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Estimation of the Near Future Wind Power Potential in the Black Sea

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Abstract: The main objective of the present study is to quantify the recent past and explore the near future wind power potential in the Black Sea basin, evaluating the possible changes. Furthermore, an analysis of the wind climate in the target area was also performed. The wind resources have been assessed using the wind fields provided by various databases. Thus, the wind power potential from the recent past was assessed based two different sources covering each one the 30-year period (1981–2010). The first source is the ERA-Interim atmospheric reanalysis provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), while the second source represents the hindcast wind fields simulated by a Regional Climate Model (RCM) and provided by EURO-CORDEX databases. The estimation of the near future wind power potential was made based on wind fields simulated by the same RCM under future climate projections, considering two Representative Concentration Pathways (RCPs) scenarios (RCP4.5 and RCP8.5) and they cover also a 30-year time interval (2021–2050). Information in various reference points were analyzed in detail. Several conclusions resulted from the present work. Thus, as regards the mean wind power potential in winter season, in 51% of the locations a significant increase is projected in the near future (both scenarios). Besides providing a detailed description of the wind conditions from the recent past over the Black Sea basin considering two major sources, the novelty of the present work consists in the fact that it gives an estimation of the expected wind climate in the target area for the near future period and at the same time an evaluation of the climate change impacts on the wind speed and wind power potential.

Keywords: wind speed; wind power; Black Sea; EURO-CORDEX; ERA-Interim

1. Introduction

The global context generated by the rapid population growth and by the development of new technologies implies an increase in the energy needs. By combining this aspect with the actual energy producing capability, which uses mainly conventional methods (natural gas, lignite, petroleum, etc.) and has a negative impact to the environment, it results that it is urgently required to find effective methods of counteraction. From this perspective, the topic of energy remains an extremely important one [1]. Globally, many policies aiming to put into practice, on medium and long-term, methods for the energy sector development were adopted. In this way, the energy sector will become more efficient and sustainable. Developing and implementing energy policies is also an important condition in order to achieve strategic goals, which will propagate further in the economic development.

Various studies show that the feed-in tariff policy mechanism is really effective in fostering the sustainability transition of the energy sector and also to promote the investments in renewable energy [2,3]. Thus, the growth of renewable resource extraction (wind, wave, geothermal, photovoltaic, and hydro, etc.) for generating electricity is pursued in the detriment of the conventional methods.

For example, the European Union sets very specific targets for 2020 and 2030, as part of its long-term energy strategy, which covers the improved energy efficiency, emission reductions, and an increased share of renewables. An energy roadmap for the year 2050 has been also devolved. This aims to reduce the greenhouse gas emissions by 80–95% until 2050 when compared to the 1990 level. Through these energy policies, the European Union desires to ensure its citizens that they can access secure, affordable and sustainable energy supplies [4,5].

An example of good practice is followed by the Romanian Ministry of Energy, thought the energy policies. The Romanians energy strategy, according to the Ministry of Energy [6], covers a 15-year interval (2016–2030), with an outlook to 2050. According to this document, the energy policy covers the strategic goals, principles, main areas of state intervention and new directions for development. This trend is followed not only by the members of the European Union as Bulgaria [7] but also by countries like Georgia, Russia, Tukey, Ukraine, etc. The principles that all countries consider are: energy security, competitive market, consumer interests of first priority, transparency, smart grids and energy storage, smart buildings with energy self-sustainability and the most important is represented by the clean energy [8–12].

One of the most permanent and sustainable renewable resources is the wind energy. According to the European Wind Energy Association (EWEA), the wind energy potential extraction has gained more and more ground. By analyzing the EWEA annual reports it can be observed a substantial growth of the energy volume extracted. Since 2014, when the installed wind power capacity was 142 GW (about 92.2% onshore and only 7.8% offshore), to 2017 the onshore and offshore cumulative wind power installation grew by 18.8% (about 16.8% onshore and only 43.6% offshore). According to this statistic, Germany (56.1 GW), Spain (23.2 GW) and the United Kingdom (18.9 GW) together represent 58% of all the cumulative installed capacity of the European Union. In the middle of the rank are countries as: Romania (3 GW), Belgium (2.8 GW), Austria (2.8 GW), Greece (2.7 GW), Finland (2.1 GW) and Bulgaria (0.7 GW) [13].

However, a deep discrepancy between the EU countries can be observed, and this also regards the onshore versus offshore capabilities. In order to grow the offshore, wind energy exploitation it is required that researchers should find first the best new locations to exploit this green energy. The amount of land still available for the wind energy exploitation is becoming limited and there are also significant environmental issues. On the other hand, the offshore locations present some advantages, especially brought by the existence of large marine areas suitable for the wind farm development. The increase in wind speed with the distance from the coastline, together with the existence of less turbulence, allow for the turbines more energy extraction than the similar operating onshore [14,15].

The results of various previous researches indicate the fact that the Black Sea wind power potential cannot be neglected, especially for the countries located in the proximity of the sea [16]. From this perspective, the objective of this paper is to present a more complete picture of the wind energy potential of the Black Sea during the present and near future periods, by using two different data sources. The novelty of the present study also arises from the fact that such a detailed analysis has not yet been carried out for this area. A significant amount of researchers studied the green energy potential of the enclosed and semi-enclosed seas by using various techniques as reanalysis data, satellite data and climate models [14,17–22].

Davy et al. [23] carried out an analysis of the climate change impacts on wind energy potential in the European domain. The study was focused on the Black Sea and conducted by using a single-model-ensemble. The authors show that in the near future the wind intensity pattern in the Black Sea basin will not suffer relevant negative impact due to climate change. This feature would make the offshore wind-farms in the Black Sea to be a viable source of energy for the neighboring countries. Another important work that illustrates the wind power potential over the Mediterranean and the Black seas is performed by Koletsis et al. [24]. The authors analyzed by exploring six regional climate model simulations for the present period and two for the future periods. These models were produced in the framework of the ENSEMBLES project. The results for the Black Sea show that this basin is a suitable environment for the green energy extraction (average wind power being estimated in the range 500–900 W/m^2, with a deviation of $\pm$50 W/m^2 during the future periods).

Onat et al. [25] conducted an analysis of the wind climate and of the wind energy potential for several regions in Turkey. The authors analyzed also a small region of the Black Sea, located in the west (Amasra) by using a five-layer Sugeno-type ANFIS model developed with MATLAB-Simulink software. The relationship between the wind speed and other climate variables was also determined and the resulted data confirm that the Amasra region is a location with a good potential for the wind energy extraction. According to this study, the average power density at 10 m height is 232 W/m^2 (nearly good), at 50 m height is 603 W/m^2 (good) and at 80 m height is 1300 W/m^2 (very good).

The wind pattern of the Black Sea was also evaluated by Onea and Rusu [17], considering 12 years of data from the U.S. National Centers for Environmental Prediction (NCEP). In that study, the authors analyzed the wind power distribution taking into account the diurnal versus nocturnal variations. According to the above mentioned study, the northwestern and northeastern sectors of the Black Sea are the most suitable for wind energy extraction. The northwestern sector of the Black Sea was also analyzed by Lin-Ye et al. [26]. Their approach considered a hybrid methodology involving the Simulating WAve Nearshore (SWAN) spectral wave-model to produce wave-climate projections. The wave model was forced with wind-fields corresponding to the two climate change scenarios.

From this perspective, the present study aims to characterize the offshore wind power potential of the Black Sea during the present and the near future, by analyzing four databases. Following this objective, the structure of the proposed work includes first a presentation of the materials and methods considered, focused on the description of the target area and of the databases taken into account. The next section presents the results providing in some reference points the wind speed and also the wind power. These relate both the 30-year period considered from the past (1981–2010) and that estimated for the near future period analyzed (2021–2050). Finally, a discussion of the results was also carried out. Thus, the novelty of this paper can be summarized as follows:

1. A detailed description of the wind conditions over the Black Sea basin from two major sources (Era-Interim and Euro-Cordex) covering the recent past (1981–2010).
2. An estimation of the expected wind climate in the near future (2021–2050) under two different RCP scenarios (RCP4.5 and RCP8.5).
3. Evaluation of the climate change impacts on the wind speed and wind energy potential by performing comparisons between the past and the future projections.

2. Materials and Methods

2.1. Target Area

In this study, the target area is the Black Sea. The Black Sea basin is under the influence of the NAO (North Atlantic Oscillations) mechanism, which causes, due to the influence of the cold air arriving from the northern regions, significant storm events during the winter [27].

Figure 1 illustrates the Black Sea basin and the geographical locations of the reference points further considered. In this study, the wind speed at 100 m height was evaluated in twenty-four points. The reference points are divided into two different categories. The first category includes the shallow water locations. More precisely, these points are in the range 29–39 m water depth (average depth being 34.9 m) and the distance to shore in the range 1.5 to 56 km (average distance to shore being 11.8 km). The second category refers to the deep water locations. These points are relatively close to shore in the range 3.6 to 109 km (the average distance to shore being 35.7 km) and a depth in the range 114 to 140 m, with an average value for the depth of 125.8 m.

Taking into account some previous studies that showed the existence of various areas in the Black Sea presenting different wind conditions, the target area was divided into five geographical zones with similar characteristics/patterns, labeled from A to E. Zone A contains seven points related to the coastlines of Romania and Ukraine (shallow water: A.n.1 to A.n.4 and deep water: A.o.1 to A.o.3), zone B contains six points (shallow water: B.n.1 to B.n.4 and deep water: B.o.1 and B.o.2) related to the coasts of Bulgaria's and the northwest of Turkey. Zone C contains two shallow water points C.n.1 and C.n.2 and only one deep water point C.o.1 located in the north and northeast of Turkey, zone D contains five points associated to the coastal environment of Georgia and Russia (shallow water: D.n.1 to D.n.3, deep water points: D.o.1 and D.o.2) and zone E with three points close to the Crimea Peninsula (shallow water: E.n.1 and E.n.2, deep water: E.o.1) (see Tables 1 and 2).

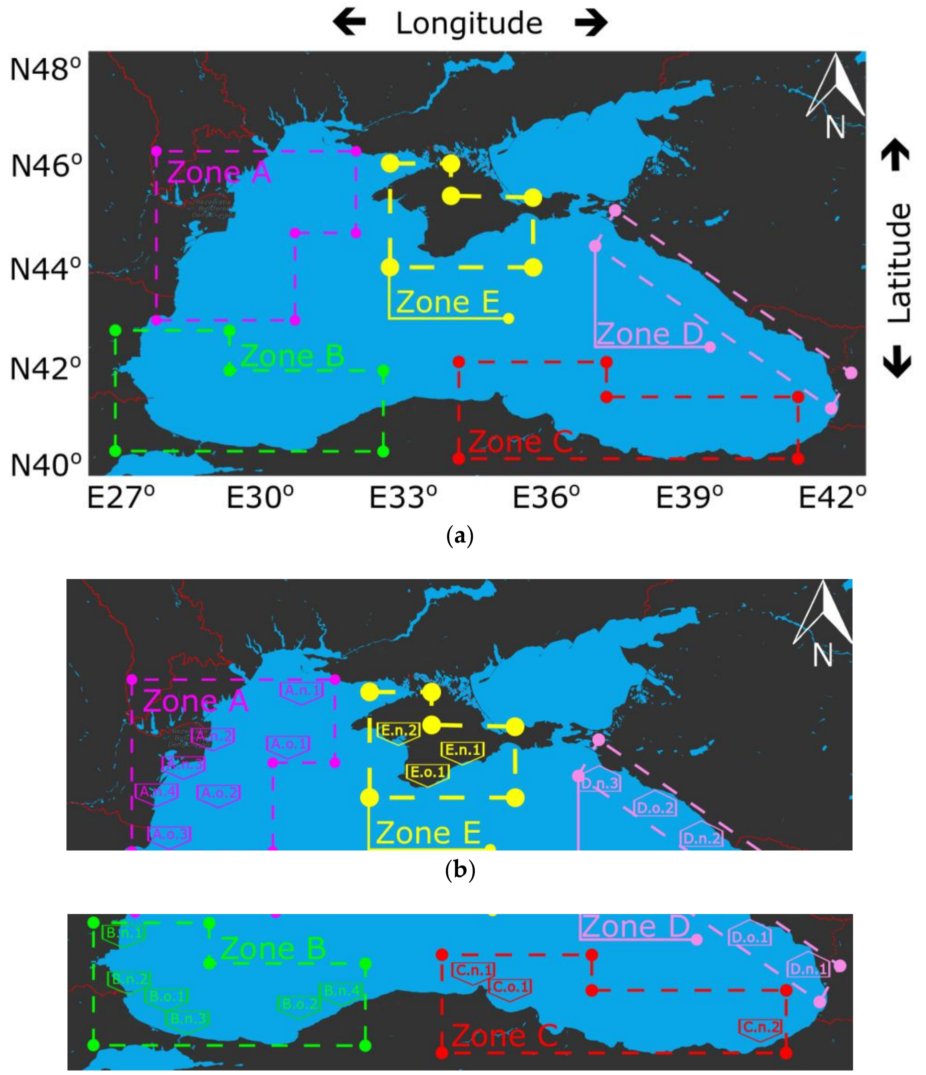


Figure 1. The geographical locations of the reference points corresponding to the 5 zones considered: zone A (shallow water points: A.n.1 to A.n.4 and deep water points: A.o.1 to A.o.3), zone B (shallow water points: B.n.1 to B.n.4 and deep water points: B.o.1 and B.o.2), zone C (shallow water points C.n.1 and C.n.2 and deep water point C.o.1), zone D (shallow water points: D.n.1 to D.n.3, deep water points: D.o.1 and D.o.2) and zone E (shallow water points: E.n.1 and E.n.2, deep water point: E.o.1); (**a**) Overview of the target zones; (**b**). The location of the points corresponding to zones A, E and a section of zone D; (**c**) The location of the points corresponding to zones B, C and a section of zone D.

Table 1. The geographical locations and the characteristics of the shallow water points.

Zone	Shallow Water Points	Latitude	Longitude	Sea Depth [m]	Distance to Shore [km]
A	A.n.1	45.75	31.50	38	56
	A.n.2	45.00	30.00	36	28.5
	A.n.3	44.50	29.40	39	33
	A.n.4	44.00	28.75	35	6.6
B	B.n.1	42.75	28.00	34	8.4
	B.n.2	42.06	28.06	36	5.6
	B.n.3	41.25	29.30	32	3.2
	B.n.4	41.65	32.15	39	2.3
C	C.n.1	42.11	35.00	39	2.9
	C.n.2	41.03	40.38	37	1.6
D	D.n.1	42.60	41.45	30	4.6
	D.n.2	43.85	39.35	37	3.2
	D.n.3	44.75	37.35	33	2
E	E.n.1	44.75	34.62	30	2.7
	E.n.2	45.00	33.35	29	16

Table 2. The geographical locations and the characteristics of the deep water points.

Zone	Deep Water Points	Latitude	Longitude	Sea Depth [m]	Distance to Shore [km]
A	A.o.1	44.75	31.50	128	101
	A.o.2	44.10	30.50	120	109
	A.o.3	43.35	29.15	114	47
B	B.o.1	41.70	28.75	123	13
	B.o.2	41.40	31.50	140	4.6
C	C.o.1	41.82	35.65	125	19
D	D.o.1	43.20	40.23	132	3.6
	D.o.2	44.34	38.30	125	5.6
E	E.o.1	44.25	34.10	126	18.3

2.2. ECMWF Dataset

One set of the data considered was obtained from the ERA-Interim database. This is a reanalysis project conducted by the European Centre for Medium-Range Weather Forecasts (ECMWF) [28]. ECMWF uses forecast models and data assimilation techniques that include a 4D analysis that has 12 h analysis windows to describe the atmosphere and oceans [29,30].

ERA-Interim is an ongoing project that comprises datasets with a various number of marine and atmospheric parameters from 1979 to the present. Among many data, it contains information about the wind speed components (u—zonal velocity and v—meridional velocity) at 10 m height. The wind speed at 10 m will be denoted as U_{10}. The data considered have a spatial resolution of 0.75° $\times$ 0.75°, cover a period of 30-years (1 January 1981 to 31 December 2010) and are dived in four hourly intervals (corresponding to 00:00:00, 06:00:00, 12:00:00, 18:00:00) for each day.

2.3. EURO-CORDEX Database

The Coordinated Regional Downscaling Experiment (CORDEX) initiated by the World Climate Research Program (WCRP), produces high-resolution 'downscaled' climate data through a global partnerships. EURO-CORDEX is the European branch of this project, where results from several RCMs were jointed to cover the European continent [31,32]. The data available have the spatial resolutions of 0.11° and 0.4°, respectively.

The EURO-CORDEX wind fields used in this study have a maximum range of 27° N $\div$ 72° N and 22° W $\div$ 45° E, with a spatial resolution of 0.11°. These data contain information about the wind speed components at 10 m height and are dived in four hourly intervals (corresponding to 00:00:00, 06:00:00, 12:00:00, 18:00:00) for each day. From this database, three types of wind fields were used in the present study. First, the evaluation (hindcast) wind fields that cover a period of 30-years (1 January

1981 to 31 December 2010) are analyzed. The wind fields are simulated by the Rossby Centre regional climate model—RCA4 model at the Swedish Meteorological and Hydrologic Institute (SMHI) and forced with initial and lateral boundary conditions provided by ECMWF ERA-Interim reanalysis data. The second and third datasets cover the 30-year interval 1 January 2021 to 31 December 2050, and there are wind fields simulated by the RCA4 model under future climate projections, considering two Representative Concentration Pathways (RCPs) emission scenarios, RCP4.5 and RCP8.5. More detailed information regarding the CORDEX scenarios for the European areas, as provided by the Rossby Centre regional climate model RCA4, are given in [33,34]. These two scenarios were simulated with the same RCM model as in the case of evaluation data, but forced by a Global Climate Model (GCM), namely EC-EARTH. In the global climate models, the related temporal evolution of atmospheric greenhouse gas and aerosol concentrations are prescribed, which then simulate the response of the climate system to the forcing. Thus, a range of potential future climate evolutions can be projected.

2.4. Data Evaluation

First, the data used in this study were evaluated in terms of daily, seasonal and yearly average. Both ERA-Interim and EURO-CORDEX databases provide the wind speed at 10 m height in terms of its components. For all the sites available and for all time scales various statistical analyses of the wind speed are conducted. Also, for each time series of the wind speeds the 5th and 95th percentiles were computed. The statistical parameters considered are the root mean square error, bias and the Pearson correlation coefficient. The root mean square error and bias are computed with the following relationships:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}, \tag{1}$$

$$Bias = \frac{\sum_{i=1}^{n}(x_i - y_i)}{n} \tag{2}$$

where n is the total number of data pairs, x is the wind speed provided by ERA-Interim, while y is the evaluation wind speed value.

Maintaining the same notation of the data, the Pearson correlation coefficient is computed with the next equation:

$$r = \frac{\sum\limits_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum\limits_{i=1}^{n}(x_i - \overline{x}) \cdot \sum\limits_{i=1}^{n}(y_i - \overline{y})}}, \tag{3}$$

where $\overline{x}$ and $\overline{y}$ are the mean values of the analyzed datasets.

The linear trend of the wind speeds was also estimated from a linear regression whose y dependent variable is represented by the wind speed time series, while the independent one is the time (x variable). The linear regression line has the following equation:

$$y = a + bx \tag{4}$$

where b is the slope of this line, and a is the intercept. The slope indicates the linear rate of wind speed change and its values can be positive or negative. A positive value corresponds to increasing trends while the negative value indicates a decreasing trend.

Taking into account that consistent wind speed measurements over the Black Sea basin are not available, a comparison between the present wind climate simulated by the RCM model with that resulted from a widely used reanalysis database is performed. In this way, the skill of the RCM wind fields to represent the present wind climate in the Black Sea basin can be determined.

Thus, the evaluation (hindcast) wind fields from EURO-CORDEX are compared with the wind fields from ERA-Interim reanalysis. The evaluation wind fields being provided by a RCM model, only statistical comparisons can be performed [35,36]. Near the Romanian coast, the wind speeds are recorded at an offshore platform, and the evaluation wind speeds were compared with these measurements by Rusu et al. [37].

3. Results

3.1. Wind Speed Analysis

This section provides a detailed analysis of the wind speed at 10 m height. First, comparisons between the present wind climate simulated by the RCM model with that resulted from a widely used reanalysis databases ERA-Interim were performed to evaluate the skill of the RCM model. Also, some comparisons between the wind fields simulated under RCP4.5 and RCP8.5 scenarios were performed in order to identify the differences induced by these two different scenarios. Actually, these are the most studied greenhouse gas concentration scenarios. Thus, RCP4.5 describes an intermediate concentration scenario with radiative forcing stabilized at around 4.5 W/m^2, while RCP8.5 describes a high concentration scenario under which the radiative forcing is expected to be higher than 8.5 W/m^2 by the end of the year 2100 [38,39]. On the other hand, the comparisons between the evaluation data and those obtained under various scenarios are indicating the possible further evolution of the wind conditions.

3.1.1. Hindcast Data

Figure 2 illustrates a comparative analysis in terms of maximum values, averages, 5th and 95th percentiles (lower than 5% and 95%) for the total time interval. In Figure 2a the values computed in each point for the present period are compared, considering the evaluation and ERA-Interim wind speeds. Some differences are observed between the magnitudes of the wind speeds. With the exception of the point B.n.3, located near the Bosporus Strait, the EURO-CORDEX Evaluation wind speeds are higher than those from ERA-Interim. The resulted values show that the difference is in average about 17% regarding the maximum computed values. At the same time, significant differences can be noticed regarding the total interval averages (12%) and for 95th (lower 95%) percentile analysis (14%).

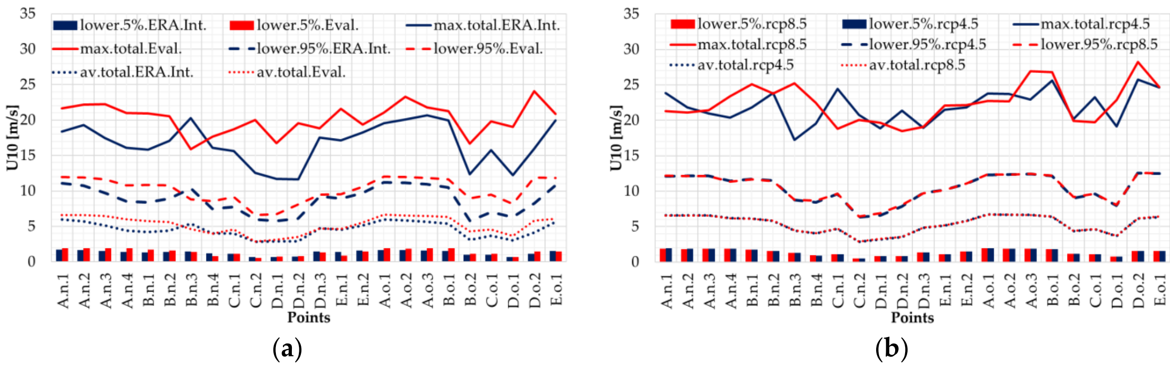


Figure 2. Analysis of the wind speed at 10 m ($U10$) height in terms of maximum values (max.total), average values (av.total), 5th percentile (lower.5%) and 95th percentile (lower.95%) values, corresponding to the reference points. (**a**) Comparison between ECMWF ERA-Interim (ERA.Int.) and EURO-CORDEX Evaluation (Eval.) wind speeds, for the 30-year period (1981–2010); (**b**) Comparison between EURO-CORDEX wind speeds corresponding to RCP4.5 and RCP8.5 scenarios for a 30-year period (2021–2050).

The analysis of the annual average values illustrated in Figures 3–6 (see also Figures A1 and A2) shows the fact that wind speed at 10 m height had and it is expected to have a different evolution in the areas considered. For instance, the data resulted in zone A (shallow water data, Figure 3) show that in the time interval 1981 to 2010, the wind speed has values varying in the range 4 to 7 m/s.

It can be noticed that the evaluation wind speed average values from RCM are higher than those from ERA-Interim. The difference is in a range of about 9% (point A.n.1) to 26% (point A.n.4).

Figure 4 illustrates two of the most representative shallow water points, close to the coastline of Bulgaria. By analyzing the data resulted for this area, it can be observed that in two points, the evaluation data are higher than ERA-Interim (point B.n.1: ≅ 26% and point B.n.2, not shown here ≅21%). In the case of the point B.n.3, the Evaluation data are lower with ≅ 16%. Regarding the point B.n.4, not shown here, both models (ECMWF ERA-Interim and EURO-CORDEX Evaluation) present similar behavior of the wind speed annual pattern evolution. According to the linear tendency, the annual means of the wind speeds show a different evolution for the period 1981 to 2010. As in zone A, in this zone the near future scenarios assess differently the wind speed pattern. Comparing the data from 1981–2010 with the near future interval for point B.n.1 it can be noticed a substantial increase of the wind speed. It is expected that the mean wind will reach values in the range of 5.7–6.6 m/s.

The wind speed analysis of two of the most representative deep water points located in zones A and B (A.o.1) and B (B.o.1) is presented in Figure 5. Regarding the deep water locations for zone A, the Evaluation wind speeds for the interval 1981–2010 are higher with approximately 9–12% than those from ERA-Interim. If zone B is analyzed, the difference between both data grows at about 15% to 29%. The data corresponding to the points associated with the coastline of Turkey are presented in Figure 6. By analyzing the data for the interval 1981–2010, in comparison with the data previously presented, it can be noticed that the wind is less intense in this area. Figure 6 also shows that according to both ERA-Interim and the Evaluation data, the mean wind speed has the tendency to increase from 1981 to 2010. No great variability of the annual averages along the entire 30-year interval is observed.

The wind pattern for the points D.n.3 and D.o.2 located in shallow water and deep water coastline of Russia, for the time interval 1981 to 2010 and 2021 to 2050 are illustrated in Figure A1. In this zone, there were analyzed initially five points (three in shallow water and two in deep water). In contrast with the previous cases, for the point located in shallow water (D.n.3), both ERA-Interim and Evaluation determined the same pattern for annual average values. This has not occurred in the case of the other points (D.n.1, D.n.2, D.o.1, and D.o.2). In these cases, the Evaluation data estimate higher wind speeds with about 8% (D.n.1), 17% (D.n.2), 47% (D.o.1) and 28% (D.o.2). By comparing the wind intensity for zone D with zone A, B, and C, here the lowest intervals in which the annual average wind speeds vary were encountered (D.n.1: 2.5–3.6 m/s, D.n.2: 2.5–4.1 m/s and D.o.2: 2.7–4.1). The wind speed at 10 m height was more intense in points D.n.3 (4.3–5.2 m/s) and D.o.2 (3.7–6.2 m/s).

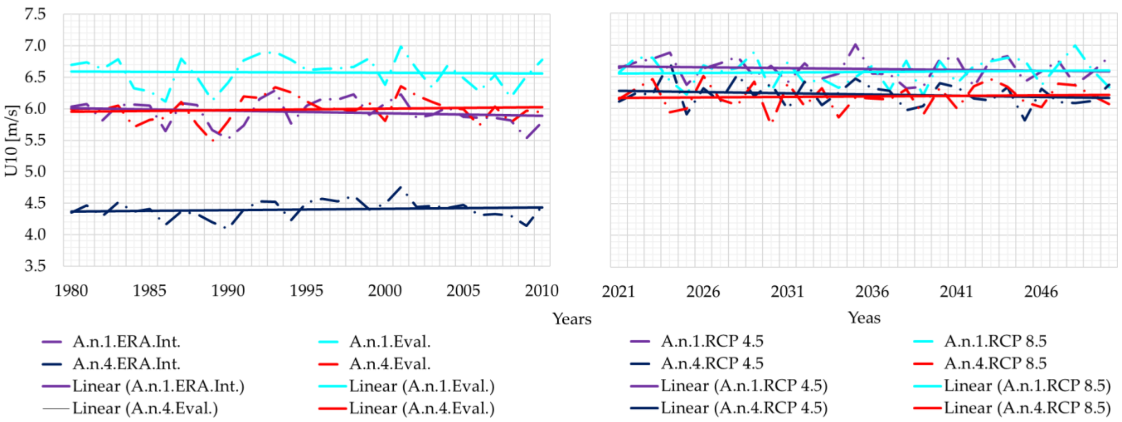


Figure 3. Annual averages of the wind speed at 10 m height for two of the most representative points located in the Romanian nearshore of. ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

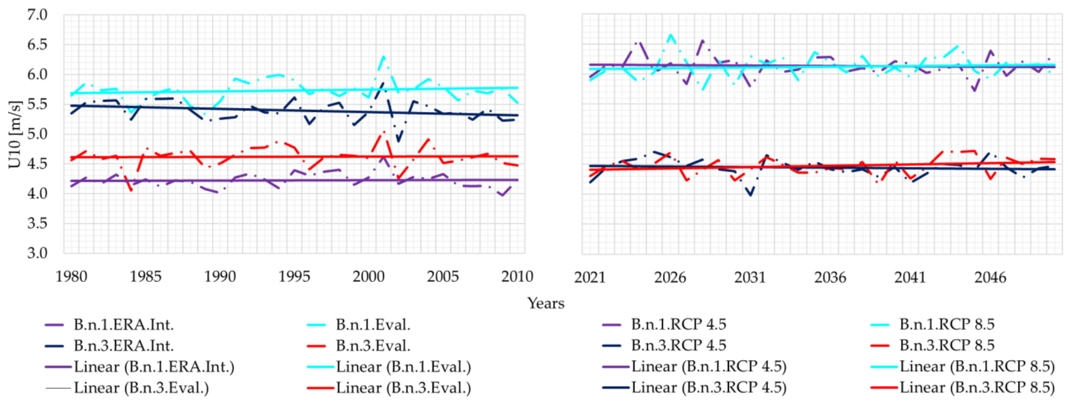


Figure 4. Annual averages of the wind speed at 10 m height for two of the most representative points located in the Bulgarian nearshore. ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

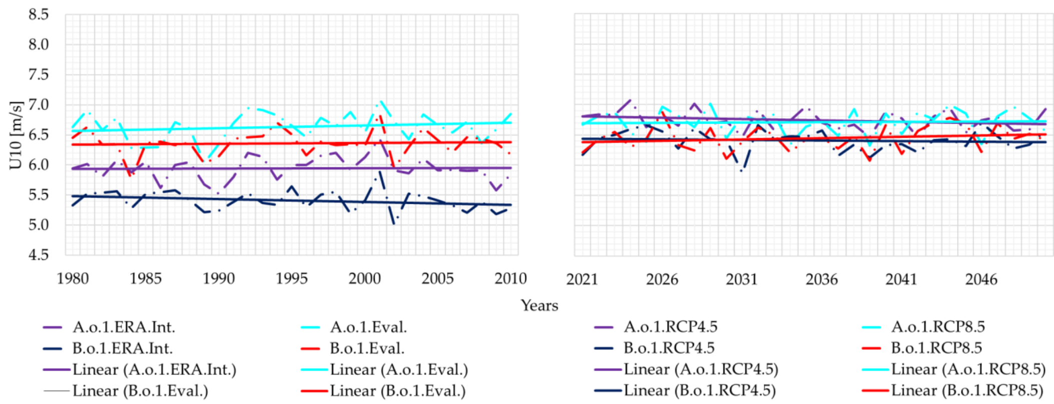


Figure 5. Annual averages of the wind speed at 10 m height annual averages for two of the most representative points located in deep water Bulgaria (B.o.1) and Romania (A.o.1). ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

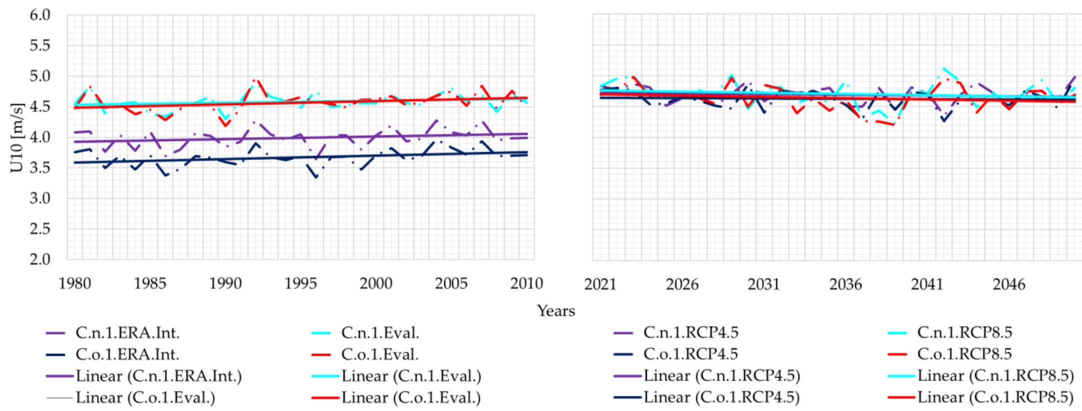
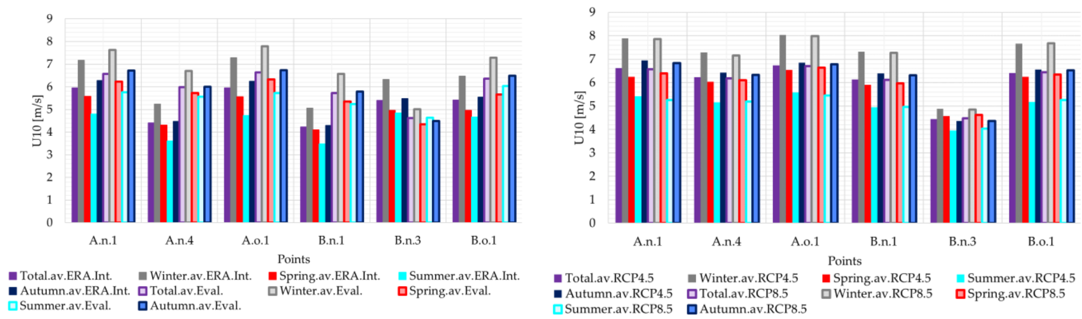


Figure 6. Annual averages of the wind speed at 10 m height for two of the most representative points located in shallow water (C.n.1) and in deep water (C.o.1) of Turkey. ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

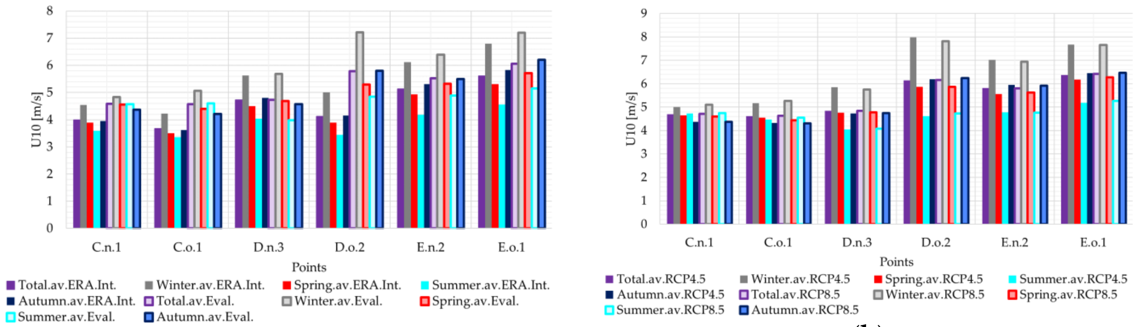
High wind speed values are encountered in the nearshore and offshore of the Crimea Peninsula. In this area, the wind speed at 10 m height was assessed for three locations, but here only the most representative results are presented. Thus, Figure A2 illustrates the annual averages of the wind speeds at 10 m height of two points located in shallow water (E.n.2) and deep water (E.o.1) of the Crimea Peninsula. By analyzing the time interval 1981–2010, it can be noticed that the wind has an uptrend evolution. Small differences are observed between both data. In the case of the point E.n.1, the Evaluation wind is higher with about 2.8%, for point E.n.2 with 7.1%, while for point E.o.1 with 7.3%.

The seasonal distributions of the wind intensity (total, winter, spring, summer, and autumn) are presented in Figures 7 and 8. By looking at these data, it can be noticed that during the winter the magnitude of the wind speed average is higher. In almost 90% of the cases presented, the wind speeds during the summer interval have the lowest values. For example, the points C.n.1 and C.o.1, which are located north of Turkey, have during summer wind speed averages almost as high as in the winter interval. However, it can be noticed that in these regions the difference between the seasonal averages is small.



(**a**) (**b**)

Figure 7. Seasonal wind speed averages at 10 m height compared with the total time averages for some representative points located in shallow water and deep water of Bulgaria and Romania coasts; (**a**) ERA.Int and Eval data, time interval 1980–2010; (**b**) RCP4.5 and RCP8.5 data, time interval 2021–2050.



(**a**) (**b**)

Figure 8. Seasonal wind speed averages at 10 m height compared with the total time averages for some representative points located in shallow water and deep water of Crimea Peninsula, Russia and Turkey coasts; (**a**) ERA.Int and Eval data, time interval 1981–2010; (**b**) RCP4.5 and RCP8.5 data, time interval 2021–2050.

The correlation level between the data provided by the ECWMF ERA-Interim databases and the EURO-CORDEX Evaluation climate model results is presented in Table 3 through the Pearson correlation coefficient. This analysis was performed considering the daily averages. By analyzing the data, it can be observed that the Pearson coefficient varies in the range 0.51–0.92. In order to evaluate the differences between the daily values, the root mean square error (RMSE) and the mean error (Bias) were also computed. The data presented in Table 3 show that RMSE is in the range 0.25–0.5 m/s. As regards the bias values, in all points they are negative (ranging from −0.25 to −0.06 m/s) indicating that the mean Evaluation wind speeds are higher than those computed for ERA-Interim.

According to the correlation levels defined in Table 4, it can be noticed that the correlation between both data ranges from a reasonable correlation to a very high correlation. More precisely, 71% of the data are in the interval of very high correlation, 25% are in the interval of high correlation and only 4% indicate a reasonable correlation. Thus, the lower RMSE and Bias values, together with the higher values of the correlation indexes, show that between the data provided by ERA-Interim and those from the RCM model there is a good agreement.

Table 3. Statistical evaluation in terms of the correlation coefficient (r) and RMSE for all 24 points.

Point	**A.n.1**	**A.n.2**	**A.n.3**	**A.n.4**	**A.o.1**	**A.o.2**	**A.o.3**	**B.n.1**	**B.n.2**	**B.n.3**	**B.n.4**	**B.o.1**
r	0.88	0.88	0.88	0.80	0.89	0.90	0.89	0.83	0.82	0.64	0.77	0.81
RMSE	0.43	0.43	0.42	0.38	0.45	0.44	0.43	0.40	0.40	0.37	0.27	0.50
Bias	−0.19	−0.19	−0.18	−0.14	−0.20	−0.19	−0.18	−0.16	−0.16	−0.14	−0.07	−0.23
Point	**B.o.2**	**C.n.1.**	**C.n.2**	**C.o.1**	**D.n.1**	**D.n.2**	**D.n.3**	**D.o.1**	**D.o.2**	**E.n.1**	**E.n.2**	**E.o.1**
r	0.76	0.51	0.88	0.65	0.80	0.92	0.88	0.91	0.90	0.68	0.87	0.90
RMSE	0.37	0.36	0.29	0.40	0.25	0.31	0.39	0.29	0.50	0.46	0.38	0.44
Bias	−0.14	−0.13	−0.09	−0.16	−0.06	−0.10	−0.15	−0.08	−0.25	−0.21	−0.14	−0.20

Table 4. Levels of interpretation of the Pearson correlation coefficient (r).

$r \in [0.8;1]$		$r \in [0.6;0.8)$		$r \in [0.4;0.6)$		$r \in [0.2;0.4)$		$r \in [0;0.2)$	
1	very high correlation	**0.79**	high correlation	**0.59**	reasonable correlation	**0.39**	poor correlation	**0.19**	very poor correlation
0.9		**0.7**		**0.5**		**0.3**		**0.1**	
0.8		**0.6**		**0.4**		**0.2**		**0**	

Based on the annual averages of the wind speeds, the linear trend in each point was computed and presented in Table 5. The ERA-Interim data shows a slight increasing (ranging from 0 to 0.132 m/s per decade) or decreasing (ranging from −0.054 to −0.002 m/s per decade) trends. The decreasing trends are found only in the western part of the Black Sea basin. These values of the linear trend are in line with those computed by Torralba et al. [40]. As regards the Evaluation data, in 23 points the linear trend has positive values from 0.004 to 0.119 m/s per decade.

Table 5. Linear trend (m/s per decade) values computed for all 24 points for recent past data.

Point	**A.n.1**	**A.n.2**	**A.n.3**	**A.n.4**	**B.n.1**	**B.n.2**	**B.n.3**	**B.n.4**	**C.n.1**	**C.n.2**	**D.n.1**	**D.n.2**
ERA-Interim	−0.041	−0.014	0.000	0.020	0.007	−0.021	−0.054	0.023	0.044	0.065	0.081	0.090
Evaluation	−0.012	0.024	0.050	0.024	0.029	0.019	0.004	0.007	0.034	0.065	0.086	0.107
Point	**D.n.3**	**E.n.1**	**E.n.2**	**A.o.1**	**A.o.2**	**A.o.3**	**B.o.1**	**B.o.2**	**C.o.1**	**D.o.1**	**D.o.2**	**E.o.1**
ERA−Interim	0.039	0.053	0.031	0.006	0.005	−0.002	−0.047	0.024	0.056	0.132	0.064	0.042
Evaluation	0.065	0.088	0.095	0.047	0.065	0.050	0.014	0.032	0.055	0.119	0.144	0.047

3.1.2. Future Projections

Another comparative analysis between the wind speeds projected by two of the future scenarios available in the framework of the EURO−CORDEX project, RCP4.5 and RCP8.5, is presented in Figure 2b. By analyzing Figure 2b it can be noticed that between both data no significant differences appear in terms of average values, 5th and 95th percentiles. On the other hand, major differences in the evaluation of the maximum wind speed values in the shallow water areas of Bulgaria and Romania are observed.

According to the near future data, both scenarios present approximately the same values in terms of annual averages, but with a lag of several years between the peaks. As previously presented, a slight difference occurs between the data from RCP4.5 and RCP8.5. In the case of zone A (deep water locations), the data for RCP4.5 scenarios are on average with 1% higher, while for zone B with almost 1% smaller than the 8.5 data. By conducting a comparative analysis of the shallow water and deep water locations for both zones A and B it can be concluded that there is no notable difference in terms of wind intensity.

The near future projections (time interval 2021–2050) near to the Turkish coast (see Figure 6) present similar average values of the wind speeds as those computed from the EURO-CORDEX Evaluation data for the present climate. The near future annual wind speed analysis does not highlight any trend. Moreover, the differences between the annual averages are lower than the previous cases.

Although the data for the interval 1981–2010 show an increase of the wind speed near to the Russian coastline (see Figure A1), both estimates an approximate constant pattern for the 30-year interval of the near future. Both RCP4.5 and RCP8.5 scenarios predict for the Crimea Peninsula region an increase of the wind at 10-m height (Figure A2).

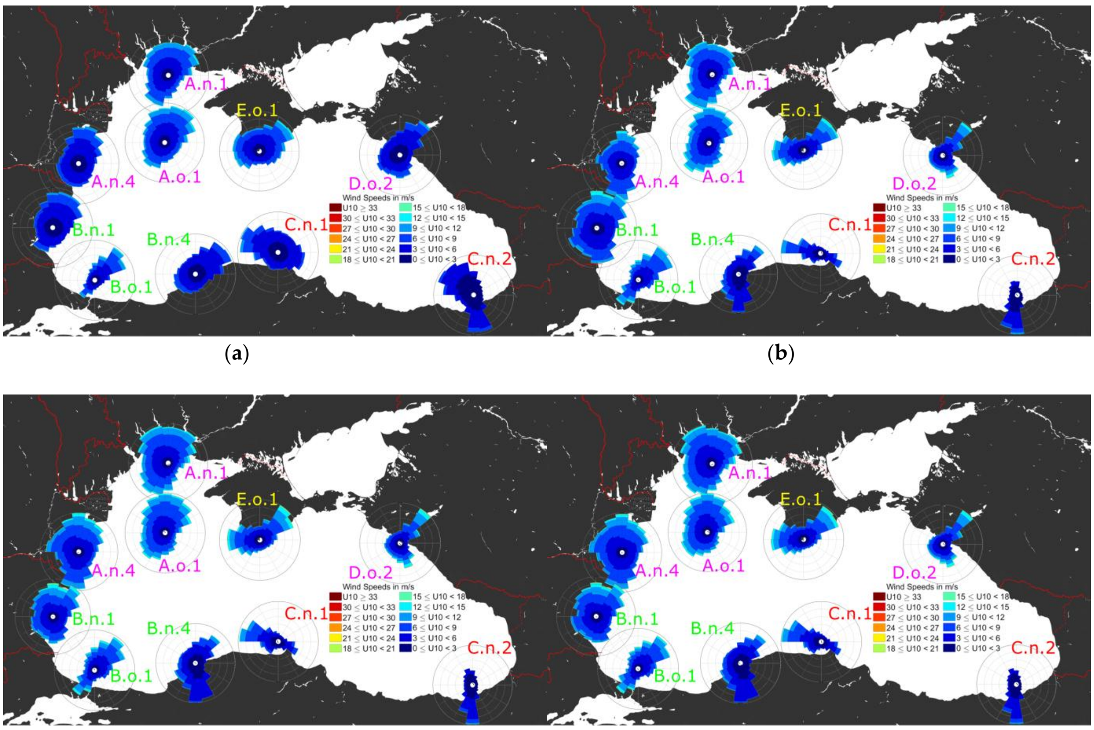
Regarding the linear tendency, for the 2021–2050 time period, the RCP4.5 scenario shows that the wind speed will have a low decrease while the RCP8.5 a small increase. The values of the linear trends computed for near future data are presented in Table 6.

Table 6. Linear trend (m/s per decade) values computed for all 24 points for near future data.

Point	**A.n.1**	**A.n.2**	**A.n.3**	**A.n.4**	**B.n.1**	**B.n.2**	**B.n.3**	**B.n.4**	**C.n.1**	**C.n.2**	**D.n.1**	**D.n.2**
RCP4.5	−0.026	−0.026	−0.040	−0.039	−0.013	−0.016	−0.022	−0.028	−0.021	−0.013	−0.013	−0.011
RCP8.5	0.016	0.023	0.016	0.015	0.025	0.018	0.044	0.016	−0.037	−0.027	0.008	0.010
Point	**D.n.3**	**E.n.1**	**E.n.2**	**A.o.1**	**A.o.2**	**A.o.3**	**B.o.1**	**B.o.2**	**C.o.1**	**D.o.1**	**D.o.2**	**E.o.1**
RCP4.5	−0.009	0.006	−0.023	−0.044	−0.042	−0.040	−0.018	−0.042	−0.012	−0.018	−0.011	0.002
RCP8.5	0.034	0.044	0.031	0.009	0.011	0.023	0.044	0.022	−0.041	−0.013	0.023	0.024

3.1.3. Directional Analysis

The four datasets analyzed contain information about the zonal and meridional velocities needed for analyzing the wind main directions from which the winds are blowing. From the wind roses presented in Figure 9, it can be observed the dominant direction and also the predominant wind speed range for all five zones studied. At a first sight, the data show that over the Black Sea there are two main wind patterns. The first pattern is more spread and it is observed in the northwest and west of the Black Sea basin. According to all the models considered, the main directions for these zones are north, northeast and southwest. However, it can be noticed that all three data from EURO-CORDEX show also that the wind blows quite often from the west. Moreover, the most frequent values of the wind speeds are in the interval 0 to 12 m/s.



(**a**) (**b**)

(**c**) (**d**)

Figure 9. Wind roses corresponding to 30-year of data (1981–2010) coming from: (**a**) ECMWF ERA-Interim and (**b**) EURO-CORDEX Evaluation; 30-year interval (2021–2050) coming from: (**c**) EURO-CORDEX RCP4.5 scenario and (**d**) EURO-CORDEX RCP8.5 scenario.

The second dominant wind pattern is narrower and occurs in the north, east, south, and southwest. However, in these zones, the wind has different directions. It can also be observed that the ERA-Interim datasets show a different wind direction pattern in comparison with the other three models for the points located north and northeast of Turkey, east of Russia and south of Crimea Peninsula. Nevertheless, the four datasets show an identical pattern for the point located in deep water, near the Bosporus Strait.

3.2. Wind Power Analysis

The near future projections of the wind power potential of the Black Sea for the time interval 2021–2050 were also computed and compared with those corresponding to the time interval 1981–2010. Nowadays, the typical hub heights for the offshore wind turbines are ranging about 100 m [41], and for this reason, the wind data at 10 m height need to be recompiled. In order to adjust the wind speed to a level of 100 m for assessing the wind energy potential and output energy generated by a certain turbine, a logarithmic method is used. This method assumes neutral stability conditions [42,43]:

$$U_{100} = U_{10} \cdot \frac{\ln \frac{z_{100}}{z_0}}{\ln \frac{z_{10}}{z_0}}, \tag{3}$$

where U_{100} represents the wind speed at 100 m height (in m/s), U_{10} is the wind speed at 10 m height, z_0 = 0.0002 m is the surface roughness of the sea surface [44,45], while z_{100} and z_{10} are the reference heights at 100 m and 10 m, respectively.

Assessing the wind energy potential implies using several key parameters as wind power density generated by a certain wind turbine [46]. The wind power density [W/m^2] potential per unit of swept area can be determined as follows:

$$P_{wind100} = \frac{\rho \cdot U_{100}^3}{2}, \tag{4}$$

where ρ is the air density (1.22 kg/m^3).

Figures 10 and A3 illustrates the annual wind power and the total time averages [W/m^2] for 12 of the most representative points considered in the Black Sea basin. As expected, for the present period (1981–2010), the wind power values computed considering the EURO-CORDEX Evaluation data are higher than those based on the ERA-Interim data, the difference ranging between 12 W/m^2 (D.n.3) to 285 W/m^2 (D.o.2). The graphs presented in Figures 10 and A3 show that, in general, the evolution of the annual averages for both emission scenarios considered presents a similar pattern, while the wind power average values computed for the entire interval are very close.

In order to evaluate the near future evolution of the wind power averages, a comparison between the values computed based on data from RCP4.5 and RCP8.5 scenarios and those that represent the present data (Evaluation data) is performed. An increase of the averages is observed in the near future, except in the case of the point B.n.3. At this point, besides the fact that the average will decrease, the variability of the annual averages along the entire 30-year interval is lower by comparison with the 1981–2010 data. In Figures 10 and A3, the wind power potential computed in 4 points (A.n.4, B.n.1, D.o.2, and E.o.1) shows a significant increase for the near future, while in the case of 7 points (A.n.1, A.o.1, B.o.1, C.n.1, C.o.1, D.n.3, and E.n.2) a slight increase is noticed.

According to the wind power averages computed for the near future, it results that the most energetic zones of the Black Sea seem to be located in the northwest (points A.n.1 and A.o.1), southwest (point B.o.1), east (point D.o.2) and the Crimea Peninsula (point E.o.1). More precisely, in these points, the averages computed for the 30-year period are higher than 500 W/m^2. Regarding zone A, the higher increase of the average wind power in the near future is observed in point A.n.4 (Figure 10b), where this will pass the level of 400 W/m^2, while in the present it is below this threshold.

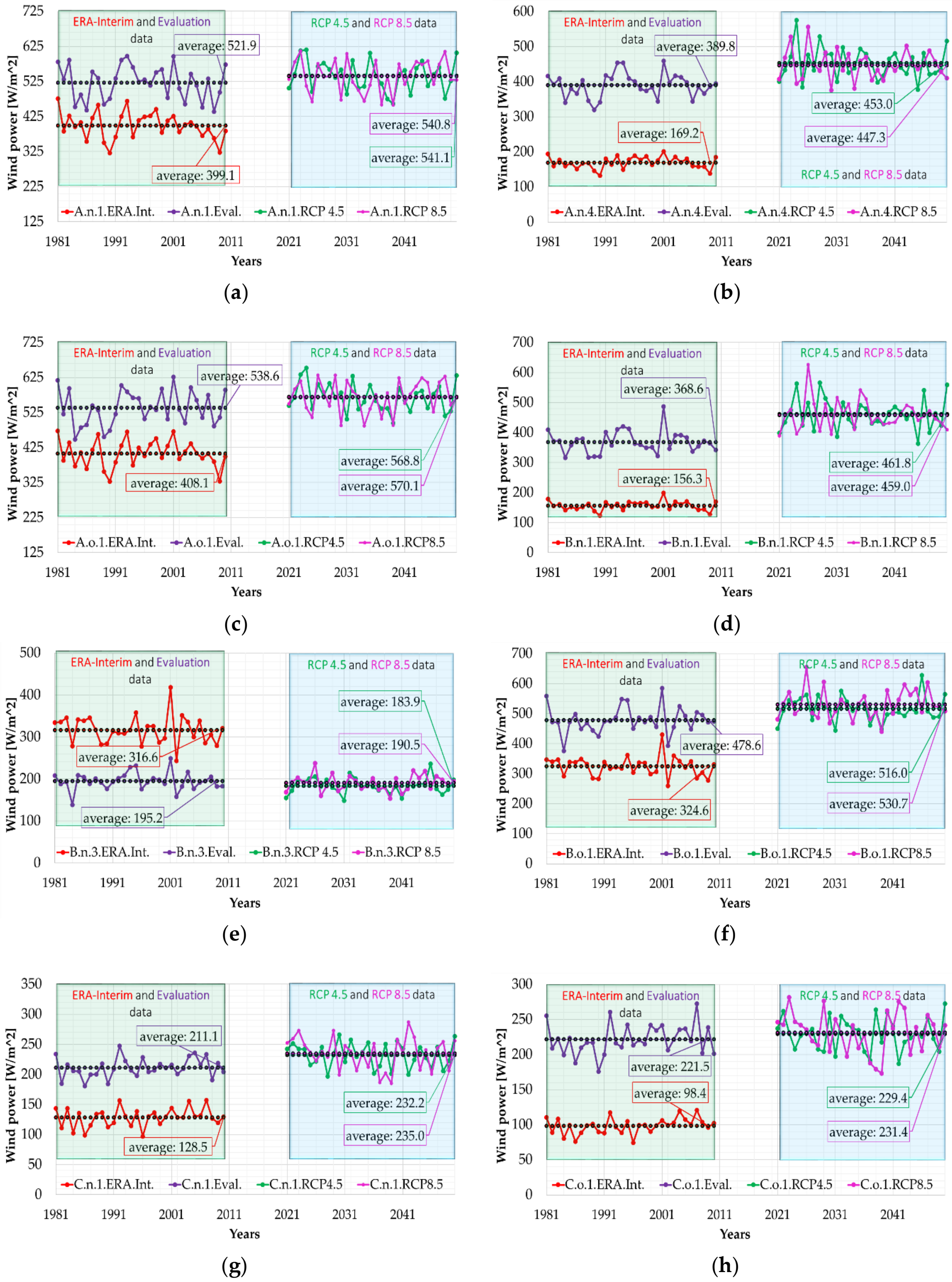


Figure 10. Annual wind power averages at 100 m height for 8 representative points: (**a**) A.n.1; (**b**) A.n.4; (**c**) A.o.1; (**d**) B.n.1; (**e**) B.n.3; (**f**) B.o.1; (**g**) C.n.1; (**h**) C.o.1.ERA.Int and Eval data, time interval 1981–2010; RCP4.5 and RCP8.5 data, time interval 2021–2050. For each dataset, the average of the wind power corresponding to the entire time interval is indicated in the box.

Regarding the zone B, two opposite cases are noticed. The averages for the points B.n.1 and B.o.1 present a significant increase. Thus, the wind power average for B.n.1 (Figure 10d) exceeds the value of 400 W/m^2, while in the case of the point B.o.1 (Figure 10f) this will be higher than 500 W/m^2. As above mentioned, an opposite behavior is found in the point B.n.3 (Figure 10e), which is located near Bosporus Strait. In the case of zone C, points C.n.1 (Figure 10g) and C.o.1 (Figure 10h), no major changes seem to be encountered in terms of the wind power averages. They will be maintained near the threshold of 200 W/m^2. As regards the reference points from the zone D, the higher increase in the average wind power is observed at the point located in deep water, D.o.2 (Figure A3b). This point represents in fact one of the most energetic locations in the Black Sea basin.

Another zone that can have a significant impact on the wind energy exploitation is zone E, situated near the Crimea Peninsula. Here, the data in the points E.n.2 (Figure A3c) and E.o.1 (Figure A3d) were studied in more detail. By analyzing these data, it can be observed that even though these two points are relatively close, the growth of the average value is higher in the deep water point E.o.1 (about 100 W/m^2), than in the shallow water point E.n.2.

The wind power averages at 100 m computed for the entire 30-year period and corresponding to the 12 reference points are now compared with the seasonal values, the results being presented in Figure 11. In this analysis, the four datasets available are also considered. The results clearly show that the winter averages are the highest, while the least energetic season is the summer. The other two seasons present almost equal values of the wind power averages.

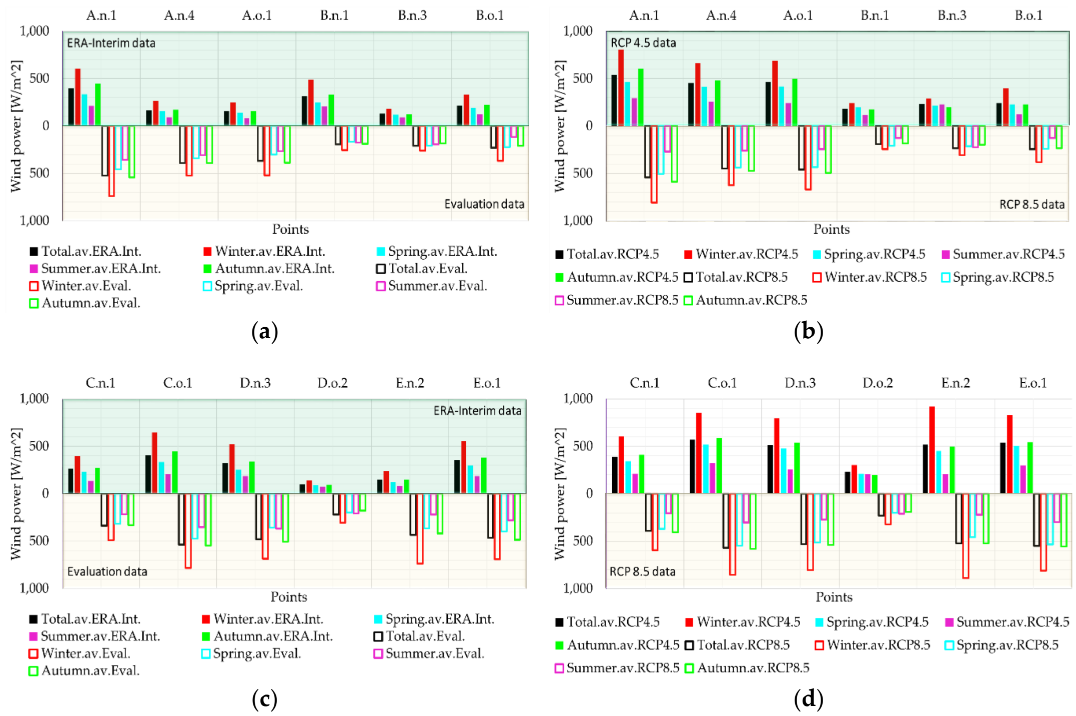


Figure 11. Seasonal wind power averages at 100 m height compared with the total time averages for 12 points considered the most representative. ERA.Int and Eval data, time interval 1981–2010; RCP4.5 and RCP8.5 data, time interval 2021–2050. Points A.n.1, A.n.4, A.o.1, B.n.1, B.n.3 and B.o.1: (**a**) ERA.Int and Eval data, (**b**) RCP4.5 and RCP8.5 data; Points C.n.1, C.o.1, D.n.3, D.o.2, E.n.2 and E.o.1: (**c**) ERA.Int and Eval data, (**d**) RCP4.5 and RCP8.5 data.

4. Conclusions

From the comparative analysis of the wind speed at 10 m over the sea level simulated by RCM from EURO-CORDEX, the RCA4 model respectively, against the data existent in ERA-Interim database, a good correlation was noticed between these two datasets in the Black Sea area. On the other hand, probably due to the fact that the spatial resolution of the RCM model is higher than that from ERA-Interim, the wind speeds provided by RCA4 in the reference points considered in the Black Sea basin are slightly higher than those indicated by ERA-Interim.

The analysis of the wind speed annual averages shows that the wind speeds at 10 m height have a different evolution in the areas considered in the Black Sea. In general, for the present period, it was observed that the Evaluation wind speed averages are higher than those from ERA-Interim with values ranging from 0.06 to 0.25 m/s. Through the linear trend, it was observed that in 75% of the cases both data have the same trend (upward trend—the maximum value is 0.144 m/s per decade).

The daily averages of the wind speeds provided by both databases present a very good correlation. The Pearson correlation coefficient varies in the range 0.51 to 0.92. More precisely 71% of the data are in the interval of very high correlation, 25% are in the interval of high correlation and only 4% have a reasonable correlation. The differences between the daily values were assessed by the analysis of the root mean square error and Bias. The results of the analysis show that RMSE is in the range 0.25 to 0.50 m/s, while the bias values, in all points they are negative (ranging from −0.25 to −0.06 m/s). Thus, the low RMSE and Bias values together with the higher values of the correlation indexes show that there is a good agreement between the data provided by ERA-Interim and those from the RCM model (Evaluation data).

As the results of the present work show, in most of the cases there are no relevant differences in the average wind speeds (smaller than 0.4 m/s) simulated under both scenarios. This is probably due to the fact that until the mid-century the differences between the two RCPs considered are not very high. According to the near future data, both scenarios present approximately the same values in terms of annual averages. Regarding the linear tendency for the period 2021–2050, the RCP4.5 scenario shows that the wind speed will have a low decrease in 92% of the points (values ranging from −0.044 to −0.009 m/s per decade) while the RCP8.5 a small increase in 83% of the cases (values ranging from 0.008 to 0.044 m/s per decade).

As regards the average wind power potential in winter season, for 51% of the reference points a significant increase was observed for the near future (both scenarios) compared with the present values, while for 41% only a slight growth. For both scenarios, a small decrease was noticed only in the point B.n.1. The most energetic zones of the Black Sea are the western part of the basin (northwest and southwest areas) and also in the east and south of the Crimea Peninsula. More precisely, in these points, the total wind power averages for the 30-year time interval are higher than 500 W/m^2. As expected, in the winter time the higher wind speeds and wind powers are encountered, while the lower values are found in the summer.

The fact that it was noticed an increase of the mean values of the wind resources in 95.6% of the reference points considered in the Black Sea, either under the RCP4.5 or RCP8.5 scenarios, can be considered beneficial from the perspective of the wind projects and this can give momentum to the installation of the wind farms in the areas already identified as having a good potential, as for example the western side of the basin. From this perspective, it is well known that some European areas are affected by a decrease of the wind resources (see for example [35,47,48]).

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

av.total	average value
CORDEX	Coordinated Regional Downscaling Experiment
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA.Int.	ERA-Interim wind fields from ECMWF
EURO-CORDEX	European branch of CORDEX
Eval.	EURO-CORDEX Evaluation wind fields
EWEA	European Wind Energy Association
GCM	Global Climate Model
lower 5%	5th percentiles analysis
lower 95%	95th percentiles analysis
max. total	maximum values
NAO	North Atlantic Oscillations
NCEP	US National Centers for Environmental Prediction
$P_{wind100}$	wind power at 100 m height
r	Pearson correlation coefficient
RCA4	Rossby Centre regional climate model
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RMSE	root mean square error
u	zonal wind velocity
U_{10}	wind speed at 10 m height
U_{100}	wind speed at 100 m height
v	meridional wind velocity
z_{10}	reference height at 10 m
z_{100}	reference height at 100 m
WCRP	World Climate Research Program
WMO	World Meteorological Organization

Appendix A

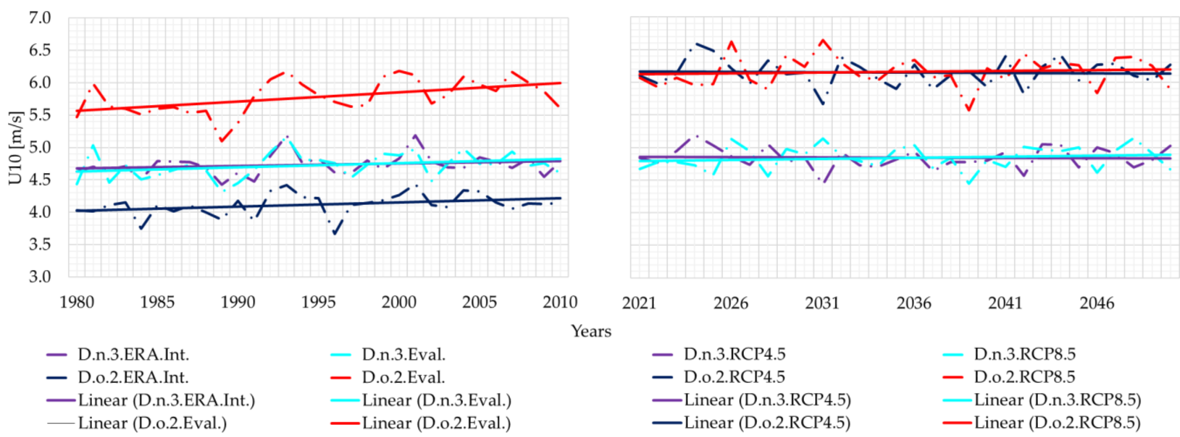

Figure A1. Annual averages of the wind speed at 10 m height for two of the most representative points located in shallow water (D.n.3) and in deep water (D.o.2) of Russia. ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

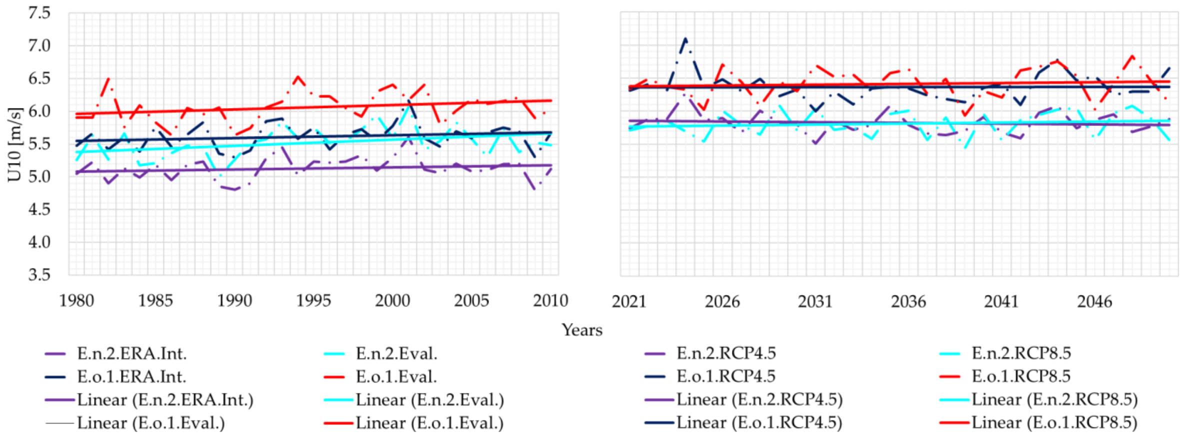

Figure A2. Annual averages of the wind speed at 10 m height for two of the most representative points located in shallow water (E.n.2) and in deep water (E.o.1) of Crimea Peninsula. ERA.Int and Eval data, time interval 1981–2010, RCP4.5 and RCP8.5 data, time interval 2021–2050.

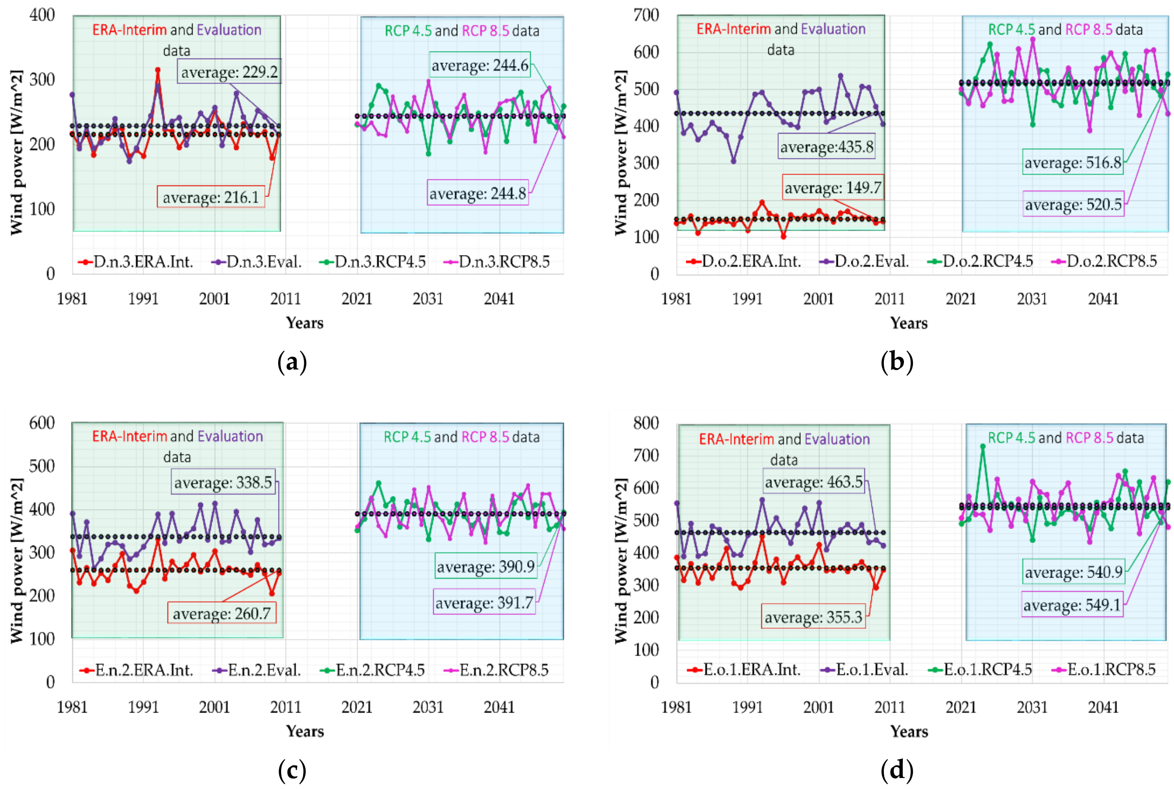

Figure A3. Annual wind power averages at 100 m height for the points: (**a**) D.n.3, (**b**) D.o.2, (**c**) E.n.2 and (**d**) E.o.1. ERA.Int and Eval data, time interval 1981–2010; RCP4.5 and RCP8.5 data, time interval 2021–2050. For each dataset, the average of the wind power corresponding to the entire time interval is indicated in the box.

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