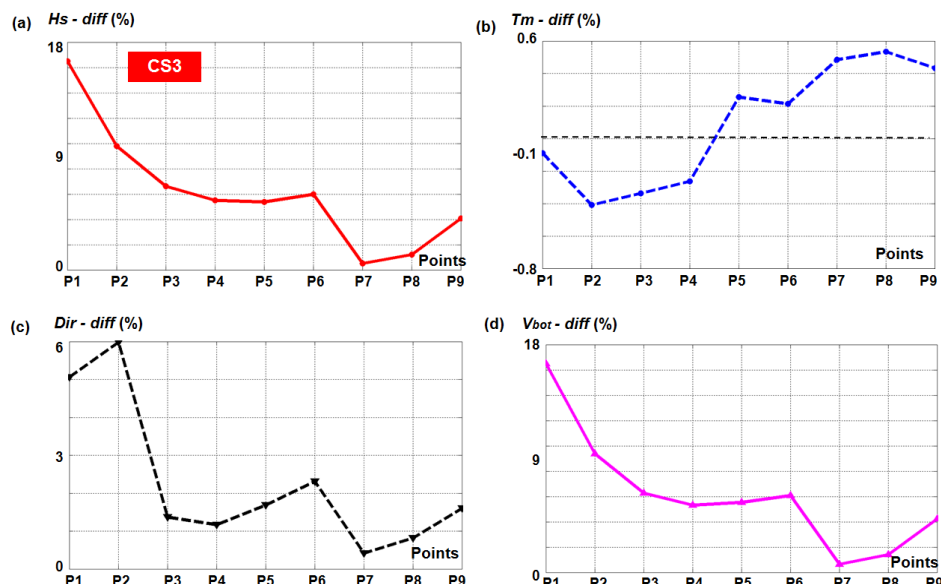


**Figure 7.** Variation of the wave parameters (in %) reported considering the no farm situation and the CS1 scenario, where: a)  $H_s$  variations; b)  $T_m$  variations; c)  $Dir$  variations; d)  $V_{bot}$  variations. The positive values indicate a decrease in magnitude in the presence of the farm, while the negative values indicate an opposite pattern.

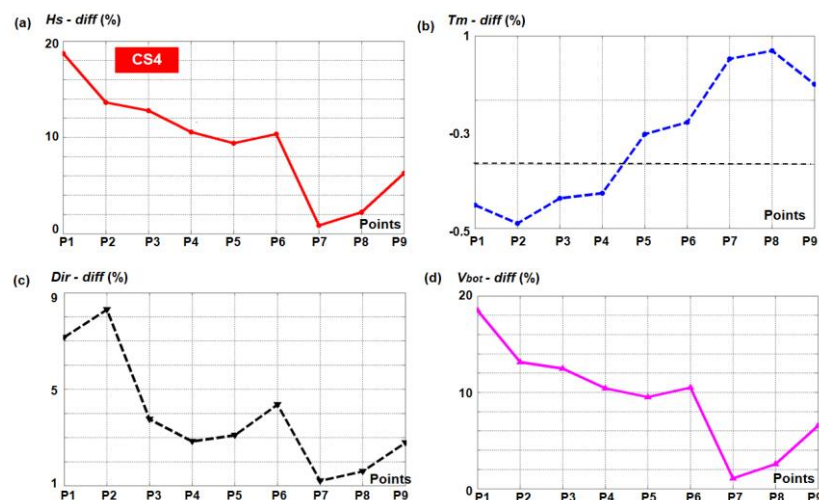




**Figure 8.** Variation of the wave parameters (in %) reported between the no farm situation and the CS2 scenario, where: a)  $H_s$  variations; b)  $T_m$  variations; c)  $Dir$  variations; d)  $V_{bot}$  variations.



**Figure 9.** Variation of the wave parameters (in %) reported between the no farm situation and the CS3 scenario, where: a)  $H_s$  variations; b)  $T_m$  variations; c)  $Dir$  variations; d)  $V_{bot}$  variations.



**Figure 10.** Variation of the wave parameters (in %) reported between the no farm situation and the CS4 scenario, where: a)  $H_s$  variations; b)  $T_m$  variations; c)  $Dir$  variations; d)  $V_{bot}$  variations.

## 4 Conclusions

The results presented in the present work highlight the coastal influence of several hybrid wind and wave farm configurations, which may operate in the vicinity of Saint George area, in the Romanian nearshore of the Black Sea. Several case studies were designed by using as a base an offshore wind farm, which has the same characteristics as the Greater Gabbard project from the UK, around which have been added several WECs deployed on a single or a two-line configuration.

An extreme scenario, associated with a winter storm, was considered for investigation and from the point of view of the operational limit of the workboats (set at 1.5 m) we can mention that no improvement was noticed in this direction, regardless of the case study considered for investigation. From the analysis of the spatial maps revealing the impact of marine farms in the target area, it was noticed that the shadow effect was induced only by the case studies CS2, CS3 and CS4, respectively.

Nevertheless, from the analysis of the values reported by the reference points P1-P9, it seems that only the presence of the offshore wind farm (the CS1 scenario) may influence the wave parameters, being reported a maximum 2% attenuation in the vicinity of the point P9 in the case of the parameters  $H_s$  and  $V_{bot}$ . As we go from the case CS1 to CS4, we can observe that the differences are more severe, being reported more consistent variations along the reference line 1, where a maximum value of 20% may be reported for the  $H_s$  parameter (CS2 scenario) compared to a 9% percentage reported for the  $Dir$  parameter (CS2 scenario). If the parameter  $V_{bot}$  decreases we expect to have an attenuation of the sediment movement since the bottom sediment will be less agitated.

Finally, it can be also mentioned that the work is ongoing, since at this moment there are no standard regulations regarding the layout of a wave farm, the main criteria being related to the optimal layout of the WECs in order to increase their energy efficiency. In general, these types of studies are focused only on the attenuation of the significant wave heights, but in fact by using multiple wave parameters it will be possible to provide a complete picture of the coastal impact induced by a marine energy farm.

## Acknowledgements

This work was carried out in the framework of the project ACCWA (Assessment of the Climate Change effects on the Wave conditions in the Black Sea), supported by the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding-UEFISCDI, grant number PN-III-P4-ID-PCE-2016-0028. The ERA20C data used in this study have been obtained from the ECMWF data server.

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