Climate Dynamics

Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections

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Abstract:	This work focused on possible impacts of climate changes on future European wind energy resource, using the latest IPCC future climate projections derived from the CMIP5 project. Although wind energy plays a key role in the goal of replacing fossil fuels by renewable energy sources, and thus minimize future climate changes, it is also sensitive to climate change itself due to hypothetical changes in the future atmospheric flow patterns. This study focuses on Europe, one of the main areas in terms of installed wind-derived electricity generating capacity in the world. This work comprised two stages: first, to assess the CMIP5 GCMs that best reproduce contemporary near surface wind speeds over Europe. The validation of these CMIP5 GCMs wind data for the contemporary period serves as a solid and important background for the upcoming CMIP5 GCMs downscaling initiatives to regional and local scales. Secondly, data from the best GCMs was used to quantify and assess future changes in the wind energetic resource and their geographical distributions over Europe, together with its intra- and inter-annual variability. Research about the GCMs wind climate future projections provides an important preliminary picture of changes in large-scale wind energetic resource over Europe. The results presented show that, although the CMIP5 global models are still not able to represent satisfactorily the contemporary wind speed climatology over Europe, the models HadGEM2-ES, HadGEM2-CC, ACCESS 1.3 and ACCESS 1.0 showed the best ability to represent the contemporary near surface wind speed climatology over Europe. Using data from these models, the future European wind energy resource tends to be lower than the one presently available, due to a decreasing tendency of the large-scale wind speeds over the current century, especially in the end of the current century and under scenarios of stronger radiative forcing. Some exceptions to this decreasing tendency of future wind speeds are detected in Central/Northern Europe, Turkey and in the Iberian Peninsula, where the wind energy resource can slightly increase in future. Changes can be expected in the intra-annual variability due to wind

	speeds decrease in cold seasons and increase in warmer seasons, particularly at the end of the current century and under scenarios of stronger radiative forcing. Oppositely, no significant changes in the inter-annual variability are expected over Europe during the current century. The validation results of this study showed the poor ability of the CMIP5 global models to represent realistically the past-present European wind speed climatology, and the use of such coarse models can be considered as somewhat over-simplistic and insufficiently detailed for the desired purposes. Notwithstanding, the findings presented herein can serve as an important background for future downscaling initiatives of CMIP5 data to regional and local scales, and should be seen as a preliminary warning that a continuous increase of greenhouse gases emissions can jeopardize our ability to mitigate such emissions, at least in what is related to the role and contribution of wind energy. However, it needs to be borne in mind the significant uncertainty associated to global models future climate projections. Thus, the information provided by these models should be seen as a preliminary picture of the large scale future tendencies of the wind energy resource, and further research focused on these themes should be performed by downscaling CMIP5 GCMs output to regional and local scales in order to better represent the topography and land use and thus better simulate near surface winds.
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Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections

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Abstract

This work focused on possible impacts of climate changes on future European wind energy resource, using the latest IPCC future climate projections derived from the CMIP5 project. Although wind energy plays a key role in the goal of replacing fossil fuels by renewable energy sources, and thus minimize future climate changes, it is also sensitive to climate change itself due to hypothetical changes in the future atmospheric flow patterns. This study focuses on Europe, one of the main areas in terms of installed wind-derived electricity generating capacity in the world. This work comprised two stages: first, to assess the CMIP5 GCMs that best reproduce contemporary near surface wind speeds over Europe. The validation of these CMIP5 GCMs wind data for the contemporary period serves as a solid and important background for the upcoming CMIP5 GCMs downscaling initiatives to regional and local scales. Secondly, data from the best GCMs was used to quantify and assess future changes in the wind energetic resource and their geographical distributions over Europe, together with its intra- and inter-annual variability. Research about the GCMs wind climate future projections provides an important preliminary picture of changes in large-scale wind energetic resource over Europe.

The results presented show that, although the CMIP5 global models are still not able to represent satisfactorily the contemporary wind speed climatology over Europe, the models HadGEM2-ES, HadGEM2-CC, ACCESS 1.3 and ACCESS 1.0 showed the best ability to represent the contemporary near surface wind speed climatology over Europe. Using data from these models, the future European wind energy resource tends to be lower than the one presently available, due to a decreasing tendency of the large-scale wind speeds over the current century, especially in the end of the current century and under scenarios of stronger radiative forcing. Some exceptions to this decreasing tendency of future wind speeds are detected in Central/Northern Europe, Turkey and in the Iberian Peninsula, where the wind energy resource can slightly increase in future. Changes can be expected in the intra-annual variability due to wind speeds decrease in cold seasons and increase in warmer seasons, particularly at the end of the current century and under scenarios of stronger radiative forcing. Oppositely, no significant changes in the inter-annual variability are expected over Europe during the current century.

The validation results of this study showed the poor ability of the CMIP5 global models to represent realistically the past-present European wind speed climatology, and the use of such coarse models can be considered as somewhat over-simplistic and insufficiently detailed for the desired purposes. Notwithstanding, the findings presented herein can serve as an important background for future downscaling initiatives of CMIP5 data to regional and local scales, and should be seen as a preliminary warning that a continuous increase of greenhouse gases emissions can jeopardize our ability to mitigate such emissions, at least in what is related to the role and contribution of wind energy. However, it needs to be borne in mind the significant uncertainty associated to global models future climate projections. Thus, the information provided by these models should be seen as a preliminary picture of the large scale future tendencies of the wind energy resource, and further research focused on these themes should be performed by downscaling CMIP5 GCMs output to regional and local scales in order to better represent the topography and land use and thus better simulate near surface winds.

Keywords: Wind energy, Climate change; CMIP5; IPCC; Global models; Europe

1 – Introduction

The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (IPCC AR5, 2013) includes the latest existent knowledge about the scientific, technical and socio-economic aspects of climate change. According to this report, the 1983-2012 period was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere. The Wold Meteorological Organization (WMO) also confirmed this global warming trend: based on measured temperatures since 1850, 13 of the 14 warmest years were observed in the 21st century. IPCC AR5 projects that global temperatures can rise 1 to 5ºC over the next 100 years, depending on the amounts of greenhouse gases (GHG) emitted and the sensitivity of the climate system. As for sea-level changes, the same report foresees a rise comprised between 28 and 98 cm by the end of the current century, and to more than 3 meters by 2300. If no GHG emission mitigation strategies are employed, the Arctic Ocean will likely become virtually ice-free in summer before the middle of the current century (IPCC AR5, 2013). This report also confirms that it is virtually certain (>95%) that human activity has been the main cause of the observed increasing temperatures since the mid-20th century. Other possible factors, such as natural internal variability of the climate system and natural external forcings (variation of solar activity, activity of volcanoes, etc.), are considered to have a marginal contribution to global warming. These human-induced climate changes are mainly forced by the continuously increasing emissions of GHG (mainly CO_2) to the atmosphere, being well established that one of the main emission sources of GHG is the electricity generation from fossil fuels combustion (IPCC AR4, 2007; IPCC AR5, 2013).

Renewable energies are a cornerstone in the reduction of GHG emissions and consequent mitigation of changes in the global climatic system. Of all the renewable energy sources presently 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 only exceeded in terms of installed capacity by hydropower (Santos et al., 2015). Europe has been leading the efforts in expanding the contribution of renewable energy sources to the overall electricity production and consumption, setting a binding target of 20% of energy obtained from renewable sources to achieve by 2020 (Carvalho et al., 2013a; Pryor and Barthelmie, 2010). Wind can provide up to one third of this target value and, considering the current wind-derived energy growth rate. It is projected that its electrical generating installed capacity can increase up to fivefold in the upcoming decade (de Vries, 2008a and 2008b).

Although wind energy growth is part of the solution to reduce GHG emissions and consequently mitigate future climate change, this renewable energy source is sensitive to climate change itself, due to hypothetical changes in the future atmospheric flow patterns. Since the wind energetic potential varies with the wind speed cubed, even apparently small variations in future wind circulation patterns and characteristics can strongly impact future wind energy production (Carvalho et al., 2012b). Variations in the future mean wind speeds and their geographical distribution will change the wind resource of a given region, while changes in its future inter- and intra-annual variability can affect the reliability of the produced wind-derived electricity (Pryor and Barthelmie, 2010). The higher the intra-annual variability (this is, the variability within a year-period), the more variable will be the injection of the produced energy into the electrical grid, causing supply-demand balancing problems and enhancing the need to perform short-term wind energy production forecasts. Inter-annual variability (the variability between different years) is a key issue for the economic feasibility of a wind farm. The typical lifetime of wind farms currently in operation is typically 20 to 30 years, and the question of whether the wind farm expected energy yield will significantly vary during its lifetime can determine the success or failure of the wind farm project as a whole.

IPCC AR5 relies on the World Climate Research Programme (WCRP) Fifth Coupled Model Intercomparison Project (CMIP5), a globally coordinated set of global coupled atmosphere-ocean general circulation models (AOGCMs) simulations (for more details see Taylor et al., 2012). CMIP5 output, the latest available data regarding future climate change projections, allows the evaluation of how the models realistically simulate the recent past and present, and provides projections of future climate changes from the present date up to 2100 (and beyond, for some models and experiments). CMIP5 is the successor of the CMIP3, which served as basis of the IPCC fourth assessment report (IPCC AR4, 2007). When compared to the older generation models used in CMIP3, the new state-of-the-art models used in CMIP5 offer higher spatial resolutions, improved physical process descriptions, improvements in the representation of external forcings and interaction between the atmosphere, land use and vegetation. Moreover, CMIP5 introduced a new breed of AOGCMs: the Earth System Models (ESMs). ESMs are currently the state-of-the-art models, expanding on AOGCMs by including additional earth system components such as atmospheric chemistry, biogeochemical cycles, aerosols, ozone, sulphur and carbon cycles (Taylor et al., 2012; Brands et al., 2013). ESMs constitute the most comprehensive tools presently available for simulating the climate system future response to external forcings, in which biogeochemical feedbacks play a key role (IPCC AR5).

CMIP5 future climate projections, called Representative Concentration Pathways (RCPs), describe hypothetical future climate scenarios based on the emissions rate of GHG (more details are available in Moss et al., 2010). These RCPs make use of a broad range of anthropogenic climate forcings, such as aerosols, GHG, land use and chemically active gases (Bracegirdle et al., 2013; Meinshausen et al., 2011). When compared to their predecessors - the IPCC AR4/CMIP3 Special Reports on Emissions Scenarios (SRES) - RCPs consider new and larger amounts of data such as socio-economic aspects, emerging technologies, land use and land cover changes (Moss et al., 2010).

This work aims to assess and quantify the impacts of the latest CMIP5 future climate projections on the wind energetic resource in Europe, one of the main areas in terms of installed wind-derived electricity generating capacity and one of the main boosters of further growth and penetration of wind-derived energy in the world. To this end, data from CMIP5 project is used to build future projections of near surface wind speed and energy density geographical distributions over Europe, and to quantify how different from the past-present are the future scenarios for wind energy production. As far as the authors are aware, there is still no published literature that addresses this issue in light of the new CMIP5 future climate projections for the European continent as a whole. However, the study of Sterl et al. (2014) focused on possible impacts of climate changes on future large-scale wind climate over the Netherlands by downscaling CMIP5 future climate projections, concluding that climate changes will not likely change Netherlands and the North Sea wind climate beyond the range of the typical natural climate variability. As for other areas of the globe, the study of Kulkarni and Huang (2014) considers CMIP5 data on the evaluation of possible changes in surface wind speeds over North American territory. This work concludes that the projected future changes in surface wind speeds are moderate and no significant changes in North American wind power potential are to be expected in the future due to GHG induced climate changes. Also the study of Chen et al. (2013) uses CMIP5 data to investigate the impact of climate change on wind speeds, but now for the Chinese territory, concluding that geographical distributions of wind speed over China at the end of the 21st century do not show significant differences when compared to those of the last 35 years. Considering earlier IPCC assessment reports and future climate projections such as the IPCC AR4/CMIP3, and also downscaling initiatives that followed them such as the PRUDENCE (Christensen and Christensen, 2007) and ENSEMBLES (ENSEMBLES, 2006) projects, there is a good background in published studies focusing on climate changes impacts in wind power resource over Europe. Pryor and Barthelmie (2010) reviewed the published literature regarding climate change impacts on wind energy. According to this review, by the end of the current century the mean wind resource in Europe can suffer small magnitude changes, with indications that wind energy density and annual mean wind speeds in winter can increase in northern Europe and decrease in the south of the continent (Pryor et al., 2005a; Bloom et al., 2008; Walter et al., 2006). Santos et al. (2015) analyzed changes in future wind energy potential over the Iberian Peninsula considering the A1B IPCC AR4/CMIP3 SRES scenario, downscaled by a regional circulation models (RCM), and concluded that these climate change projections show significant decreases in the future wind energy production potential over most of the Iberian Peninsula. Pryor et al. (2005b) performed a statistical downscaling of one global circulation model (GCM) on the Baltic States and projected a decrease of the wind speed and energy density by 2071-2100. Cradden et al. (2012) assessed if climate changes could affect wind energy development in the UK, considering three different IPCC AR4/CMIP3 SRES scenarios. The authors concluded that the typical UK wind speed intra-annual variability (higher in winter and lower in summer) could be larger in the future due to climate changes, but did not find any conclusive evidence of a marked future change in wind energy resource in any area of the UK. To sum up, until the present moment there is in the published research a consensus that no significant changes in future European wind climate are to be expected due to climate warming. Instead, natural variability seems to be the main reason for changes in global decadal and centurial wind climatology, and this will likely continue to be in the upcoming century. Nevertheless, and although significant uncertainty still remains on how future wind climatologies will change over Europe, several recent studies have reported a decline tendency in observed near-surface wind speeds and in indices based on wind power generation during the past decades in Europe (Bakker et al., 2013; Brázdil et al., 2009; Pirazzoli and Tomasin, 2003; Smits et al., 2012; Vautard et al., 2010).

The significant uncertainty of these projected climate changes should be borne in mind. GCMs show strong limitations in realistically represent past and present wind climates (mainly related to their coarse spatial resolution), whilst RCMs downscaling of these GCMs output show high inter-model variability and uncertainty regarding the climate change signal (Pryor and Barthelmie, 2010). Nevertheless, the continuous effort devoted to the evolution of GCMs (AOGCMs and ESMs included), RCMs and their input data poses the challenge to continuously investigate their latest future climate projections. Several CMIP5 data downscaling projects are currently under progress, namely the CORDEX project (http://wcrp-cordex.ipsl.jussieu.fr/) and, more specifically, the EURO-CORDEX branch of the CORDEX project that downscales CMIP5 data for Europe (http://www.euro-cordex.net/). Thus, it becomes relevant to compare and assess the performance of the several GCMs, in order to select the one(s) with the best performance(s) as candidate(s) for downscaling applications. This work also aims to assess the performance of CMIP5 GCMs in what is related to their ability to realistically represent past and present near surface wind climatology in Europe. This validation is expected to be of great value to downscaling initiatives focused on climate change impact on wind energy, since no information is presently available regarding the individual performance of each CMIP5 GCM in representing contemporary near surface winds. Brands et al. (2013) highlighted the importance of GCM validation for downscaling applications, assessing which CMIP5 GCMs show better ability to reproduce present climate conditions in Europe and Africa and, therefore, can be seen as the best candidate(s) for use in downscaling applications. The authors concluded that the CMIP5 ESM models HadGEM2-ES and MPI-ESM-LR outperform the other models along the lateral boundaries of the several CORDEX regional domains.

Thus, the present work comprises two main stages. First, near surface wind speed data from 21 CMIP5 GCMs are compared against a reanalysis dataset, in order to identify the GCM(s) that best reproduce contemporary near surface wind speeds over Europe. After, data from these GCMs is used to preliminarily quantify and assess future changes in the large-scale wind energetic resource and their geographical distributions over Europe, together with its intra- and inter-annual variability. While the validation of CMIP5 GCMs wind data for the contemporary period will serve as a solid and important background for the upcoming CMIP5 GCMs downscaling initiatives to regional and local scales focused on wind energy, research about the GCMs future wind speed projections will provide an important preliminary picture of potential changes in large-scale wind energy resource over Europe.

2 – Data and methodology

2.1 – CMIP5 data and experiments

CMIP5 GCMs near surface wind data regarding the past-present period and two RCPs future climate projections were considered in this work. This near surface wind data reports to 10 m above ground/mean sea level, while typical wind turbines are placed at 80-120 m above ground/mean sea level. Since the CMIP5 GCMs do not provide output regarding winds at these heights, this near surface 10 m wind data was considered as the best estimator of the wind at typical wind turbines height. Although near surface winds are lower than the ones at 80-120 m, both are highly correlated (Kulkarni and Huang, 2014). Since the aim of this work is to compare past-present with future winds and not to quantify them, it can be expected that changes between past-present and future near surface winds are of similar magnitude to the ones expected at higher heights.

Past-present near surface wind data was extracted from the historical run, performed to characterize the contemporary period (1986-2005). This run was forced by observed atmospheric composition changes, both from anthropogenic and natural sources, and time-evolving land cover (Taylor et al., 2012). Future wind data was obtained from future climate projections of two RCPs. One somewhat pessimistic, although realistic, which basically assumes that no GHG mitigation actions will be employed in the upcoming decades and GHG emission rates will continue to grow at the rates witnessed in the last decades (the RCP 8.5); and a more optimistic scenario, which foresees a reduction of GHG emissions, the RCP 4.5.

RCP 8.5 is a “business as usual” emission scenario, characterized by escalating GHG emissions and high concentration levels of these gases in the atmosphere. RCP 8.5 can be seen as the projection of future GHG concentration and radiative forcing if no emissions mitigation strategies are employed until the end of the 21st century. The numerical value assigned to a RCP translates its radiative forcing present in 2100. Thus, RCP 8.5 radiative forcing (CO_2 equivalent emissions) peaks at 2100 with a value of 8.5 W.m^{-2}, approximately 1370 ppm of CO_2 equivalent concentration. The RCP 4.5 is a midrange stabilization scenario, where GHG emissions are mitigated by policy actions, strategies and technologies, employed to achieve emission targets before 2100 (Taylor et al., 2012). In this scenario, the radiative forcing and GHG emissions peak around 2070-2080 with a value of 8.5 W.m^{-2}

(approx. 650 ppm of CO_2 equivalent concentration) and stabilizes further on, remaining constant beyond this peak.

For both RCPs, the following time windows were considered: near future, ranging from 2016 to 2035; medium-term future, from 2046 to 2065; and long term future, from 2081 to 2100. The spatial domain considered in this work was based on the EURO-CORDEX one, but slightly expanded in order to include the Portuguese Azores and Madeira archipelagos, and the Spanish Canary islands.

2.2 – Validation of CMIP5 models

For the assessment of which CMIP5 GCMs best describe the contemporary wind resource over Europe, all CMIP5 models with available daily average near surface wind speed data for the historical and the two RCPs here considered were selected. The models that fulfilled these requisites are listed in Table 1.

Table 1 – Main characteristics of the considered CMIP5 models

Model	**Modelling Center**	**Type of GCM**	**Horizontal resolution** (lat/lon)
ACCESS 1.0	CSIRO-BOM (Australia)	ESM	1.25º / 1.875º
ACCESS 1.3	CSIRO-BOM (Australia)	ESM	1.25º / 1.875º
BNU-ESM	GCESS (China)	ESM	2.8º / 2.8º
CanESM2	CCCma (Canada)	ESM	2.8º / 2.8º
CMCC-CMS	CMCC (Italy)	AOGCM	2º / 2º
CNRM-CM5	CNRM-CERFACS (France)	AOGCM	1.4º / 1.4º
CSIRO-Mk 3.6.0	CSIRO-QCCCE (Australia)	AOGCM	1.9º / 1.9º
GFDL-CM3	NOAA GFDL (USA)	AOGCM	2º / 2.5º
GFDL-ESM2G	NOAA GFDL (USA)	ESM	2º / 2.5º
GFDL-ESM2M	NOAA GFDL (USA)	ESM	2º / 2.5º
HadGEM2-CC	MOHC (UK)	ESM	1.25º / 1.875º
HadGEM2-ES	MOHC (UK)	ESM	1.25º / 1.875º
IPSL-CM5A-LR	IPSL (France)	ESM	1.875º / 3.75º
IPSL-CM5A-MR	IPSL (France)	ESM	1.25º / 2.5º
IPSL-CM5B-LR	IPSL (France)	ESM	1.875º / 3.75º
MIROC-ESM	MIROC (Japan)	ESM	2.8º / 2.8º
MIROC-ESM-CHEM	MIROC (Japan)	ESM	2.8º / 2.8º
MIROC5	MIROC (Japan)	AOGCM	1.4º / 1.4º

MPI-ESM-LR	MPI-M (Germany)	ESM	1.9º / 1.875º
MPI-ESM-MR	MPI-M (Germany)	ESM	1.9º / 1.875º
MRI-CGCM3	MRI (Japan)	AOGCM	1.125º / 1.125º

The validation of these models was performed as follows. First, and due to the fact that these 21 models have different native horizontal resolutions (Table 1), all models historical near surface wind speed grids were remapped to a regular 1.5º lat/lon grid (an intermediate resolution given the native resolutions of all models). Afterwards, 20-year historical wind speed medians (instead of the mean, in order to avoid normality fitting restrictions and outlier contamination) were computed from the daily near surface wind speed time series for all models and grid points, and each model historical wind speed median grid was compared with ERA-Interim wind speed 20-year median grid. ERA-Interim reanalysis were selected as "real wind" data source, not only because they are widely recognized as a superior quality reanalysis product (especially for the European territory), but also because it is the official validation dataset used for the CORDEX CMIP5 dynamical downscaling initiatives (Brands et al., 2013). The most important aspect to assess in terms of validation is if the wind speed data from the CMIP5 GCMs and from ERA-Interim come from the same continuous distribution. Since wind speeds are generally not normally distributed, the non-parameteric two-sample Kolmogorov-Smirnov (KS) test (Gibbons and Chakraborti, 2011) was applied to the CMIP5 GCMs and ERA-Interim wind speed datasets for each grid point, with a 5% significance level. The KS test tests the null hypothesis that two samples belong to the same continuous distributions (with the same shape and location), against the alternative hypothesis that they are from different distributions (different in shape and/or location). The CMIP5 GCMs with the highest number of grid points where the KS test shows that their wind speed data is from the same distribution as ERA-Interim were considered the ones that better represent the contemporary (historical) period wind climatology over Europe and, consequently, those used to assess climate change impacts on wind energy.

For the following sections, data from these selected GCMs was organized in a multi-model ensemble (MME) strategy where, for each time period and RCP, data from the selected

GCMs was concatenated into one multi-model ensemble. This multi-model ensemble strategy is a way to minimize the individual model biases, since it is expected that the multi-model ensemble mean (or median) shows lower uncertainties and better results than each individual model (Pires et al., 2014). This fact is supported by several studies that compared individual models and multi-model ensemble means with observed data (Räisänen and Palmer, 2001; Pierce et al., 2009; Annan and Hargreaves, 2010).

2.3 – Impacts of climate change on future wind energy resource

MME data was used to evaluate climate change impacts on future wind energetic resource over Europe. These impacts were quantified and assessed in three different categories: (i) future changes in the wind speed and energy density medians; (ii) intra- and (iii) inter-annual variability of the wind speed and energy density.

2.3.1 – Climate change impacts in future wind energetic resource

The main and most direct mechanism from which climate change can affect future wind energetic resource is by altering the average wind speed (and consequently the available wind energy density) of a given area. To assess possible changes in future wind speed and wind energy density in Europe (and their respective geographical distributions) due to climate changes, MME historical daily wind speed and energy density data was compared to future daily wind speed and energy density data, for the two RCPs and three future time windows considered. The wind energy density (also called wind power flux) is derived from equation 1, where U is the wind speed and ρ is the air density (the standard value of 1.225 kg.m^{-3} was assumed).

$$P_{flux} = \frac{1}{2} * \rho * U^3 \tag{1}$$

Changes in future wind energetic resource were evaluated by comparing, for each grid point, the wind speed and energy density historical and future 20-year MME medians, for all RCPs and time windows. The existence of statistically significant differences between the historical and future medians is evaluated by applying the Mann-Whitney (or Wilcoxon rank sum) non-parametric test (Gibbons and Chakraborti, 2011), with a 5% significance level. The Mann-Whitney test tests the null hypothesis of two data samples belonging to continuous distributions with equal medians, against the alternative that they do not.

To further detail future changes in the wind energetic resource, the aforementioned methodology was repeated but now in a seasonal perspective. For this purpose, all data and analysis were divided into seasons: Winter, comprising the months of December, January and February; Spring, with the months of March, April and May; Summer, corresponding the months of June, July and August: and Autumn, between September and November. Changes in future wind energetic resource were evaluated by comparing, for each grid point, the wind speed and energy density historical and future MME medians of the four seasons, for all RCP's and time windows. The Mann-Whitney test for the difference of medians was again used to assess the statistical significance of differences in the seasonal medians.

2.3.2 – Climate change impacts in future wind energy intra-annual variability

In order to analyze future changes in the wind energetic resource intra-annual variability, annual median absolute deviations (MAD) were computed for the historical and future wind speed and energy density MME data. MAD (Sachs, 1984) is a non-parametric measure of the sample variability around its median, and is given by the following equation:

$$MAD = median\ [|X_i - \ median(X)|] \qquad (1)$$

MAD can be considered as a non-parametric equivalent of the standard deviation or variance. It is a very robust scale estimator, with the best possible breakdown point (50%, the double of the interquartile range) and its influence function has the sharpest bound among all scale estimators (Rousseeuw and Croux, 1993).

Annual MAD data series were computed for each historical and future 20-year periods, resulting in three-dimensional grids where the temporal dimension has 20 elements (20 years). Each one of these temporal element is an annual MAD, the median absolute deviation regarding that year. After, the median of these annual MADs was computed for each grid point, in order to produce an estimate of the average intra-annual variability of each 20-year period (the historical and future 20-year periods). Differences between the historical and future annual MAD medians were quantified and analyzed. For each grid point, differences between historical and future wind speed and energy density annual MAD medians can be seen as indicators of changes in wind speed and energy density intra-annual variability. The statistical significance of these annual MAD median differences was evaluated with the Mann-Whitney test, with a significance level of 5%.

2.3.3 – Climate change impacts in future wind speed and wind energy density inter-annual variability

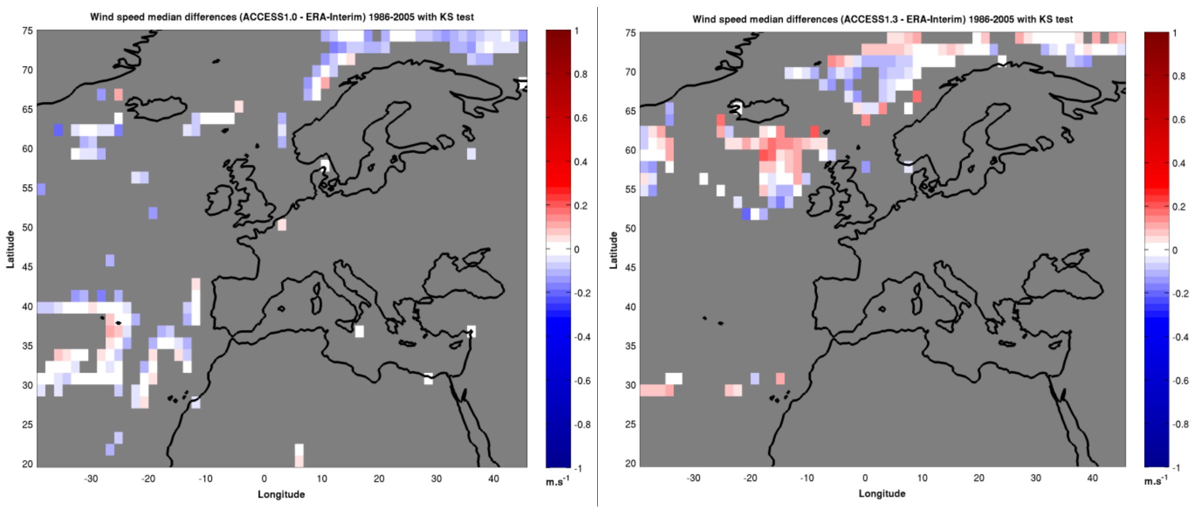
To assess hypothetical changes in future inter-annual variability, all daily wind speed and energy density MME data was averaged to annual wind speed and energy density records. Although wind speeds are not usually normally distributed, annual mean wind speeds can be realistically characterized by a normal distribution (European Wind Energy Association, 2009). These annual mean wind speed and energy density data series were computed for each historical and future 20-year periods, resulting in three-dimensional grids where the temporal dimension has 20 elements (20 years). Each one of these temporal element is the annual mean wind speed and energy density regarding that year. The standard deviation of each one of these annual means data series will quantify their inter-annual variability. Thus, differences between the standard deviations of two annual means data series will quantify changes in the inter-annual variability.

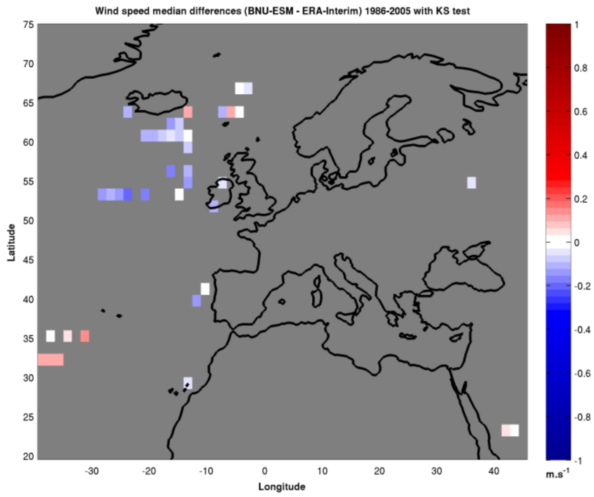
For each grid point, the differences between historical and future standard deviations were analyzed and the respective statistical significance of such differences computed. Statistical significance of standard deviation differences was evaluated using the F-test with a significance level of 5% assuming, as previously mentioned, that wind speed and energy density annual means data series can be fitted to a normal distribution. The F-test asses the null hypothesis that the data in two samples comes from normal distributions with the same variance, against the alternative hypothesis that they come from normal distributions with different variances.

3 – Results and discussion

3.1 – Validation of CMIP5 models

The validation results of the 21 CMIP5 models are presented here. Figure 1 shows the differences between ERA-Interim and each model historical wind speed medians, together with the KS test output. For grid cells where the KS test shows statistically significant differences, the grid cell is coloured in grey. For grid cells where the KS test does not show statistically significant differences (this is, the model grid cell is in accordance with ERA-Interim), the grid cell is coloured according to the ERA-Interim and CMIP5 model wind speed median difference for that grid cell.




Wind speed median differences (BNU-ESM - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
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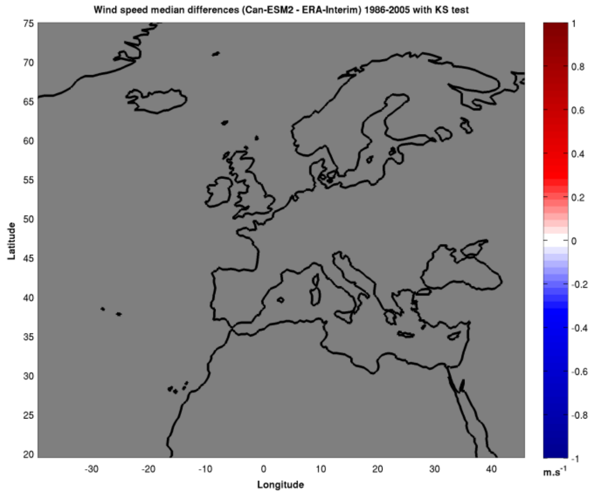
Wind speed median differences (Can-ESM2 - ERA-Interim) 1986-2005 with KS test
Latitude
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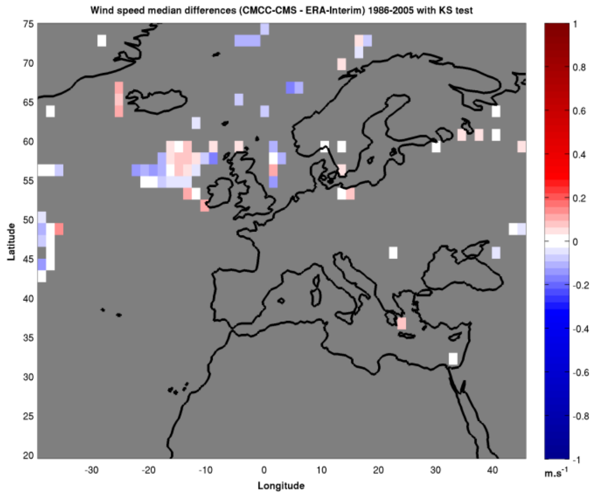
Wind speed median differences (CMCC-CMS - ERA-Interim) 1986-2005 with KS test
Latitude
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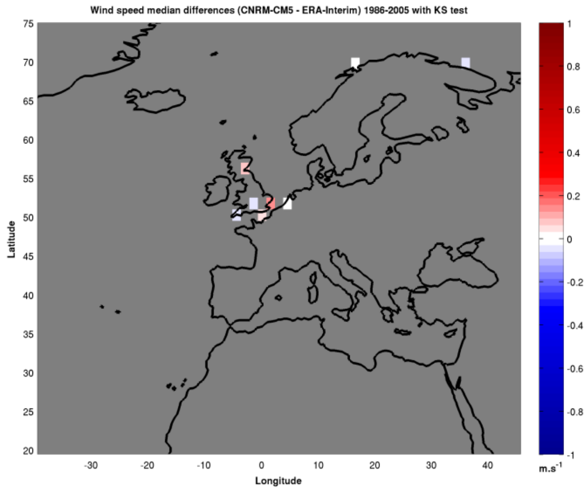
Wind speed median differences (CNRM-CM5 - ERA-Interim) 1986-2005 with KS test
Latitude
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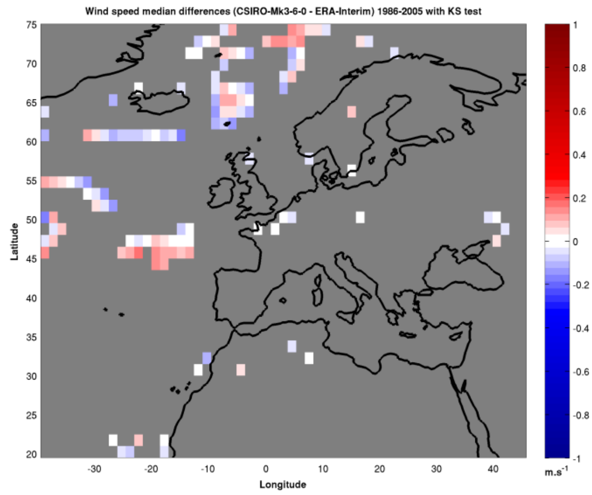
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Latitude
Longitude
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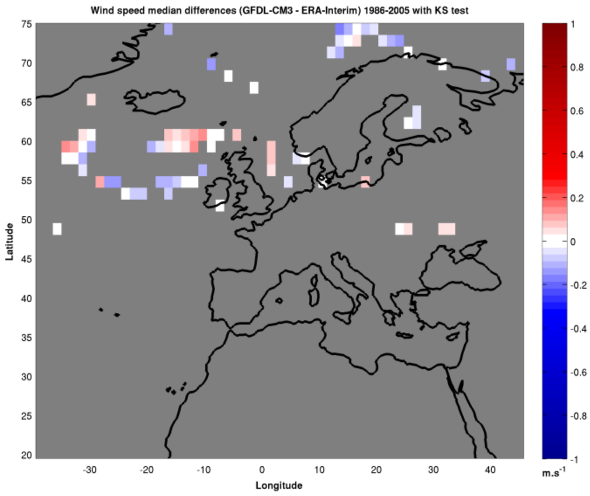
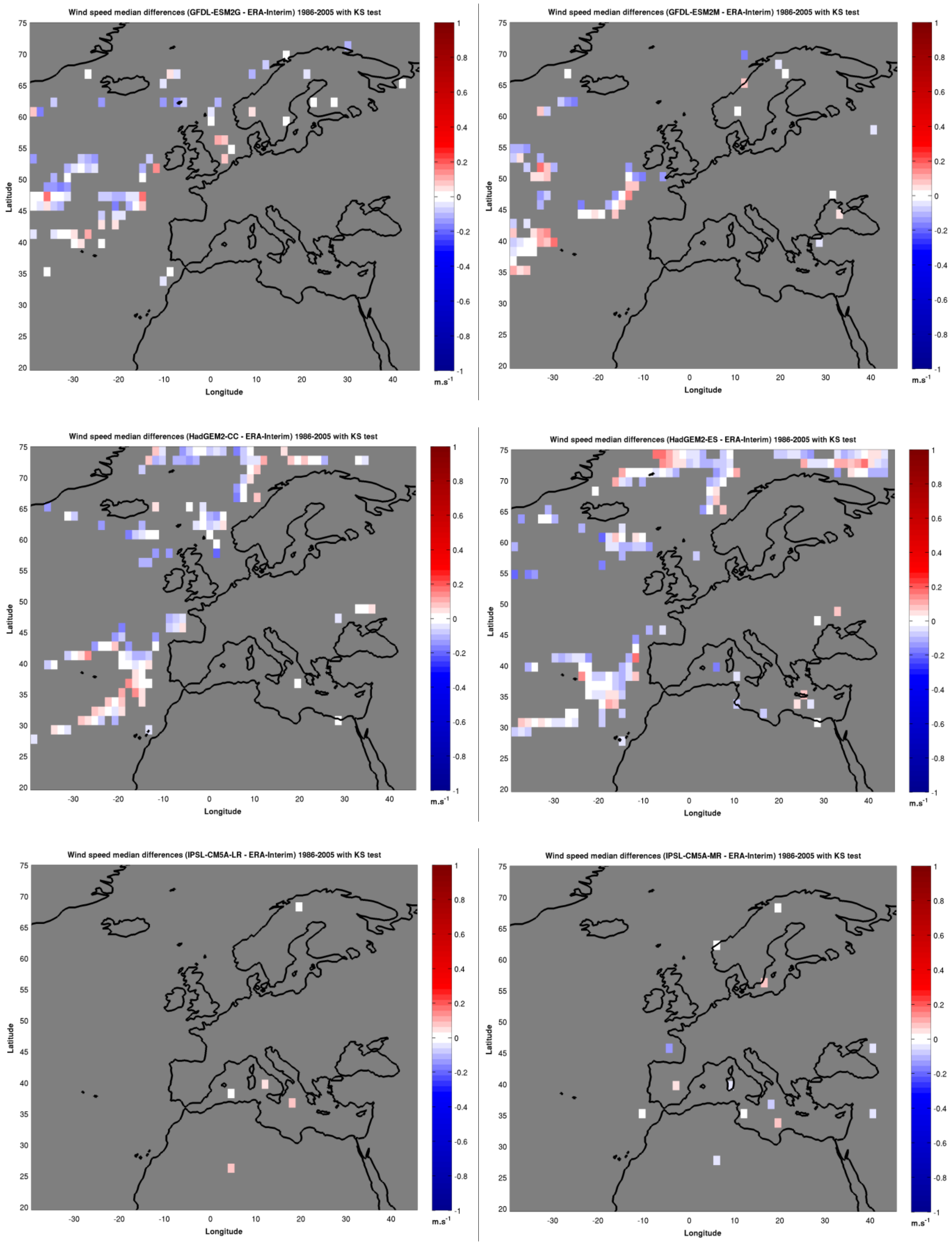

Wind speed median differences (GFDL-CM3 - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
m.s-1


Wind speed median differences (GFDL-ESM2G - ERA-Interim) 1986-2005 with KS test
Wind speed median differences (GFDL-ESM2M - ERA-Interim) 1986-2005 with KS test
Wind speed median differences (HadGEM2-CC - ERA-Interim) 1986-2005 with KS test
Wind speed median differences (HadGEM2-ES - ERA-Interim) 1986-2005 with KS test
Wind speed median differences (IPSL-CM5A-LR - ERA-Interim) 1986-2005 with KS test
Wind speed median differences (IPSL-CM5A-MR - ERA-Interim) 1986-2005 with KS test
Latitude
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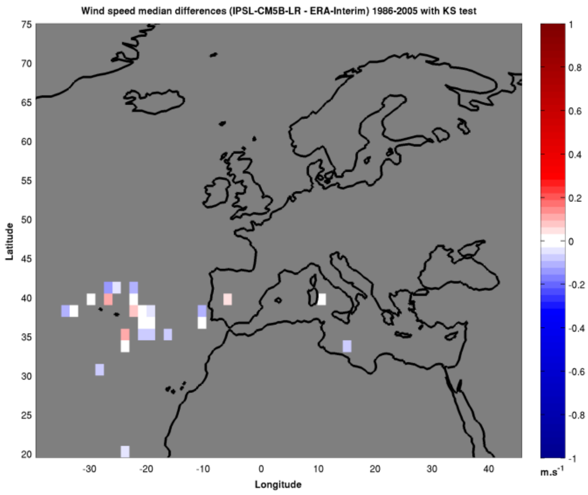
Wind speed median differences (IPSL-CM5B-LR - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
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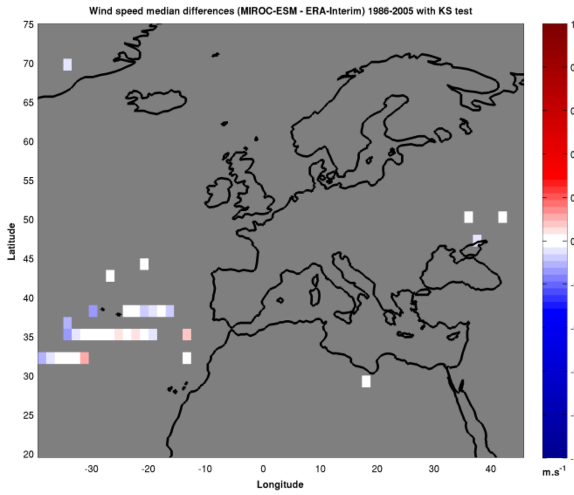
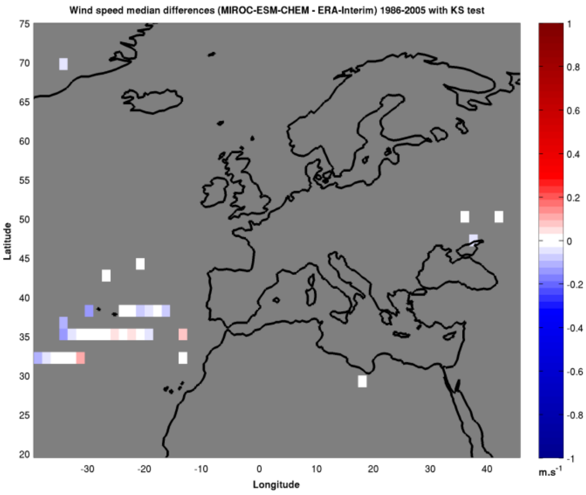
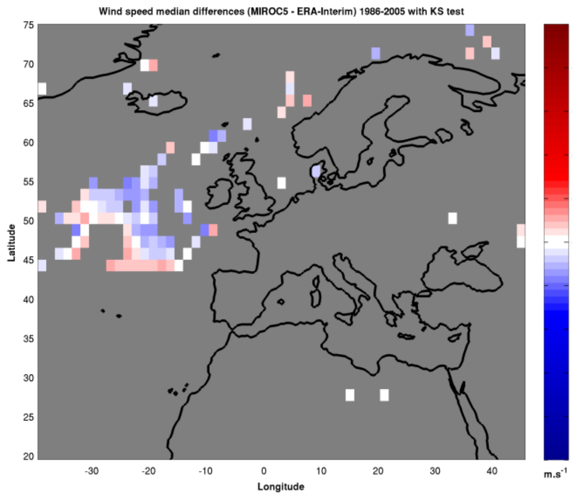

Wind speed median differences (MIROC-ESM - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
m.s-1


Wind speed median differences (MIROC-ESM-CHEM - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
m.s-1


Wind speed median differences (MIROC5 - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
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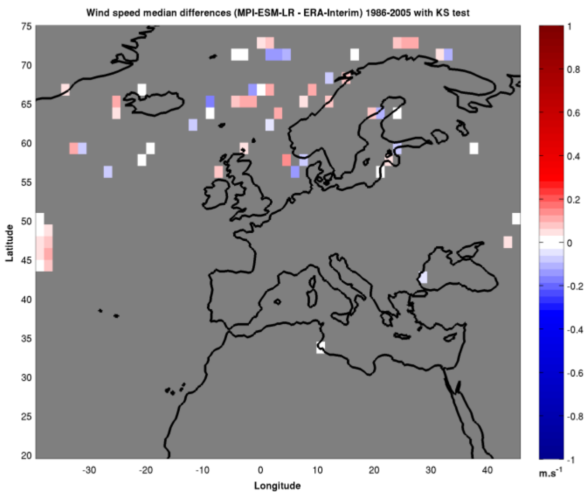
Wind speed median differences (MPI-ESM-LR - ERA-Interim) 1986-2005 with KS test
Latitude
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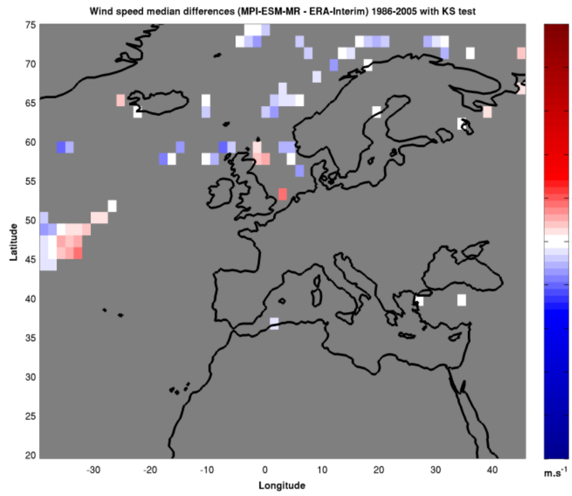
Wind speed median differences (MPI-ESM-MR - ERA-Interim) 1986-2005 with KS test
Latitude
Longitude
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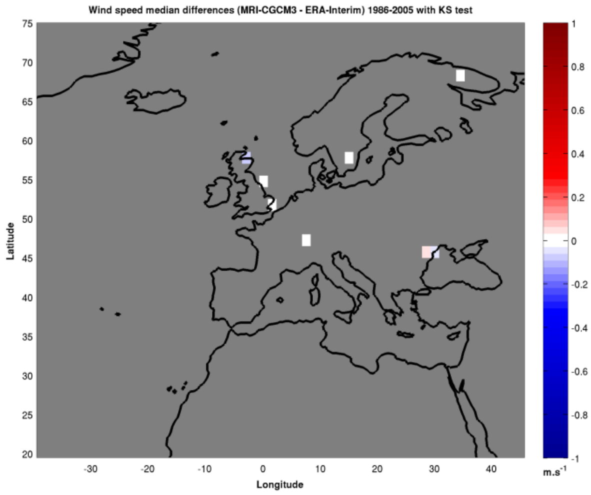


Figure 1 – Wind speed median differences (CMIP5 model minus ERA-Interim) with a KS test (5% of significance level)

Figure 1 shows that, in general, none of the CMIP5 GCMs is able to satisfactorily represent the wind speed distributions over Europe. In all models, the majority of the grid points show different wind speed distributions from those from ERA-Interim. These results, although not encouraging, are not wholly surprising and it was previously reported that GCMs are not typically able to accurately reproduce contemporary wind climates or historical trends (Pryor and Barthelmie, 2010). The typical GCMs coarse resolution does not allow an accurate representation of near surface meteorological variables such as near surface winds, due to a weak representation of the Earth's surface. Near surface winds depend strongly on the surrounding terrain characteristics, mainly topography and land use (which determines the surface roughness). Thus, a limited representation of the terrain characteristics will lead to substantial errors in the representation of near surface atmospheric flows (Carvalho et al., 2012a; 2013b; 2014a; 2014b; 2014c; 2014d; Alvarez et al., 2013). Chen et al. (2012) investigated possible causes of the differences between nine CMIP5 GCMs near surface wind fields and reanalysis output, by examining the differences between geopotential height gradients from the GCMs and the reanalysis, reporting that the upper air pressure gradients characteristics are considerably better captured by the GCMs than the near-surface wind speeds. This finding supports the hypothesis that the GCMs topography and land use weak representation may be one of the major error sources in the simulation of near-surface wind speeds, not properly simulating the atmosphere-surface coupling and interaction. Not surprisingly, the CMIP5 GCMs grid points that are in accordance to ERA-Interim are mostly located in ocean areas, where limitations in the representation of surface characteristics are obviously attenuated. McInnes et al. (2011) also reported that a 19 CMIP3 AOGCMs ensemble exhibit lower skills over land areas, by comparing this multi-model ensemble winds with reanalysis winds for the period 1981-2000. The interaction between the surface and adjacent atmosphere will ultimately result in medium- to small-scale atmospheric circulations. Thus, this type of global models has their strength in representing large-scale meteorological and climatic trends. Albeit reanalysis products, such as ERA-Interim, usually have similar resolutions and suffer from the same terrain representation limitations, they incorporate and assimilate significant amounts of observed meteorological data. Therefore, unlike pure GCM output, reanalysis products may be able, at least to some extent, to depict medium-scale wind circulations and this fact can explain the differences detected between CMIP5 GCMs and ERA-Interim reanalysis.

Nevertheless, from Figure 1 four GCMs stand out with the highest number of grid points similar to ERA-Interim in terms of wind speed distributions: HadGEM2-ES (180 valid grid points), ACCESS 1.3 (177 valid grid points), ACCESS 1.0 (174 valid grid points) and HadGEM2-CC (137 valid points). Also for these models, the differences between their wind speed medians and ERA-Interim ones is relatively small. Oppositely, CanESM2 (with no valid grid points), IPSL-CM5A-LR (5 valid grid points), MRI-CGCM3 and CNRM-CM5 (both with only 8 valid grid points) are the models with worst performance. Therefore, the HadGEM2-ES, HadGEM2-CC, ACCESS 1.0 and ACCESS 1.3 GCMs were chosen as the models that best represent contemporary wind speed climatology and the ones that may have the best performance in simulating future wind climate due to climate change. Thus, data from these four models was used to build the MME dataset. The overall superiority of HadGEM2-ES model (as well as its earlier CMIP3 version, the HadGEM2) was previously reported in other studies such as Brands et al. (2013) and Brands et al. (2011). These differences among the several CMIP5 GCMs performances in representing contemporary wind climates should be seriously considered in dynamical downscaling applications focused on wind energy, given the typical equiprobable treatment of the driving models in these dynamical downscaling studies (Brands et al., 2013). Only the models with the best performances should be used as source of initial and boundary data in dynamical downscaling applications, in order to minimize RCM (or RCMs ensemble) simulations errors.

Thus, the use of GCM models such as the ones here tested can be considered as somewhat over-simplistic and insufficiently detailed to analyze these issues, due to their inherent limitations and uncertainties. Adding to this fact, these results revealed the inability of the CMIP5 global models here considered to realistically represent the past-present European wind speed climatology. Nevertheless, it is expected that information from GCMs can provide, at least, a preliminary picture of future changes in the large-scale European wind speed climatology.

3.2 – Climate change impacts in future wind energetic resource

Climate change impacts on future wind energy resource and their respective geographical distributions in Europe are analyzed in this section. To this end, MME wind speed and energy density historical and future 20-year medians are compared and the statistical significance of such differences assessed. Figures 2 and 3 show wind speed (left column) and energy density (right column) median differences (future vs. historical) for RCP 8.5. Grey colour represents areas with no median differences according to the Mann-Whitney test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

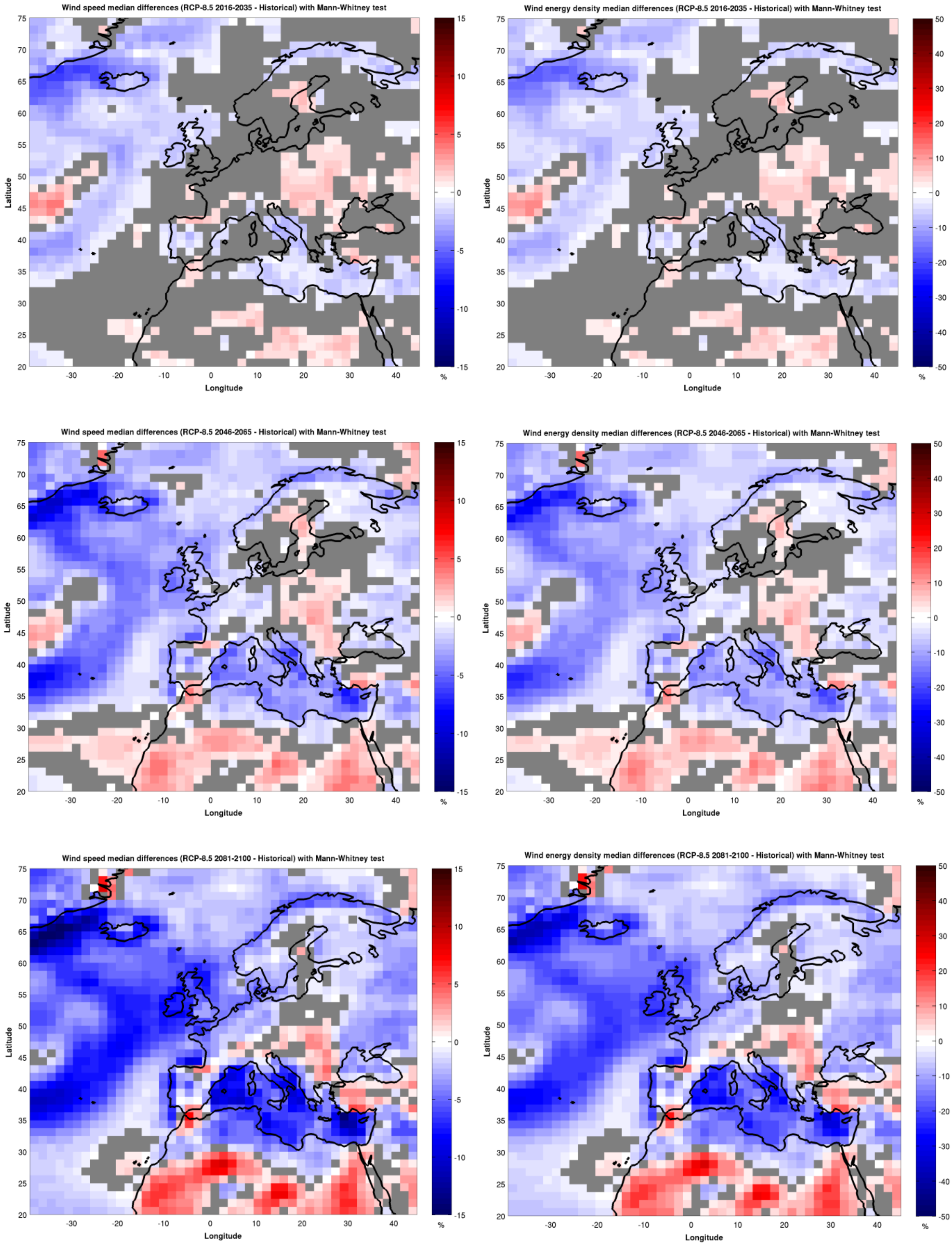


Figure 2 – Wind speed (left column) and energy density (right column) median differences (future minus historical) with Mann-Whitney test - RCP 8.5. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

According to Figure 2, if no GHG emissions mitigation strategies are employed (RCP 8.5), there is a tendency for a cutback in future wind speed and energy density in Europe. The exceptions are some areas located in Central Europe (reaching up to Northern Europe), Turkey, offshore areas adjacent to Madeira and Canary archipelagos and in the southern and northern tips of the Iberian Peninsula, where the wind power resource can slightly increase in the future. This reduction is clearly stronger in offshore areas than in onshore ones.

These differences, together with increasing number of grid points statistically different from the historical period, are clearly more marked for the medium and long-term future. For the short-term future (2016-2035), the majority of the grid points do not show statistically significant changes from the past-present period and, even when there are statistically significant changes, they are relatively small in magnitude (typically lower than 5% for the wind speed and than 10% for the energy density). For the medium-term future (2046-2065), the number of grid points statistically different from the past-present winds increase together with the magnitude of changes, although lower than 7-10% for the wind speed and 15-20% for the energy density. By the end of the century (2081-2100), practically all the grid points show statistically meaningful differences from the past-present period and the magnitude of changes is clearly higher, reaching up to 10-15% in terms of wind speed and 30-40% for the energy density. In this period, the areas that show a modest increase in the average wind speed and energy density are fewer, and the decrease of the wind energetic potential is more pronounced.

It should be noted that, since the energy density varies with the wind speed cubed, the percentual differences shown in Figure 2 are similar for the wind speed and energy density grids due to the colour scale chosen, where the energy density scale limits are about three times higher than the wind speed ones. Next, Figure 3 shows the same analysis but considering now the RCP 4.5 medium mitigation scenario.

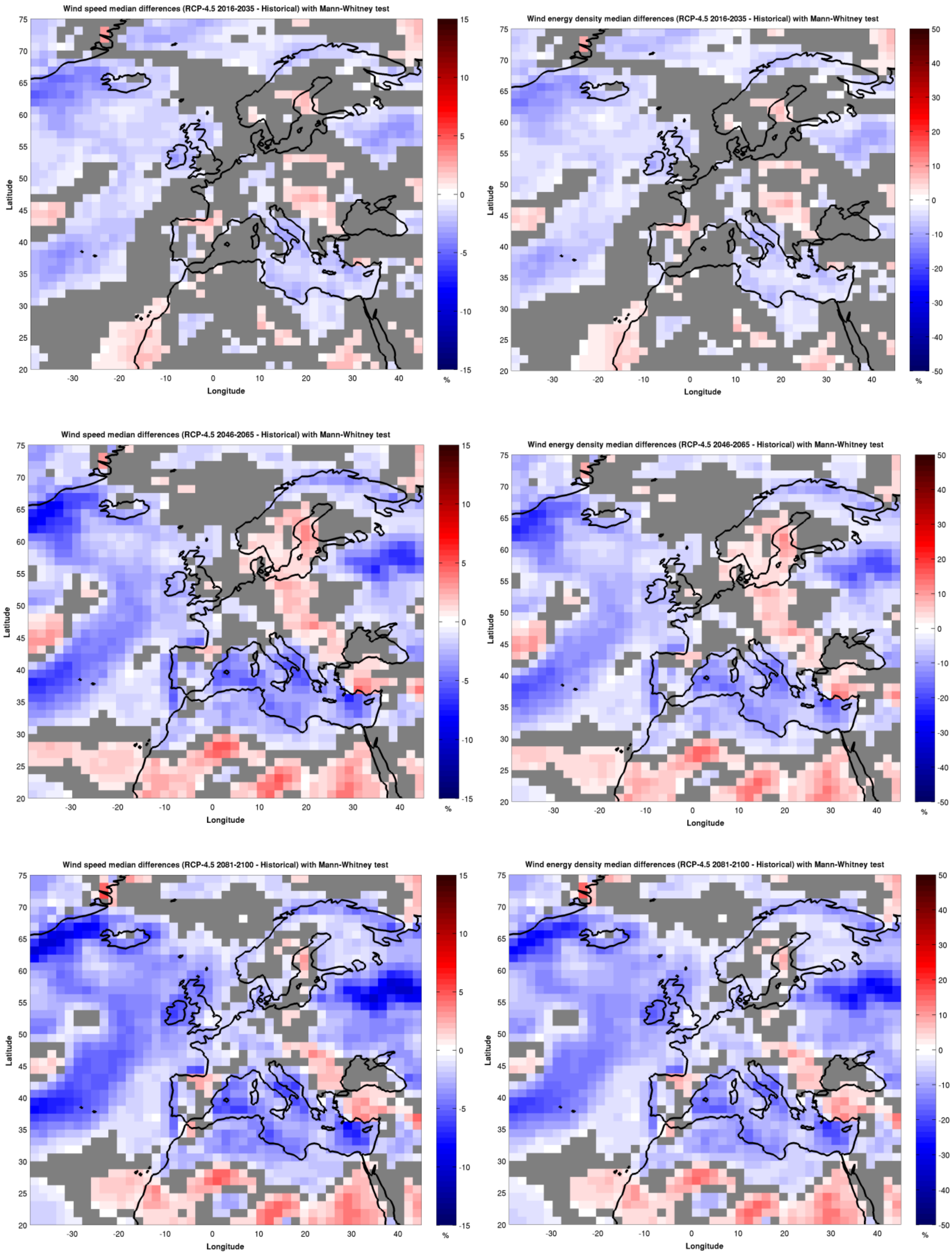


Figure 3 – Wind speed (left column) and energy density (right column) median differences (future minus historical) with Mann-Whitney test - RCP 4.5. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

The future outlook and geographical variation of the wind energy resource under this scenario, which considers GHG emissions mitigation actions, is similar to the one described by the RCP 8.5 scenario (Figure 2). However, under this scenario the differences between past-present and future wind energetic resource are considerably lower (both in terms of increase/decrease of the wind energetic resource) than the ones witnessed under the RCP 8.5, particularly for end of the century. To further analyze and detail the future tendencies of wind energetic resource over Europe, Figures 4 and 5 show the same analysis of Figures 2 and 3 for the wind energy density, but now divided by seasons.

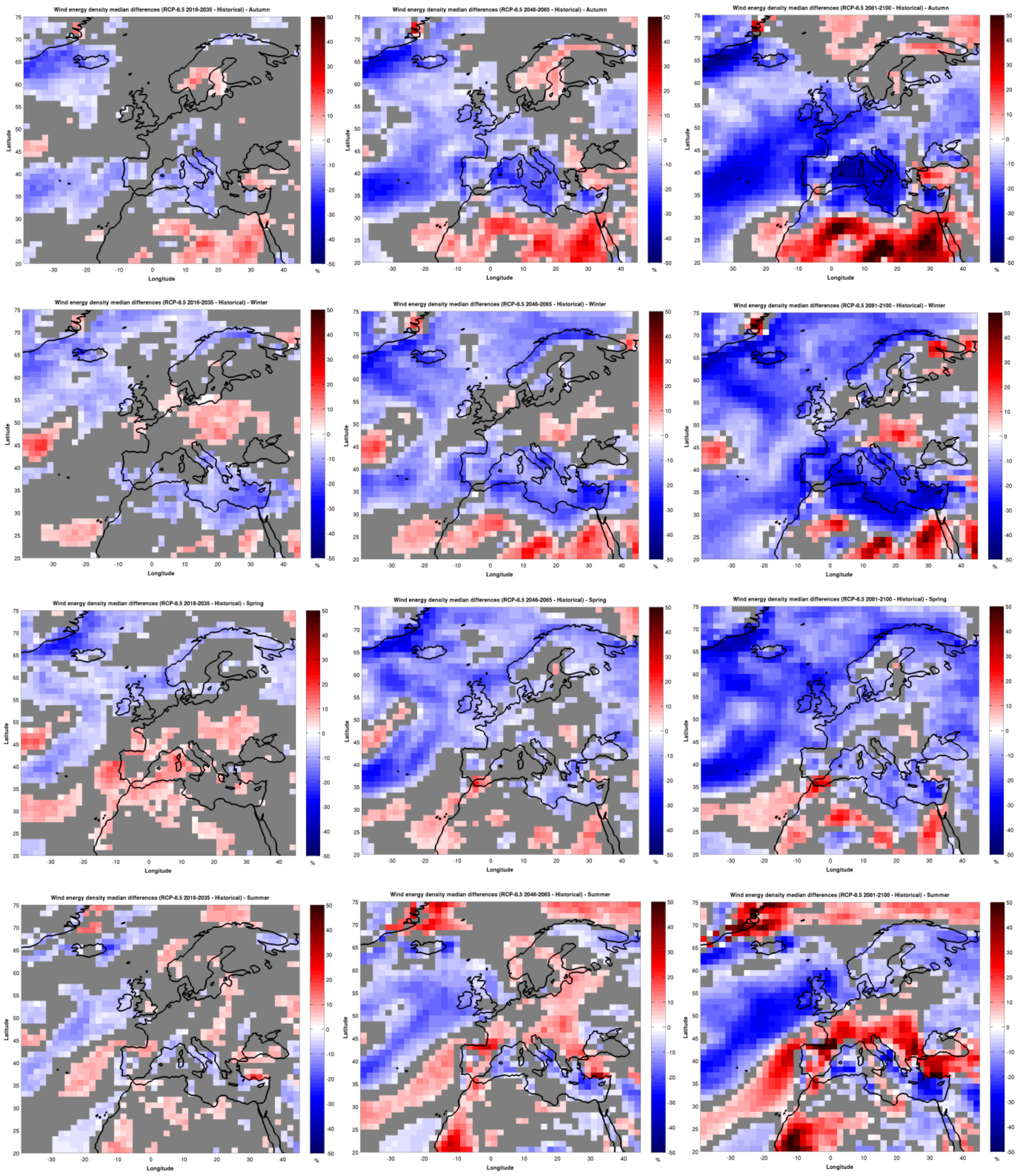


Figure 4 – Seasonal RCP 8.5 wind energy density median differences (future minus historical) with Mann-Whitney test. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second, third and fourth lines are for Autumn, Winter, Spring and Summer periods, respectively.

According to Figure 4 there is some seasonality in the changes of the wind energy density. Although in almost all seasons there is a general tendency for the future wind energy density to be lower than in the contemporary period (specially in Autumn and Spring for the medium and long term future), in Summer periods almost all Europe (with the exception of the Scandinavian Peninsula and Eastern Europe) can see its wind energetic resource increase. All of these tendencies show increasing magnitudes with time.

In Autumn, practically all Europe shows a generalized tendency for a cutback in the wind power resource, with a strong decrease of the wind energy densities in the Mediterranean area. The exceptions are seen in some areas located in Northern and Central Europe (short and medium-term futures), in Turkey (medium and long-term futures) and in the offshore areas adjacent to the Canary and Madeira archipelagos. Winter periods show similar trends and patterns to the Autumn ones, but here the exceptions for the reduction of the wind energy densities are more localized in Central Europe and in offshore areas around the Madeira and Canary archipelagos (with the exception of the long term future projections). In Spring periods, although the near-term future projections show a generalized increase in the wind energy density across Europe (with the exception of Northern areas), the medium and long-term future projections show opposite tendency. For these periods, practically all European territory shows a decrease in the wind energy density, the only exceptions being the southernmost tip of the Iberian Peninsula and the offshore areas adjacent to the Madeira and Canary archipelagos. In Summer, while the Scandinavian Peninsula and eastern areas of Europe show lower future wind energy densities, central and southern Europe shows a strong increase of the wind energetic resource. This is particularly visible for the long-term future.

Figure 5 shows the same information as Figure 4 but now for the RCP 4.5.

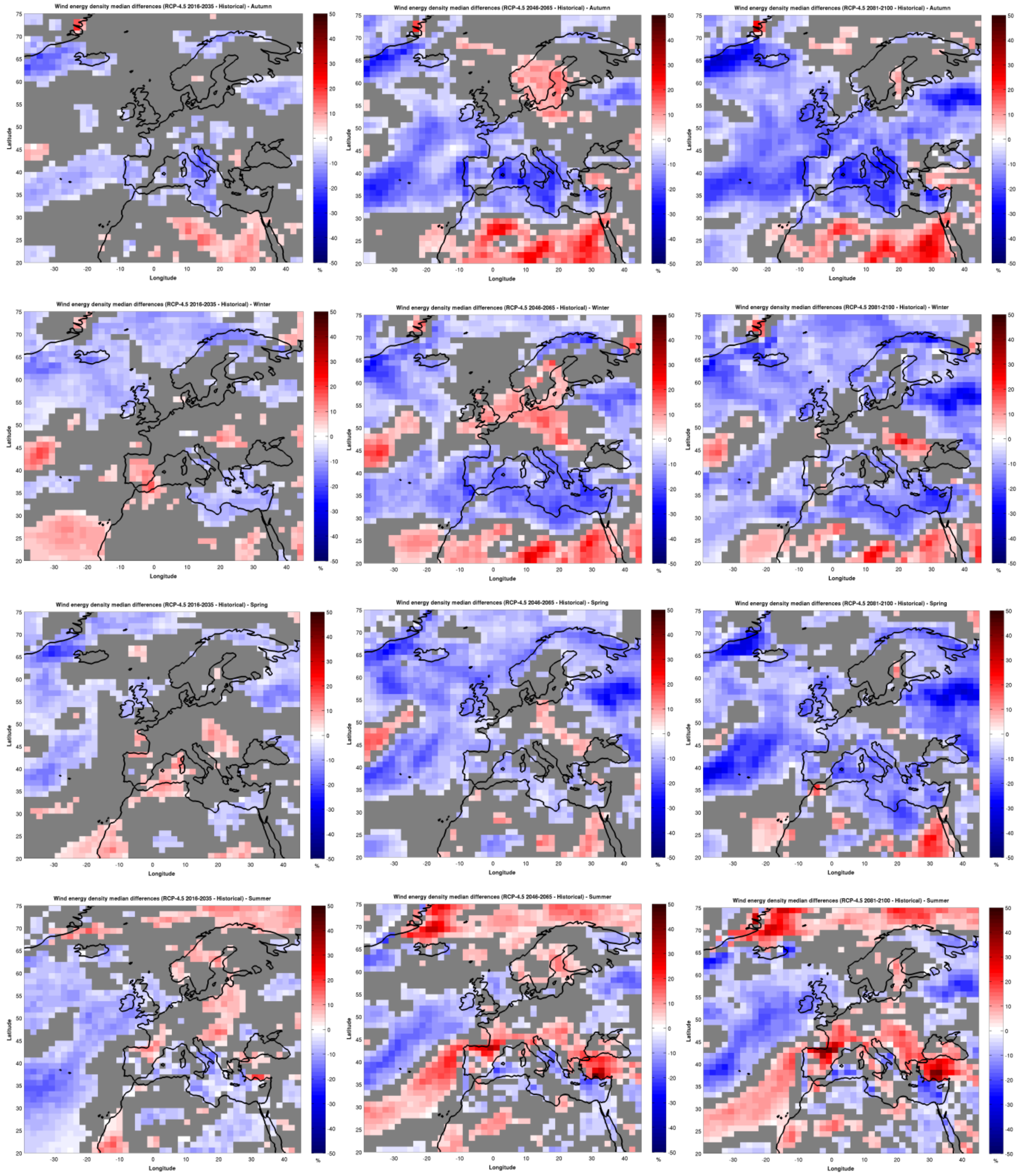


Figure 5 – Seasonal RCP 4.5 wind energy density median differences (future minus historical) with Mann-Whitney test. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second, third and fourth lines are for Autumn, Winter, Spring and Summer periods, respectively.

Figure 5 shows that in, similarly to what was seen in Figures 2 and 3, the major difference between RCP 8.5 and RCP 4.5 is that the latter shows lower differences between contemporary and future wind energy resource. This is also true when this analysis is divided into seasons. Nevertheless, these seasonal differences between contemporary and future wind energy density are still present, albeit somewhat smoothed under this mid-range GHG emission scenario.

From Figures 2 and 3, a general tendency for a decrease of future wind speeds and energy densities over Europe becomes noticeable. Although some areas show an opposite tendency (some areas located in Central Europe reaching up to Northern Europe, Turkey and the southern and northern tips of the Iberian Peninsula), with a modest increase in future wind energetic resource, the negative trends are clearly dominant both in magnitude and geographical distribution. These tendencies magnify in time, since the variations of the wind energetic resource are lower for the near-term future and higher in the end of the current century. Furthermore, it is clear that these changes and tendencies are higher under scenarios of stronger radiative forcing. When analyzing the future variation of the wind energetic resource in a seasonal perspective (Figures 4 and 5), it is detectable a seasonality in the variation of the wind energy density. While in Autumn and Spring there is a tendency for the future wind energy density to be lower than in the contemporary period (with some localized exceptions in Central/Northern Europe), in Summer almost all Europe (with the exception of the Scandinavian Peninsula and Eastern Europe) shows an opposite tendency, with an increase in its wind energetic resource. All of these tendencies show increasing magnitudes with time and under stronger emission scenarios.

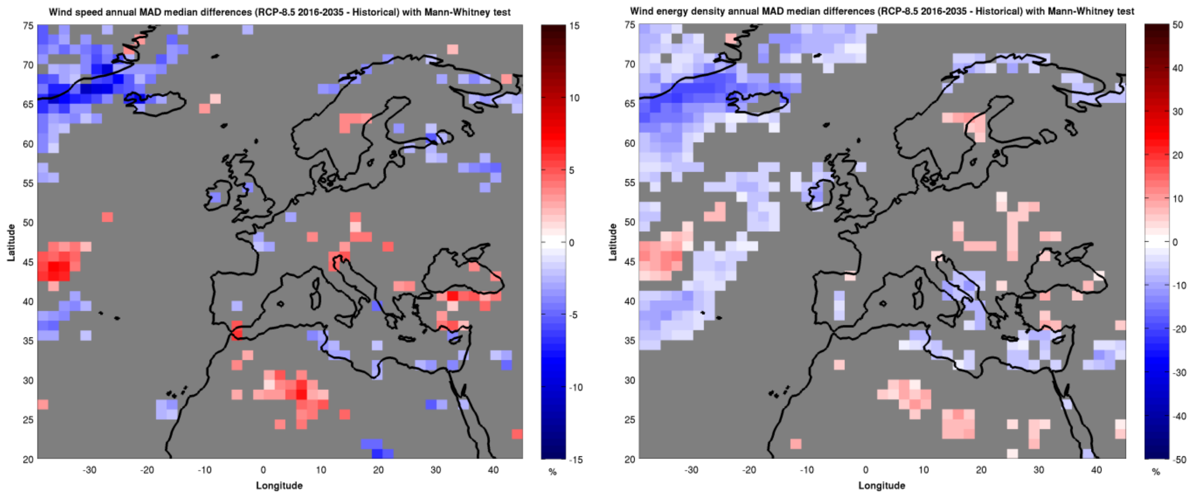
Although it is not straightforward to find a direct and objective cause for these tendencies due to the non-linear dependence of near-surface winds with a wide range of meteorological and terrain features, some studies that investigated CMIP5 data reported findings that can be related to this issue: decreasing trends in cyclone number and frequency in most of the North Atlantic and Europe (Eichler et al., 2013; Zappa et al., 2013); decrease of extreme cyclones events and in storm track activity in the Northern Hemisphere (Chang et al., 2012); and an increased frequency of the negative phase of the North-Atlantic Oscillation (NAO) under future warming (Cattiaux et al., 2013). A negative phase of the NAO is related to a weakening of its two pressure centres (Azores high and Iceland low), leading to lower zonal winds (mainly westerlies), together with fewer and weaker cyclones (Pryor et al., 2005a). Thus, a future decrease in the storm activity, number and intensity of cyclones in Europe and a tendency for the NAO to be more negative can explain the tendency for future lower wind speeds across Europe.

It becomes pertinent to discuss the obvious differences between the future tendencies of wind speeds over Europe projected by CMIP5 and its predecessor, CMIP3. The latter projected that by the end of the current century the wind energy density and annual mean wind speeds can increase in northern Europe and decrease in the south of the continent, especially in Winter (Pryor et al., 2005a; Bloom et al., 2008; Walter et al., 2006). Several authors (Pryor and Barthelmie, 2010, and references therein) reported that such findings are consistent with a tendency present in CMIP3 future climate projections toward a positive phase of the NAO (Rauthe et al., 2004), a poleward displacement of the storm track (Pryor and Barthelmie, 2003) and an increase of midlatitude cyclones intensity over the North Atlantic, particularly in Winter (Nolan et al., 2011). Ergo, it becomes clear that CMIP5 and CMIP3 modelling results show different trends and future wind climatology projections over Europe and its driving mechanisms. This fact is not surprising given the aforementioned differences in the GCMs used in CMIP3 and CMIP5. One of the differences between these two generations of GCMs that can have a strong impact in realistically simulating future near-surface winds is that CMIP5 GCMs are able to incorporate land use and land cover changes that are frequent over time (Moss et al., 2010). CMIP3 GCMs may not realistically update these changes over their simulations in their boundary conditions, as reported by Vautard et al. (2010). Aside differences in the GCMs design, Cattiaux and Cassou (2013) studied the differences between CMIP5 and CMIP3 trends in the wintertime Northern Annular Mode (NAM, also known as the Arctic Oscillation). The NAM directly influence European climate through changes in its regional feature, the NAO (Ambaum et al., 2001). Cattiaux and Cassou (2013) reported that CMIP3 future projections showed a positive NAM trend, while CMIP5 revealed an opposite (negative) trend, and these differences are mostly related to the CMIP5 faster sea ice depletion in early winter and stronger warming in the western tropical

Pacific in late winter, which will remotely influence the NAM through teleconnection mechanisms. Also, Cattiaux et al. (2013) found that CMIP5 models, oppositely to CMIP3 ones, project a stronger winter North-Atlantic jet stream than observed, suggesting an increased frequency of the NAO negative phase under future warming. Furthermore, Chang et al. (2012) reported that CMIP5 models project a larger decrease in the Northern Hemisphere (NH) storm track activity than CMIP3 models. Thus, it appears that CMIP5 and CMIP3 projected opposite trends in future NAO phases, and CMIP5 models foresee a larger decrease in NH storm activity when compared to CMIP3 results. These findings can be related to CMIP5 and CMIP3 different projections of future near-surface winds over Europe.

3.3 – Climate change impacts in future wind energy intra-annual variability

To assess climate change impacts on future wind energetic resource intra-annual variability, historical and future MME wind speed and energy density annual MAD medians are compared and the statistical significance of such differences assessed. These results are presented in Figures 6 and 7.



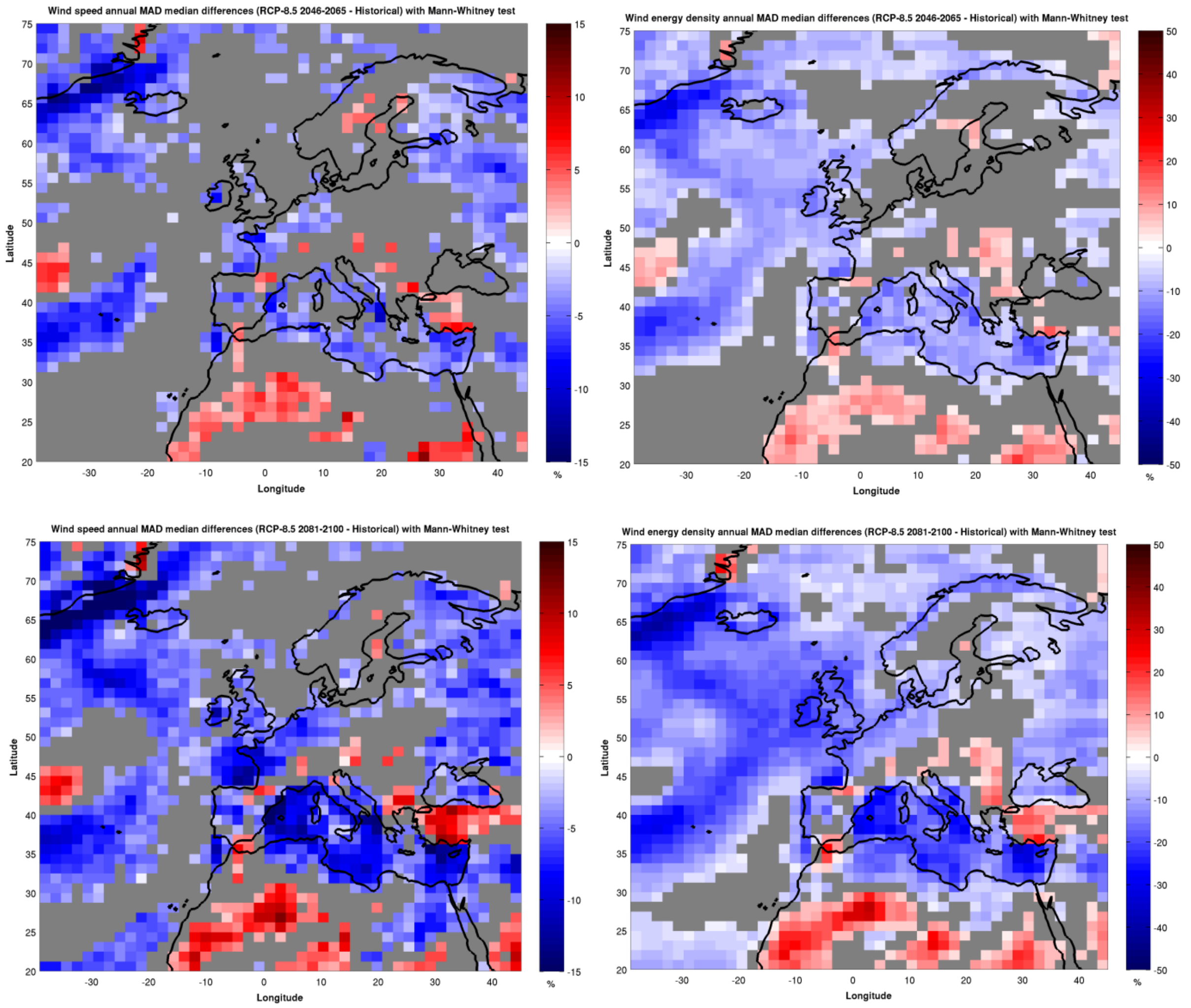
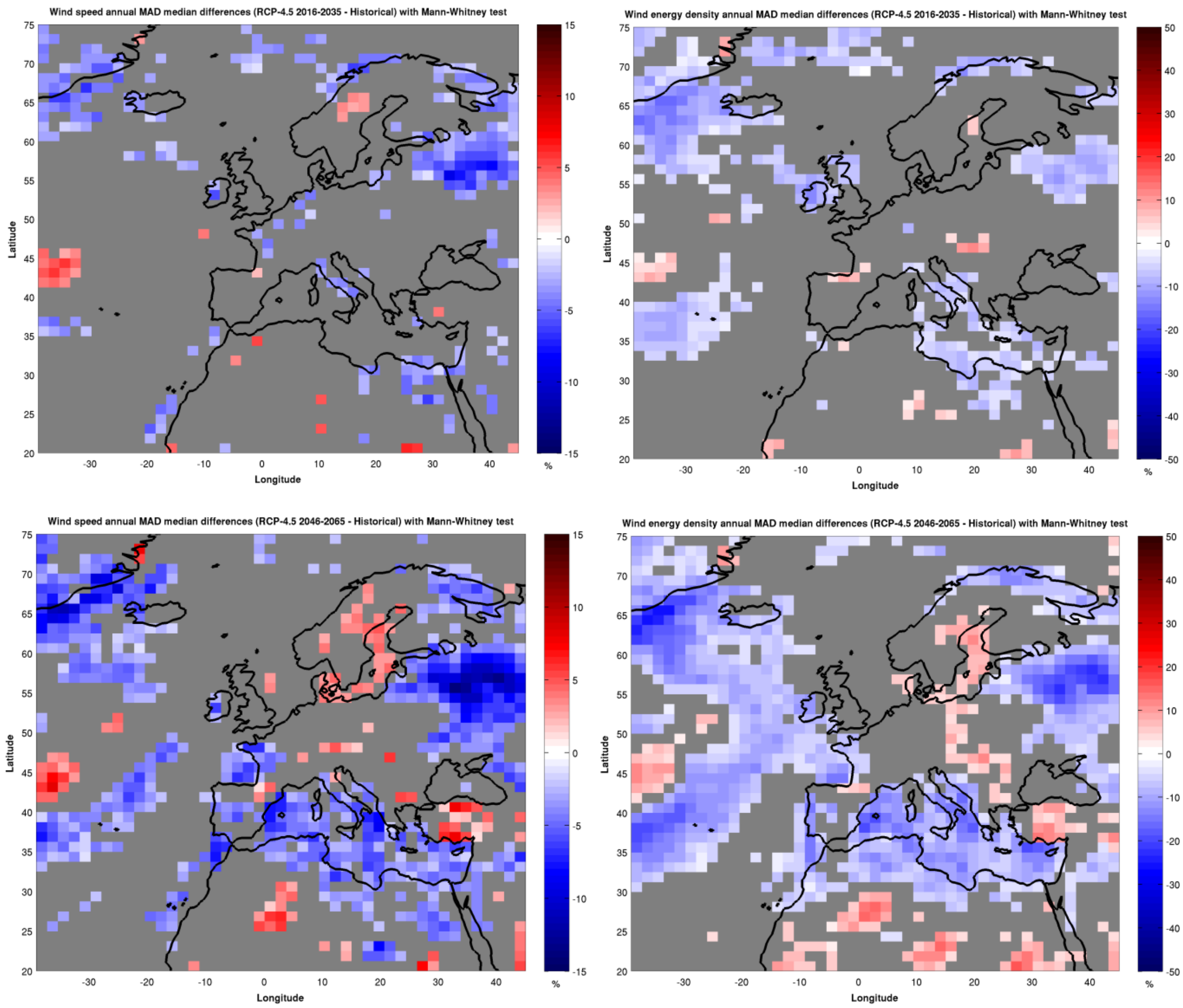


Figure 6 – Wind speed (left column) and energy density (right column) MAD median differences (future minus historical) with Mann-Whitney test - RCP 8.5. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

According to Figure 6, in the short-term future (2016-2035) no significant changes in the wind speed and energy density intra-annual variability are to be expected, since only a small number of grid points show statistically significant MAD median differences between the contemporary and short-term future. Although the differences are more significant for the wind energy density than for the wind speed, in European mainland almost all grid points show statistically negligible differences. However, for the medium and long-term future the panorama is considerably different. For these periods, the wind speed and energy density intra-annual variability are expected to be significantly lower, especially in the end of the current century. In the medium-term future (2046-2065), the wind speed and energy density intra-annual variability trends are somewhat homogeneous in Europe, decreasing around 2-

10% in terms of wind speed, corresponding to about 10-30% in terms of wind energy density. This tendency is present practically in all European territory, with the exceptions of some localized areas in the Iberian and Scandinavian Peninsula, Turkey and in central Europe. The long-term future shows similar geographical patterns and signal for the wind speed and energy density intra-annual variability changes, but with intensified magnitudes: the wind speed intra-annual variability can decrease up to 8-15%, while the wind energy density intra-annual variability can be reduced in about 15-40%. This negative trend of the wind speed and energy density intra-annual variability is more pronounced in the Mediterranean area, whereas some areas located in Turkey and Central Europe can see the intra-annual variability increase. Figure 7 shows the same information but now considering RCP 4.5 data.



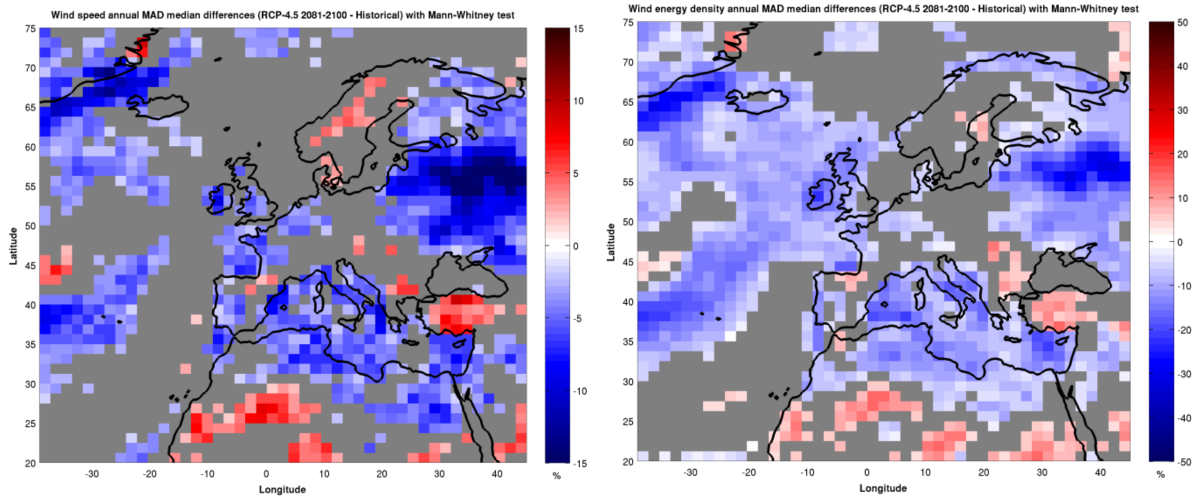


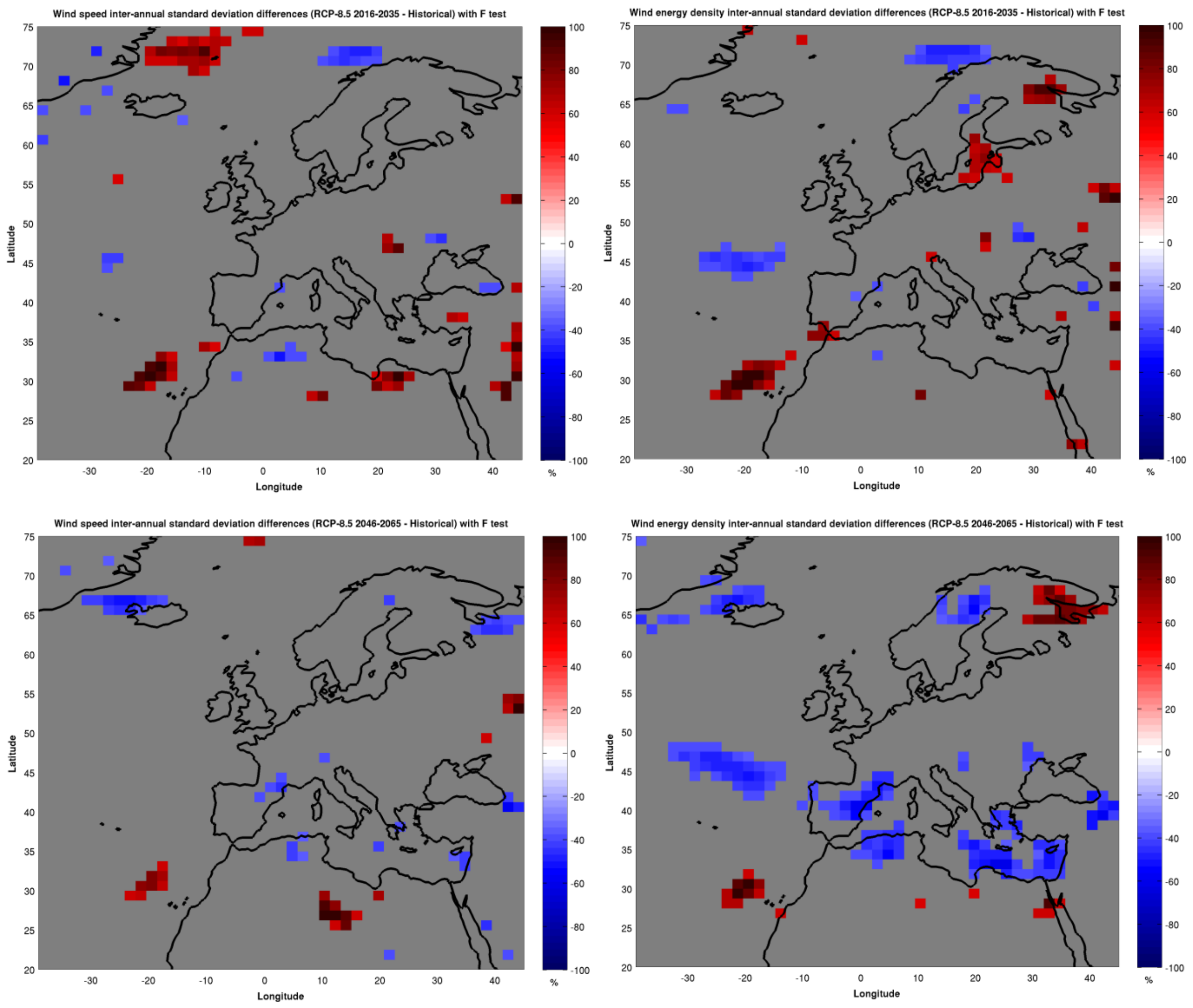
Figure 7 – Wind speed (left column) and energy density (right column) MAD median differences (future minus historical) with Mann-Whitney test - RCP 4.5. The grey colour represents areas without median differences according to a Mann-Whitney test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

The expected changes in the wind speed and energy density intra-annual variability considering RCP 4.5 data are very similar to the ones expected with RCP 8.5, although with lower magnitudes. Similarly to what was seen for RCP 8.5, RCP 4.5 foresees a generalized decrease in the wind speed and energy density intra-annual variability all over European territory, more marked in the medium and long-term futures. The exceptions are again seen in Turkey and in some localized areas in Central/Northern Europe.

Bearing in mind that, typically, average wind speeds tend to be higher in cold seasons and lower in warmer ones, the results presented in the previous section (Figures 4 and 5) are consistent with the general decrease in the wind speed and energy density intra-annual variability here detected: if in Winter the wind speed and energy density tend to be lower and in Summer they tend to be higher, the difference between Winter-Summer wind energetic resource will be lower and, hence, lower will its intra-annual variability be (the typical variation the wind speed and energy density within a year). This reduction of the wind energy density intra-annual variability, particularly if it reaches 30-40% of its current value, is of great interest for the electrical grid operators, since the offer-demand grid balance can be easier to maintain with a less variable wind-derived electricity injection.

3.4 – Climate change impacts in future wind speed and wind energy density inter-annual variability

In order to assess climate change impacts in future wind speed and wind energy density inter-annual variability (this is, the variability between different years), differences in the standard deviation between historical and future wind speed and energy density annual means data series are computed and their statistical significance assessed with the F-test. These results are shown in Figures 8 and 9.



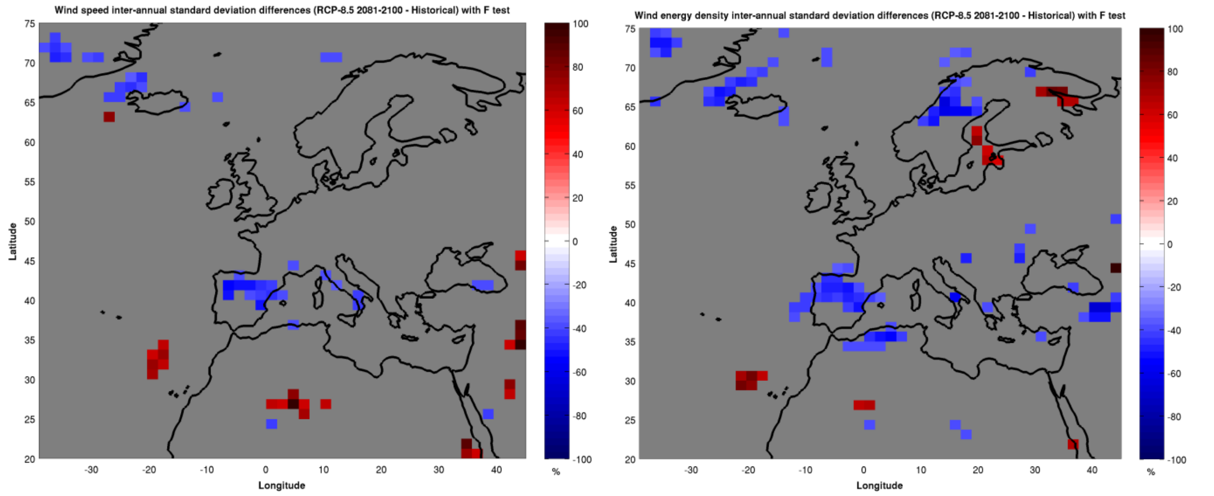
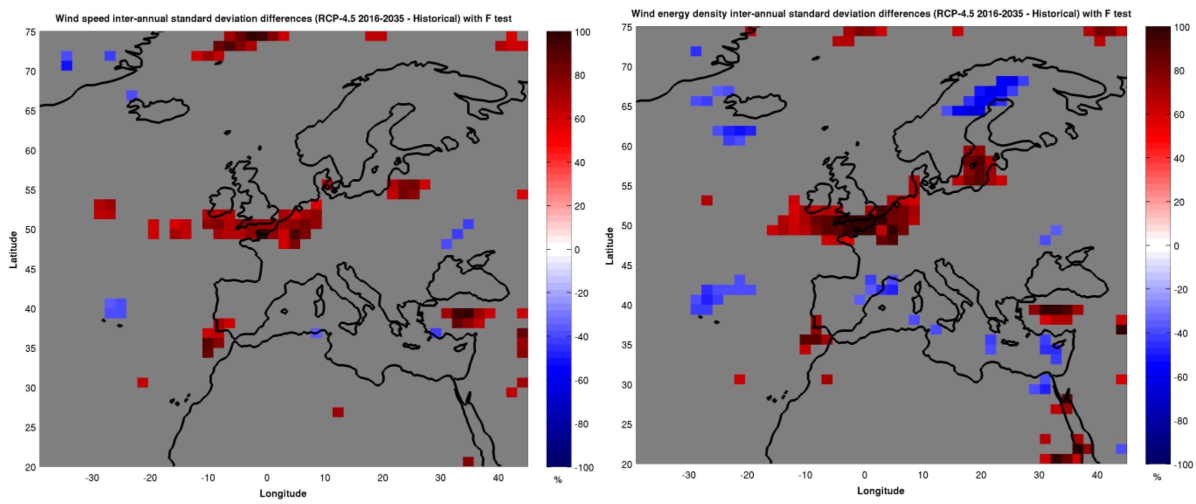


Figure 8 – Wind speed (left column) and energy density (right column) standard deviation differences (future minus historical) with the F-test - RCP 8.5. The grey colour represents areas without median differences according to a F-test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

According to Figure 8, no significant changes are to be expected in the inter-annual variability for the wind speed and energy density over Europe until the end of the current century. For all future periods, the great majority of the grid points show statistically not significant differences when compared to the contemporary period inter-annual variability. Although when such differences are statistically significant they are high in magnitude (reaching up to an increase of 100% a decrease of 60-70%), these statistically significant grid points are scattered and no conclusive trend, geographical or temporal, is detectable. Figure 9 shows the same analysis but now considering RCP 4.5 data.



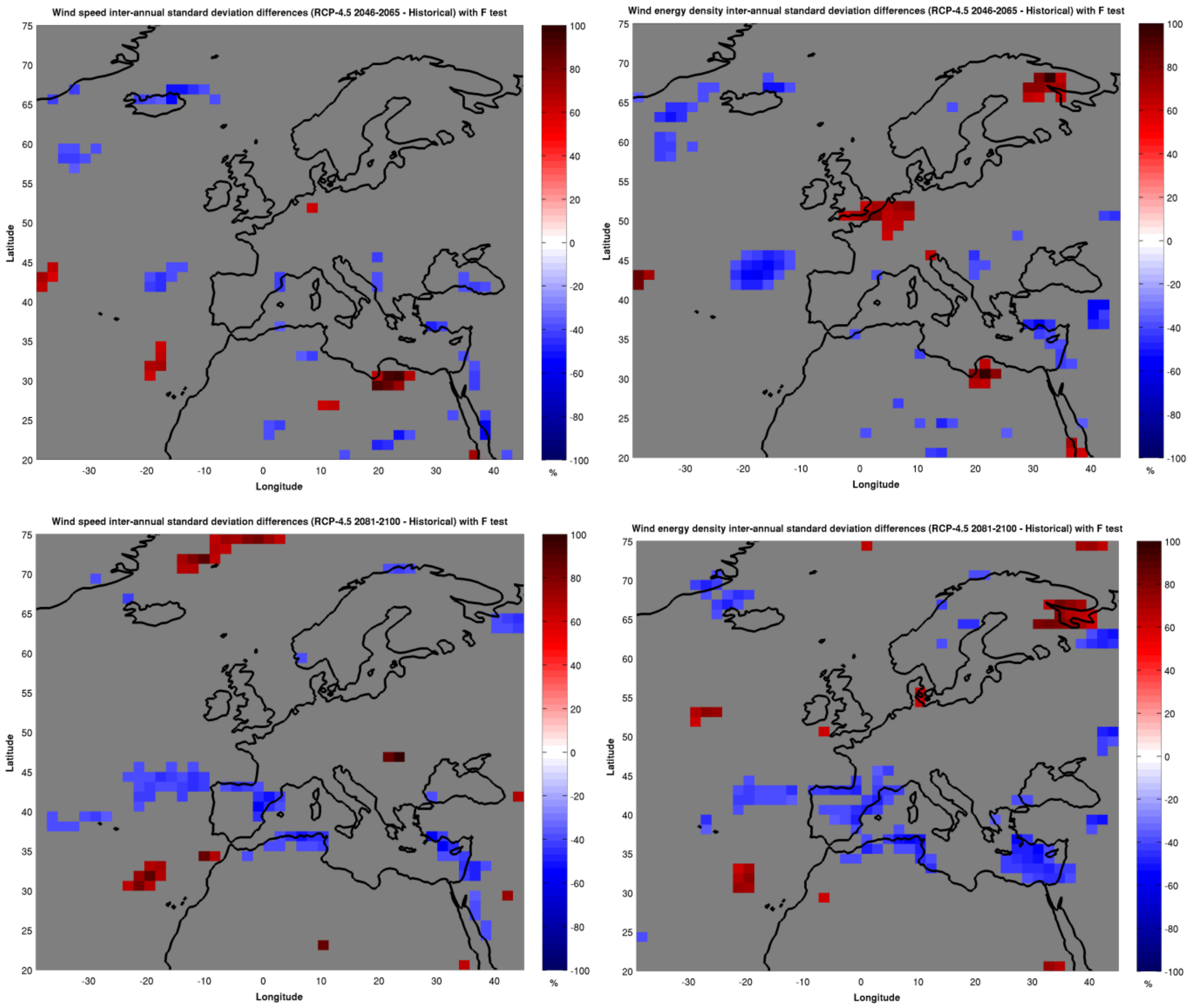


Figure 9 – Wind speed (left column) and energy density (right column) standard deviation differences (future minus historical) with the F-test - RCP 4.5. The grey colour represents areas without median differences according to a F-test (5% significance level). The first, second and third lines are for the short-term, medium-term and long-term future, respectively.

Figure 9 shows similar geographical and temporal changes of the wind speed and energy density inter-annual variability of Figure 8. Thus, also when considering future climate projections of RCP 4.5 scenario no significant changes are to be expected in the inter-annual variability for the wind speed and energy density. Considering the information presented in Figures 8 and 9, it is advisable to adopt a conservative point of view in this issue and consider that no significant changes are to be expected in the inter-annual variability for the wind speed and energy density over Europe until the end of the current century.

4 – Conclusions

This work aimed to provide a large-scale picture of future changes in European wind resource due to climate changes, using the latest IPCC future climate projections derived from the CMIP5 project. This work comprised two stages: first, to assess the GCMs that best reproduce contemporary near surface wind speeds over Europe. Secondly, data from the best GCMs was used to quantify and assess future changes in the large-scale wind energetic resource and their geographical distributions over Europe, together with its intra- and inter-annual variability. The main conclusions of this work can be summarized as follows:

- The CMIP5 GCMs HadGEM2-ES, HadGEM2-CC, ACCESS 1.3 and ACCESS 1.0 are the models that showed the best ability to represent the European contemporary near surface wind speed climatology over Europe described by the ERA-Interim reanalysis. Near surface wind speed data from these models was used to assess future projections of wind speed climatology over Europe. However, it should be highlighted that all tested CMIP5 GCMs showed poor results in accurately representing past-present European wind climatology. Additional efforts should be employed to improve the performance of these models.

- The future European wind energetic resource is predicted to be lower than the one available at present, due to a decreasing tendency of the large-scale wind speeds over the current century. Although some areas (located in Central Europe reaching up to Northern Europe, Turkey and the southern and northern tips of the Iberian Peninsula) can show a modest increase in future wind energy resource, negative trends are clearly dominant both in magnitude and geographical distribution. These tendencies increase in time, since the variations of the wind energy resource are lower for the upcoming decades and higher by the end of the current century. They are also higher under scenarios of stronger radiative forcing. Although in the upcoming decades (2016-2035) no alarming changes in the wind energetic resource are to be expected (lower than 10% for the “business as usual” scenario and below 5% for the midrange GHG emission mitigation RCP), the panorama drastically changes for the last decades of the current century (2081-2100), where the reduction in the wind energetic resource over Europe can reach an alarming 30-40% (when considering RCP 8.5).

- Seasonality is also patent in the variation and changes in the future wind energy resource. While in Autumn and Spring there is a tendency for the future wind energetic resource to be lower than in the contemporary period (with some localized exceptions in Central/Northern Europe), in Summer almost all Europe shows an opposite tendency (with the exception of the Scandinavian Peninsula and Eastern Europe), with an increase in its wind energetic resource. Again, these tendencies magnify in time and they are higher under scenarios of stronger radiative forcing that consider less GHG emission mitigation actions.

- No significant changes in the wind speed and energy density intra-annual variability are to be expected in the period 2016-2035. However, for the medium (2046-2065) and long-term (2081-2100) future the panorama is considerably different. For these periods, the wind speed and energy density intra-annual variability are expected to be significantly lower (except in Turkey and in some localized areas in Central/Northern Europe), especially in the end of the current century (around 15-40%). These tendencies are also higher under scenarios of stronger radiative forcing.

- In terms of inter-annual variability, no significant changes are to be expected over Europe during the current century. The statistical analysis revealed that the differences between past-present and future inter-annual variability, although sometimes high in magnitude, are not statistically significant. Thus, no conclusive trends, geographical or temporal, are detectable.

Although the validation results of this study showed the inability of the CMIP5 global models to realistically represent the past-present European wind speed climatology, and the use of such coarse models can be considered as somewhat over-simplistic and insufficiently detailed for the desired purposes, the findings of this work can serve as an important background for future downscaling initiatives of CMIP5 data to regional and local scales and should be seen as a preliminary warning that a continuous increase of greenhouse gases emissions can jeopardize our ability to mitigate such emissions, at least in what concerns the role and contribution of wind energy. By negatively affecting future wind energy resource, climatic changes can weaken wind power active and vital contribute to reduce greenhouse gases emissions. However, it needs to be strongly emphasised that there is significant uncertainty associated to global models future climate projections that, together with the poor ability of the CMIP5 global models to accurately represent the past-present wind climate over Europe due to their intrinsic limitations, provides limited confidence to the future outlook of the European wind energy resource projected by these models. Thus, the information provided by these models should be seen as a preliminary picture of the large scale future tendencies of the wind energy resource, and further research focused on these themes should be performed by downscaling CMIP5 GCMs output to regional and local scales in order to better represent the topography and land use and thus better simulate near surface winds.

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