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ORIGINAL ARTICLE

Climate change impacts on wind power generation for the Italian peninsula

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Abstract
Wind energy is one of the key renewable resources contributing to climate change mitigation policies in national and international energy transition strategies. However, climate change itself can affect the availability of wind resources, due to possible future changes in large-scale circulation pattern. This study aims to understand whether how and to what extent current and future climate change is affecting wind producibility in Italy. In this analysis, the 10 m wind speed from Euro-CORDEX regional climate models was bias-corrected using MERIDA meteorological reanalysis and the wind producibility is calculated, using a reference turbine chosen among the most commonly installed in Italian wind farms. The changes in the availability of wind resources from the reference period 1986–2005 for the short (2021–2050), medium (2051–2080), and long term (2071–2100) are analyzed, considering both the RCP 4.5 and RCP 8.5 scenarios. The results show a prevalently weak and not statistically significant climate signal for the RCP 4.5 scenario, while a more pronounced and significant signal is highlighted for the RCP 8.5 scenario in the medium and long term, indicating a decrease in wind producibility. Specifically, the conclusions suggest that future planning of wind producibility should mainly focus in some specific areas of the eastern Italian coast and in the south-east Italian regions, mostly in the off-shore areas. In these regions, indeed, the RCP 8.5 scenario shows the lowest decrease in the overall annual producibility, while, for the RCP 4.5 scenario, the medium and the long term foresee a slight increase in wind producibility at the annual level, while, in the short term, an increasing trend is observed mostly in the spring season.

Keywords Climate change · Renewable sources · Wind energy · Energy transition

Introduction

The impact of climate change on the Italian electricity and energy system became increasingly important in the recent decades. Extreme events, such as heavy rainfall, wet snow, heat waves, and extreme droughts, strain the energy system, increasing the occurrence of disruptions and affecting the quality and the continuity of the energy supply (Faggian et al. 2017; Lacavalla et al. 2017; Bonanno and Lacavalla 2020).

In order to take action in mitigating climate change, the energy production system is progressively orienting toward the use of renewable energies which are fundamental to move forward in the energy transition for the next decades.

Comparing the percentage contribution of wind production over the total electricity produced (IEA 2022; Terna 2020), the European contribution doubled every 5 years from 2000, reaching in 2020 more than 20% of the total, while, for Italy, the percentage remained lower, at approximately 7% of the total due to the smaller spatial extent of the country and due to its lower windiness. The 90.5% of the total installed wind power in Italy is available in the major islands (Sicily and Sardinia) and in the southern regions, that are the windiest areas of the country, with more than 1 GW of installed power in each of these regions (GSE 2020).

According to the Italian Integrated National Energy and Climate Plan—PNIEC (PNIEC 2019) and the Long Term Strategy—LTS (LTS 2021), a major expansion of wind farming in Italy is planned in the upcoming decades. By 2030, an increase of around 1.5 times in installed capacity

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is expected, compared to the 10.8 GW available in 2020, which is going to triple by 2040 and quadruple by 2050. Another important aspect to underline is the future strategic role of the off-shore wind farms, which are planned to expand in different areas of the central and southern Italy, with an expected percentage of 30–40% of installed capacity over the total.

The increasing demand for renewable energy in the coming decades, therefore, requires a deep understanding of the accessibility to wind resources and of the susceptibility of these resources to climate change. Climate change is in fact able to affect the availability of wind resources and its variability due to changes in large-scale circulation (Gonzalez et al. 2019).

In recent years, several studies analyzed the impact of climate change on wind speed and on wind energy production in Europe, using both global (GCMs) and regional climate models (RCMs) (Barstad et al. 2012; Pryor et al. 2020; Hueging, et al. 2013; Tobin et al. 2015; Moemken et al. 2018). Most of these studies analyzed different emission scenarios and different downscaling techniques and agreed on a general increase in wind energy production in Northern Europe and a decrease in Southern Europe for the upcoming decades, even if with some differences in magnitude in the calculation of the expected changes. Focusing on the Mediterranean region, the First Mediterranean Assessment Report (Cherif et al. 2020) assesses with medium confidence that a limited wind speed reduction is expected almost everywhere over the Mediterranean Sea, except for the Aegean Sea and northeastern inland areas, where an increase of wind speed is expected. The study of Obermann-Hellhund et al. (2018) also shows the impact of climate change on Mistral and Tramontane, two typical mesoscale winds in southern France, using a combination of RCMs and GCMs models. According to that work, significant changes are expected for Tramontane wind, even if a more significant variation is expected in wind frequency than in average wind speed. Finally, the study of Reale et al. (2021) uses a set of 7 model simulations from the Med-CORDEX initiative (Ruti et al. 2016) to analyze the cyclones activity and the associated wind fields in the future projections according to the RCP 8.5 scenario in the Mediterranean region. The study highlights a general decrease in the occurrence and the intensity of cyclones that crosses the central part of Italy, Tyrrhenian Sea, parts of the Anatolian Peninsula, parts of the Balkan area, and parts of the North Africa and an overall weakening and a consequent change in wind regimes in the above-mentioned regions.

Other studies also showed changes not only in average wind speed, but also in inter-annual and seasonal variability across Europe due to climate change (Hueging et al. 2013; Weber et al. 2018).

Moreover, it is important to underline that the long-term trends for wind speed and wind power production are still rather contained compared to the trends related to temperature increase (IPCC 2022). This, together with a higher natural variability of wind, makes more challenging the study of long-term wind trends, especially on multi-decadal time scales, than performing the same analyses on other atmospheric variables, like, for example, temperature.

Some studies (Pryor et al. 2020; Wohland et al. 2019, 2021) confirmed this fact, proving that natural wind variability prevails over the anthropogenic long-term trends. Consequently, the observed trends of wind speed on short time scales (on the order of decades) are attributable to the internal climate variability at lower frequencies.

This study focuses on the expected impacts of climate change on wind power generation, with a particular interest on the Italian peninsula. In particular, we consider an ensemble of Euro-CORDEX regional climate models, and we analyze the anthropogenic signal related to the wind power production. First, a temporal analysis of the 10 m wind variable is performed, to highlight the high internal variability with respect to the anthropogenic climate signal and the differences between land and sea grid points in terms of variability and trends; secondly, a bias correction to 10 m wind speed projection of Euro-CORDEX climate models is applied, using the MERIDA reanalysis (Bonanno et al. 2019) and finally the wind producibility is calculated considering a reference turbine. The power producibility climate scenario for the short (2021–2050), medium (2051–2081), and long term (2071–2100) is calculated for the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenario, with a detailed analysis of the signal uncertainty.

After an introduction on the state of the art and on the objectives of this study, given in the present chapter (Chapter 1), the study is organized as follows: Chapter 2 presents the data used and methodology, Chapter 3 illustrates the analyses of the results and, finally, Chapter 4 draws conclusions on the plausible and most preferable areas for the expansion of wind power farms on the Italian territory and proposes ideas for the continuation of these studies.

Data and methods

Regional climate models and meteorological reanalysis

In this study, an ensemble of regional climate models from the Euro-CORDEX project (Jacob et al. 2014) is used, at a spatial resolution of 12 km and 3-h temporal resolution for the RCP scenarios 4.5 and 8.5. The Euro-CORDEX models represent a dynamic downscaling of several global models from the CMIP5 project (CMIP5 2010). The decision to use a 3-hourly temporal resolution instead of a daily one

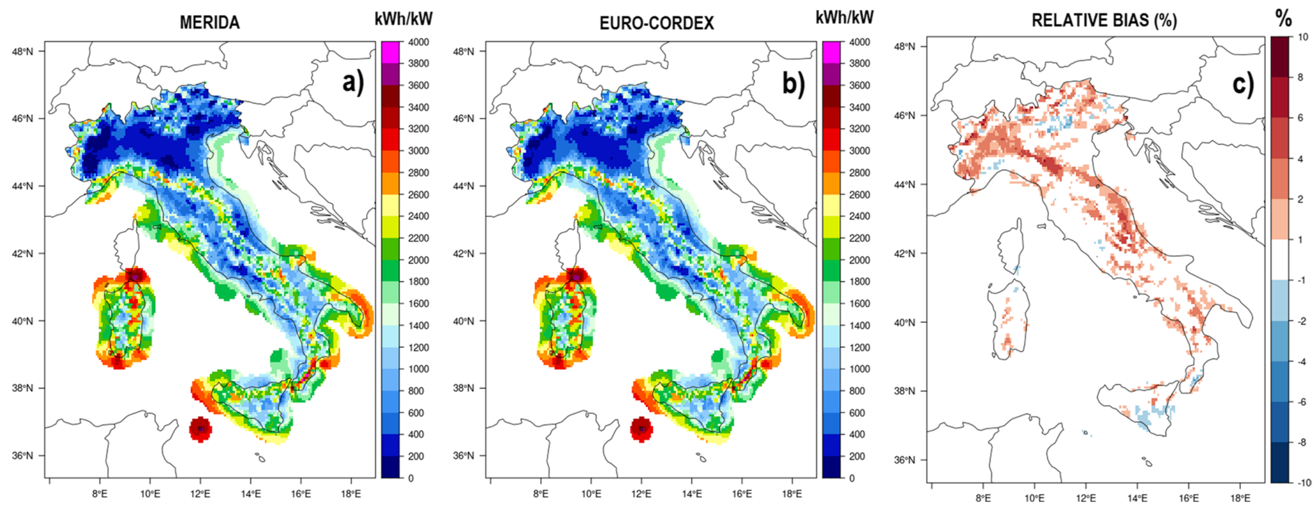

Fig. 1 Wind producibility comparison (in kWh/kW or equivalent hours h) of MERIDA reanalysis (**a**) and of ensemble mean of the bias-corrected Euro-CORDEX models (**b**). **c** show the relative bias B_{rel}

accounts the fact that small changes in wind speed during the day can lead to major changes in energy production, since the power produced by turbines scales with the cube of wind speed. Because of this non-linear relationship, considering a daily temporal resolution instead of a 3-hourly would thus lead to a possible inaccurate estimation of the wind power production. For this reason, the model simulations that are considered in this study are the ones that are available at 3-h temporal resolution for both of the RCPs considered. See Fig. S1 in the electronic supplementary material for details about the Euro-CORDEX domain and the domain that was selected for this study, centered on the Italian peninsula. See Table S1 in the electronic supplementary material for the lists of 11 Euro-CORDEX global and regional climate models selected for this study.

In addition to that, MERIDA reanalysis (Bonanno et al. 2019) at 7 km of spatial resolution is used. This dataset represents a dynamic downscaling over the Italian domain of the ERA5 global reanalysis (Hersbach et al. 2020) for the period 1986–2020, using the WRF-ARW model (Skamarock et al. 2008). The use of reanalysis is necessary to perform a bias correction of 10 m wind speed of the Euro-CORDEX simulation, since reanalysis assimilates observations to reproduce the best possible representation of what was actually observed in the past. In the next chapter, the methodology used to analyze climate models and reanalysis simulations for 10 m wind speed is described.

Temporal analysis of 10 m wind speed

This part of the analyses focuses on studying the temporal evolution of the average climate signal over Italy and on assessing the differences in trend between land and sea points, in order to understand the partitioning of the climate signal between the internal variability and the proper anthropogenic signal. The strategic interest in analyzing these results over the sea resides in the necessity to provide information on the possibility to install off-shore wind turbines in the next decades, as planned by the Italian government (LTS 2021). The monthly mean of the 10 m wind speed anomalies is computed both for Euro-CORDEX simulations and ERA5 reanalysis. Monthly means are computed starting from the 3-hourly wind speed variable and the monthly average is calculated to better highlight the temporal variation and trends of wind speed in future scenarios with a less noisy signal than using the 3-hourly output. The higher resolution MERIDA reanalysis has currently a temporal extension not sufficient to derive a complete climatological overview for both trend and internal variability of 10 m wind speed observed in the past and, hence, it was not considered in this analysis. Anomalies are calculated with respect to the reference period 1971–2005 and are spatially averaged over the Italian domain (Fig. 1b). The calculation is performed both for land and sea grid points and for the two RCP scenarios.

Calculation of wind producibility and wind density

For the calculation of wind power producibility, a reference turbine is chosen among the most commonly used in the Italian wind farms. The chosen reference turbine is a VESTAS V112—3000 kW, with cut-in speed of 3 m/s, rated wind speed of 15 m/s, cut-off wind speed of 25 m/s, and minimum and maximum rotor height of 84 and 119 m, respectively (the power curve is available at https://www.thewindpower.net/turbine_en_413_vestas_v112-3000.php).

Because the reference turbine rotor height is on the order of around 100 m, it is necessary to extrapolate the corresponding wind speed height from the Euro-CORDEX models and MERIDA reanalysis, since the model data is not available at that height. Starting from the 10 m wind speed (available both in the Euro-CORDEX models and in the MERIDA reanalysis), the 100 m wind speed is obtained using the following Eq. (1) (Tobin et al. 2015; Hueging et al. 2013):

$$u = u_r \left(\frac{z}{z_r} \right)^{\alpha} \quad (1)$$

where u is the wind speed to the desired height level, u_r is the reference wind speed at the reference level z_r, z is the desired height, and α is the coefficient of the power law. For this equation, the desired height is set at 100 m, reference level is 10 m, and the value of the α coefficient is commonly set for simplicity equal to 0.14 (Olaofe 2016), even if it can vary depending on the roughness of the surface, the presence of obstacles, and on the atmospheric stability. For open water, instead, an exponent of 0.11 is used, because it is considered more appropriate (Hsu et al. 1994).

The same calculation is also performed over sea grid points enclosed within a buffer of 40 km from the coastline, where offshore wind turbines are likely to be installed. Wind production is finally calculated from the power curve of the reference wind turbine, associating each wind speed value to the corresponding power produced. In addition to that, wind producibility at the annual scale is obtained dividing the total annual wind energy production by the nominal power of the plant (3000 kW), for each grid point. However, because of the 3-hourly temporal resolution of wind speed data, it is first necessary to multiply the total annual energy production by 3, assuming that wind speed remains constant during each 3-hourly time frame. Some tests were also performed using more complex time interpolation techniques (linear and spline interpolation), but since the results of the tests did not show any significant difference on the final values of annual wind producibility, the simplest method of assuming constant wind over the 3 h was chosen.

Bias correction

The 10 m wind speed from the Euro-CORDEX models was bias-corrected before entering Eq. 2. An accurate wind estimate is very important due to the sensitivity of the turbine response to wind speed. In fact, wind turbines only work optimally within a specific wind speed range. Outside the cut-in and cut-off wind speed range, wind turbines do not produce any energy. Hence, it was necessary to correct the model bias from the Euro-CORDEX ensemble members with MERIDA reanalysis, in the attempt of reproducing as realistically as possible the wind climatology and the trends in the historical period.

The technique used for the bias correction is the Empirical Quantile Mapping (EQM, Gudmundsson, et al. 2012), that corrects the distribution function of simulated wind speeds for each Euro-CORDEX simulation, in order to be consistent with the observed distribution given by MERIDA reanalysis. In order to do that, a quantile-specific transfer function is added, as determined by the difference between simulated and observed empirical cumulative distribution functions. One of the many advantages of this technique is that it acts not only on mean and variance, but it affects the whole distribution. In addition to that, this method does not require any assumption on the underlying distribution for the variable considered, thus resulting in a very versatile tool for correcting the bias of many climate variables.

The EQM technique allowed us to perform the bias correction of the Euro-CORDEX climate models, downscaling the wind speed from the original 12 km spatial resolution to 7 km resolution of MERIDA reanalysis. The wind speed from the downscaled and bias-corrected fields was extrapolated from 10 to 100 m height using Eq. 2 and the wind producibility was calculated. A comparison for the historical period 1986–2005 was finally performed to assess how well the climatology of wind producibility of the bias-corrected Euro-CORDEX ensemble mean agrees with MERIDA reanalyses.

A comparison between MERIDA reanalysis and the bias-corrected Euro-CORDEX models was performed to demonstrate the positive contribution of the bias correction with the EQM technique. For each grid point, a relative bias B_{rel} was computed with respect to the nominal power of the reference turbine ($P_{\mathrm{nom}} = 3000$ kW) with the following Eq. (2):

$$B_{\mathrm{rel}}(\%) = 100 \left(\frac{P_{\mathrm{EUCORDEX}} - P_{\mathrm{MERIDA}}}{P_{\mathrm{nom}}} \right) \quad (2)$$

where P_{EUCORDEX} and P_{MERIDA} are the average producibility over the period 1986–2005 for Euro-CORDEX ensemble and MERIDA respectively.

Wind producibility scenarios and uncertainty analysis on electricity market area[1]

Wind producibility scenarios are obtained considering the wind producibility percentage variations of the ensemble mean for each grid point, with respect to the reference period

[1] Electricity market areas are aggregates of geographical areas characterized by the same zonal price of energy. The electricity system is, in fact, divided into portions of transmission networks for which there are physical limits of energy transit with the corresponding neighboring areas, to ensure the security of the electricity system. The Italian market areas represented in Fig. 3 and Fig. 4 on the right and are: NORD—Northern Italy, CNORD—central and northern Italy, CSUD—central and southern Italy, SUD—southern Italy, SICI—Sicily, SARD—Sardinia.

1971–2005, in the short (2021–2050), medium (2051–2080), and long term (2071–2100) and both for annual and seasonal producibility (DJF = Dec-Jan-Feb, MAM = Mar-Apr-May, JJA = Jun-Jul-Aug, and SON = Sep-Oct-Nov). These analyses are performed for different RCPs and are overimposed with the Italian electricity market areas[1] to facilitate the identification of the Italian geographical areas where a certain change in wind producibility is expected.

In addition to that, an analysis of the uncertainty of the signal is also carried out in order to take into account the reliability of the signal itself for the different time periods considered (short, medium, and long range). The methodology used to calculate the uncertainty of the signal takes into account both the statistical significance of each model of the ensemble and the concordance in sign among the different members of the ensemble. The statistical significance is obtained with a Wilcoxon statistical test (Wilcoxon 1945) to investigate whether, for wind producibility, the future distribution differs from the distribution for the reference period 1971–2005. A certain number of models is selected (60% of the total), in order to consider the signal reliable, according to one of the two criteria above mentioned. The condition of statistical significance (as obtained from the Wilcoxon test mentioned above) is considered more stringent than the concordance in sign and if this first condition does not occur, the climate signal is not considered reliable; if the statistical significance occurs for at least 60% of the models, but with no concordance in sign, then the signal is considered with a lower level of reliability; if both conditions are satisfied, the signal is considered reliable.

Analysis of results

Comparison between climatological wind producibility of Euro-CORDEX ensemble and MERIDA reanalysis

The aim of this comparison is to assess how well the climatology of wind producibility of the bias-corrected Euro-CORDEX ensemble mean agrees with MERIDA reanalysis, for the historical period 1986–2005. In fact, raw outputs of climate models in the historical period are not usually capable to represent exactly the same statistical properties of the observations, because of the intrinsic model approximations in the representation of physical processes, model discretization, and coarse spatial resolution (Sippel et al. 2016). These RCM biases can bring some inaccuracies in the representation of wind producibility in some areas of the domain, especially in those with complex orography (Alps, Appenines). Hence, a bias correction was necessary to correct the climate model outputs toward a more realistic representation of wind producibility over the analyzed domain.

An overall good agreement between MERIDA reanalysis and the bias-corrected Euro-CORDEX models is highlighted from the comparison (Fig. 3), demonstrating the positive contribution of the bias correction with the EQM technique.

The relative bias B_{rel} (Fig. 1c) shows high positive bias mostly in the areas with the lowest wind producibility values (e.g., northern Italy). When the values of wind producibility are higher, the bias is very small or not significant. Given this result, in the next chapter, the unbiased wind producibility scenario is analyzed to derive information about the impacts of climate change.

Temporal analysis of Euro-CORDEX and ERA5 10 m wind speed

Applying the methodology illustrated in Chapter 2, the temporal analysis of the 10 m wind speed for the Euro-CORDEX climate models and for the ERA5 reanalysis is performed over the Italian domain. The results show a general decrease of the anthropogenic climate signal of the 10 m wind speed, especially starting from the middle of twenty-first century and for the RCP 8.5 scenario, with a steeper descent over sea grid points (Fig. 2).

From the analyses, it is also highlighted a certain spread on the Euro-CORDEX ensemble and a large multi-decadal variability associated to each model, as evident from the wide oscillations of the 10 m wind speed anomaly through past and future decades. This strong variability is also confirmed by the ERA5 reanalysis 10 m wind speed anomaly. Moreover, the study of Zeng et al. (2019) using wind data from in situ stations worldwide shows clearly this multi-decadal variability on historical time series. In Europe, the same study shows a significant drop in wind speed in the last decades of the twentieth century followed by an increase from the year 2000 to the present. The causes of these oscillations can be related to the 10-year variability of large-scale oceanic/atmospheric circulations and, in particular, the wind speed oscillations in the European area are well explained by the fluctuations of the NAO (North Atlantic Oscillation).

Separating the climate signal for sea and land grid points highlights how variability is much higher for sea grid points. Each individual model oscillation represents its intrinsic internal climate variability, which differs among each member of the model ensemble and contains in itself the embedded anthropogenic climate signal. Having an ensemble mean of many different model members allows to filter out the internal climate variability and the stochastic component of model uncertainty, assuming that the models do not have any systematic error, and

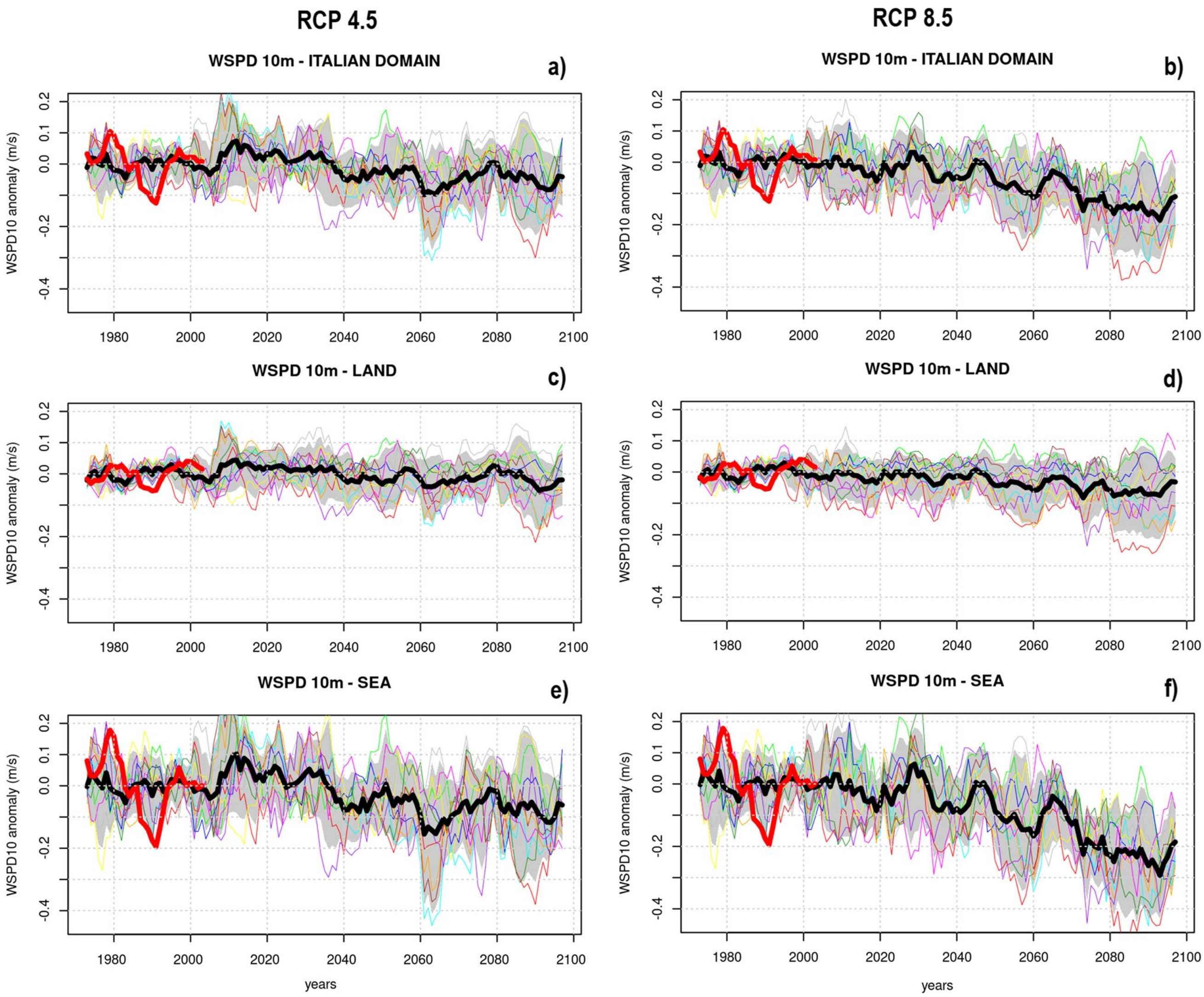

Fig. 2 10 m monthly wind speed anomaly for the of Euro-CORDEX model runs, calculated on the reference period 1971–2005. Results are shown on the full size of the domain (land plus sea grid points) (first row, **a** and **b**), on the land-only grid points (second row, **c** and **d**), and on the sea-only grid points (third row, **e** and **f**), for the RCP 4.5 (first column, **a**, **c**, and **e**) and RCP 8.5 (second column, **b**, **d**, and **f**) scenarios. In each panel, the colored lines of the spaghetti plots represent each member of Euro-CORDEX models run from the one listed in Table 2.1. A legend to associate each member of the Euro-CORDEX model to a color is also given in Fig. S3 in the supplementary material. The black line represents the ensemble mean of the Euro-CORDEX models and the gray bands are the 5th and 95th percentile of the Euro-CORDEX models distribution, calculated for each month. In red, the ERA5 10 m wind speed anomaly is also represented, as the main reanalysis dataset reference for this study

obtaining, as a result, the anthropogenic climate signal (black line in Fig. 2).

In summary, these analyses show that the 10 m wind speed anomalies present significant differences both in terms of internal variability and anthropogenic climate signal, between the two RCP scenarios and, even more differences, between land and sea grid points. These prove the importance of distinguishing the analyses of climate signal among different areas of the Italian territory and in particular between land and off-shore areas, in order to better isolate the climate signal for future wind power generation planning over Italy.

Analysis of wind producibility for RCP 8.5 and RCP 4.5 scenarios

Results for the RCP 8.5 scenario

Analyzing the results for the RCP 8.5 scenario (Fig. 3), it is evident an annual decrease in wind producibility, especially in the medium and long term and more pronouncedly on the off-shore areas of the west coast and on the SICI and SARD electrical market areas. Focusing on the different results by season, the decrease in wind producibility is

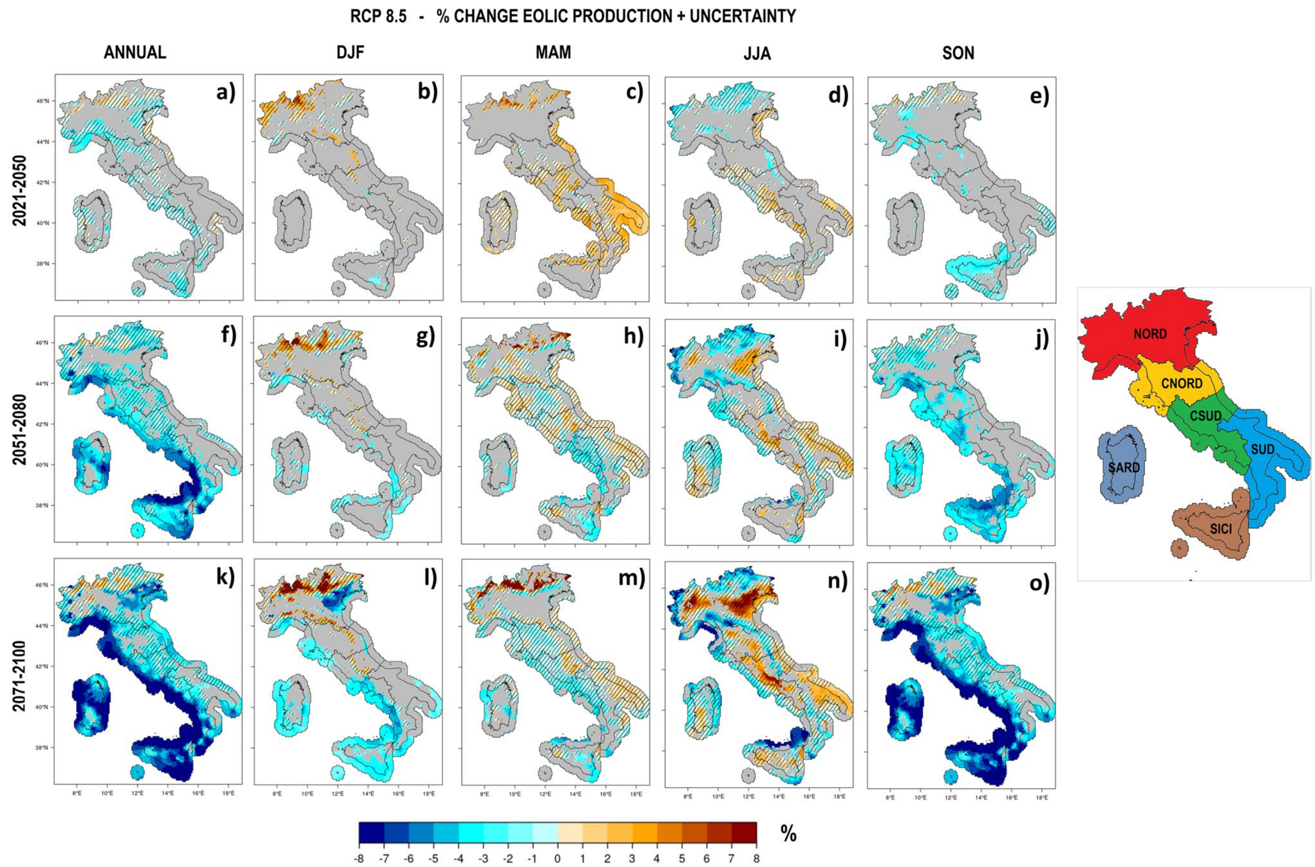

Fig. 3 Percentage change in wind producibility for the short (2021–2050), medium (2051–2080), and long term (2071–2100) at annual level and for the different seasons (DJF, MAM, JJA, and SON) according to the RCP 8.5 scenario with respect to the reference period 1986–2005. The anthropogenic climate signal is represented together with the associated level of reliability. Gray areas indicate that the climate signal is not reliable, colored areas with diagonal lines show a low level of reliability (at least 60% of models have a statistically significant signal), and colored areas represent a reliable climate signal (at least 60% of models have a statistically significant signal and at least 60% of models have a signal with a concordant sign)

stronger during autumn (SON). In terms of climate signal reliability (see Chapter 2.5), lower values are observed in the short term than in medium and long term, in which the reliability progressively increases. In the short term, the increase in wind production is evident in the SUD market area for the spring period (MAM), especially in the south-east, with an higher reliability on the off-shore area (about + 3–4% increase). SICI market area shows a decrease of about 3–4 in the autumn season with an high reliability in the northern part of the island. In the medium term, the overall reliability of the climate signal increases over the whole Italian peninsula. A reliable decrease in wind producibility emerges both in autumn (SON) and in the annual producibility, with a percentage variation of 3–5% on the west coast, SICI, and SARD and of the 7% on the corresponding off-shore area. On the other seasons, there is an increase in wind producibility during the summer period (JJA) on the easter plains in the NORD market area, and on some regions of the CSUD area and on the south-east of the off-shore area in the SUD area, with a low level of reliability. In the long term, the most important and significant variations with a high reliability of the signal are highlighted on different portions of the Italian territory, especially on the off-shore areas of the western coast and on the SICI and SARD market areas. In the inland areas, significant and reliable decreases of around 3–5% are observed at the annual scale, with higher values in off-shore regions, where more than 8% decrease in wind producibility is expected locally. The decrease on the off-shore regions of the east coast is somehow contained, around 3–5%, and with a low level of reliability. In the summer season (JJA), there is an increase in wind producibility in the areas of the eastern plains in the NORD market area (with peaks of 8% or higher) and on the south-east part of the SUD area (around 3–4%), with a locally reliable signal. Finally, also a significant increase (higher than 8%) can be found in the Alps during winter (DJF) and spring (MAM) but with a low level of reliability.

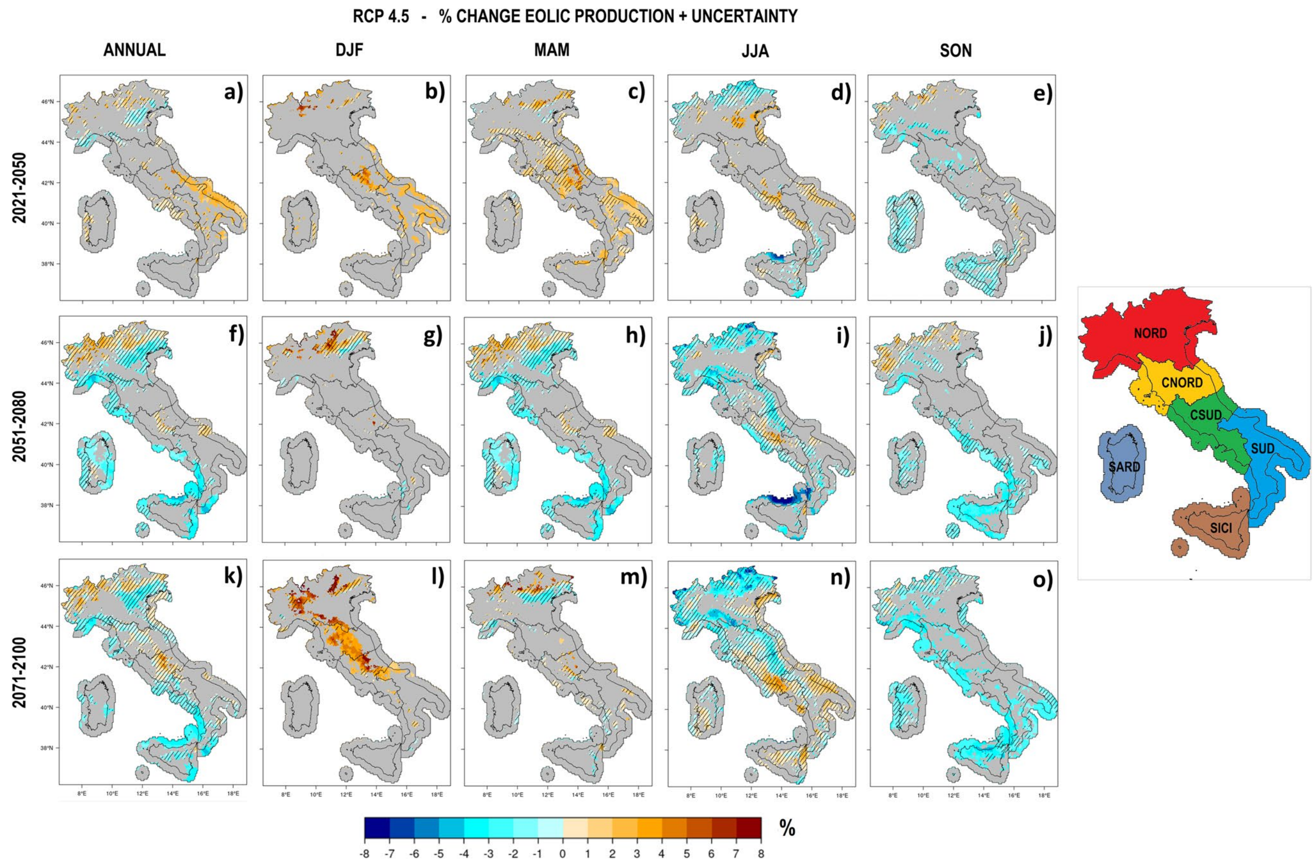

Fig. 4 As in Fig. 3, but for RCP 4.5 scenario

Results for the RCP 4.5 scenario

The results for RCP 4.5 scenario (Fig. 4) are more complex to analyze, because wind producibility changes are smaller and the climate signal is more spatially heterogeneous and with a lower level of reliability. In the short term and at the annual scale, only the SUD market area and, in particular, the south-eastern off-shore area shows a significant and reliable signal of increase in wind producibility (around 3–4%), mainly associated to winter (DJF) and spring (MAM) seasons.

In the medium term, at the contrary, there is a reliable decrease (2–3%) in wind producibility in some off-shore areas of the Tyrrhenian coast, SICI and SARD market areas, particularly in spring (MAM) and autumn (SON). A decreasing signal is also noticeable across the Po Valley, while an increase, even if with a low level of reliability, is highlighted on the Alpine region. Big differences are also highlighted in analyzing the results over the different seasons: in many cases, an increase in wind producibility is observed in winter (DJF), with a marked decrease in autumn (SON).

This same behavior, even amplified, is observed for the analyses on the long term, with a decrease of around 4% in the off-shore areas of the west coast and in the SUD, SICI, and SARD market areas, mainly in the autumn season. At the contrary, in winter, a reliable signal increases on the mountains in central Italy and in some flat areas in the NORD market area, with values of around 5–7%. At the annual level, this contrasting decreasing and increasing behavior among different seasons has the effect of compensating and smoothing out the climate signal and consequently reducing its reliability on different areas of the Italian territory.

Summary and conclusions

In this study, the impact of climate change on the availability of future wind resources is analyzed. The study compares an ensemble of 11 Euro-CORDEX regional climate models that represent the state of the art in climate studies at 12 km resolution, with the 7 km resolution MERIDA meteorological reanalysis. The MERIDA reanalysis is also used to perform a bias correction of the Euro-CORDEX models ensemble for the wind variable. Wind bias correction is fundamental in this type of study because wind production from a generic type of wind turbine depends on specific wind speed thresholds (cut-in and cut-off) and outside this range the

Table 1 Percentage change in wind producibility over the short (2021–2050) (1st row), medium (2051–2080) (2nd row), and long term (2071–2100) (3rd row) on the market areas/regions that experience a reliable change in wind producibility, for RCP 4.5 (from 2nd to 4th column) and RCP 8.5 scenarios (from 5 to 7th column)

	RCP 4.5			RCP 8.5		
	Market area/region	Season	Variation (%)	Market area or region	Season	Variation (%)
Short term	South-eastern SUD off-shore	Annual	3–4% increase	SUD	Spring	3–4% increase
				SICI	Autumn	3–4% decrease
Medium term	West coast, SICI, SARD	Annual	2–3% decrease mainly off-shore	West coast, SICI, SARD	Annual and autumn	5% decrease on-shore 7% decrease off-shore
Long term	West coast, SUD, SICI, SARD	Mostly autumn (less pronounced at annual scale)	3–4% decrease	West coast, SICI, SARD	Annual and autumn	3–5% decrease in land >8% decrease off-shore
	Mountains in central Italy, flat areas of NORD	Winter	5–7% increase	NORD eastern plains	Summer	7–8% increase

wind turbine does not produce any energy. A bias in wind speed would therefore lead to underestimation or overestimation of wind power production. In this study, the VESTAS V112—3000 kW was chosen as a reference wind turbine, selected among the wind turbines that are most commonly installed in the Italian wind farms. Starting from the reference wind turbine power curve, the production values and the wind producibility are calculated, both for the on-shore part and the off-shore areas of the Italian territory within a buffer of 40 km from the Italian coast. The percentage change in the Euro-CORDEX ensemble mean from the reference period 1985–2005 is calculated for the short (2021–2050), medium (2051–2080) and long term (2071–2100). In addition to that, an uncertainty analysis of the signal is also provided, based on the concordance in sign of the models and on the statistical significance of the climate signal for each member of the ensemble mean.

In the following paragraph, we summarize the results of these analyses for both the “business as usual” RCP 8.5 scenario and the RCP 4.5 scenario (Table 1). From this summary, we can draw some guidelines on the expected changes in wind producibility in a climate change scenario.

The climate signal for wind producibility shows very small variations and high uncertainty for the short term, making therefore the signal highly unreliable. A reliable increase (of around 3–4%) can be observed only in RCP 4.5 for the south-east off-shore area of SUD market area. RCP 8.5 shows a reliable increase of 3–4% only in spring season in SUD and 3–4% decrease in SICI market area in autumn season. The reliability increases in the medium term and even more in the long term for the RCP 8.5 scenario, where the signal is stronger and statistically significant in a wider portion of Italian territory. In the medium term, according to RCP 4.5 scenario, a reliable decrease of 2–3% in wind producibility is expected for the west coast, SICI, and SARD market areas at annual scale. RCP 8.5 scenario shows a decrease in the same areas but both at annual scale and in autumn, with about a 5% variation on-shore and 7% off-shore. In long term, the RCP 8.5 scenario shows the most important reduction in wind producibility, especially in the western off-shore areas of the peninsula and on the SICI and SARD market areas, both at annual scale and in autumn, reaching averages values of about 3–5% on-shore and greater than 8% off-shore. The eastern plains of NORD market area also show a reliable variation of wind producibility in summer season with an increase of about 7–8%. Finally, the RCP 4.5 exhibits a decrease of about 3–4% in the west coast, SICI, and SARD market areas, mostly in the autumn season and an increase of 5–7% in winter in the mountain areas of Central Italy and in the flat areas of the NORD market area.

These results indicate that changes in seasonal time scales are very relevant. For this reason, the percentage ratio between the seasonal wind producibility was compared with the annual total for each market area in historical period 1986–2005 from the Euro-CORDEX ensemble (see Fig. S2 in the electronic supplementary material). This analysis highlighted that in the majority of the market areas, the season with the maximum wind producibility is the winter, followed by autumn and spring, each contributing with a quarter of the total annual producibility. Summer is the season with the lowest wind producibility, especially in SICI market area. Considering the previous results, shown in Table 1, it is possible to state that the expected climate-related variation of wind producibility mainly occurs in the seasons of the year with the highest production of wind power.

These results suggest an important conclusion: the future installations of new off-shore wind farms, as requested by the Long Term Strategy (LTS 2021) guidelines by 2050, will not be negatively affected by climate change. The study highlights, indeed, that the expected climate signal for wind producibility will remain small and not statistically significant in the short term. Moreover, some areas will likely be less affected than others by climate change. Specifically, the study highlights that future planning on wind producibility must mainly develop focusing on the areas on the eastern Italian coast and on the south-east regions, mainly in the off-shore areas. In these regions, indeed, the lowest decrease in producibility is expected for the RCP 8.5 scenario at the annual level for the medium and the long term and, in MAM season, a slight increase in producibility is foreseen for the RCP 4.5 scenario, in the short term.

The planning of future renewable energy systems should therefore consider not only the long-term trends in wind speed, but also the multi-decadal fluctuations of wind energy linked to internal climate variability, as the time scale of these fluctuations (decadal scale) is around the same order of magnitude of the average life cycle of a wind farm (15–20 years).

For future work, it might be interesting to investigate how potential climate-related changes in intra-daily and inter-annual variability can affect the continuity of energy production. In addition to that, since wind producibility depends on specific wind speed thresholds, another possible further investigation could focus on understanding how the results of the wind producibility scenarios may vary with the type of wind turbines used. The wind turbine used as a reference for this study is, in fact, one of the most currently used on the Italian territory, but in the off-shore areas, the types of wind turbines used may vary, with different characteristics in terms of produced power from the ones used in the mainland. In the same way, it will be useful to understand how climate producibility signal could change using new types of turbines that are likely to be installed in the upcoming decades.

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Data Availability This research is based on public dataset Euro-CORDEX (https://cordex.org/data-access/) and MERIDA meteorological reanalysis (https://merida.rse-web.it/).

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