A Projection of the Wind Energy in the Black Sea along the 21st Century

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Abstract. The objective of this study is to assess the future wind power potential in the Black Sea based on the wind fields provided by the most recent regional climate projections achieved in the framework of EURO-CORDEX project. The climate change impacts on the wind speed magnitude will bring changes in the local wind power generation. From this perspective, changes in the wind power potential along the 21st century in some reference locations of the Black Sea basin are investigated under the RCP4.5 scenario. The recent wind power conditions for a 30-year period (1976-2005) are assessed based on the results provided by the same RCM (Regional Climate Model) used to generate the future climate projections of the wind fields. The impact of the climate change on the future wind power potential is evaluated by comparisons between historical data and near-future (2021-2050) and more distant future (2071-2100) projections. Under the scenario considered, an increase of the mean wind power was observed until the middle of the 21st century, followed by a small decrease. From the seasonal analysis resulted that, in the reference points located on the western side, the projection of the wind energy in winter time suggests an increase until the end of the century. On the other hand, the linear regressions adjusted to the annual means do not indicate a significant trend.

1 Introduction

In the last years, renewable power capacity installations have an increasing trend in Europe, and the wind power is one of them with the highest growing in 2017, exceeding all estimates [1]. All new wind power installations in 2017 accounted for 55.2% (15.6 GW), followed by solar PV with 21.5% (6 GW). In the EU, the annual increased of the wind power installations have a steady trend over the past 12 years, with three countries (Germany, Spain and UK) covering together more than half of all wind power installations [2,3].

According to a study of International Renewable Energy Agency (IRENA) [4], the role of offshore wind power in providing clean and affordable energy is also increasing due to the decrease of its levelized cost of electricity (LCOE). Besides other factors, the increase of turbine size helps the cost reductions due to the increase of the wind output. In the same study is mentioned that in the North Sea and the Atlantic Ocean are installed 90% of the global offshore wind capacity. Thus, last year in September the world's largest offshore wind farm located in the Irish Sea became operational, besides others Europe's offshore wind big capacities installed in the UK, Germany and Denmark. The expansion of this market is growing and it is moving beyond the European leaders to other continents where various countries have plans to develop their offshore wind capacities.

Although the installation of the offshore wind farms is moving nowadays farther from shore, into deeper water, in search of areas with better wind resources (water depths of up to 40 meters and as far as 80 kilometers from shore), however, there are still some limitations because the turbines are rooted in the seabed. The new technological developments of the floating offshore wind projects will induce also a new dynamics for this industrybringing an increase of the economic potential of the offshore wind technology [5]. Taking into consideration that the wind energy resources have no uniform distribution over regions or seasons, long-term evaluations of these resources in the areas of interest are absolutely necessary. Nowadays, the data regarding the wind speeds in the target areas can come from various sources. The availability of site observational data is often limited. Even when they are available, there are limitations in terms of both time and surface coverage.

The progress made in satellite measurements has led the development of the surface wind observational databases over large areas that are now increasingly used for the offshore wind power evaluations [6,7]. The development of the new computing capacities for numerical modelling is creating the possibility to be carried out long-term simulations used widely for the evaluation of the offshore wind resources [8-12]. Recently, in the context of the climate change, simulations of the future wind fields were carried out under different scenarios and various studies analyzed the impact will bring in offshore wind exploitation [13-15].

In this study, the changes in the wind power potential along the 21st century in some reference locations of the

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Black Sea basin are investigated under RCP4.5 scenario [16]. Such greenhouse gas emission scenario corresponds to a stabilization of radiative forcing after the 21st century at 4.5 W/m². The impact of climate change on future wind power potential is evaluated by comparisons between historical data (1976-2005) and near-future (2021-2050) and future (2071-2100) projections

2 Wind climate in the Black Sea

The Black Sea is a semi-enclosed basin (Figure 1) connected to the Mediterranean Sea (Bosporus Strait) and Azov Sea (Kerch Strait). Generally, the wind features in semi-enclosed/enclosed basins are complex and high resolution wind fields (temporal and spatial resolution) are necessary for an accurate evaluation of them [17].

The wind fields simulated by the same Regional Climate Model (RCM), namely the Rossby Centre regional climate model – RCA4 model [18] from SMHI (Swedish Meteorological and Hydrologic Institute) are used in this study. These high-resolution wind fields (spatial resolution of 0.11°, temporal resolution 6-hour) are provided by the EURO-CORDEX database [19,20], the European branch of the Coordinated Regional

Downscaling Experiment (CORDEX). The RCA4 model was forced with initial lateral boundary conditions provided by EC-EARTH Global Climate Model (GCM).

The wind fields contain information about the wind speed components at 10 m above the sea level (U_{10} denotes the wind speed) and three different analyses have been carried out based on them. The first analysis is related to the recent wind fields for a 30-year period (1976-2005), denoted as historical data. The second and third analyses are related to the projections of the wind fields under RCP4.5 scenario for the near-future (2021-2050) and future (2071-2100).

The evaluation of the wind climate is made in 20 reference points represented in Figure 1 by black circles. In the foreground, the grid points corresponding to water depths between 25-60 m are represented with red colour, the points located in depths ranging 60-95 m are marked with green colour, while the points corresponding to depths between 95-130 m are represented with yellow. The 9 reference points located in the nearshore (red zone) are noted counter-clockwise with N, the 7 points that are in middle depth water (green zone) and the last 4 points from deeper water are noted with M and O, respectively.
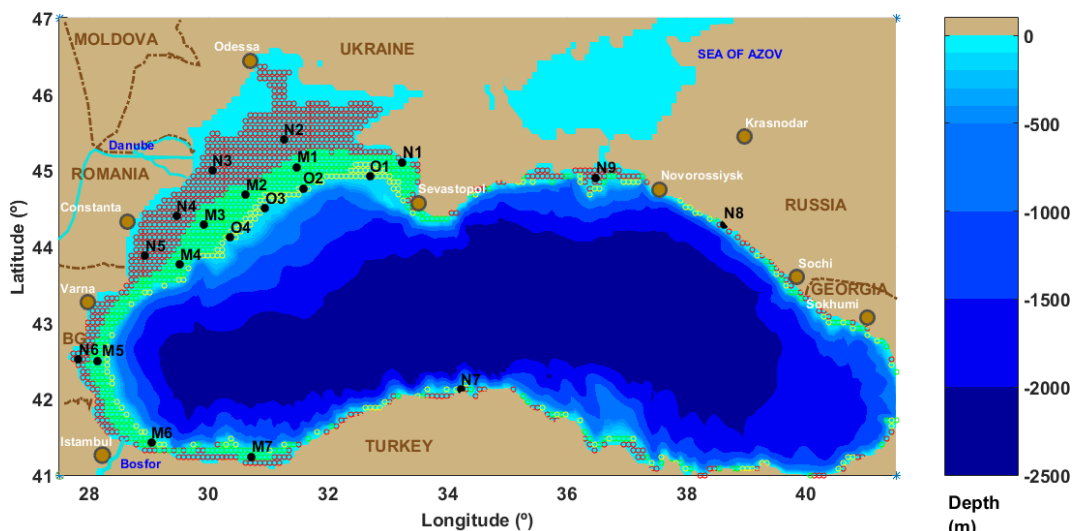

Fig. 1. The bathymetric map of the Black Sea basin and the location of the reference point used for local evaluation.
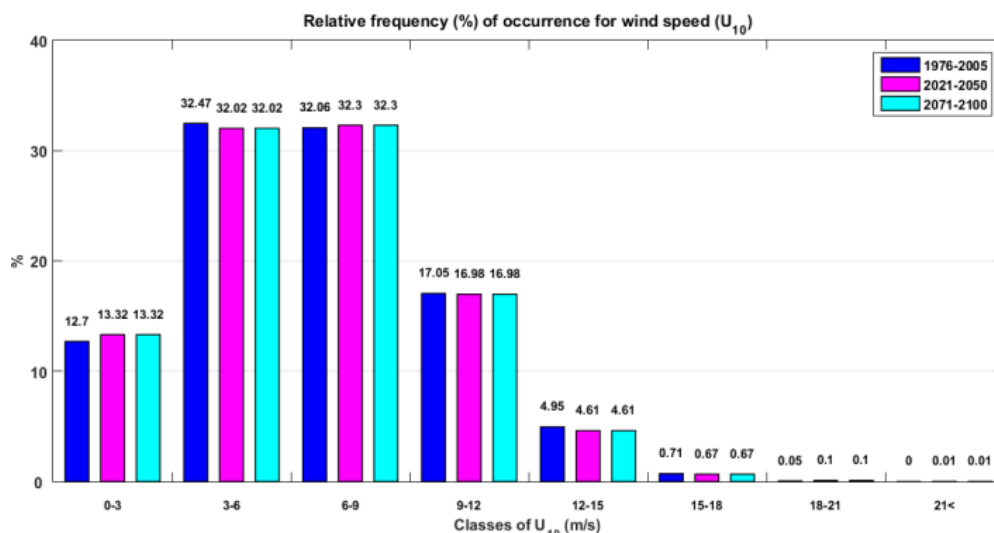

Fig. 2. Comparisons between U_{10} classes simulated at the location M3 for the three 30-year time slices considered.
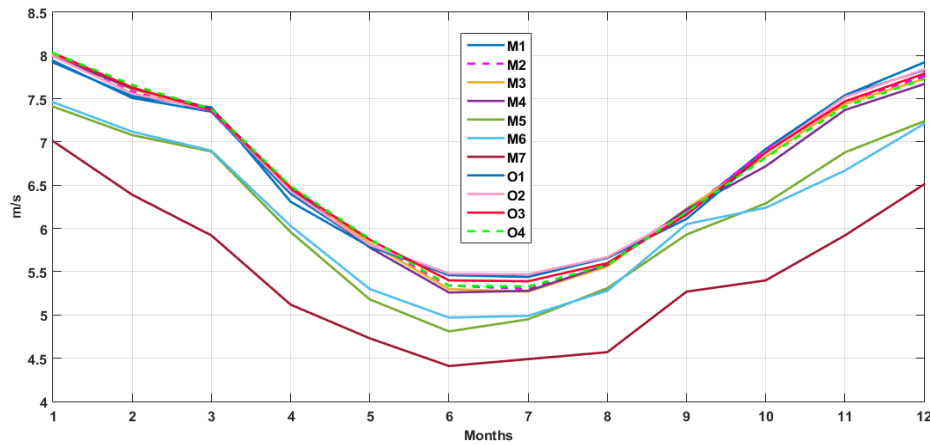
Fig. 3. Monthly variations of the U_{10} means in 11 reference points located in the middle and deep water depths (denoted by M and O) for the historical period (1976-2005).
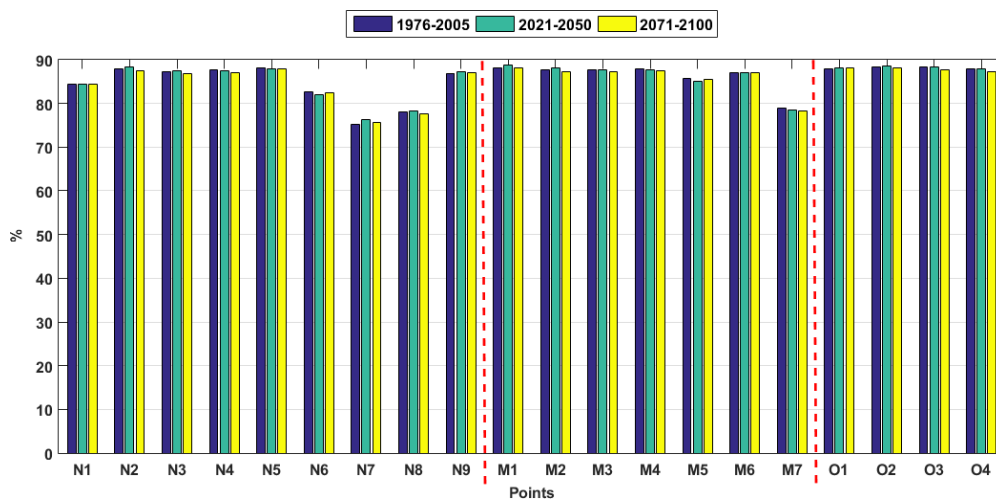

Fig. 4. Percentage of the wind speeds (U_{80}) in the range between the cut-in and cut-off values (functional range 3.5-25 m/s) in all reference points

Figure 2 presents a comparison between the wind speeds simulated for historical period and those for near-future and future periods at the location M3. The comparison of the U_{10} classes shows that the relative frequency of occurrences has similar values for all three periods, only for the class 0-3 m/s higher values (about 0.6%) there are in case of both projections, compared with historical wind speeds. The same feature was also observed in all other points (not shown here).

It is well known that in the Black Sea monthly/seasonal variability of the wind speeds exists [21]. For this reason, an evaluation of the monthly variation of the U_{10} means was made. In Figure 3 the graphs corresponding to the points located in the middle and deep water depths (11 points) are represented for the historical period (1976-2005).

From Figure 2 it can be observed that in the months December and January the U_{10} means are around 7.5-8 m/s in all points (except in M7), while in summer June and July the means are between 4.5-5 m/s.

3 Assessment of the wind power

The wind power density P (W/m^2) per unit of the swept area is computed based on the information regarding the wind speed using the relationship [22]:

$$P = \frac{1}{2}\rho_{air}U_z^3 \tag{1}$$

with ρ_{air} the air density has the value of 1.225 kg/m3 and U_z being the wind speed at a height z.

Because the wind speed at a height of 10 m over the sea level is usually provided by databases, it will be necessary to extrapolate it at the height where the wind turbines are estimated to operate. In the last years, the typical height for offshore wind exploitation has grown at around 80 m [23]. The wind speed at a high level can be computed using a logarithmic law [24]. This approach established that the wind speed U_z (in the present case z is considered to be 80 m) can be expressed as:

$$U_z = U_{zref}\frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)} \tag{2}$$

where U_{zref} is, in fact, the known wind speed U_{10} at the height z_{ref} (in this case 10m), while the value of the sea surface roughness length z_0 is taken 0.0002 m over the sea.

Based on time series of wind speed U_{10} available in each reference point, U_{80} and the correspondent power density P are computed. In this way, for each reference point, three time series of U_{80} and P have resulted, corresponding to the three 30-year periods considered in this study. Depending on the wind turbine characteristics, the electrical power is produced only for a range of wind

speeds defined by the cut-in and cut-off values that in general are ranging between 3.5-25 m/s [25].

Considering the U_{80} values, the percentage of the wind speeds inside the functional range conditions was computed in all reference points and Figure 4 shows the results obtained. As expected, the highest percentages are in all points located in deep water (higher than 85%), but in some other points comparable percentages can be found (e.g. N2-N5 and M1-M5). However, must be highlighted that all these points are located in the western part of the Black Sea basin.

The next of the wind power analysis is represented by the evaluation of the same statistical parameters that will give us an indication of the wind power potential in the target area. The statistical parameters considered are: Mean - mean value, Max - maximum value, Std - standard deviation, 50th and 95th percentiles and they were computed based on their standard definitions. The results obtained for mean and standard deviation are presented in Figure 5, while those related to 50th and 95th percentiles in Figure 6. For some selected reference points these statistics can be found also in Table 1.

The identification of some trends existing in wind power evolution is also important. This can be observed using the annual means of the wind power, some results are presented in Figure 7 for the point M3.
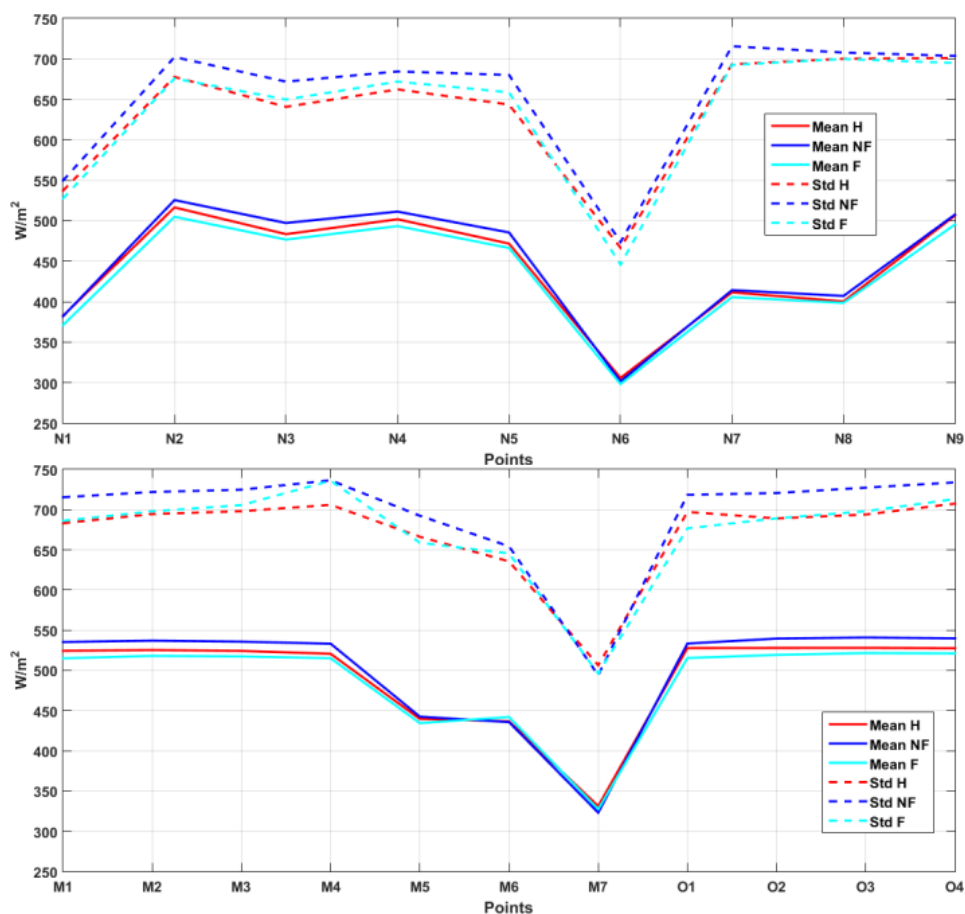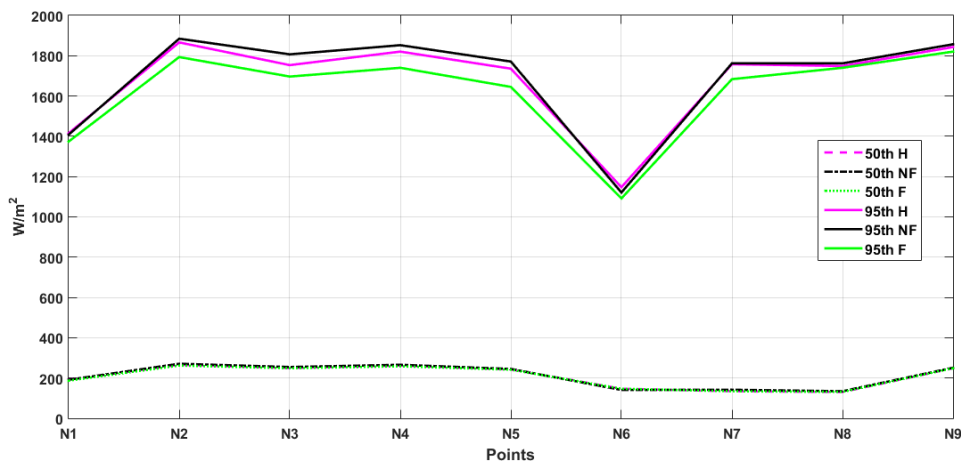

Fig. 5. Comparisons between mean (Mean) and standard deviation (Std) wind power in the reference points at 80 m, for historical (H), near future (NF) and future (F) periods.
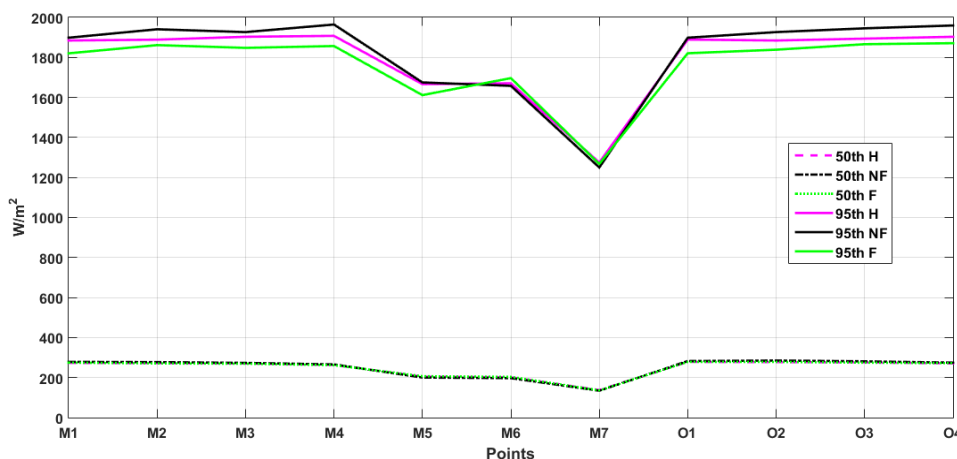
Fig. 6. Comparisons between the mean 50th and 95th percentiles of wind power computed in the reference points at the hub height of 80 m, historical (H), near future (NF) and future (F) periods.
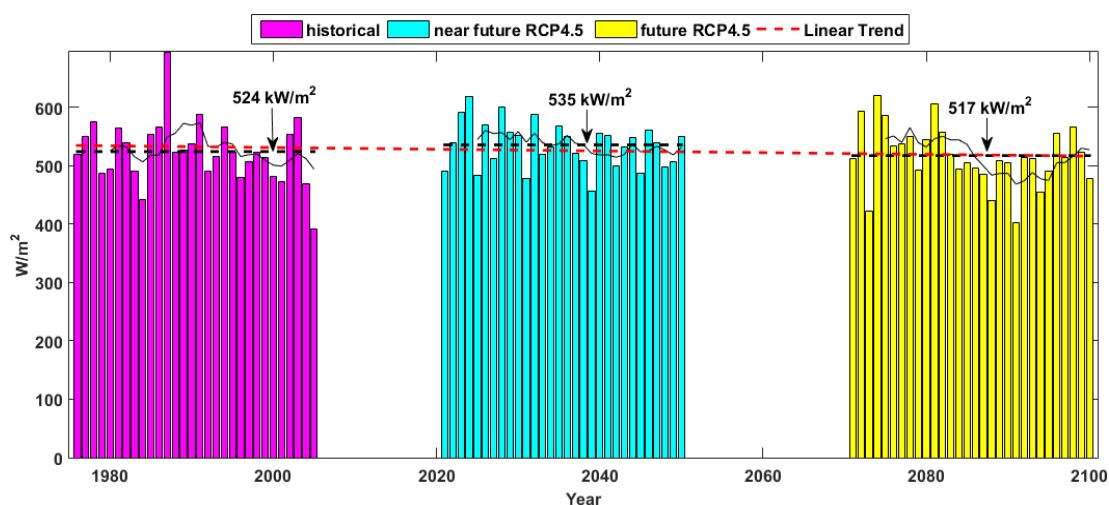

Fig. 7. Annual means of the wind power at the height of 80 m above the sea level for the point M3 computed for historical data and, near future and distant future projections under RCP4.5 scenario. The linear trend is indicated by the red dashed line.

The highest mean values of the wind power there are in all deep water points, for all time periods considered, with values ranging between 500-550 W/m^2. The same feature is maintained for the points M1-M4 located in middle depths. As regards the nearshore points, only in the locations N2, N4 and N9 are reached values around 500 W/m^2. The standard deviations have the highest values in the same point as the means (about 700 W/m^2).

Table 1. Wind power characteristics in some reference points at 80 m for historical (H), near future (NF) and future (F) periods.

Points		Mean (W/m^2)	Max (W/m^2)	Std (W/m^2)	50th (W/m^2)	95th (W/m^2)
H	**N2**	516	9112	677	265	1866
	M1	524	8340	683	273	1880
	O2	528	8503	689	277	1884
NF	**N2**	525	10649	702	270	1884
	M1	535	13417	715	278	1898
	O2	540	13555	720	285	1926
F	**N2**	504	12693	675	262	1793
	M1	515	12909	686	274	1820
	O2	519	13728	689	278	1838
H	**N3**	483	7767	641	250	1753
	M2	525	9152	694	272	1888
	O3	528	9639	694	276	1893

NF	**N3**	497	10502	671	254	1806
	M2	537	12140	721	277	1940
	O3	540	12349	727	281	1945
F	**N3**	476	13027	649	248	1696
	M2	518	12012	697	271	1861
	O3	521	12044	698	274	1866
H	**N4**	501	8093	662	261	1820
	M3	524	10693	698	270	1902
	O4	527	15151	707	270	1903
NF	**N4**	511	9099	684	265	1852
	M3	535	10546	724	273	1926
	O4	539	15375	733	274	1959
F	**N4**	493	21749	672	258	1740
	M3	517	15849	706	269	1847
	O4	521	17148	713	272	1871

The 50th percentile values illustrated in Figure 6 are ranging between 150-300 W/m^2 for all reference points and time periods. Between the 95th percentile values computed in the reference points are higher differences. Thus, values around 1900 W/m^2 are found at all points denoted by O, for the points from M1 to M4, and also in N2. In the points from N3 to N5, these values are in the range 1600-1800 W/m^2, while in all other points 95th are lower than 1600 W/m^2. No significant differences

between the 95th percentiles computed for different time periods were observed.

The evolution of the statistical parameters from nearshore to deep water is more evident analyzing the values presented in Table 1, for the points located along a perpendicular to the shore. Small differences are between the values in M and O points, while those between N and M points are greater.

The annual means of the wind power presented in Figure 7, and also the wind power mean computed for each 30-year time period (dashed black line), indicate that until the middle of the 21st century an increase of the wind energy will occur under RCP4.5 scenario. After this, a very small decrease in the mean wind power over the period 2071-2110 (about 3% in relation to 2021-2050) is projected. This evolution is also indicated by the linear trend fitted to the annual means. From the seasonal analysis of the mean wind power in each point it was observed (not shown here) that, especially in nearshore points, all the mean wind power projections computed for summer time are smaller than the values computed for historical data.

4 Conclusions

In the present work, an analysis of the wind climate and wind power potential in the Black Sea was carried out. This was focused on the evaluation of the main changes expected to occur along the 21st century. Some reference locations were considered for this analysis.

The wind energy resources for three-time intervals were evaluated, each one covering a 30-year period: historical data (1976-2005), near-future (2021-2050) and more distant future (2071-2100) projections, respectively.

Following the results of the analysis, under the RCP4.5 scenario, an increase of the mean wind power was observed until the middle of the 21st century, followed by a small decrease. This decrease seems to be induced especially by the decrease of the wind power in the summer time. The linear regressions adjusted to the annual means do not indicate a significant trend.

Acknowledgment

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