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Wind energy resource over Europe under CMIP6 future climate projections: What changes from CMIP5 to CMIP6

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ABSTRACT

The impacts of climate change on the future European wind resource were investigated according to two of the latest future climate scenarios of CMIP6. Towards the end of the current century SSP2-4.5 projects that some small localized areas can experience an increase in the future wind energy resource (around 15–30 % in eastern Ukraine and Turkey). However, all other European areas will experience a significant decrease (5–15 %), particularly towards the end of the current century in the British Isles, Poland, western Ukraine and northern Norway (10–20 %). For the same time period, SSP5-8.5 projects a decrease in future wind energy resource in practically all of Europe (10–20 %), particularly at northern Norway, Poland and western Ukraine (25–30 %). There is significant uncertainty in changes in the wind resource inter- and intra-annual variability, although SSP2-4.5 projects an increase of the latter over Iberia and eastern Ukraine.

These results reveal that CMIP6 future wind resource projections for Europe show relevant differences when compared to CMIP5. Unlike CMIP5, CMIP6 does not project an increase in wind resource for Northern Europe, showing a strong decline for practically all of Europe by the end of the century (SSP5-8.5). CMIP6 projects a strong increase in wind resource in future summer in some areas of southern Europe, whereas CMIP5 projected the opposite (decrease in southern Europe during summer). Unlike CMIP5, in CMIP6 stronger radiative forcing scenarios not only enhance the differences when compared to milder scenarios, but also change the spatial patterns of changes in the wind resource.

1. Introduction

Renewable energies play a fundamental role in the reduction of greenhouse gases (GHG) emissions, a fundamental step to mitigate dramatic changes in the future global climate system. According to Europe's 2030 Climate and Energy Strategy plan, the European Commission aims to reduce its GHG emissions by 40 % (when compared to the 1990's) and to obtain a 27 % quota of renewable sources on its total electricity consumption by 2030 [1]. Of all the renewable energy sources used for electricity generation, wind is one of the leaders in terms of installed generating capacity, fastest growth and technological maturity, being the second leading renewable energy source worldwide in terms of installed capacity, following hydropower. In 2019, installed wind power capacity in Europe grew by 27 % relative to 2018, and wind-derived energy accounted for 15 % of the total electricity consumption in the European Union [2].

However, wind power is very sensitive to climate change itself, since future changes in the wind flow characteristics will significantly change the electricity production from wind [3]. Since the wind energetic potential varies with the wind speed cubed, even small variations in future wind flow characteristics will strongly impact the wind-derived electricity production [4]. The expected wind farms lifetime is typically in the order of 20–30 years, being therefore crucial to estimate how wind energy resources may change over the next decades, especially under global warming scenarios. Besides changes in the future mean wind speeds that will impact the wind resource of a given region, changes in the wind inter- and intra-annual variability can affect the reliability, profitability and stability of the produced electricity [5].

Future climate projections provided by Global Climate Models (GCMs) are the main source of information for the investigation of climate change and related impacts. The Intergovernmental Panel on Climate Change (IPCC) Assessment Reports are based on the Coupled

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Model Intercomparison Project (CMIP), a collaborative climate modelling framework coordinated by the World Climate Research Programme (WCRP). Currently, CMIP is in it's sixth phase (CMIP6) and it constitutes the latest state-of-the-art global future climate scenarios which will serve as basis for the IPCC 6th Assessment Report scheduled to be released in 2021 [6].

Future changes in the European wind resource under climate change scenarios have been previously investigated using data from CMIP6 predecessor, CMIP5 (and respective downscalings from the CORDEX project). The published research based on CMIP5 future climate projections seems to agree in a wind resource increase in northern Europe and a decrease over southern Europe, an increase of the intra-annual variability (seasonality) and no conclusive evidences of changes in the inter-annual variability [3,5–7]. More recently [8], performed a review of climate change impacts on European offshore wind energy resources analyzing a wealth of published literature that used a wide range of older future climate projections, including CMIP5 and CORDEX. According to this review, there is an agreement on the decrease of the offshore wind energy resouce over Europe, except for some areas (northern Europe, the northwest portion of the Iberian Peninsula, the Gulf of Lyon, the Strait of Gibraltar and the northwest coast of Turkey) that show no change or even an increase in wind power. There are also recent papers that analyze this issue zooming in key European areas for wind energy exploitation [9]: analyzed climate change impacts on the Iberian Peninsula and surrounding ocean wind energy resources using data from a high-resolution (~12 km) multi-model ensemble from the CORDEX project. After validating the CORDEX multi-model ensemble (MME) with ERA5 reanalysis, the authors reported a general decrease of the wind energy resource over most of the onshore and offshore Iberian Peninsula, except some regions such as Galicia; the Atlantic coast of Galicia and north of Portugal; the Ebro, upper Douro and Guadalquivir valleys; the Strait of Gibraltar and Cape Gata. Still for the Iberian Peninsula [10], also used data from the EURO-CORDEX project, but bias-corrected with in-situ wind data, and reported a future wind resource reduction in most of the western Iberian Peninsula. For other areas of the globe, recent studies [11,12] analyzed climate change impacts on the US wind energy resource using data from a high-resolution (~12 km) multi-model ensembles from the North America CORDEX project. MMEs were first validated with ERA-Interim reanalysis and in-situ wind observations, and afterwards used to assess that wind power is projected to decrease over large areas of the US western and eastern onshore and offshore coasts, although central US can experience increased wind speed during some seasons. Also for China, a recent study assessed climate change impacts on the future chinese wind energetic resource [13] using a multi-model ensemble composed by several models from the CORDEX project. Firstly, MME was validated with ERA5 reanalysis and in-situ wind measurements, and then used to find a general wind power decrease throughout the 21st century for China offshore areas. For African regions also recent studies analyzed the impacts of climate change in the wind energy resources [14]: used a MME composed by several GCMs from CMIP6 future climate scenarions to assess future changes in wind energey resource over West Africa. A validation with ERA5 reanalysis was performed, showing that the CMIP6 MME is able to realistically represent the near-surface wind characteristics across most of West Africa, and also that MME performed better than individual most models in representing the near-surface wind fields over the study area. The authors project a robust increase in the wind energy resource over the Guinea coast, and a decrease over the Sahel region [15]. focused on climate change impacts on Northwestern African offshore wind energy resource using a MME composed by 19 simulations from the CORDEX-Africa project. MME was first validated with a model-observations hybrid product (Cross-Calibrated Multi-Platform ocean wind vectors, CCMP), and then used to show that the wind energy resource is projected to increase (decrease) in the northern (southern) offshore areas. A very similar study [16], in what is related to future climate projections data, validation and analyses methodologies, assessed climate change impacts but now on Southwestern African offshore wind energy resource, concluding that an increase of the offshore wind resource is projected for Namibia and South African western coasts, while a decrease is projected for Angolan coastal areas.

The methodologies used in this published literature support the ones used in the present study, mainly in what is related to the use of multimodel ensembles composed by several models and the validation of the future climate projections with reanalyses datasets. Moreover, from the referenced published literature several challenges in this topic of research remain, mainly in what is related to the resolution of the future climate projections (higher spatial resolution is needed for added confidence in the results), agreement between the different models projections (some models agree/disagree in the climate change signal and magnitude of the changes) and realism of the projected climate change scenarios.

Considering the wealth of previously published studies pertaining climate change impacts on wind energy, the key question is whether such research should be revisited in the light of newer generations of future climate scenarios, improved GCMs and understanding of the climate system. In CMIP6, the future climate projections are driven by a new set of GHG emissions and land use scenarios, evolving from a combination of new future pathways of societal development, the Shared Socioeconomic Pathways (SSPs) [6]. SSPs combine socioeconomic and technological development with future climate radiative forcing, and characterize the future development of the society as a whole more realistically, considering the present and future social, economical and political scenarios. Although CMIP6 is still underway, recent research gives indication that, when compared to CMIP5, major improvements are to be expected in the CMIP6 GCMs, updated land use, GHG emissions and respective concentrations. For example [17], found that the CMIP6 version of the Beijing Climate Computing GCM is much closer to observations than its CMIP5 version in the global mean and trends of surface and tropospheric air temperature, circulation and climate variability at different spatio-temporal scales, variations of precipitation and sea surface temperatures [18]. reported major improvements of CNRM-CM6 GCM (included in CMIP6) over CNRM-CM5 (included in CMIP5), with the former providing a better representation of the climate system mean state and variability. In what is directly related to the wind fields [19], found that present-day zonal wind biases have been reduced from CMIP5 to CMIP6 GCMs.

It should be borne in mind that GCMs spatial resolutions are typically too coarse to accuratelly quantify the wind resource of a given area. Thus, the goal of this study is to investigate future changes in the European wind resource in terms of its large-scale changes, which are indicative of what can be expected at smaller spatial scales. Within this context, this work aims to carry out the first study on future changes in the European large-scale wind resource in the context of climate change, both for onshore (over land) and offshore (over ocean) areas, using the latest global future climate projections of CMIP6. Focus will be also given to differences between CMIP5 and CMIP6 future projections for the European wind energy resource.

2. Data and methods

2.1. CMIP6 future climate projections

European future wind energy resource under climate change will be investigated according to two different CMIP6 future climate projections that reflect two distinct paths of human evolution: SSP2-4.5, a more sustainable one, assumes a middle-of-the-road scenario with some GHG emission reductions; and SSP5-8.5, a business as usual scenario which assumes a fossil-fueled development with very limited actions to decrease GHG emissions.

According to Ref. [6], SSP2-4.5 assumes a world that follows a path in which social, economic and technological trends are similar to contemporary patterns, where development proceeds unevenly among countries, with slow progress in achieving sustainable development goals. Environmental systems degrade, although the global energy demand declines. SSP2-4.5 projects CO2 emissions growing until 2040 and then steadily declining until the end of the century, with a radiative forcing peaking at 4.5 W/m2 by 2100 that corresponds to a global mean air temperature increase of about 2.5 °C when compared to pre-industrial era, and of about 1.5 °C compared to our current era. SSP5-8.5 is based on a fossil-fueled development, with strong investments in health and education coupled with high global energy demand resulting from energy intensive lifestyles. Although this allows a rapid growth of the global economy, the consequences are rapid environmental degradation. SSP5-8.5 projects CO2 emissions growing strongly until 2080 and then slightly declining until the end of the century, with a radiative forcing peaking at 8.5 W/m2 by 2100 that translates into a global mean air temperature increase of about 5 °C when compared to pre-industrial era, and of about 4 °C compared to our current era [6]. SSP5-8.5 and SSP2-4.5 are the CMIP6 analogs of CMIP5 RCP-8.5 and RCP-4.5 scenarios, considering similar annual trends of total radiative forcings and global temperature changes.

CMIP6 offers climatic data from a wide number of GCMs. Daily and monthly 10 m wind data (sfcWind variable in CMIP6) was downloaded from the Earth System Grid Federation (ESGF) data portal (https://esgf-node.llnl.gov/) for all GCMs with horizontal resolutions higher than 1.25° in latitude and longitude and with data for the historical, SSP2-4.5 and SSP5-8.5 future climate scenarios. Three 20-year reference time periods were considered in this study, the same ones to be used in the upcoming IPCC AR6: 1995–2014 (historical, which serves as baseline), 2046–2065 (medium-range future) and 2081–2100 (long-range future). 15 GCMs, described in Table 1, fulfilled these requirements.

Since the GCMs have different native spatial resolutions, all the models need to share the same spatial grid to assess the wind climate change signal. Thus, all models wind data grids were remapped to a common 1.125° latitude/longitude grid with 51,200 points (the lowest spatial resolution among the 15 GCMs), following an area-weighted bilinear interpolation. With all GCMs datasets on a common grid, the data was then aggregated into MMEs. MME strategy usually shows better and more reliable results than single-model experiments and is an effective way to minimize the individual model uncertainties, as shown by several studies that compared individual models and multi-model ensemble statistics with observed data [3,20,21].

Table 1
CMIP6 simulations: GCMs, institutions and spatial resolutions.

GCM	Institutions	Horizontal resolution	Number of grid points (global)
AWI-CM-1-1-MR	Alfred Wegener Institut (AWI) - Germany	0.938° lat x 0.938° lon	73,728
BCC-CSM2-MR	Beijing Climate Center (BCC) - China	1.125° lat x 1.125° lon	51,200
CAMS-CSM1-0	Chinese Academy of Meteorological Sciences (CAMS) - China		
CESM2-WACCM	National Center for Atmospheric Research (NCAR) - USA	1.25° lon x 0.938° lat	55,296
CMCC-CM2-SR5	Euro-Mediterranean Center on Climate Change (CMCC) Foundation - Italy	1.25° lon x 0.938° lat	55,296
CMCC-ESM2			
EC-Earth3	EC-Earth-Consortium (12 European countries)	0.703° lat x 0.703° lon	131,072
EC-Earth3-Veg			
EC-Earth3-CC			
FGOALS-f3-L	Institute of Atmospheric Physics of the Chinese Academy of Sciences (CAS)	1.25° lon x 1° lat	51,840
FIO-ESM-2-0	First Institute of Oceanography (FIO), China	1.25° lon x 0.938° lat	55,296
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI-M) - Germany	0.938° lat x 0.938° lon	73,728
MRI-ESM2-0	Meteorological Research Institute (MRI) - Japan	1.125° latx 1.125° lon	51,200
NorESM2-MM	Norwegian Climate Center (NCC) - Norway	1.25° lon x 0.938° lat	55,296
TaiESM1	Research Center for Environmental Changes (RCEC), Academia Sinica, Taiwan	1.25° lon x 0.938° lat	55,296

2.2. - CMIP6 wind data extrapolation and validation

Before investigating the wind resource climate change signal, a validation of the wind data from all the CMIP6 models listed in Table 1 was carried out to assess their ability to realistically represent the real wind climate over Europe for the baseline period (1995–2014). The ECMWF ERA5 reanalysis [22], spanning from 1950 up to the present with a 0.25° latitude/longitude grid resolution, was used as validation for the CMIP6 wind data. Although ERA5 is not a purely observational product, reanalysis are commonly assumed close enough to observations to be used as a reference for climate studies.

Since wind turbine hubs are usually placed at a height of 80–120 m above ground level for onshore areas (or above mean sea level for offshore areas), wind speeds at 100 m were obtained from ERA5 through the Copernicus Climate Change Service Climate Date Store [23]. ERA5 100 m wind grids were also remapped to a 1.125 latitude/longitude grid to match the CMIP6 grid resolution.

Since CMIP6 only has wind data available at 10 m, the CMIP6 models 10 m wind speed data needs to be extrapolated to a height of 100 m to match the ERA5 wind data. In wind energy estimation studies, two expressions are usually used to extrapolate wind speeds to higher elevations: the logarithmic wind profile and the wind power law. The logarithmic wind profile is generally considered to be a better estimator of the mean wind speed in the lowest 10–20 m of the planetary boundary layer. Between 20 m and 100 m, both methods produce reasonable predictions of mean wind speed (in neutral atmospheric conditions). From 100 m to near the top of the atmospheric boundary layer, the power law produces more accurate predictions of mean wind speed assuming neutral atmospheric conditions [24]. Thus, the wind power law was used to extrapolate the CMIP6 10 m wind to 100 m following equation (1):

$$\frac{WS_z}{WS_{z_{ref}}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$

where WS_Z is the wind speed (in metres per second) at a height z (in metres), and WS_{Zref} is the known wind speed at a reference height Zref. The exponent α is an empirically derived coefficient that varies with the atmospheric stability. For a neutrally stable atmosphere,α is approximately 1/7, or 0.143 [25–27], a value commonly used in wind resource assessments. However, an exponent of 0.14 is only suitable for open land surfaces, while over water 0.11 is more appropriate [27].

Since ERA5 also provides 10 m wind speeds, a tuning was carried out to obtain the α values that provide a 100 m wind extrapolation that better match ERA5 native 100 m wind. For that, the ERA5 10 m wind were extrapolated to 100 m using equation (1) and different α values were tested, over land and water, through an iterative process. The α values that minimized the differences between the extrapolated and original 100 m ERA5 winds were then used to extrapolate the CMIP6 10 m wind to 100 m a.g.l/a.s.l. (0.17 for land areas and 0.06 for water bodies).

Afterwards, the CMIP6 100 m wind speed data (WS) was validated with the original ERA5 WS by analyzing, for each gridpoint of the European domain, the overlap percentage (OP) between the CMIP6 and ERA5 WS data. OP measures the degree of similarity between the modeled (CMIP6) and reference (ERA5) WS probability density functions (PDFs), and was computed following equation (2) described in Ref. [28]:

$$OP = \sum_{1}^{n} \text{minimum}(Z_m, Z_0).100 \tag{2}$$

where n is the number of wind speed bins used to calculate the PDFs (26 in this study), Z_m and Z_0 are the frequency of the wind speed values in a given bin from CMIP6 and ERA5 data, respectively. An OP equal to 100 % means that the CMIP6 data perfectly matches the reference (ERA5) data. This methodology has been used in several studies to validate and compare modeled and observed wind speed projections under climate change scenarios [8–10,12].

In addition to OP, differences between the CMIP6 models and ERA5 WS medians for the historical period were also analyzed to validate CMIP6 wind data. The statistical significance of these differences of medians was evaluated by the Mann-Whitney non-parametric test [29] with a 5 % significance level, which tests the null hypothesis of two data samples belonging to continuous distributions with equal medians, against the alternative that they do not.

Finally, the CMIP6 models which showed higher OP values and lower WS median differences (see section 3.1 for these results) were then used to build MMEs of present and future surface wind, from which differences between the present and future were assessed.

2.3. Changes in the future european wind energy resource

Future changes in the European wind resource were assessed by analyzing the differences between the baseline (historical) and future CMIP6 MME WS data, in terms of the median differences between WS historical (1995–2014) and future (2046–2065 and 2081–2100) periods.

Also changes in the wind power density (WPD) were analyzed. Since the WPD varies with the wind speed cubed, small changes in the wind speed can lead to significant changes in the wind resource. WPD at 100 m (WPD) was computed from WS following equation (3), where ρ is the air density (1.225 kg/m^3 at 288.15 K and 1000 hPa) and WS is the wind speed at the selected hub height (100 m).

$$WPD = \frac{1}{2}.\rho.WS^3 \tag{3}$$

To quantify the uncertainty associated with the wind climate change signal, the spread of the differences between the baseline (historical) and future CMIP6 MMEs was assessed. This MME spread was quantified in terms of the median absolute deviations (MAD) of the differences between the baseline (historical) and future CMIP6 MMEs. MAD is a non-parametric measure of the sample variability around its median (dispersion), consisting of a non-parametric equivalent of the standard deviation or variance [29] and is given by equation (4):

$$MAD = \text{median}[|X_i - \text{median}(X)|] \tag{4}$$

To show MAD and the median of the differences between the baseline (historical) and future CMIP6 MMEs in the same spatial map, stippling is used in grid points where MAD is higher than 50 % of the median of MME changes. For example, if in a given gridpoint the median of the differences between the baseline (historical) and future CMIP6 MMEs is of 2 m/s, stippling is used if MAD of the differences between the baseline (historical) and future CMIP6 MMEs is higher than 1 m/s at that gridpoint. The size of the stippling is proportional to MAD magnitudes. Thus, a larger stippling corresponds to higher MME spread and, consequently, higher uncertainty in the climate change signal.

To investigate future changes in the seasonality and intra-annual variability of the wind resource, the same analysis was also performed seasonally. To analyze future changes in the inter-annual variability of the European wind resource, the WPD MME data from CMIP6 was averaged to annual time series for the historical and future 20-year periods, resulting in three-dimensional grids where the temporal dimension has 20 elements (20 years). The differences between historical and future annual WPD variances quantify their inter-annual variability: the lower the variance of the 20-year annual WPD time series, the lower will be the inter-annual variability. For each grid point, the differences between historical and future variances were computed and the respective statistical significance of such differences evaluated using the two-sample F-test of equal variances [29] with a 5 % significance level, which tests the null hypothesis of two data samples belonging to continuous distributions with equal variances, against the alternative that they do not.

Finally, future changes in the frequency of wind speeds not useable for wind energy production were also analyzed. These are very relevant for the wind energy exploitation industry since the current wind turbines cannot produce energy from wind flows with speeds below 3–3.5 m/s (called the cut-in speed) and above 25 m/s (cut-off speed). For that, the difference in the number of days per year with WS below cut-in and above cut-off wind speeds between the baseline and the two future periods were analyzed. MAD was again used to quantify the CMIP6 MME uncertainty associated with the detected differences.

3. Results and discussion

3.1. Validation of the CMIP6 historical (baseline) daily 100 m wind speeds

First, OP and differences in the medians between each CMIP6 model and ERA5 WS for the historical period (1995–2014) were computed. The average OP and median differences between each CMIP6 model and ERA5 WS for all European domain (absolute values) are shown in Table 2.

The CMIP6 models which showed OP values higher than 75 % and WS differences lower than 1 m/s were selected to be included in the CMIP6 MME to be used in the climate change signal analysis (7 CMIP6 models, highlighted in bold in Table 2).

To validate the resulting CMIP6 MME, Fig. 1 shows OP (left panel) and the differences in the medians of the CMIP6 MME and ERA5 WS (right panel) for the historical period (1995–2014).

Fig. 1 left panel shows that, overall, OP is relatively high, averaging to about 77 % for the whole European domain. However, it is also clear that some areas show higher OP values than others, with oceanic areas and inland areas without relevant topographic features showing OP

Table 2
Overlap percentage (OP) and median differences between each CMIP6 model and ERA5 100 m wind speed (WS) for the historical period.

CMIP6 GCM	OP % (averaged for all Europe)	Median differences (m/s) (averaged for all Europe, absolute values)
AWI-CM-1-1-MR	77	0.64
BCC-CSM2-MR	68	0,90
CAMS-CSM1-0	62	1.36
CESM2-WACCM	76	0.67
CMCC-CM2-SR5	68	0.95
CMCC-ESM2	68	0.84
EC-Earth3	84	0.30
EC-Earth3-Veg	84	0.33
EC-Earth3-CC	85	0.31
FGOALS-f3-L	73	0.89
FIO-ESM-2-0	64	0.99
MPI-ESM1-2-HR	75	0.67
MRI-ESM2-0	69	1.07
NorESM2-MM	75	0.74
TaiESM1	66	0.97

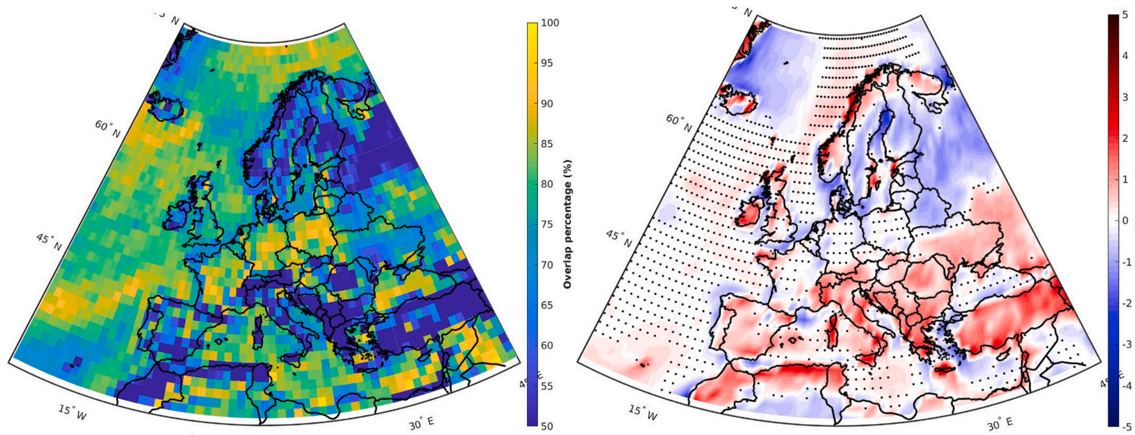

Fig. 1. Overlap percentage (OP, left panel) and differences in the medians (right panel) between the CMIP6 multi-model ensemble (MME) and ERA5 100 m wind speed (WS). Stippling in the right panel indicates areas where the differences in the medians are not statistically significant according to the Mann-Whitney test.

values in the range of 80–95 %. European regions located in areas with complex terrain (mountainous regions or areas with complex coastlines) have lower OP values, mainly the Alps, Pyrenees, the Apennines (throughout Italy), Balkan and Scandinavian mountain ranges, Carpathian and Pindus (Greece) mountains, and Turkey (which has a complex topography in practically all of its territory).

Fig. 1 right panel shows a spatial map of the differences between CMIP6 MME and ERA5 WS medians for the baseline period, which is coherent with OP results: lower differences over ocean and Central European areas without relevant topographic features, while mountainous regions and coastal areas show higher differences. While CMIP6 seems to show a tendency to overestimate the wind speeds over southern Europe, the opposite is seen for northern regions where a slight underestimation tendency is present. Nonetheless, the wind speed differences between CMIP6 MME and ERA5 over Europe are relatively low, averaging to about 0.4 m/s for all the domain and, locally, rarely surpassing 1 m/s.

This poorer performance of GCMs in areas of complex terrain is well known and is related to the GCMs coarse horizontal resolution (around 120 km for the CMIP6 data used in this work). Due to this coarse resolution, the GCMs representation of complex terrains is over-simplified [30]. In these areas, GCMs usually represent mountain ranges (valleys) with lower (higher) elevation than in reality, and the coastlines and terrain roughness lengths are usually smoothed due to their low

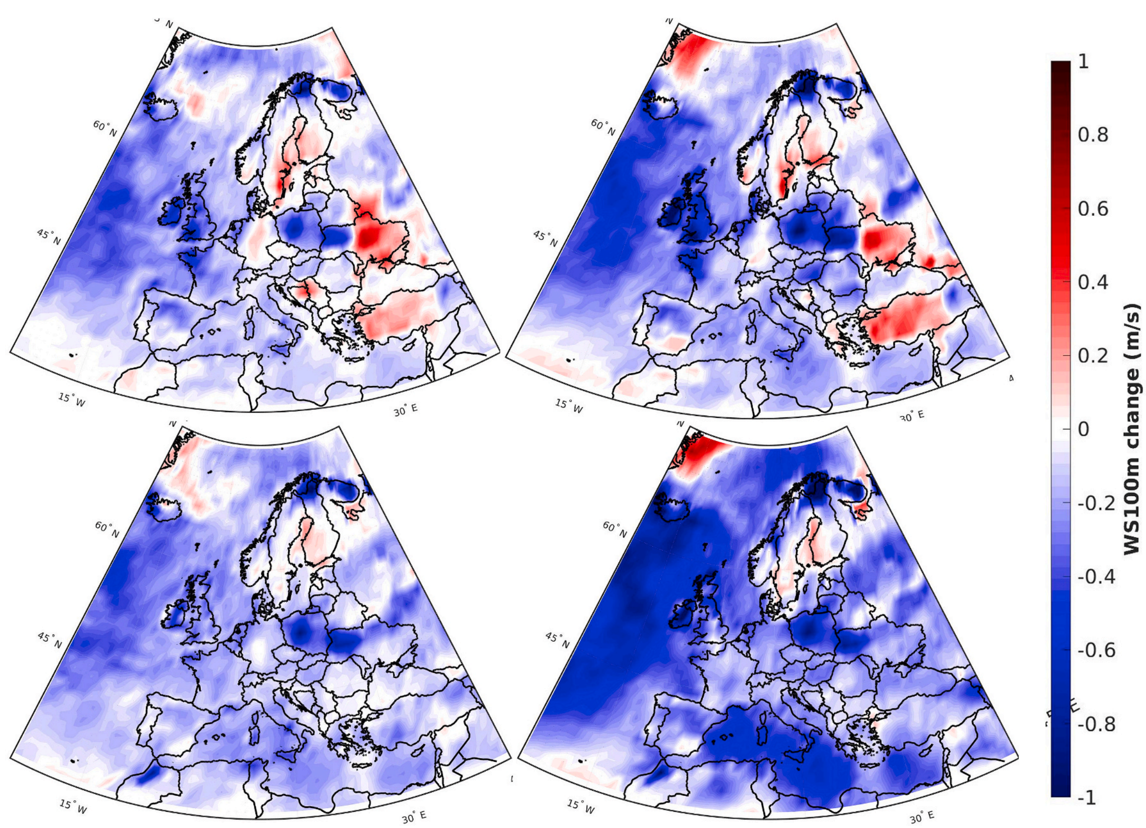

Fig. 2. Median differences between the baseline (1995–2014) and 2046–2065 (left panels) and 2081–2100 (right panels) periods for the annual mean 100 m wind speed (WS) according to SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) future climate projections. Stippling indicates areas where MME spread is higher than 50 % of the plotted differences, with the dots size proportional to MME spread magnitude.

topographic resolution. This limited representation of terrain features, such as topography, coastlines and roughness length, has strong impacts on the simulation of near-surface wind, or wind within the planetary boundary layer as is the case with wind at 100 m that are strongly influenced by the terrain features. In addition, complex topography regions are prone to terrain-induced meso-to local-scale wind flows that are not properly represented by GCMs also due to their coarse spatial resolution. These kind of limitations of atmospheric models are thoroughly analyzed in studies such as [30]. Oceanic areas are relatively flat regions with low roughness values, and with a little spatial and temporal variation of these features, which is why GCMs usually show better performance in simulating the wind field over the ocean.

3.2. Changes in the future european wind energy resource

3.2.1. Spatial patterns of future changes in the 100 m wind speeds and wind power density

Fig. 2 shows spatial maps of the projected changes between the baseline (1995–2014) and the two future periods (2046–2065, left panels, and 2081–2100, right panels) in the annual mean WS according to SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) future climate projections.

Fig. 2 shows that, according to SSP2-4.5 (top panels), the future 100 m wind speeds do not differ significantly from the present-time ones, with some areas showing relatively small decreases (Poland, western France, northern Iberia, northern Norway, western Ukraine, British Isles and North Atlantic ocean areas located west of them) and others an increase (Turkey, eastern Ukraine, southern Finland and Sweden). While for the medium-term future these changes are relatively small (never exceeding 0.5 m/s), they are slightly higher for the long-term future, reaching 0.6–0.8 m/s around the British Isles, Poland, western Ukraine and northern Norway. SSP5-8.5 (bottom panels) also projects small changes in the 100 m wind speeds for the medium-term future, with decreases similar to the ones seen in SSP2-4.5, both in terms of magnitudes and localization. For the long-term future, the wind speed decrease is clearly enhanced when compared to SSP5-8.5 medium-term future and SSP2-4.5 long-term future. This is particularly visible in the Mediterranean, Poland, western Ukraine, northern Norway, British Isles and surrounding Atlantic areas, where WS is projected to decrease between 0.6 and 1 m/s.

Comparing the projections of SSP5-8.5 and SSP2-4.5, the most striking feature is that the wind speed increases projected by the latter are not seen for SSP5-8.5, which projects a decrease of wind speeds practically all over Europe. For both future scenarios and time periods, the detected changes show high confidence since MME spread is very low (no stippling present).

Fig. 3 shows the same information as Fig. 2 but now for WPD.

Fig. 3 shows that the relatively small projected changes in the future 100 m wind speeds lead to significant changes in the future wind resource over Europe. The spatial patterns of changes (both increases and decreases) are coincident with what was seen in Fig. 2 for the wind speeds: while SSP2-4.5 projects mixed changes, with some areas witnessing a decrease and others an increase in the available 100 m WPD, SSP5-8.5 projects a strong decrease of WPD over practically all of Europe, particularly towards the end of the current century. For both future climate scenarios, the spatial patterns of the projected WPD changes for the mid-term future are very similar to the ones seen for the long-term future, but with lower magnitudes.

For the mid-term (long-term) future, SSP2-4.5 projects WPD increases in eastern Ukraine and Turkey of around 10–20 % (15–30 %), and smaller ones in localized areas in southern Finland and Sweden (around 5–10 % for both future periods). In all other European areas

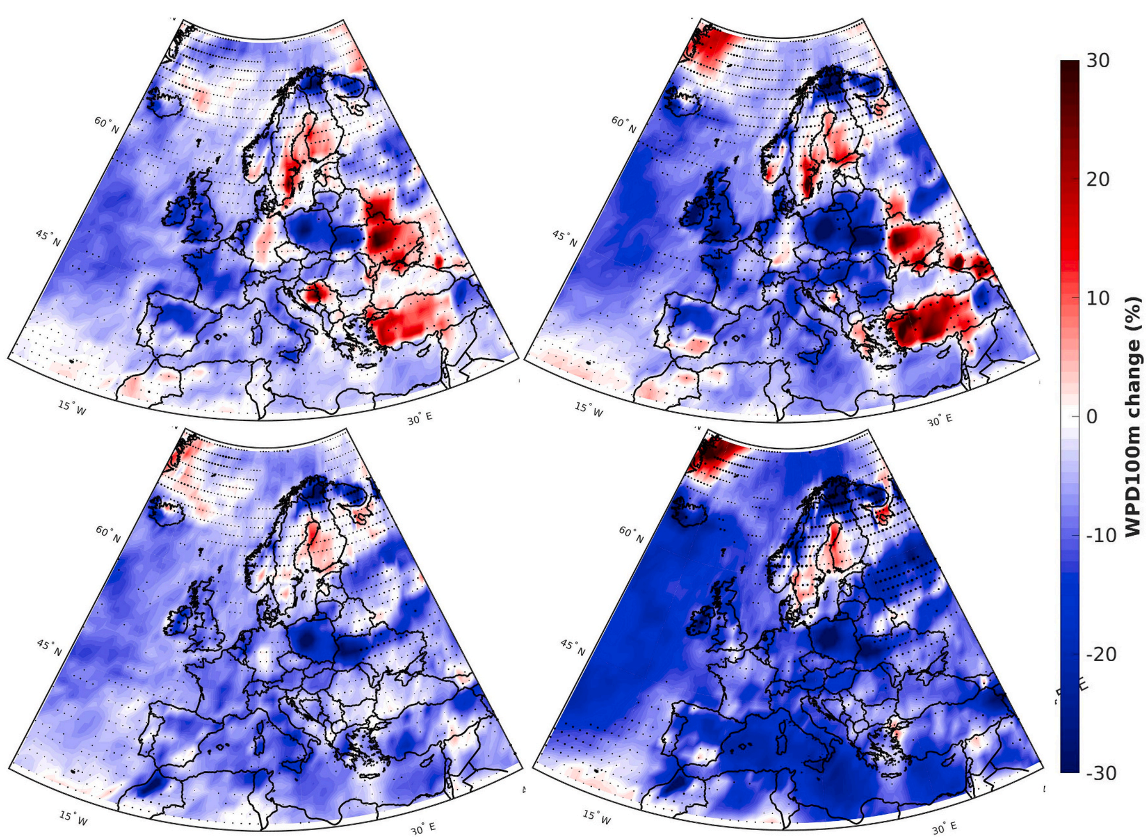

Fig. 3. Median of the percentual differences between the baseline (1995–2014) and 2046–2065 (left panels) and 2081–2100 (right panels) periods for the annual mean WPD according to SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) future climate projections. Stippling indicates areas where MME spread is higher than 50 % of the plotted differences, with the dots size proportional to MME spread magnitude.

there is a projection of WPD decreases of around 5–15 % (10–20 %), except in the British Isles, Poland, western Ukraine and northern Norway, where they can reach 20 % (30 %) of decrease.

SSP5-8.5 projects a decrease of the wind resource practically for all European territory: while for the mid-term future the projected decreases are of around 5–15 % for (reaching 20–25 % in Poland, western Ukraine and northern Norway), for the long-term future the decreases are of around 10–20 % for practically all of European territory, but particularly strong in northern Norway, Poland and western Ukraine where they can reach 25–30 %. For both future periods, the only exception is a small localized area in the North Sea which shows no relevant changes or even a slight increase of WPD, of around 5 %. In terms of uncertainty, for both future climate projections and future periods there are some areas where MME spread is above 50 % of the detected WPD changes, but mainly located in areas where the WPD are of smaller magnitude.

These results show relevant differences when compared to the changes in the wind resource over Europe projected by CMIP5 future climate scenarios. For CMIP5 there is a solid consensus in the published literature pointing to an increase in North and Central Europe and decrease in the Mediterranean, both stronger towards the end of the century and under stronger radiative forcing scenarios [3,5,7,31,32]. However, according to CMIP6 the wind resource increase projected for Northern Europe is limited to a small area in the vicinity of the North Sea, and Central Europe is projected to experience a WPD decrease (except for SSP2-4.5 where eastern Ukraine can witness an increase in its wind resource). Moreover, and unlike what was seen for CMIP5, stronger radiative forcing scenarios in CMIP6 do not only enhance the differences when compared with milder scenarios, but they also show significantly different spatial patterns of the wind resource changes. While SSP2-4.5 projects that some areas can show a WPD increase (eastern Ukraine and Turkey), SSP5-8.5 projects the opposite for these areas, this is, a decrease in WPD for practically all of Europe (except for some areas in the vicinity of the North Sea).

3.2.2. *Seasonality of the climate change signal in the wind resource: intra-annual variability*

To analyze how WPD changes vary intra-annually, Fig. 4 (for SSP2-4.5) and 5 (SSP5-8.5) show the same information of Fig. 3 but now at seasonal scale. The first (second) row of Figs. 4 and 5 shows the differences between the baseline (1995–2014) and the 2046–2065 (2081–2100) period. From left to right, the seasons are spring, summer, fall and winter.

Fig. 4 shows that according to SSP2-4.5 there is not a clear and marked seasonality in WPD present vs. future variations since for each season the spatial patterns and magnitudes of WPD future changes do not show remarkable differences. The main exceptions are in the Iberian Peninsula and adjacent Atlantic offshore area, where WPD is projected to increase in summer and decrease in all other seasons, and in eastern Ukraine, where WPD increase is stronger in fall and winter. The seasonal changes appear to be similar in terms of spatial patterns for both future periods, although for the long-term future the magnitudes of the changes seem to be higher, particularly in summer.

However, there is a relative uncertainty in these seasonal changes particularly towards the end of the century, where MME spreads are high practically for all of Europe. Thus, it can be concluded that, for both future periods, SSP2-4.5 does not project significant changes in the 100 m WPD intra-annual variability, except for the regions aforementioned, where it might increase. Fig. 5 shows the same information as Fig. 4 but now for SSP5-8.5.

Similarly to what was seen in Fig. 4 for SSP2-4.5, Fig. 5 shows that in the Iberian Peninsula and adjacent Atlantic offshore areas WPD is projected to increase in summer and decrease in all other seasons. However, SSP5-8.5 shows relevant differences when compared to SSP2-4.5: in Turkey and Balkans WPD increase only occurs in summer, decreasing in all other seasons; WPD decrease is clearly stronger in summer (except in Iberia, Balkans and Turkey where it increases); in winter seasons there are some areas in northeastern Europe which show increases in WPD; and SSP5-8.5 projects higher seasonal differences for the long-term future when compared to the 2046–2065 period. Although the spatial patterns are very similar for both future periods, the magnitude of the changes is clearly higher for the period 2081–2100, especially in summer where WPD strongly decreases in the British Isles, central and northern Europe (reaching 30 % of decrease). According to these results, SSP5-8.5 projects some changes in the wind energetic resource intra-annual variability. However, and similarly to what was seen in Fig. 4

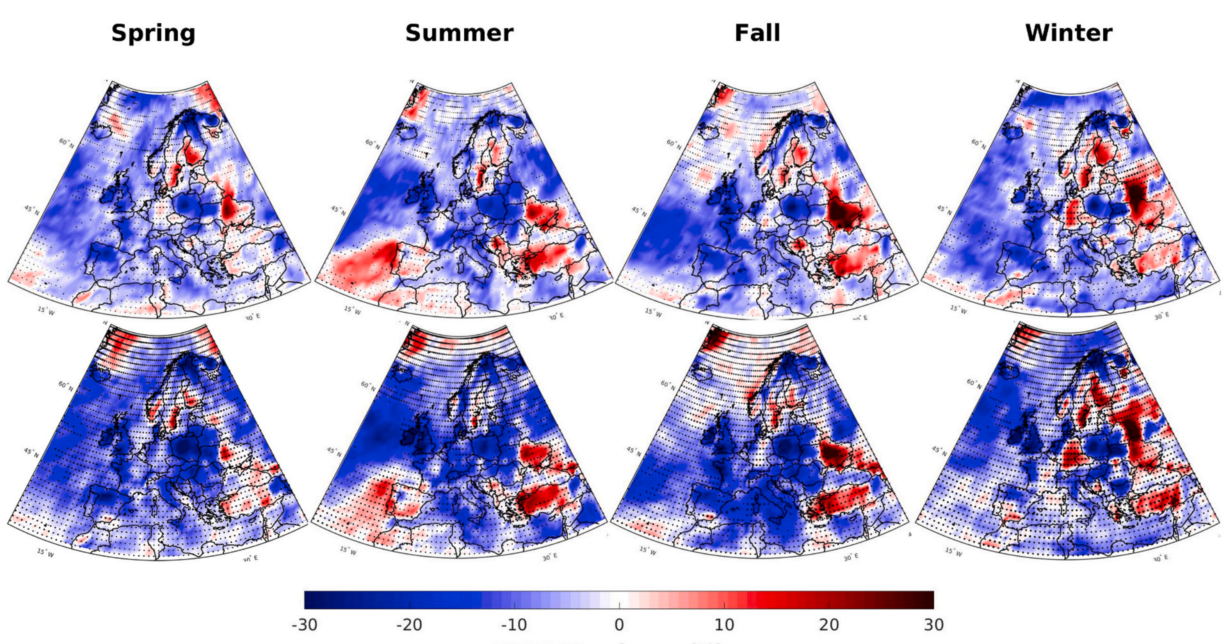

Fig. 4. Baseline vs. SSP2-4.5 seasonal percentual differences for WPD. The first (second) row shows to the median percentual differences between the baseline (1995–2014) and the 2046–2065 (2081–2100) period. Stippling indicates areas where MME spread is higher than 50 % of the plotted differences, with the dots size proportional to MME spread magnitude.

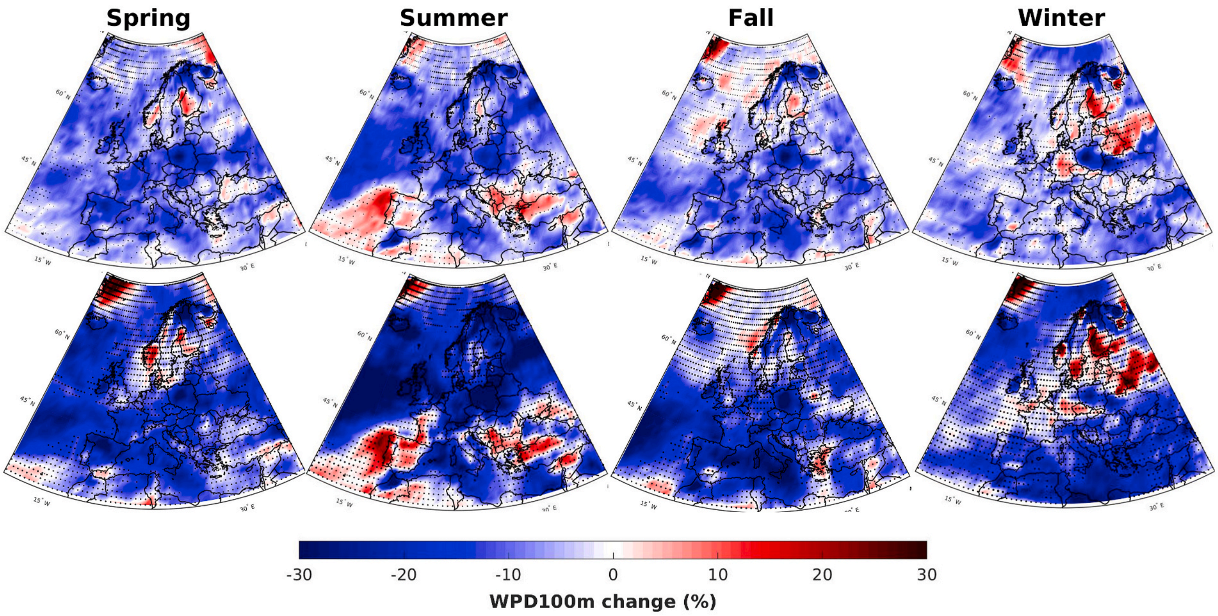

Fig. 5. Baseline vs. SSP5-8.5 seasonal differences for WPD. The first (second) row shows to the percentual differences between the baseline 1995–2014 period and the 2046–2065 (2081–2100) period. Stippling indicates areas where MME spread is higher than 50 % of the plotted differences, with the dots size proportional to MME spread magnitude.

for SSP2-4.5, there is substantial uncertainty in these seasonal changes particularly towards the end of the century, where MME spreads are high practically all over Europe.

The results presented in Figs. 4 and 5 suggest an increase in the intra-annual variability of the wind resource in the British Isles and adjacent ocean areas, Turkey, Balkans, Iberia and Northeast Europe, being more significant towards the end of the century and under stronger radiative forcing scenarios. These findings are in agreement with those reported by Ref. [7] using a CMIP5 MME. However, for the other European areas, the changes in the intra-annual variability of the 100 m WPD are not

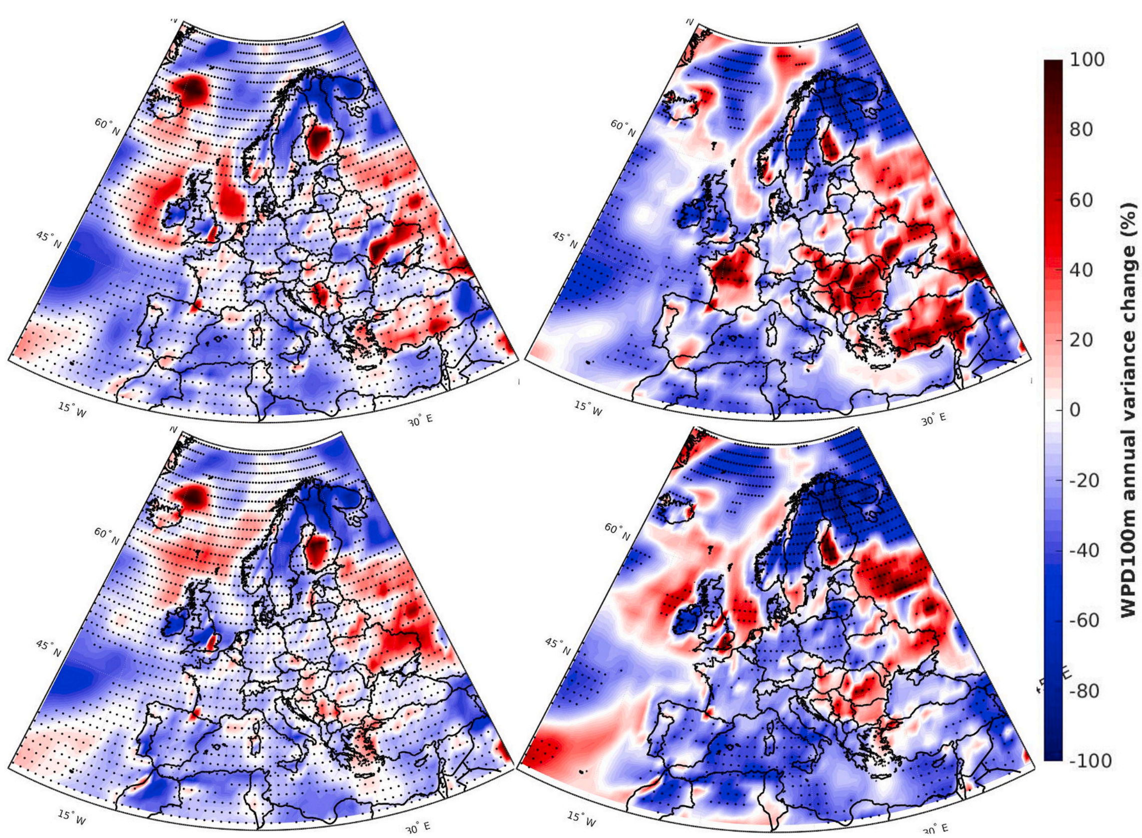

Fig. 6. Median differences between the baseline (1995–2014) and 2046–2065 (left panels) and 2081–2100 (right panels) for the WPD variance according to SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) future climate projections. Stippling indicates areas where the variance differences are not statistically significant according to the F-test.

conclusive. Other studies based on CMIP5 climate projections reported increases in wind resource in northern Europe in winter seasons and a decrease in southern Europe in summer [5,7]. Although the results here presented using CMIP6 climate scenarios confirm the increase in WPD in northern Europe during winter, they also show that, unlike CMIP5, the Iberian Peninsula and Turkey are projected to witness a relevant WPD increase in the summer, and that the summer WPD decreases are clearly stronger over the British Isles (and adjacent ocean areas), central and northern Europe.

3.2.3. Changes in the 100 m WPD inter-annual variability

Fig. 6 shows spatial maps of the projected changes between the baseline (1995–2014) and the future periods (2046–2065, left panels, and 2081–2100, right panels) in the 20-year annual WPD variance according to SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels).

Fig. 6 shows that for the middle of the current century (left side panels), both future climate scenarios do not show statistically significant changes in the inter-annual variability, although the magnitudes of the changes in the future variances are rather large. For the end of the current century (right side panels), both future climate scenarios shows statistically significant changes in the wind resource inter-annual variability for many areas of Europe, although the magnitudes of such changes are relatively small (below 10–15 %). The areas where such changes are high in magnitude are the same ones where the F-test shows that these differences, although large, are not statistically significant. These results are in line with previous studies that did not report relevant changes in the inter-annual variability of the European wind resource [3,7].

3.2.4. Non-useable wind speed events: change in the occurrence frequency

Fig. 7 shows the difference in the number of occurrences, per year, of days with mean WS below cut-in and above cut-off wind speeds between the baseline and the 2046–2065 (left panels) and 2081–2100 (right panels) periods under the SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) scenarios.

According to Fig. 7, both future climate projections show increased occurrences of non-useable wind speeds for practically all of Europe, particularly SSP5-8.5. However, SSP2-4.5 projects some areas where these occurrences are expected to decrease (Turkey, eastern Ukraine and some areas in the vicinity of the North Sea). There is a clear spatial correlation between the areas where the occurrences of these wind speeds are projected to increase (decrease) and the areas where, according to Figs. 2 and 3, the wind resource is projected to decrease (increase). This is, the areas where WPD is projected to increase (decrease) coincide with the areas where it is expected that the occurrence of wind speeds outside the cut-in and cut-off speeds will decrease (increase). However, for both future climate projections and future periods, there is a considerable uncertainty associated to these changes due to the relatively high MME spreads. The exceptions are over the Mediterranean, Italy, southern Poland and western Ukraine, where the changes show higher confidence (lower MME spreads). Thus, the reduction or increase of the wind resource can be attributed, at least partially, to the higher or lower occurrence of wind speeds that the wind turbines cannot convert into electricity. This is in accordance with [33], which reported a future increase of occurences of 100 m wind speeds below cut-in over Europe under CMIP5 climate change scenarios.

4. Conclusions

This work investigated future changes in the European large-scale wind resource in the context of climate change using a multi-model ensemble composed by simulations from the latest future climate

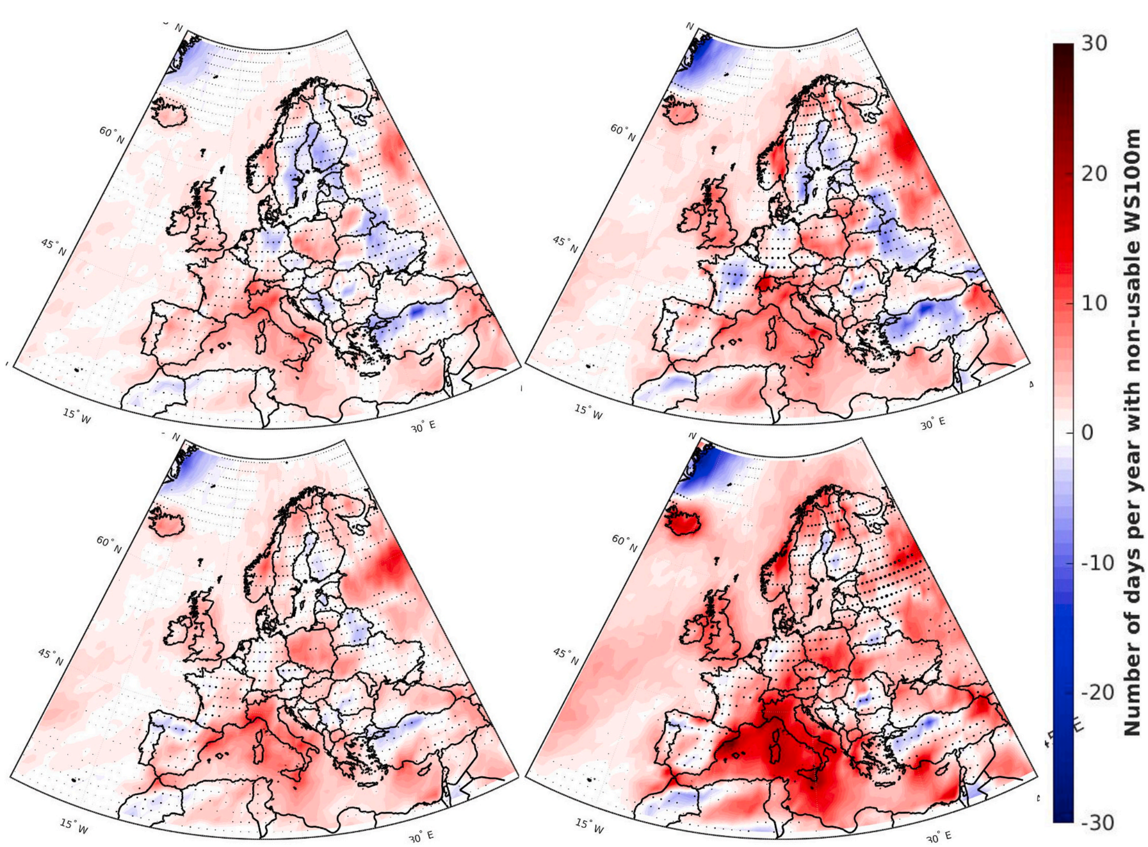

Fig. 7. Difference in the number of occurrences per year of days with WS below cut-in and above cut-off wind speeds between the baseline and the 2045–2065 (left panels) and 2081–2100 (right panels) periods under the SSP2-4.5 (top panels) and SSP5-8.5 (bottom panels) scenarios. Stippling indicates areas where MME spread is higher than 50 % of the plotted differences, with the dots size proportional to MME spread magnitude.

scenarios of the CMIP6 project. The most relevant conclusions from this study can be summarized as follows:

» While SSP2-4.5 projects mixed changes, with some areas witnessing a decrease and others an increase in the available 100 m wind resource, SSP5-8.5 projects a strong decrease of the wind resource over practically all of Europe, particularly towards the end of the current century.
» For the mid-term (long-term) future, SSP2-4.5 projects wind resource increases in eastern Ukraine and Turkey of around 10–20 % (15–30 %), and of around 5–10 % for both future periods in localized areas in southern Finland and Sweden. In the British Isles, Poland, western Ukraine and northern Norway SSP2-4.5 projects a decrease of the wind energetic potential of around 20 % (30 %), while in all other European areas the decrease is of around 5–15 % (10–20 %).
» SSP5-8.5 projects a decrease in future wind energy resource in practically all of Europe: while for the mid-term future the projected decreases are of around 5–15 % for (reaching 20–25 % in Poland, western Ukraine and northern Norway), for the long-term future the decreases are of around 10–20 % for practically all of European territory, but particularly strong in northern Norway, Poland and western Ukraine where they can reach 25–30 %. The only relevant exception is in the vicinity of the North Sea, where no changes or even a small increase of around 5 % is projected for both future periods.
» For both future periods, SSP2-4.5 does not project significant changes in the wind resource intra-annual variability, except for Iberia and eastern Ukraine, where the intra-annual variability might increase. Although SSP5-8.5 projects higher intra-annual variability of the wind resource over practically all of Europe, there is high uncertainty in these seasonal changes due to large spreads between the CMIP6 models. In terms of inter-annual variability of the wind resource in Europe, no relevant changes are projected under any CMIP6 scenario.

The results presented in this study point out that CMIP6 future climate projections seem to show relevant differences when compared to CMIP5 in terms of future wind resource projections in Europe. The most striking differences are that:

» CMIP6 does not project an increase in wind energy resource for Northern Europe as CMIP5 did, projecting instead a strong decline for practically all of Europe by the end of the current century, particularly clear under the SSP5-8.5 scenario.
» CMIP6 projects that many areas of southern Europe (Iberia, Turkey, Balkans) will experience a strong increase in the wind resource in future summer, while CMIP5 showed the contrary (a future decrease of wind resource in summer over southern Europe).
» Unlike what was seen in CMIP5, stronger radiative scenarios in CMIP6 not only enhance the future changes when compared to milder scenarios, but also significantly change the spatial patterns of the wind resource future changes.

Besides differences in the design and the assumptions (RCPs vs. SSPs) of the CMIP5 and CMIP6 future climate projections, the causes of these differences between CMIP5 and CMIP6 future projections of the near-surface wind could also be related to differences in the way that the former (CMIP5) and the more recent generation of GCMs (CMIP6) simulate the large-scale atmospheric circulation and boundary layer processes, the main drivers of near-surface wind. Previous research shows agreement that the general pattern of wind changes projected by CMIP5 were linked to a projected northward shift and eastward extent of the North Atlantic jet and storm track, and changes in cyclonic activity over Europe [3,7,34–36]. Although no studies have yet been conducted investigating in detail future large-scale atmospheric circulation changes according to CMIP6. Therefore, CMIP6-projected wind resource changes in Europe cannot be currently linked to large-scale atmospheric circulation changes driven by CMIP6. However [19], investigated the midlatitude atmospheric circulation during winter using CMIP6 GCMs and reported a decrease in zonal wind over northern and southern Europe, which appears to be consistent with the 100 m wind speed reductions shown in this study.

Nonetheless, it should be borne in mind that changes in near-surface winds cannot be attributed solely to large-scale atmospheric circulation changes, since these are not always consistent with them. Near-surface winds are also strongly affected by planetary boundary layer processes and local effects such as, meso-to local-scale thermal circulations, topography and land-use. As an example [37], reported that the projected ensemble mean UK surface wind speed change in CMIP5 is very low, even though it lies in a region where the projected storm track change should increase near-surface wind speeds. Thus, the search for the causes of future changes in near-surface winds is a complex topic that must be investigated taking into account both large-scale and meso-to small-scales processes, including those of the planetary boundary layer.

It should also be noted that, besides changes in near-surface wind speeds, there are other factors driven by climate change that may impact future wind energy production. For example, surface air temperatures in Europe are projected to increase significantly during the current century according to CMIP6 [38], and this leads to a reduction in the air density, which in turn would reduce the wind energetic density and wind-derived electricity production. Thus, considering both the projected warming and the reduced near-surface wind speeds in Europe for the current century, the future wind energy resource in Europe may be even lower than what was shown in this study, which does not take into account future air temperature increases and respective changes in air density.

Finally, it should be also noticed that global climate projections are inherent to a relative uncertainty, due to errors and limitations of GCMs and several assumptions made when designing future climate scenarios, especially when these models are run for several decades in free-running simulations. Moreover, the use of several different global climate models in the detection of climate change signals is always associated with a certain degree of uncertainty, linked to the different ways that the several models portray the future climate characteristics. This was shown in some of the results here presented, in which the CMIP6 spread among the several models was indicative of some uncertainty in the reported present vs. future changes. In addition to this, the results presented for the areas where the CMIP6 baseline wind data validation (section 3.1) showed poorer results should be viewed with added caution.

All the results presented in this work clearly indicate a significant decrease in the European wind energy resource in the upcoming decades. However, it is also clear that a path that includes effective GHG emissions reductions (SSP2-4.5) will result in much smaller decreases (or even increases in some areas), than a fossil fuel based path (SSP5-8.5), especially towards the end of the century. This is particularly important since it shows that a more severe global warming scenario implies that our ability to mitigate the same global warming is much more limited in what is related to renewable energy production.

Author contributions

David Carvalho: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Writing. Alfredo Rocha: Methodology, Formal analysis, Review & Editing. Xurxo Costoya: Methodology, Formal analysis, Review & editing. Maite deCastro: Formal analysis, Review & Editing. Moncho Gómez-Gesteira: Formal analysis, Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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