WIND CLIMATE SCENARIOS IN THE BLACK SEA BASIN UNTIL THE END OF THE 21ST CENTURY

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Abstract. The objective of the present work is to provide a comprehensive picture of the future wind dynamics in the Black Sea until the end of the 21st century. The results of the climate wind models are analyzed considering three RCP (Representative Concentration Pathway) scenarios, RCP2.6, RCP4.5 and RCP8.5. Two different time intervals (each of 40 years) have been defined, near future (2021–2060) and distant future (2061–2100). For comparison, considering ERA5 data a 40-year time interval from the recent past (1980–2019) was also analyzed. The analysis is focused on two directions. The first is related to the maximum wind speeds at 10 meters, and the results indicate that higher wind speeds are expected in the Black Sea. Considering the high expansion of the offshore wind industry, the second direction is related to the analysis of the average wind power at 100 meters. According to the data analyzed, the coastal areas from the western and northwestern sides of the Black Sea are more energetic. Furthermore, in these nearshore areas, a relative enhancement of the wind power density between 20% and 50% is expected. Some hot spots that represent appropriate locations for future wind projects are also identified.

Key words: Black Sea, climate change scenarios, wind, 21st century, extreme speeds, average power.

1. INTRODUCTION

The Black Sea is a semi-enclosed basin located in the southeast of Europe, east of the Balkans Mountains and west of the Caucasus [1]. This sea can be considered as the most distant extension inside the European Continent of the Atlantic Ocean to which is linked via the Mediterranean Sea through the Turkish Straits Dardanelles and Bosphorus [2, 3]. The Black Sea has some unique features, being the largest inland body of water in the entire world and also the largest meromictic basin [4]. This means that the deep water does not mix with the surface water layer that receives oxygen from the atmosphere. As a result, more than 90% of the deep water in the Black Sea is anoxic [5]. The circulation features of the sea

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are mainly determined by the topography of the basin and also by the river outflows. These induce a stratified water structure on the vertical. The only water exchange is with the Mediterranean Sea. Inflow from the Mediterranean has a higher salinity and density than the outflow, creating a classic estuarine circulation. This means that the inflow of dense water from the Mediterranean Sea occurs at the bottom of the basin while the outflow of fresher Black Sea surface-water is near the surface and it is with about 43% higher than the inflow [6].

Taking into account its position, the climate of the Black Sea is influenced by air masses coming from several directions, especially continental, polar, and marine tropical. These last ones (marine tropical air masses) occur due to the winds blowing from the southwest and coming from the Mediterranean Sea. On the other hand, the polar winds are usually blowing from the north-northeast inducing very often low temperatures and storm conditions [7]. The North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO) influence the short-term patterns of the wind climate above the Black Sea basin and create conditions for the formations of cyclones by transporting cold air over the warm sea [8, 9]. On the other hand, these two systems decrease the impact of the polar air masses that are moving in winter coming from the north and also are directly related with the high winter storms characteristic for the Black Sea basin [10].

The historical data, as well as several scientific works [11, 12], are pointing towards the western coast of the Black Sea as having higher wind conditions with mean wind velocities (at 10 meters above the sea level) greater than 8 m/s for winter time and of about 5 m/s for the summers [13]. It can be also noticed that a high seasonal variability is characteristic to the western side of the sea, unlike the eastern side that indicates more stable conditions [14]. High storms are noticed in winter in the western side of the sea with wind speeds often exceeding 25 m/s in the nearshore areas [15, 16]. Furthermore, the general wind patterns, induced either by the polar or the Mediterranean airflows, is significantly changed by the topographic particularities of this geographic area generating local winds some of them of high intensity. A relevant example in this direction is represented by the Bora wind that is characteristic to the northeastern side of the sea [17]. Such Bora events are characterized by wind speeds greater than 15 m/s for time intervals between 1 to 3 days (almost 80% of the cases), very seldom exceeding 10 days (less than 1%) [18]. In fact, the Bora events are strong downslope winds coming from the Caucasus Mountains and generated by the collapsing of the cold northeast Arctic wind in the Black Sea. Historical data show that the strongest bora winds occur in general in the Tsemes Bay of the Black Sea near the Russian port of Novorossiysk, and they can reach extremely high velocities going up even to 60 m/s [19].

In this context, the objective of the present work is to assess the future expected wind conditions in the basin of the Black Sea corresponding to two different time intervals, each of 40 years. These are the near future time interval 2021–2060 (denoted as NF) and the distant future interval 2061–2100 (denoted as DF). Three RCP (Representative Concentration Pathway) climate scenarios are considered for these two 40-year time intervals NF and DF. These are RCP2.6, RCP4.5 and RCP8.5. In parallel, another 40-year period (1980-2019) covering the recent past (denoted as RP) is considered for providing a valid criterion of comparison.

As regards the data processed and analyzed for the recent past, the reanalysis database ERA5 [22] is considered in the present study. ERA is the acronym of "ECMWF Re-Analysis", while ECMWF stands for European Centre for Medium-Range Weather Forecasts. For the two 40-year time intervals, corresponding to the near and distant future, the wind data provided by a Regional Climate Model (RCM) are processed and analyzed [23]. Various studies focused on the dynamics of the Black Sea area [24, 25] indicate a significant enhancement of the maximum wind speed for the very near future followed also by a slight increase in terms of average wind power [26]. Another tendency is related to the fact that this enhancement is higher in the western side of the Black Sea.

From this perspective, it has to be highlighted at this point that the present work brings significant elements of novelty and added value in relationship with the previous works above mentioned. First, most of the previous papers are focused a 30-year near future period until 2050, while the present work provides a much wider perspective going with the estimations of the wind dynamics until the end of the 21st century. Second, three RCP scenarios are analysed. These are RCP2.6, assuming a decrease of the CO_2 emissions starting with 2020, RCP4.5 according to which the peak of the emissions will be reached in 2040 followed by decay, and RCP8.5 that assumes an increase of the emissions along the entire 21st century and afterwards. The first scenario can be considered as the most optimistic, the second as a realistic one, while the third as the most dramatic. However, although RCP2.6 was considered only a few years ago as being rather unrealistic, the COVID19 pandemic lead to a significant decay of the CO_2 emissions in 2020 and together with more coherent measures [27] to reduce the emissions through long-term strategies for rebuilding *a clean planet for all* made this scenario also possible and even quite probable. In this context, the present work provides a more comprehensive picture for the possible scenarios concerning the expected wind dynamics in the Black Sea basin covering the entire spectrum of possible climate dynamics.

Thus, taking into account the above considerations, the present work is focused first on the assessment of the expected dynamics of the extreme events, especially as regards the magnitude and the locations of occurrence for the maximum values of the wind speed. The second issue targeted in the present work is related to the evaluation of the average wind power. Several studies [28-30] showed that offshore wind farms can be efficient in the coastal environment of the Black Sea. Furthermore, *The European Green Deal* communicated publicly in December 2019 [27] assumes very ambitious targets for the offshore wind in Europe, going from the actual capacity of 12GW (for Europe without UK) to a target of 60GW in 2030 and 300GW in 2050. Of course, to achieve such targets, besides requiring relevant technological advances, a significant geographical extension of the offshore wind farms from the Baltic and North Seas to the entire European nearshore at the Atlantic Ocean is assumed, together also with a valorization of the nearshore places with potential from the Mediterranean and the Black Seas. On the other hand, it has to be underlined that the present work while giving a general and wider perspective on the expected wind conditions in the basin of the Black Sea until the end of the 21st century under different climate change scenarios, cannot provide reliable information on the local scale effects, as for example the Bora winds. Such events should be the objective of separate works considering different data sources.

2. MATERIALS AND METHODS

2.1. THE FUTURE CLIMATE SCENARIOS ANALYZED

For the two periods considered (each of 40 years), near future (2021-2060) and distant future (2061-2100), respectively, data coming from the regional atmospheric model, version 4 (RCA4) [31] have been processed and analyzed. This climatic model is operated by the Rossby Centre of the Swedish Meteorological and Hydrological Institute (SMHI). The above mentioned wind data are publicly available and the resolutions considered are 0.11 degrees in the geographical space, while the time resolution is six hours.

Four RCP pathways have been defined for modelling future wind climate in the framework of the fifth Assessment Report (AR5) produced at the initiative of the Intergovernmental Panel on Climate Change (IPCC) [32]. These initial Representative Concentration Pathways defined are RCP2.6, RCP4.5, RCP6, and RCP8.5 and they are identified after the values of the radiative forcing estimated at the end of the 21st century (which are 2.6 W/m^2, 4.5 W/m^2, 6 W/m^2, and 8.5 W/m^2, respectively). Since then, other climate scenarios were also defined, as for example RCP1.9, RCP3.4 and RCP7.

In this study, three different RCP scenarios are considered and for them, the wind data are processed and analyzed corresponding to the two 40-year time intervals defined for the future, NF and DF, respectively. These are RCP2.6, RCP4.5 and RCP8.5, covering in this way a wide range of possibilities. According to the first climate scenario considered (RCP2.6), the decay of the CO_2 emissions started in 2020. This was considered a few years ago as a very optimistic scenario, even rather unrealistic. However, the COVID19 pandemic reduced in a drastical way many industrial activities as well as the international traveling and tourism and in these conditions RCP2.6 became nowadays very credible. The second scenario, RCP4.5, which initially was thought as the most realistic one, considers that the emissions peak will be in the year 2040 and it will be followed by stagnation and even a decay of the CO_2 emissions. Finally, RCP8.5 is the most pessimistic scenario assuming that the emissions will continue to be enhanced all along the 21st century and afterwards.

The boundary conditions of the regional model that has a higher resolution in the geographical space are provided by the Global Climate Model (GCM). These Global Climate Models describe the most significant physical processes over the entire earth (including atmosphere, ocean, and land). Such models are at this moment the most advanced frameworks for providing credible projections as regards the the climate change effects. However, as in any modelling process, various sources of uncertainty still exist. Some examples are the feedback mechanisms in the numerical models or averaging of the proprieties over a large scale. In [33] more details are presented as regards the configuration and forcing of the climatic wind model and also the procedures taken into account for the initialization of these RCPs. The main approach considered is that the response of the climate is a function on the the forcing history as well as on the global warming induced by the greenhouse effect. The starting point for this global warming (climatological base) is the year 1850 and it goes to the year 2100. Under such conditions, the expected temperature range for this warming is [1.5–4.4] °C. The inferior limit corresponds to the scenario RCP2.6 while the superior to RCP8.5. Thus, these GCMs may deliver different responses even if the same forging is considered, this depending mainly on the feedback mechanisms and processes that are considered in the model.

The wind data delivered by the RCA4 atmospheric model, and that are further processed and analysed, have a spatial resolution of 0.11 degrees, and the temporal resolution considered is six hours. Having as basis this information, for each RCP (2.6, 4.5 and 8.5) two analyses are performed separately. The first is for the future 40-year time interval (2021–2060), denoted as near future (or NF), while the second corresponds to the 40-year interval (2061-2100), denoted in the present work as distant future (or DF).

2.2. DATA CONSIDERED FOR THE RECENT PAST

ERA5 reanalysis database [34] is considered in this work for the evaluation of the past wind conditions in the basin of the Black Sea. Wind data were processed and analysed for the 40-year time interval 1980–2019, denoted as the recent past (RP). ERA refers to a series of research projects developed at the European Centre for Medium-Range Weather Forecasts and various datasets used in wind assessments have been generated in the framework of these projects. ERA5 is preceded by the ERA-Interim database [35] and is the most recent global atmospheric reanalysis database developed at the European Centre for Medium-Range Weather Forecasts. This database covers the time interval from 1950 and going the present days, five days behind the actual time. It provides wind fields with a time resolution of one hour and the resolution in the geographical space is 0.25° × 0.25°. Furthermore, other parameters related to the environmental data are also delivered, as for example the atmospheric pressure fields [35]. The wind speed values at 10 meters height above the sea level have been considered and analysed in the present work with a time resolution of 6 h (for 00:00-06:00-12:00-18:00 UTC, respectively).

2.3. THEORETICAL BACKGROUND

In a first approach, the data files containing the values of the wind speeds at 10 meters above the water level in the grid points defined for each data set have been downloaded. As mentioned before, the resolution in the geographical space is 0.11° for the climatic models (RCA4) and 0.25° for the wind hindcast (ERA5), while the time resolution considered is 6 hours and 3 hours, respectively. These data were first analysed for the three time intervals defined, especially focusing on the extreme events and the annual maximums of the wind speeds.

As a second step, the average wind power was evaluated at the reference height of 100 meters above the sea level. This is because there is an obvious tendency in the technologies related to the offshore wind to develop large wind turbines, increasing thus the operational height [37]. Following this approach, the logarithmic law (equation 1) was applied to translate the wind speeds from 10 to 100 meters is [38]:

$$U_z = U_{z_{ref}} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}, \tag{1}$$

where U_z is the wind speed at the operational height z (with z=100m above the sea level in this case). U_{zref} is the wind speed corresponding to the reference height $z_{ref,}$ which is 10 meters above sea level for all four datasets ERA5, RCP2.6, RCP4.5 and RCP8.5. z_0 is the surface roughness length, and an average value of 0.0002 meters is considered in the present work for this parameter [39]. Using the translated values of the wind speed, the power density of the wind (P_{wind} in $W\cdot m^{-2}$) is computed. This parameter indicates the energetic capacity of the wind and it was evaluated using equation (2), [40]:

$$P_{wind} = \frac{1}{2}\rho_{\boldsymbol{air}}\left(U_z\right)^3 \tag{2}$$

In the above equation ρ_{air} is the air density, with an average value of 1.225 $kg\cdot m^{-3}$ and U_z is the wind speed at the operational hub height (100 meters above sea level in this case), [41].

3. RESULTS AND DISCUSSIONS

3.1. THE DYNAMICS EXPECTED FOR THE MAXIMUM WIND SPEEDS IN THE FUTURE AGAINST THE RECENT PAST

An analysis of the dynamics of the wind conditions expected in the future (corresponding to the two 40-year time intervals NF and DF) against the recent past (RP) will be carried out in this section. The first part is dedicated to the analysis of the wind speeds at 10 meters height above sea level (U_{10}). Thus, in order to provide a first picture of the general wind conditions in the basin of the Black Sea, Fig. 1 illustrates the mean wind speeds U_{10} from ERA5, values averaged for the 40-year period 1980–2019. In this figure, the location of the maximum averaged value of the wind speed ($U10_{max}$ = 6.56 m/s), is also indicated. This is in the north of the Black Sea, south of the Kerch Strait.

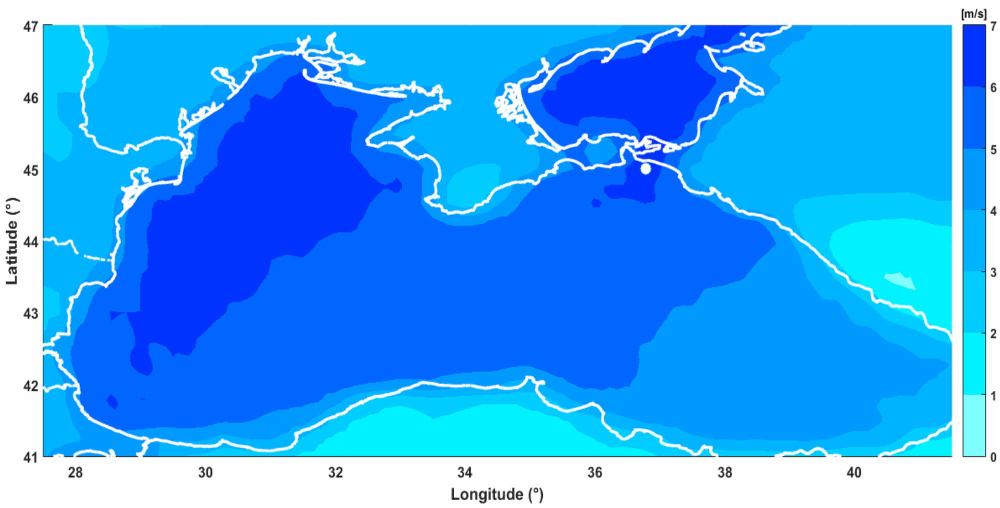
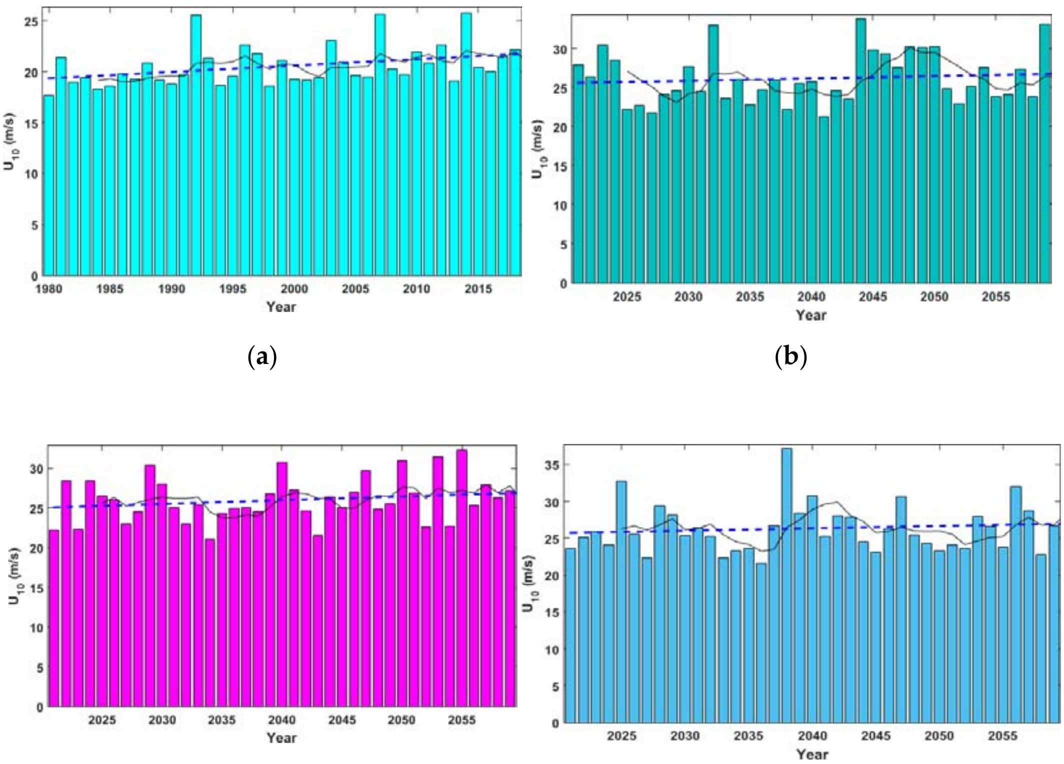


Fig. 1 – Mean wind speed U_{10} from ERA5, values averaged for the period 1980-2019, $U10_{max}$ = 6.56 m/s.

Further on, the emphasis will be put on the extreme wind speeds. Figure 2a presents the annual maximum series of the wind speeds for the recent past period (1980–2019), while Figs. 2b, 2c and 2d the wind speeds annual maximum series corresponding to the near future period (2021–2060) for RCP2.6, RCP4.5 and RCP8.5, respectively. The linear trends and the five-year running averages are also represented in these figures. It can be noticed from Fig. 2 that the linear trends indicate for all situations a tendency of enhancement of the maximum wind speeds, tendency that is more accentuated for the recent past, than for the near future periods. At the same time, according to the model data analyzed, the maximum wind speeds in the recent past are slightly higher than 25 m/s, while in the near future maximum wind speed values higher than 30 m/s are expected. Furthermore, for the scenario RCP8.5 even wind speed values higher than 35 m/s can occur, as it results from Fig. 2d.

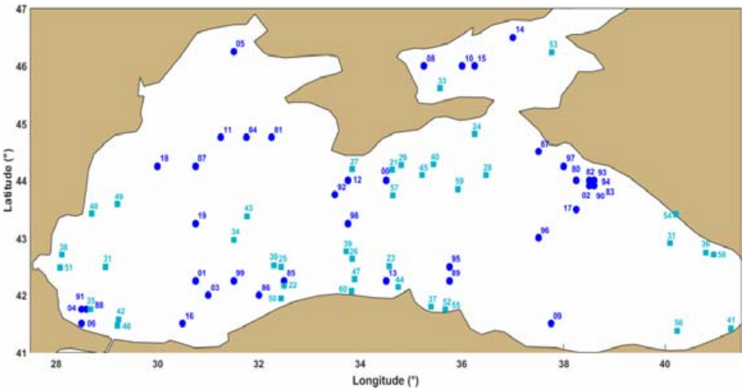


(**a**) (**b**)

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

Fig. 2 – U_{10} annual maxim series (bars): a) recent past period (1980–2019); b) RCP2.6, near future period (2021–2060); c) RCP4.5, near future period (2021–2060); d) RCP8.5, near future period (2021–2060). The linear trend is represented with dashed blue line, while the five-year running average is the solid black line.

The geographical positions of the U_{10} annual maximums, blue circles for data from RP (1980–2019), and squares for data from NF (2021–2060) are presented in Fig. 3. From this figure it can be noticed a tendency of moving the locations of the annual maximums of the wind speeds towards the south and especially in the southeastern side of the Black Sea. This tendency of moving the locations of the annual maximums in the southern direction appears to be less significant for RCP2.6 and more significant for scenario RCP4.5. This behavior is also reflected by the fact that in the recent past four maximums are located in the Sea of Azov, while in the future there are still expected two maximums according to RCP2.6, but no maximum corresponds in this area for RCP4.5 and RCP8.5.



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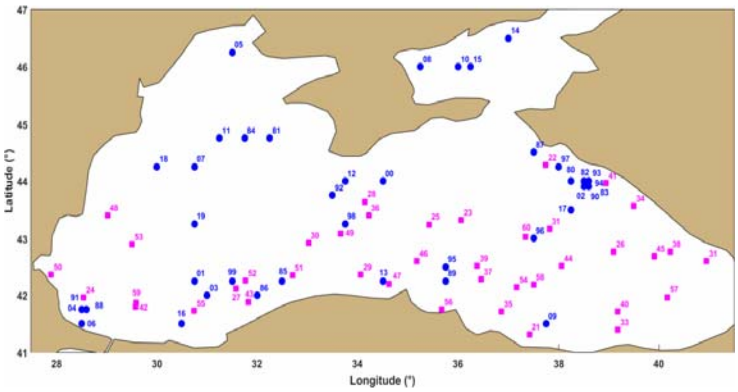

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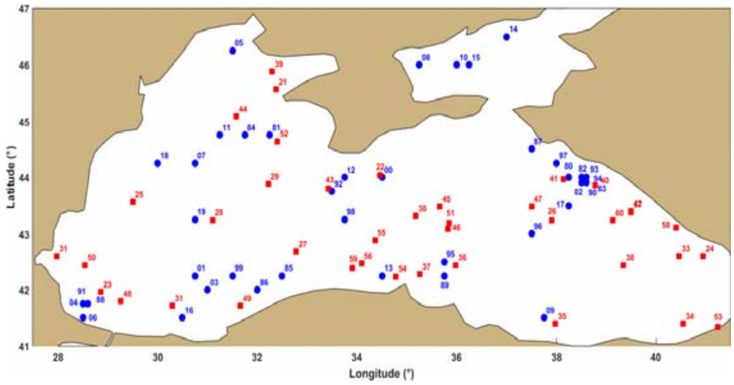
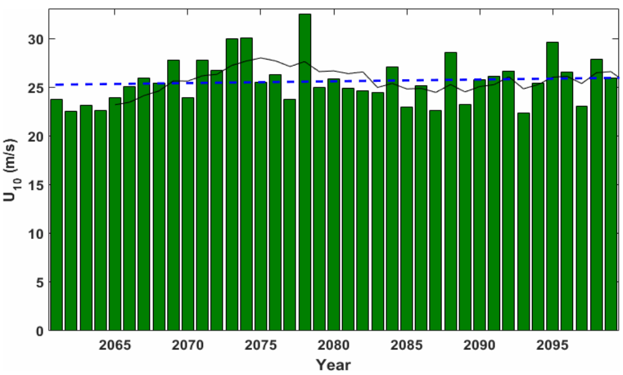


(**c**)

Fig. 3 – Geographical positions of the U_{10} annual maximums, blue circles for data from RP (1980–2019), squares for data from NF (2021–2060) a) NF results considering scenario RCP2.6; b) NF results considering scenario RCP4.5; c) NF results considering scenario RCP8.5.

Going now to the distant future period (2061–2100), Figs. 4a, 4b and 4c present the wind speeds annual maximum series for RCP2.6, RCP4.5 and RCP8.5, respectively. The linear trends and the five-year running averages are also represented in the figures. This time, the linear trends indicate in general a constant tendency, being noticed a small enhancement only for RCP8.5. As in the case of the NF time interval, maximum wind speeds higher than 30 m/s are also expected in DF, while for RCP8.5 wind speeds with values higher than 35 m/s may occur. Figure 5 presents the geographical positions of the U_{10} annual maximums, blue circles for data from RP (1980–2019), and triangles corresponding to data from DF (2061–2100). Again, it can be noticed the tendency of displacement of the annual maximums towards the south, together with the concentration in the southeastern side of the Black Sea of the locations where these annual maximums are expected to occur. No maximum is expected in the Sea of Azov for scenario RCP2.6, but the results indicate one annual maximum value located in the south of the Sea of Azov in the case of RCP4.5.



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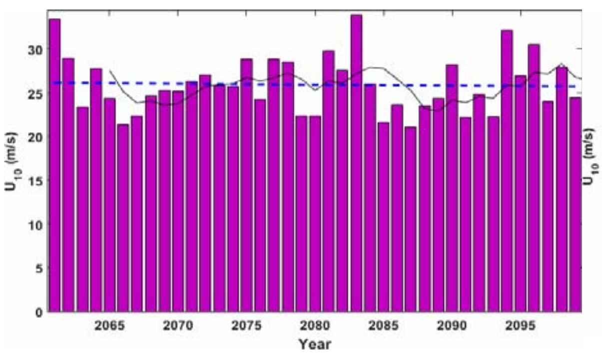
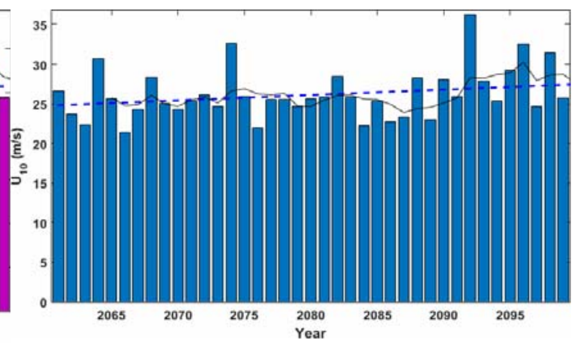




(**b**) (**c**)

Fig. 4 – U_{10} annual maxim series (bars) for distant future period (2061–2100): a) RCP2.6; b) RCP4.5; c) RCP8.5. The linear trend is represented with dashed blue line, while the five-year running average is the solid black line.

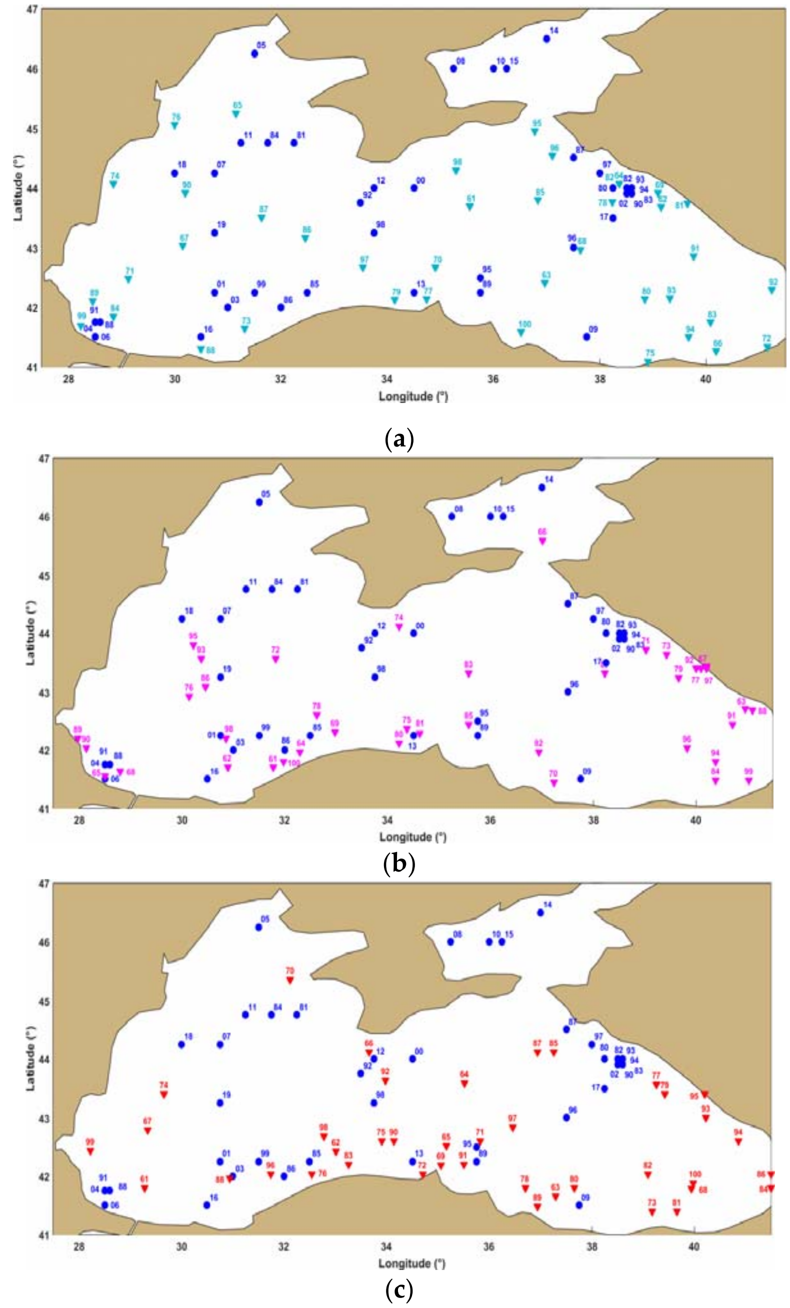


Fig. 5 – Geographical positions of the U_{10} annual maximums, blue circles for data from RP (1980–2019), triangles for data from DF (2061–2100) a) DF results considering scenario RCP2.6; b) DF results considering scenario RCP4.5; c) DF results considering scenario RCP8.5.

The most relevant information concerning to the top three highest storms for the three time intervals considered (RP, NF and DF) and respectively for the three future climate scenarios RCP2.6, RCP4.5, and RCP8.5 are presented in Table 1. The information includes the exact date and location of the occurrence as well as the value of the corresponding maximum wind speed. Looking at the data presented in this table, it can be noticed that a significant enhancement of the maximum wind speeds is expected in the near future in relationship with the recent past. This increase is with about 30% for the scenarios RCP2.6 and RCP4.5 (slightly higher for RCP2.6) and goes to almost 50% for the scenario RCP8.5. Thus, according to the climate wind models analyzed this maximum would occur in 2038 (11/06h06) and the maximum expected wind speed value is 37.13 m/s. As regards the distant future period, the situation is rather similar with that from the near future and only for the scenario RCP4.5 a small increase (with about 5%) of the maximum wind speed is expected. Another observation that can be made at this point is that in the near future RCP2.6 indicates higher maximum wind speeds than RCP4.5 while in the distant future time interval there is an opposite tendency. In both future time intervals the highest wind speeds are expected for RCP8.5.

Table 1

Top three highest storms for the three time intervals considered (RP, NF and DF) and the three future climate scenarios RCP2.6, RCP4.5, and RCP8.5, respectively

Data	**Time frame**	**Geographical position Longitude (°)/ Latitude (°)**	**Wind speed (m/s)**
RP-ERA5	2014/09/24h03	37.00 / 46.50	25.79
	2007/11/11h00	30.75 / 44.25	25.67
	1992/11/15h03	33.50 / 43.75	25.58
NF-RCP2.6	2044/09/23h06	34.74 / 42.14	33.74
	2059/10/30h12	35.92 / 43.85	33.02
	2032/10/01h18	40.09 / 42.90	33.01
NF-RCP4.5	2055/09/18h00	30.74 / 41.73	32.36
	2053/10/23h18	29.51 / 42.89	31.42
	2050/11/19h00	27.90 / 42.36	31.01
NF-RCP8.5	2038/11/06h06	39.34 / 42.44	37.13
	2025/09/27h18	29.50 / 43.56	32.70
	2056/09/23h12	34.09 / 42.47	31.95
DF-RCP2.6	2078/10/22h12	38.24 / 43.76	32.49
	2074/09/24h18	28.85 / 44.07	30.07
	2073/11/11h12	31.32 / 41.65	29.95
DF-RCP4.5	2083/12/04h18	35.58 / 43.32	33.88
	2061/12/17h12	31.78 / 41.70	33.41
	2094/12/15h18	40.38 / 41.80	32.15
DF-RCP8.5	2092/09/24h06	33.98 / 43.64	36.24
	2074/10/31h12	29.66 / 43.40	32.58
	2096/12/22h18	31.74 / 42.04	32.52

Further on, in order to provide a better picture of the wind conditions associated to the highest storm corresponding to each scenario considered, the spatial distribution over the entire sea basin of the scalar wind fields and the velocity vectors (U_{10}) are also represented and analyzed. Thus, Fig. 6 illustrates the conditions corresponding to the highest storm from the recent past period, according to the ERA5 data (time frame – 2014/09/24-h03). From the analysis of the wind fields presented in this figure, as well as of those corresponding to the next two storms from the recent past presented in Table 1 (the time frames 2007/11/11h00 and 1992/11/15h03), not illustrated, it results that the highest storms in the Black Sea basin correspond in the recent past period analyzed to the winds blowing from west to east. It has to be highlighted at this point that the dominant wind direction in the Black Sea is from east to west, but as the results show the highest storms are when the wind is opposite to this general wind blowing pattern. Figure 7 presents the expected wind conditions for the highest storms corresponding to each future scenario NF and DF for RCP2.6, RCP4.5 and RCP8.5, respectively. It can be noticed that cyclonic forms are characteristic to the future extreme storms for all RCP scenarios.

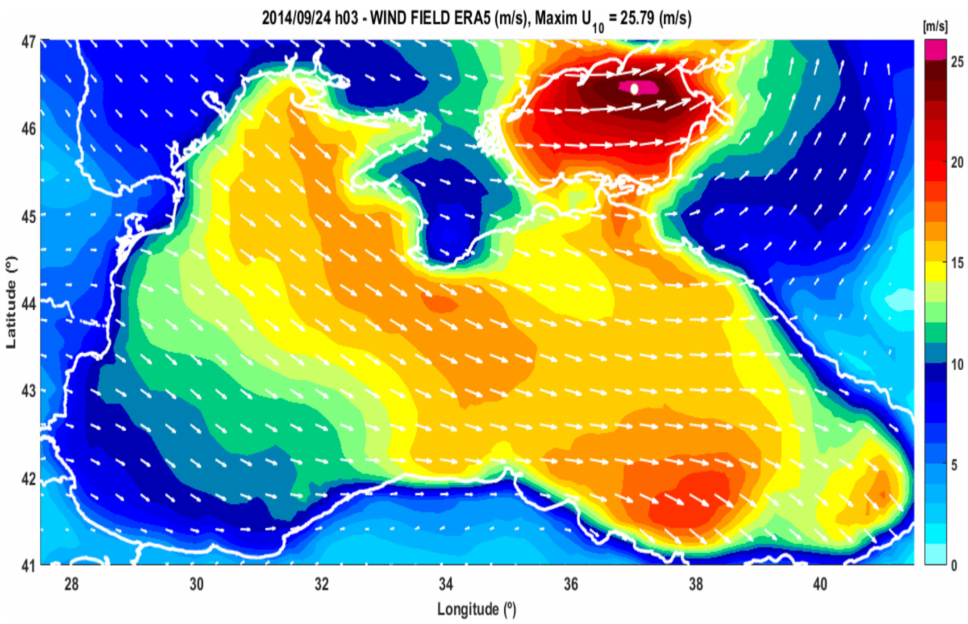


Fig. 6 – The scalar wind fields and velocity vectors (U_{10}) for the highest storm corresponding to the recent past, considering the ERA5 data, time frame – 2014/09/24-h03.

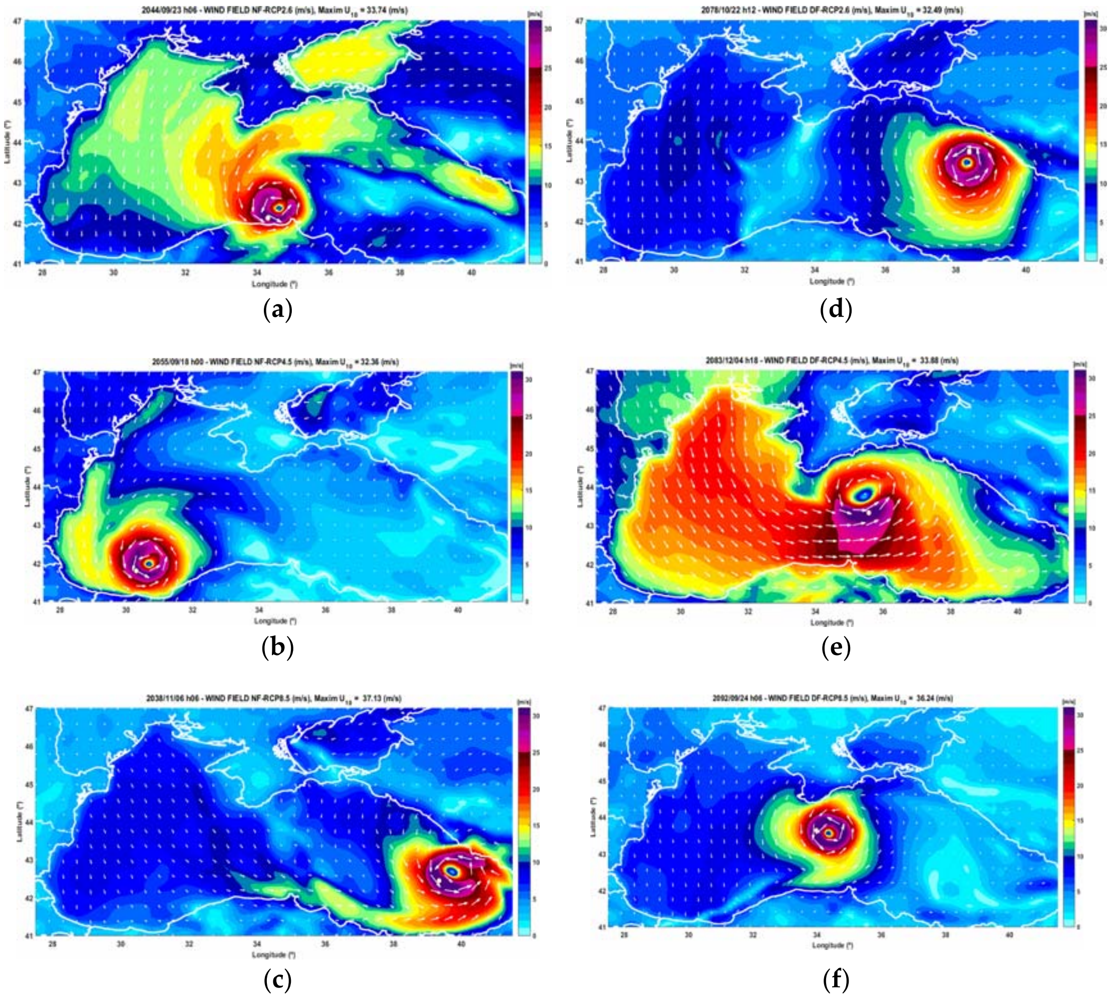


Fig. 7 – The scalar wind fields and velocity vectors (U_{10}) for the highest future expected storms over the Black Sea basin for: a) NF-RCP2.6 on 2044/09/23h06; b) NF-RCP4.5 on 2055/09/18-h00; c) NF-RCP8.5 on 2038/11/06-h06; d) DF-RCP2.6 on 2078/10/22h12; e) DF-RCP4.5 on 2083/12/04-h18; f) DF-RCP8.5 on 2092/09/24h06.

3.2. Evaluations of the wind power

The spatial and temporal distributions of the mean wind power density (P_w) at 100 meters over the sea level is analyzed in this section. Thus, the mean wind power density distribution averaged for the 40-year time interval corresponding to the recent past (1980–2019) is presented in Fig. 8. It can be noticed from this figure that in the western and northwestern sides of the sea the coastal environment is characterized by average wind power values between 400 W/m^2 and 450 W/m^2. Similar values are also characteristic for the entire nearshore of the Sea of Azov.

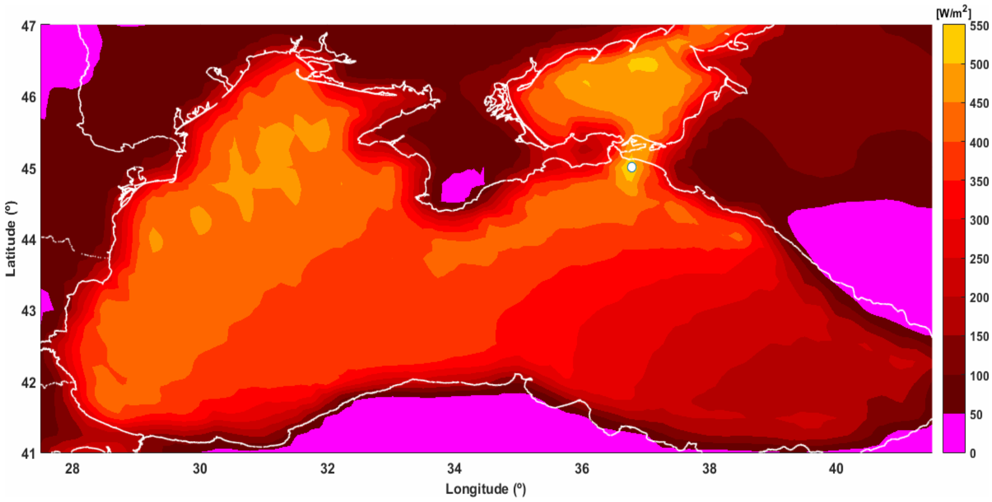


Fig. 8 – Spatial distribution of the mean wind power density P_w along the Black Sea basin. Results for the 40-year recent past period (1980–2019), the position and the value of the maximum mean wind power ($P_{w\text{-max}}$ = 548 W/m^2) is also indicated.

Further on, in order to investigate the changes expected in terms of mean wave power at 100 meters above the sea level an evaluation parameter is considered. This is the normalized difference between the future (NF or DF, respectively) and the RP time intervals and it is denoted as E_{RC}, expressing in percentage the relative change in terms of mean wind power between the future and recent past periods. This indicator is computed with the relationship:

$$E_{RC} = \frac{P_{eF} - P_{WP}}{P_{WP}} \times 100 \,. \tag{3}$$

In the equation above P_{WF} is the mean wind power corresponding to the 40-year future periods (near or distant future) and P_{WF} represents the mean wind power for 40-year period that corresponds to the recent past.

From this perspective, Fig. 9 illustrates the **r**elative variations of the wind power in the Black Sea basin, near future period (2021–2060) against recent past period (1980–2019), while Fig. 10 presents the **r**elative variations of the wind power in the Black Sea basin, distant future period (2061–2100) against recent past period (1980–2019). From these figures it results that enhancements of the wind power between 20% and 60% are expected in the coastal environment of the Black Sea. Some hot spots (locations with significant increase of the average wind power) can be also noticed in the western and northern coastal environments of the sea. These areas present already more wind power resources than the average and the higher increase expected for the wind power in the future indicates them as being more appropriate for the development of the future wind projects.

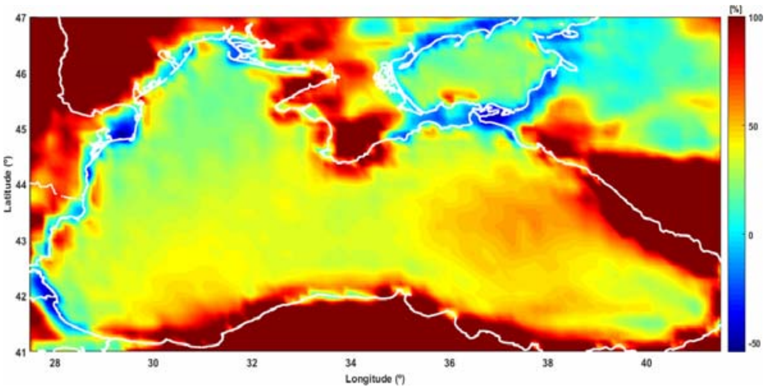
Furthermore, in order to assess better the future wind dynamics, Fig. 11 presents the relative variations of the wind power in the Black Sea, distant future period (2061-2100) against near future period (2021–2060). From this figure it can be noticed that, while under scenario RCP2.6 an increase in the range (2–6%) in terms of average wind power is expected in the distant future in comparison with the near future period, a slight decrease is expected in DF in comparison with NF for the other two RCP scenarios. This decrease is higher if considering scenario RCP4.5 (3–4%) while for RCP8.5 a decrease with less than 2% is expected.

Finally, Table 2 presents the maximum values of the mean wind power density and their geographical locations corresponding to the three time intervals considered (RP, NF and DF) and the three future climate scenarios RCP2.6, RCP4.5, and RCP8.5, respectively. From this table it can be noticed that in the near future period the highest expected wind power density average value is 617.7 W/m^2 and corresponds to RCP4.5 while for the distant future time interval the highest expected average value of the wind power density is 625.2 W/m^2 and corresponds to RCP2.6.

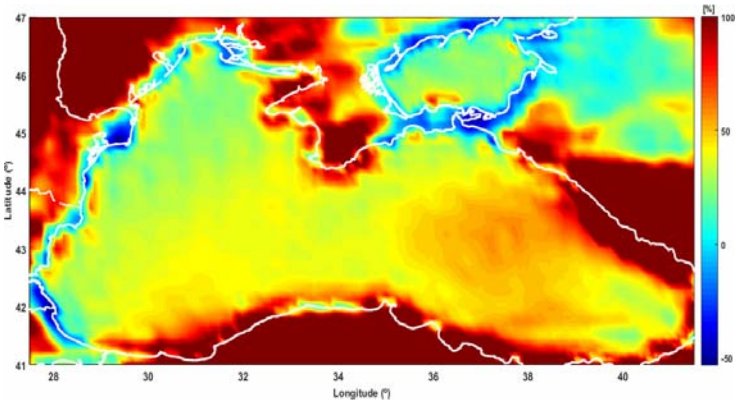
Table 2

Maximum values of the mean wind power density and their geographical locations corresponding to the three time intervals considered (RP, NF and DF) and the three future climate scenarios RCP2.6, RCP4.5, and RCP8.5, respectively

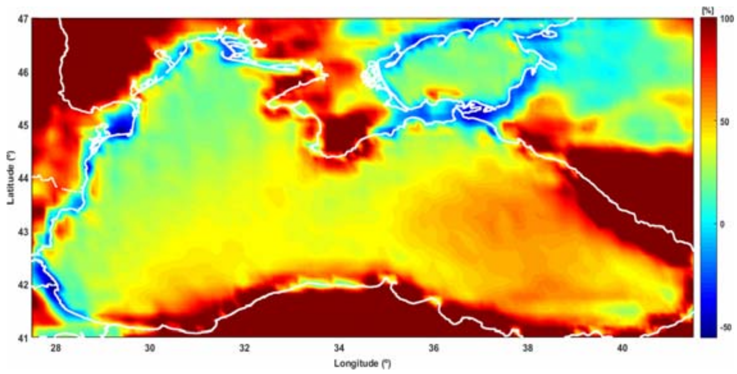
Time period (scenario)	**Longitude (°)**	**Latitude (°)**	**P_w (W/m^2)**
Recent past (ERA5)	36.78	45.02	548.8
Near future (RCP2.6)	38.54	44.12	614.5
Near future (RCP4.5)	36.93	46.28	617.7
Near future (RCP8.5)	38.46	44.04	614.8
Distant future (RCP2.6)	36.86	46.28	625.2
Distant future (RCP4.5)	36.94	46.28	598.2
Distant future (RCP8.5)	36.94	46.28	610.9



(**a**)

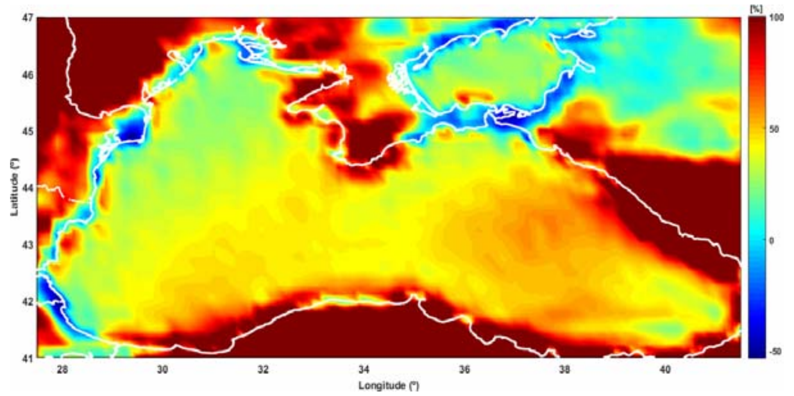


(b)



(**c**)

Fig. 9 – Relative variations of the wind power in the Black Sea basin, near future period (2021–2060) against recent past period (1980–2019): a) results of RCP2.6 compared with ERA5; b) results of RCP4.5 compared with ERA5; c) results of RCP8.5 compared with ERA5.



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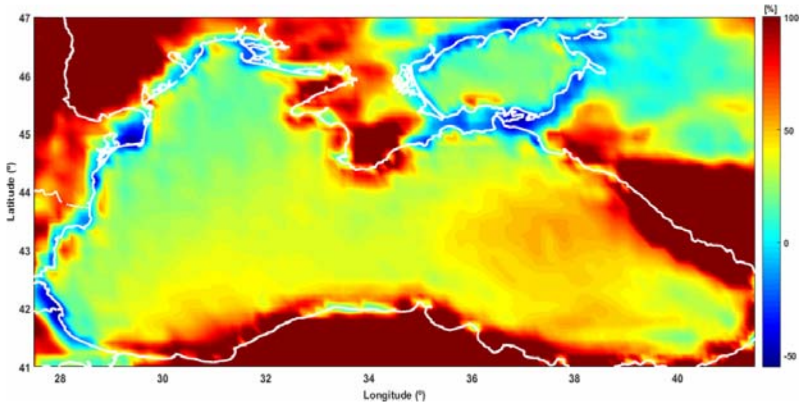
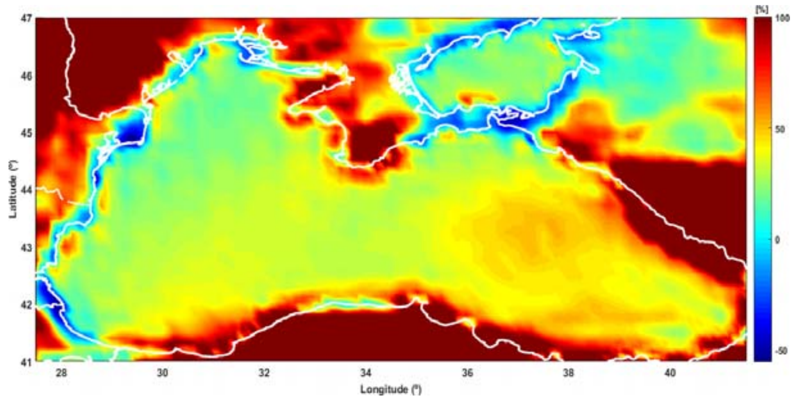
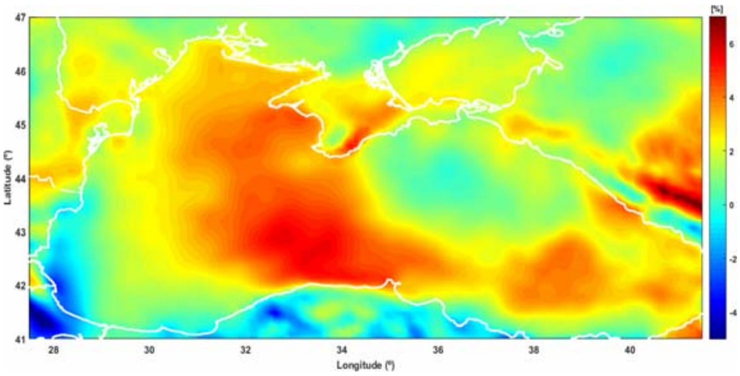


(**b**)



(**c**)

Fig. 10 – Relative variations of the wind power in the Black Sea basin, distant future period (2061–2100) against recent past period (1980–2019): a) results of RCP2.6 compared with ERA5; b) results of RCP4.5 compared with ERA5; c) results of RCP8.5 compared with ERA5.



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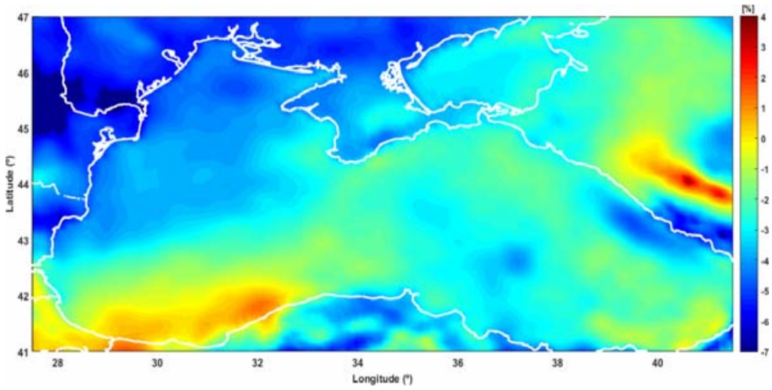

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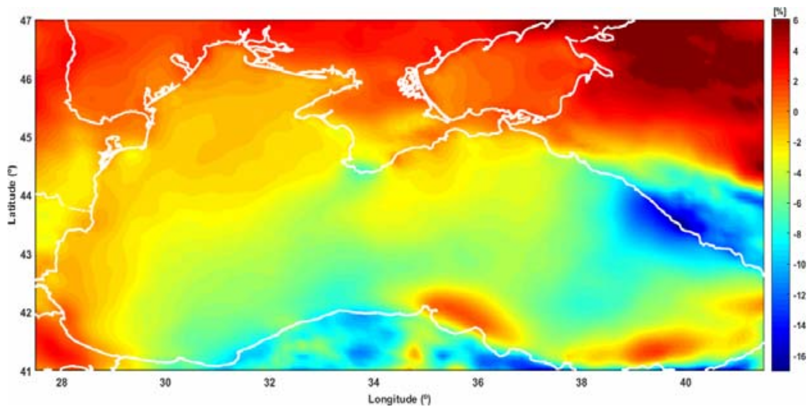

(**c**)

Fig. 11 – Relative variations of the wind power in the Black Sea, distant future period (2061–2100) against near future period (2021–2060): a) results for RCP42.6; b) results for RCP4.5; c) results for RCP8.5.

4. CONCLUSIONS

The objective of this work was to analyze the storm conditions in the Black Sea. As a first step, using a validated modelling system a 30-year hindcast, covering the time interval 1987–2016, has been performed. In this way, the main storms that occurred in the recent past have been identified and analyzed. The next step was to perform projections concerning the expected storm conditions in the basin of the Black Sea corresponding to the near future time interval (2021–2050). For this reason, the same wave modelling system was considered, but this time the climatic wind fields were used to force the model.

An analysis of the expected wind conditions across the Black Sea basin is carried out in the present work until the end of the 21st century. For this, the 80-year time interval from the future is structured in two 40-year times intervals, 2021–2060 denoted as near future (NF) and 2061–2100 denoted as distant future (DF). For both of them, three different RCP scenarios are considered (RCP2.6, RCP4.5, and RCP8.5) and the corresponding results of the climate wind models have been processed and analyzed. In order to have a criterion of comparison the wind data from the recent past period (1980–2019) coming from ERA5 data base were also analyzed.

The study was focused on two directions. The first is related to the extreme wind speeds at 10 meters height above the sea level and the results show that if in the past the maximum wind speeds seldom exceed the value of 25m/s, for the future significant enhancements might be expected. Thus, wind speed values higher than 30 m/s and the cyclonic forms associated to the extreme storms expected in the future indicate a high similitude with the first category hurricanes from the Atlantic Ocean. The extreme values correspond to RCP8.5 and this indicates that the continuous enhancement of the CO_2 emissions would have as a result a significant unbalance of the sea climate characterized by higher variability in terms of wind speeds intensity and directions. As regards the locations of the annual maximums of the wind speeds it can be observed also a tendency of migration in the southern/southeastern directions, with a probability of higher occurrences of the locations of the annual maximums wind speeds in the southeastern side of the Black Sea.

The second research direction is related to the evaluation of the mean wind power at 100 meters over the sea level. This is made from the perspective that the offshore wind industry is rapidly expanding and various wind projects are prepared to be developed also in the Black Sea. The results show that the coastal environments corresponding to the northwestern and western sides of the sea are more energetic with average wind power densities between 400 and 450 W/m^2 along extended areas, and also with some energy peaks indicating average wind power values greater than 500 W/m^2. Furthermore, the climate wind models show for the near future period a relative enhancement of the wind power in these coastal areas with values between 20% and 50%. Compared to the near future, in the distant future period a relative enhancement of the wind power is expected for RCP2.6 (between 2–6%), while a decay of up to 5% is expected for RCP4.5 and RCP8.5, and this decay is slightly higher for the scenario RCP4.5.

Finally, it has to be highlighted that the significant enhancement in terms of extreme winds is not expected to be accompanied also by a proportional increase of the extreme waves. Thus, a wave prediction system based on the SWAN (acronym from Simulating WAves Nearshore) spectral phase averaged wave model [42, 43] has been implemented and extensively validated in the basin of the Black Sea [44, 45] against both in situ measurements and satellite data. On this basis, hindcast analyses have been performed for the last four decades evaluating also the magnitude of the extreme storms. Furthermore, using the same wave modeling system forced with climatic wind fields, corresponding to the RCP scenarios 4.5 and 8.5, simulations have been carried out for the future periods focused especially on the analysis of the extreme storm events [46, 47]. The results show that in the past the significant wave heights corresponding to the extreme storms in the Black Sea were sometimes even greater than 14 meters. On the other hand, for the future, although the extreme winds are expected to be considerably higher (as the results of the present work indicate), the maximum expected significant wave heights in the Black Sea are lower than 12 meters. These results, which at a first sight seem to be a paradox, are in fact due to the cyclonic wind behavior corresponding to the future extreme storms expected in the Black Sea. Thus, the limited fetches and the rapid variations of the directions characteristic to these cyclonic winds do not favor the development of the high waves and, although more energy is transferred from the wind to the waves in such conditions, an important part of this energy is dissipated through whitecapping and wave breaking.

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ABBREVIATIONS

AR5	Fifth Assessment Report
DF	Distant future time interval (2061-2100)
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation

ERA	ECMWF Re-Analysis
IPCC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
NF	Near future time interval (2021-2060)
P_{wind}	Wind power
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RP	Recent past time interval (1980-2019)
SMHI	Swedish Meteorological and Hydrological Institute
SWAN	Simulating Waves Nearshore
U_z	Wind speed at the height *z*
UTC	Coordinated Universal Time
z_0	Surface roughness length

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