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Environmental Research Letters

OPEN ACCESS

RECEIVED
21 June 2015

REVISED
26 December 2015

ACCEPTED FOR PUBLICATION
1 February 2016

PUBLISHED
4 March 2016

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LETTER

Climate change impacts on the power generation potential of a European mid-century wind farms scenario

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Keywords: climate change impacts, wind energy, regional climate modelling, Europe

Supplementary material for this article is available online

Abstract

Wind energy resource is subject to changes in climate. To investigate the impacts of climate change on future European wind power generation potential, we analyze a multi-model ensemble of the most recent EURO-CORDEX regional climate simulations at the 12 km grid resolution. We developed a mid-century wind power plant scenario to focus the impact assessment on relevant locations for future wind power industry. We found that, under two greenhouse gas concentration scenarios, changes in the annual energy yield of the future European wind farms fleet as a whole will remain within ±5% across the 21st century. At country to local scales, wind farm yields will undergo changes up to 15% in magnitude, according to the large majority of models, but smaller than 5% in magnitude for most regions and models. The southern fleets such as the Iberian and Italian fleets are likely to be the most affected. With regard to variability, changes are essentially small or poorly significant from subdaily to interannual time scales.

1. Introduction

A drastic reduction of greenhouse gas (GHG) emissions is imperative to avoid irreversible damages from global warming. The European Union has drafted the objective of cutting emissions by 80% below the level of 1990 by 2050. Wind power, as a low-carbon mature energy, will play a key role in meeting such a target by providing a substantial share of European electricity supply. The current wind power capacity installed in Europe is almost 130 GW, covering ~10% of the electricity needs (EWEA 2015), and could exceed 400 GW by 2050 (European Climate Foundation 2010, European Commission 2014).

Wind energy is however sensitive to changes in climate in several ways. The near-surface wind resource is affected by changes in large-to-local scale atmospheric circulation (e.g. Najac *et al* 2009, Jerez and Trigo 2013, Jerez *et al* 2013), as well as by changes in land cover or aerosol concentration levels (Vautard *et al* 2010, Bichet *et al* 2012). Changes in extreme events such as storms, floods and icing can also lead to increased (or decreased) damages on wind turbines and alter their efficiency (Pryor and Barthelmie 2010, 2013).

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Previous studies, based on downscaled climate projections, suggest that changes in near-surface wind speed induced by climate change along the 21st century will lead to changes in local wind power generation potential of up to 10%–20% in magnitude over most of Europe (e.g. Pryor and Barthelmie 2010, Hueging *et al* 2013, Reyers *et al* 2015, Tobin *et al* 2015). The resulting alteration of the power production considering current and near-term national wind farm fleets will not exceed 15% in magnitude by the end of the century in any European country (Tobin *et al* 2015). Despite the substantial uncertainties in future climate projections, some robust signals emerged indicating an overall increase in the wind power generation potential over Northern Europe (Baltic Sea), the Aegean Sea and the Bosporus and a decrease over the overall Mediterranean region and the Atlantic ocean (e.g. Bloom *et al* 2008, Barstad *et al* 2012, Hueging *et al* 2013, Reyers *et al* 2015, Tobin *et al* 2015).

The objective here is to complement these existing works by assessing future wind power generation potential in Europe using a multi-model and multi-scenario ensemble of the most recent regional climate projections achieved in the framework of the European branch of the COordinated Regional climate Downscaling EXperiment (CORDEX) called EURO-CORDEX (Jacob *et al* 2013). These simulations are produced with the state-of-the-art regional climate models (RCM) downscaling some of the state-of-the-art CMIP5 global climate model (GCM) projections (Taylor *et al* 2012), forced by the new GHG concentration scenarios, the so-called representative concentration pathways (RCP, Moss *et al* 2010). These simulations offer a spatial resolution of 12 km over Europe which is unprecedented in a coordinated initiative aimed at producing large multi-model and multi-scenario regional climate projections ensembles (the spatial resolution was 50 km in PRUDENCE (Christensen *et al* 2007) and NARCCAP (Mearns *et al* 2009) initiatives, 25 and 50 km in the ENSEMBLES project (Van der Linden and Mitchell 2009). The high-resolution may allow to better capture local-scale circulations (especially near coastlines and over complex terrains), and extremes. Although the 12 km-resolution EURO-CORDEX simulations do not provide an obvious improved skill with regard to large scale mean climate (Kotlarski *et al* 2014), when compared to the 50 km corresponding simulations, they exhibit higher skills in capturing small scale mean and extreme precipitation (Prein *et al* 2016) and extreme winds (Balog *et al* 2015). The large-scale wind climatology has been found to be sensitive to the model grid spacing (Pryor *et al* 2012). Therefore, grid spacing is likely to influence projected wind changes. Some recent studies have used high resolution, such as 10 km in Gonçalves-Ageitos *et al* 2015, but are based on a unique model, which does not allow to draw robust conclusions due to model spread (Pryor *et al* 2005, Rasmussen *et al* 2011, Tobin *et al* 2015).

The ensemble used here consists of 18 simulations produced using seven RCMs driven by five GCMs. Nine of these simulations were carried out under the moderate RCP4.5 scenario (corresponding to a 4.5 W m^{-2} radiative forcing in year 2100) and nine under the more extreme RCP8.5 scenario (corresponding to 8.5 W m^{-2} radiative forcing in year 2100). Such an ensemble approach allows exploring and comparing a relatively wide range of uncertainties from emission scenarios as well as GCM and RCM model formulation.

This work is particularly focused on relevant and plausible locations for wind power industry by mid-century, a horizon when it is expected to be well deployed, both onshore and offshore. For this purpose, a scenario of wind power capacity installed by 2050 spatially resolved across Europe has been elaborated. Implications of a changing climate for mean energy yield are then investigated at two scales: the regional scale of the power grid, as it matters for power supply and energy mix considerations, and the local scale of wind power plants which is informative for economic viability of the latter.

In addition, this work aims at assessing changes in the variability of production at several timescales. Although this aspect is of high importance for power grid operating, which is impacted by high-frequency variability and for energy supply demand balance planning, it has been addressed in very few studies and mostly at the broad inter-annual scale (Pryor *et al* 2005, Pryor and Barthelmie 2010, Hueging *et al* 2013).

2. Models and methods

2.1. Regional climate projections

The multi-model ensemble of regional climate projections used in this study is a subset of the comprehensive EURO-CORDEX ensemble, and corresponds to the simulations that were available at the time this study has been undertaken. The nine GCM–RCM combinations comprising the ensemble are described in supplementary section 1-1 (available at stacks.iop.org/ERL/11/034013/mmedia).

The RCM output used to drive the wind turbine-generated power is the wind speed at 10 m height at a three-hourly frequency. This allows accounting for sub-daily wind variability and potential changes therein which may affect mean wind power generation because of the nonlinear relationship between wind and extracted wind power, and avoids the need for temporal disaggregation as done in Tobin *et al* (2015).

The evaluation of simulated mean 10 m wind speeds against ISDLite stations (Smith *et al* 2011) and QuikSCAT satellite surface wind speed observations (Ruti *et al* 2008) highlights a reasonable level of model skill with a better model performance over ocean than over land (the 10 m wind speed climatology is shown in supplementary section 1–1 figure S1). Over the ocean, model biases are within ± 0.5 m s^{-1}, with a spatial

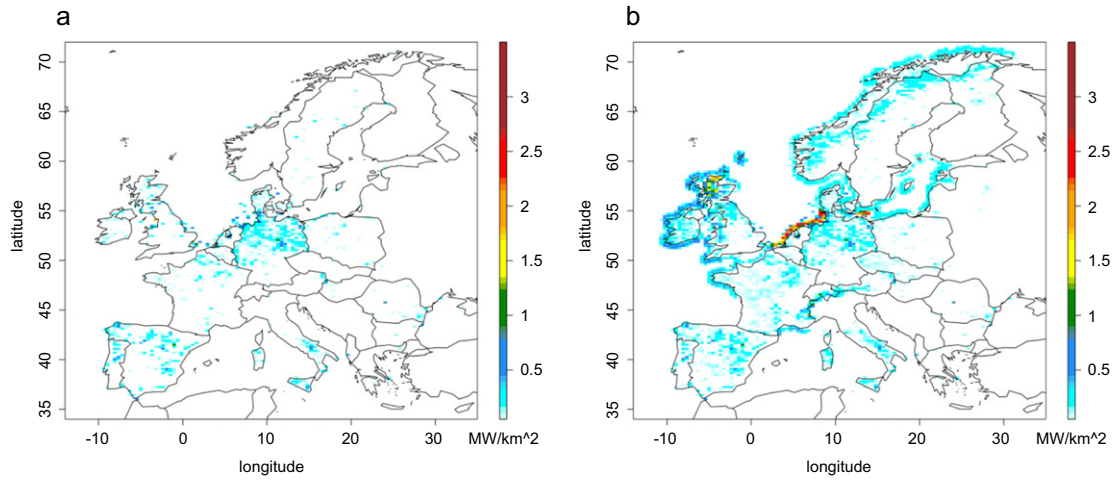

Figure 1. (a) Installed wind power capacity in 2013 (in operation and under construction). Source: thewindpower.net (b) projected installed wind power capacity by 2050, based on the ECF 2050 objective assuming a 80% renewable energy share in power mix. This objective has been spatially disaggregated using the CLIMIX tool (Jerez *et al* 2015). This scenario includes the 2013 current installations.

correlation between observed and simulated spatial patterns of 0.9, while over land, biases are positive (except for the ARPEGE model) often exceeding 1 m s^{-1}, and the correlation is around 0.5 (see supplementary section 1–1 figures S2-S3). The lower correlation can be partly explained by the spatial scale difference between model grid-cell averaged wind and local station measurements. We did not correct biases because of the too coarse temporal and spatial resolution of observational reference data (50 km daily data for QuikSCAT and scarcity of ISDLite station data in some areas) compared with the model resolution. Moreover, the work of Tobin *et al* (2015) showed that correcting biases (with regards to the particular technique used in this previous study) leads to comparable results as those using raw data with regard to relative change signals.

Since future changes in wind power variability are one focus of this study, the ability of the models to reproduce the variability of near-surface wind speed for a range of temporal scales is also evaluated against ISDLite and QuikSCAT data (see supp. section 1–1 for the calculation and evaluation of variability). The models perform again better over ocean than over land, and better at the sub-daily and daily scale than at longer timescales (supplementary section 1–1 figures S4–S7). At all timescales, the order of magnitude of simulated variability is reasonable (RMSE values from ~0.1 m s^{-1} for the interannual scale to 0.4 m s^{-1} at the interdaily scale). Some difficulties in reproducing the wind speed variability over land were detected, in terms of correlation, especially at the interannual scale, which may be due to weak values characterizing interannual variability. Note that the presence of missing values in ISDLite datasets, unequally distributed over the time series, forms a potential jeopardy for the proper evaluation of wind speed variability over land at the different time scales. Also, the evaluation time period over ocean is too short (2000–2004) for reliably estimating the interannual variability. Therefore, model deficiencies with regard to the simulation of the surface wind speed variability might be less strong than the present evaluation suggests.

2.2. Wind power

We used both current installed capacity and a scenario of future installations. For current capacity (~120 GW as of 2013), we used turbine characteristics given by a public data base (http://www.TheWindPower.net, figure 1(a)). In order to simulate a 2050 wind farms fleet, we used an energy mix scenario designed by the European Climate Foundation (ECF 2010), assuming 80% overall GHG emission reduction by 2050 in Europe, with a share of 80% of renewables in the European power mix, the other 20% being distributed among nuclear power and carbon capture and storage. It involves ~435 GW of installed wind power capacity distributed over the 27 European Union countries (as of 2010, thus excluding Croatia) plus Switzerland and Norway. This amount is shared out among distinct onshore and offshore objectives over nine regions in the alluded ECF pathway (supplementary section 1–2 table S3 and figure S8). This capacity is distributed at the grid-cell level using the CLIMIX approach (Jerez *et al* 2015), which assumes installations in proportion to wind resource quality and in inverse proportion to population density, and excluding land cover unsuitable for wind turbine installations (e.g. forests). The resulting scenario of wind power installations is shown in figure 1(b) (see supplementary section 1–2 for further details).

Generated wind power was calculated using the methodology developed in Tobin *et al* (2015) (and in other studies, e.g. Hueging *et al* 2013, Reyers *et al* 2015), which is described in supplementary section 1-2. In addition, sensitivity tests related to the wind speed assessment at the turbine hub height and

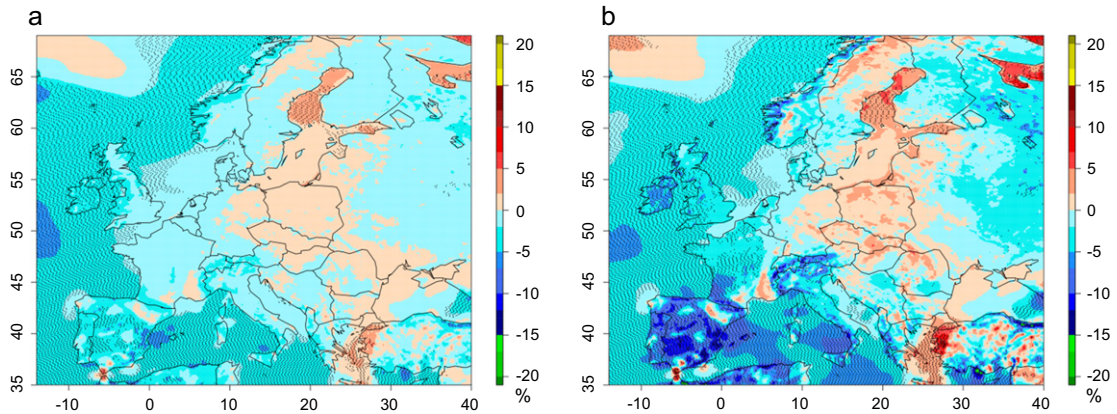

Figure 2. Ensemble mean future changes in wind speed at 10 m (a) and wind power generation potential (b) at the end of the century (2071–2100) relative to the recent 1971–2000 period under scenario RCP8.5. The black dots indicates where the changes are robust (95% significance over the model ensemble, according to Wilcoxon–Mann–Whitney test, and sign agreement over 80% of the models).

to the turbine technology were performed here to further validate the methodology (supplementary sections 1-2 and 2-3).

3. Results

3.1. Patterns of change in mean wind speed and wind power generation potential

The patterns of changes in mean wind speed, inferred from the ensemble mean over whole Europe for the end of the century, are shown in figure 2(a) for RCP8.5 and supplementary section 2–1 figure S9(a) for RCP4.5. Changes in wind power potential reflect changes in wind speed, with a slightly enhanced magnitude, especially over southern regions under the RCP8.5 scenario (figure 2(b) and supplementary section 2–1 figure S9(b) for RCP4.5). Consistent with previous studies, robust and significant decreases are found over most of the Mediterranean region and to a lesser extent over the Atlantic Ocean; robust and significant increases are projected over the Bosporus–Aegan Sea, the Gibraltar Strait and over the northern Baltic Sea. These patterns of change are found for both scenarios, with enhanced magnitude by a few percent in the RCP8.5 case (the magnitudes of wind power changes are of 5%–10% in the RCP8.5 scenario in figure 2(b) against 0%–5% under the RCP4.5 assumption in supplementary section 2–1 figure S9). The robust decrease found in previous studies (Tobin *et al* 2015) over the Alpine mountains are substantially less pronounced in the present findings.

Near-surface wind speeds are the result of a geostrophic component, directly linked with large-scale pressure patterns, and an ageostrophic component, related to mesoscale processes. Changes in wind speed at 850 hPa, which level is supposed to be on average above the top of the boundary layer and thus considered as quasi-geostrophic, bear a similar large-scale pattern as near-surface wind speed changes (see supplementary section 2–1 figure S10 changes for three models). This suggests that changes in 10 m wind speed are mainly driven by changes in large-scale circulation. However, large differences between changes in 850 hPa and 10 m wind speed are found over water in some northern regions (e.g. around Iceland, over the Northern Baltic Sea). In these regions, the 10 m wind speed is increasing, which could be linked with sea ice melting (see supplementary section 2–1 figures S10(c), (f), (i)). This link between near-surface wind speed and sea ice cover would deserve further investigation but is beyond the scope of this study. Moreover, the sensitivity tests performed in the supplementary material suggest that the sea ice melting effect apparent in the 10 m wind speed may not be impacting wind at higher levels such as at the turbine hub heights, around 100 m (supplementary section 1–2 and figures S14–S16 in section 2–3). Therefore the confidence in the projected wind power increase over northern Baltic Sea is low.

3.2. Changes in mean energy yield of 2050 wind power plants

3.2.1. At the regionally interconnected power grid scale

While projected climate change is progressing across the 21st century in response to increasing GHG forcing, the ensemble averaged yield in annual energy produced by the entire European wind farm fleet installed by 2050 will be stable (figure 3(a)). Under the scenario RCP4.5, it will remain unaltered until the late 2070s where it starts to slightly decrease up to 1% by 2080. Under the scenario RCP8.5, it starts to decrease in mid-century to reach a 2% loss by 2080. The bulk of the model ensemble projects changes lying within ±2% and ±3% around the ensemble mean for the RCP4.5 and RCP8.5 scenarios respectively. Thus it is unlikely that European 2050 fleet mean yield, as a whole, will deteriorate by more than 5%, even under the extreme RCP8.5 scenario. At the seasonal scale,

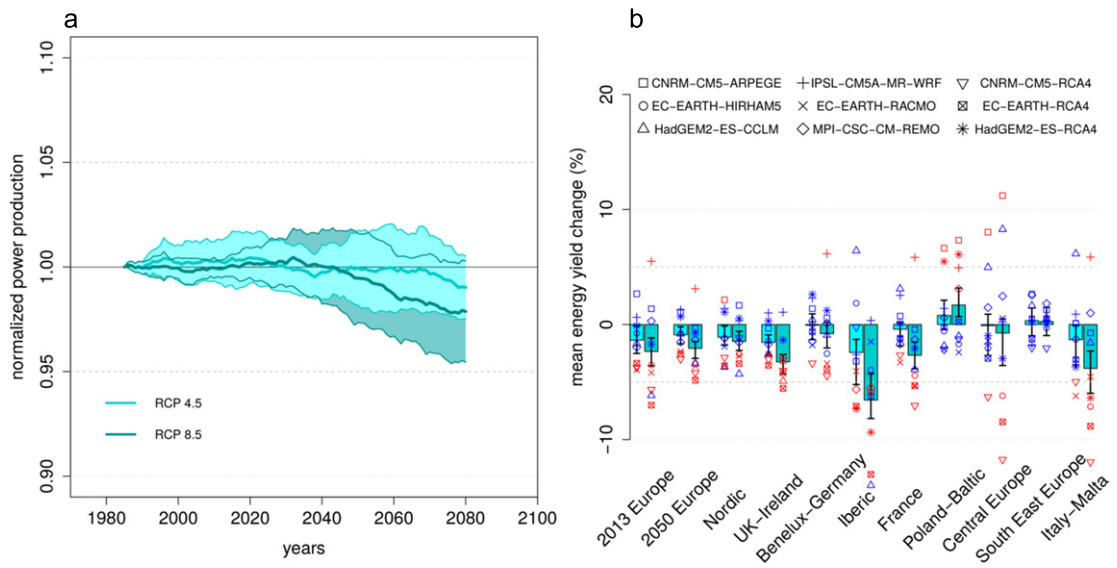

Figure 3. (a) Evolution under changing climate of the mean annual energy yield of a European 2050 wind farm fleet scenario under the RCP4.5 (cyan) and RCP8.5 (blue) scenarios. The thick curves correspond to the model ensemble mean, the thin lines to the ± standard deviation of the model ensemble. A 30 year smoothing average has been applied to the annual time series. The values are normalized by the 1971–2000 mean value. (b) Changes in mean annual energy yield for the European 2013 and 2050 fleets and for the fleets of the nine regions defined by ECF (2010). The colored wide bars indicate the model ensemble mean for RCP4.5 (left, cyan) and RCP8.5 (right, blue). The thin bars indicate the 95% level confidence interval as computed using the Wilcoxon–Mann–Whitney test. Model individual changes are represented by differing symbols: symbols are red when changes are significant at the 95% level using the Wilcoxon–Mann–Whitney test.

changes are similar, except in summer under RCP8.5 for which the spread among models is strongest and yield losses could reach about 10% according to the most sensitive models (see supplementary section 2–2 figure S11).

At country (or group of countries) scale, annual energy yields of 2050 installations are also projected to be weakly altered by the end of the century (figure 3(b)). Under the RCP4.5 scenario, the ensemble mean indicates slight significant decreases (by 1%–3%) for the Nordic region (N), UK and Ireland (UKI), Iberian Peninsula (Ib) and Italy (It) while showing a slight increase (1%) over the Poland–Baltic region and no significant changes for France (F), Benelux-Germany (BG), Central (CE) and South-East Europe (SEE). The projected changes are slightly enhanced under the RCP8.5 scenario: according to the ensemble mean, Ib and It yields will decrease by around 5% and BG and F yields by 1% and 3% respectively. The spread over the model ensemble is limited (by a few percent) especially for UKI, N and SEE, which gives confidence in the order of magnitude projected by the ensemble mean. The spread is larger over the other regions, in particular over Ib, It and CE, with differences among significant individual model signals reaching 15%–20%. However, for all models, country-scale yield change magnitudes do not exceed 10% under RCP4.5 and 15% under RCP8.5. Note that these changes can be of the same order of magnitude as natural historical year-to-year variability (see supplementary section 1–1 table S2).

For most of the regional fleets and for a large majority of models, changes in seasonal yield will remain within about ±5% under both scenarios by the end of the century (supplementary section 2–2 figure S12). The Iberian fleet, however, is likely to experience a more pronounced decrease in Spring (by 10% on average over the ensemble under the scenario RCP8.5) and in autumn (by 15%). The Italian fleet will also undergo a decrease reaching 10% in autumn. Changes in energy yield exhibit a noticeable seasonality over some regions, in particular over Ib, which will experience a summer increase of more than 5% as assessed by the ensemble mean. The spread and level of inconsistency (opposite significant signals) among models are strongest in summer. The range of projected seasonal changes covered by the whole ensemble, considering all regions, is about [−20%, 15%] in autumn, [−10%, 10%] in winter, [−15%, 15%] in spring and [−20%, 15%] in summer by the end of the century.

Ensemble mean changes projected under the RCP4.5 and RCP8.5 scenarios have the same sign but with enhanced magnitude (by a few %) under RCP8.5. The sensitivity to the emission scenario depends on regions (e.g. Nordic and SEE versus France, Iberia, Italia). It is also model-dependent in terms of magnitude but also with respect to the direction of change (see comparison between both RCPs for different symbols on figure 3(b), and figure S13 in supplementary section 2–2; e.g. for Italy the red down triangles and the red multiplication signs in figure 3(b)). The inter model uncertainty is larger than the emission scenario uncertainty. Based on this multi-model ensemble, the

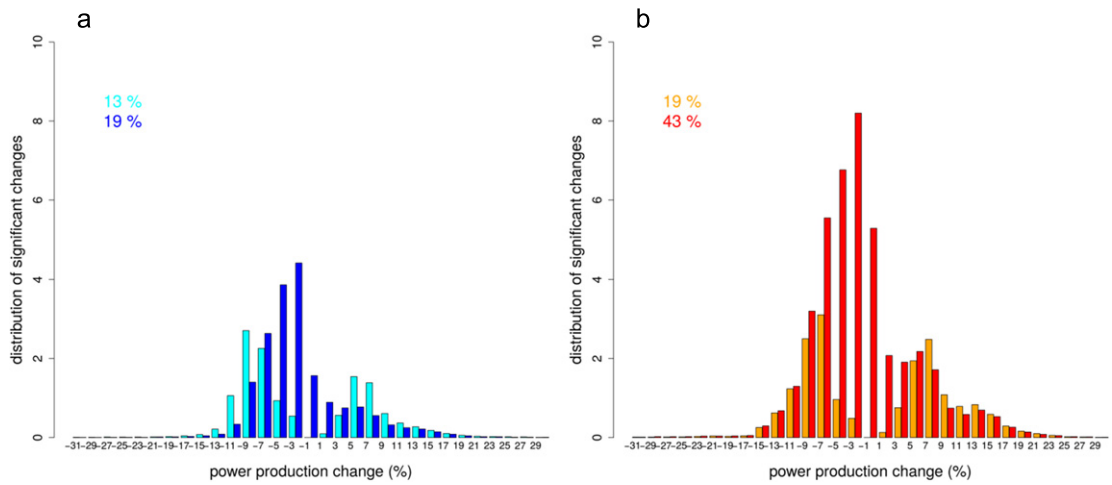

Figure 4. (a) Frequency distribution of changes in mean annual yield at the grid point scale for mid-century (2031–2060) (cyan) and for late century (2071–2100) (blue), for scenario RCP4.5. The distributions are computed only over grid cells enclosing wind power installations (GCWP) and inferred from the full model ensemble. Only GCWP experiencing significant changes at the 95% level are reported in the distributions. The bin width is 2%, the amount of pixels is expressed in % of the total amount of GCWP. The total amount of GCWP with significant signal is included in the left upper corner of the figure (also in % of the total amount of GCWP). (b) Same as (a) but for RCP8.5, for mid-century (orange) and late century (red).

contribution of the GCM and the RCM formulation to the signal uncertainty are of similar importance, as indicated by the comparison of signal spread for differing GCMs driving the same RCM (e.g. star, crossed out square, triangle-down symbols in figure 3(b) and figure S13) with signal spread associated with differing RCMs driven by the same GCM (e.g. triangle-down and square, or circle and crossed out square symbols in figure 3(b) and supplementary section 2–2 figure S12). This signal spread comparison is emphasized in figure S13 in supplementary section 2-2.

3.2.2. At the wind power plants local scale

The integration of wind power plants production into the power grids at the regional scales allows compensating effects potentially leading to attenuated signals. The quantification of gains and losses in energy yield at the wind power plant scale, which may be potentially stronger, is relevant for long-term management of wind farms and their economic viability.

Over the whole model ensemble, 13% of the 12 km grid cells enclosing wind power installations in 2050 (hereafter GCWP) will experience significant changes in energy yield by mid-century and 19% by late century under scenario RCP4.5. Under scenario RCP8.5, the proportion of GCWP exhibiting significant changes amounts to 19% of all GCWPs by mid-century and rises to 43% by the end of the century. Figure 4 shows that stronger emissions (RCP4.5 versus RCP8.5) as well as more advanced climate change in time (mid-century versus end of the century period) lead to increased GCWP proportion experiencing significant changes, but not to a wider range of magnitudes of change: nearly all significant changes lie within [−15%, +20%] for both mid and late century periods and both scenarios. The shape of the significant change frequency distribution differs between mid and late century periods in a similar way for both scenarios: mid-century changes are characterized by a bimodal distribution, centered around the 0% change and with maxima of about [−8%,−6%] and [6%, 8%] on each side, while the late-century change frequency distribution is unimodal, slighlty shifted towards negative values and exhibiting a weak positive skewness. Overall, negative changes prevail over positive changes. Thus, for both scenarios, increased yield loss assessed for the end of the century over the whole European fleet in comparison with mid-century changes mainly stem from a strong increase of the number of GCWP with very slight changes (~a few percent), and not from an increase in the number of GCWP with change magnitudes stronger than 5%–7%, which is even smaller (figure 4). Therefore, even at the local scale, i.e. at the scale of wind power plants, climate change will induce minor or even no changes in energy yields for a large part of the fleet, and limited changes for the rest.

3.3. Changes in power production variability of 2050 wind power plants

Power production variability and changes therein are here assessed at the scale of regional fleets, i.e. the scale of power grids, which is of relevance to issues of energy supply demand balance.

Table S2 in supplementary section 1-1 highlights that for the level of production variability strongly depends on regions and considered timescales. It also shows that changes in the configuration of the European wind power plants fleet lead to substantial changes in variability at all timescales. For instance, from the 2013 European fleet to the 2050 fleet scenario, the production variability is anticipated to approximately reduce by a factor of two, due to

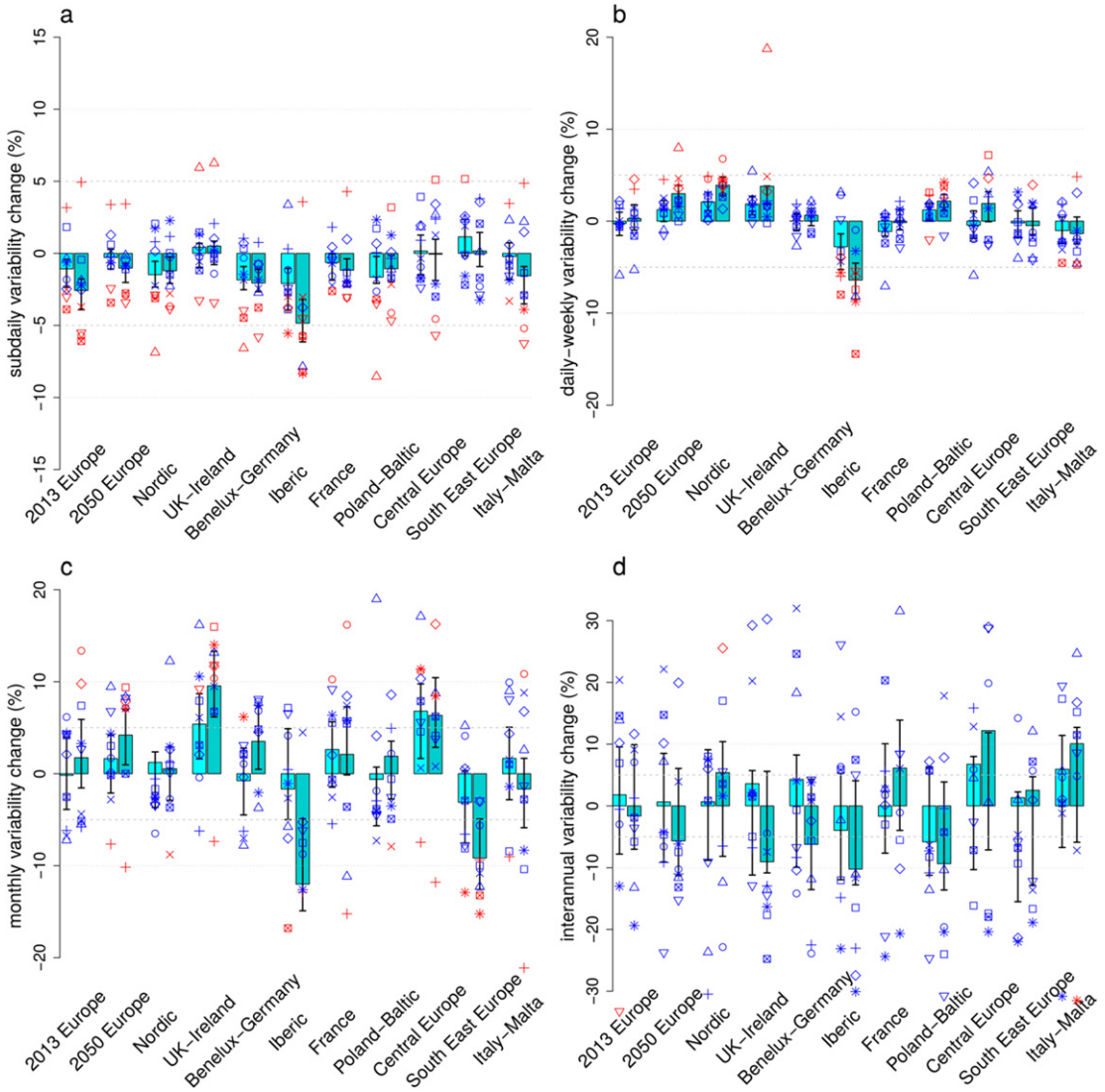

Figure 5. (a) Same as figure 2(b) but for changes in sub-daily variability. (b) Same as (a) but for changes in inter-daily variability. (c) Same as (a) but for inter-monthly variability. (d) Same as (a) but for inter-annual variability. The signal significance is calculated using the Wilcoxon–Mann–Whitney test applied to annual values.

aggregation of weakly correlated or uncorrelated productions.

3.3.1. At the sub- and inter-daily timescales

Figure 5(a) shows a tendency for a slight decrease in sub-daily variability for most regional fleets and for most of the models, smaller than 5% for the ensemble average. The strongest decrease is projected for the Iberian region under the RCP8.5 scenario, which may be consistent with the projected decrease in mean wind climate given the fact that wind speed is usually characterized by a Weibull distribution (e.g. Pryor *et al* 2006). Some model inconsistencies with regard to the sign of significant changes are found among the various ensemble members, but in terms of magnitude almost all projected individual changes barely exceed 5% in relative. Given the magnitude of the production variability (supplementary section 1–1 table S2), this will lead to slight absolute changes.

Changes in variability tend to be slightly more pronounced at the inter-daily scale and are positive over most of the fleets, except over the Iberian Peninsula where a decrease is projected (figure 5(b)). Changes are however not substantial (within ±5% for most of the regions) for the large majority of models and under both scenarios, with the strongest magnitude of changes emerging for the Iberian Peninsula under the RCP8.5.

3.3.2. At the monthly and interannual timescales

Projected changes in monthly variability are overall of greater magnitude than at the sub-daily and inter-daily scales (figure 5(c)). The model ensemble mean shows most pronounced changes for UKI and CE, which may undergo a 5%–10% increase in variability, and for Ib and SEE, which would experience a decrease by 10% under the RCP8.5 scenario. Such decrease over the Iberian Peninsula is consistent with the production increase in

summer, when the winds are weakest, and with projected decreases in autumn, winter, when the winds are strongest (see supplementary section 2–2 figure S12). The spread among the models is relatively large and there are opposing signs in the changes, but the overall order of magnitude of the changes remains within 15% for all models. Again, these changes expressed here in relative terms will not give rise to substantial changes in absolute terms (see supplementary section 1–1 table S2 for indication on mean variability).

Projected changes in interannual variability are characterized by stronger magnitudes and spread among models than changes in the variability at any of the other time scales considered here (figure 5(d)). The ensemble mean shows changes within 10%, but for most fleets, single models project changes beyond ±15%, reaching ±30% for some of them. Positive changes of 30% could mean substantial changes in interannual variability, having implications for the year-to-year energy planning. However, most of the assessed changes are not significant.

4. Conclusions and discussion

The purpose of the present study was to assess the climate change effects on the wind power generation potential in Europe, separately from other effects such as those related to technology changes, human-induced land use changes and wind farms deployment. We found that, under two GHG concentration scenarios, the annual energy yield of the European wind farms as a whole, as projected to be installed by 2050, will remain stable (within ±5% for all climate models) across the 21st century. However at country to local scales, wind farm yields will undergo changes up to 15% in magnitude, according to the large majority of models, but smaller than 5% in magnitude for most regions and models. The Iberian Peninsula power production is likely to be the most affected, with a robust reduction projection of yield by 5%–10% at the annual scale, by 15% in autumn, by the end of the century under the RCP8.5 scenario. The Italian fleet is also likely to experience similar yield reduction. This is partly due to a decrease in geostrophic winds, i.e. a change in large-scale circulation patterns. By contrast, the Poland–Baltic fleet energy yield may benefit from climate change, which may be due to sea ice melting. However, the confidence level in this latter result has been proven to be low.

Differences among scenarios are more pronounced towards the end of the century than at mid-century, consistent with the divergence essentially occurring after 2050. Changes in fleet yields are overall enhanced by a few percent from RCP4.5 to RCP8.5. This mainly stems from a larger number of turbines undergoing slight changes rather than from a small number of turbines undergoing larger changes. Uncertainties associated with emission scenarios are dominated by model uncertainty, though, and the GCM- and RCM-related uncertainty contribute to this model uncertainty to a comparable extent. However, to confirm the latter statement, a wider ensemble of GCM and RCMs is required.

This study corroborates previous findings both in terms of magnitude and patterns of changes (e.g. Pryor and Barthelmie 2010, Barstad *et al* 2012, Nolan *et al* 2012, Hueging *et al* 2013, Tobin *et al* 2015), and confirms the necessity for a multi-model ensemble-based assessment given the model-induced spread in the results (e.g. Pryor *et al* 2005, Rassmussen *et al* 2011, Tobin *et al* 2015). An analysis of the same EURO-CORDEX ensemble at the 50 km resolution has been carried out (not presented here), which leads to similar results despite some differences found at the local scale for individual model signals. In particular, it corroborates that high-resolution does not lead to stronger changes in wind speed and wind power generation potential. However, the high resolution could allow to better assess wind extreme events-induced impacts on wind power installations.

With regard to variability, changes are essentially small on short and longer timescales (magnitude of changes are smaller than 5%–10% in relative terms). For some models, the interannual variability can however be substantial (30%), but signals are poorly significant.

At the European and regional scales, such climate change-induced effects on wind power production are small in comparison with the growth in installed capacity both in terms of mean and variability. Those effects will also likely be largely offset by wind power technology improvements : for instance, we estimated from a subset of the model ensemble an increase of several tens of percent in wind power production under current climate, depending on models and regions, if the wind turbines were chosen 150 m high instead of 90 m high (not shown). Moreover, the projected changes are assessed at the century scale. At the time horizon relevant for wind power investors, which is 10–20 years, changes will be much smaller. Therefore, these climate change effects will not jeopardize the development of wind energy in Europe. However, such long-term assessment is informative for long-term energy mix planning. Thus the improvement of accuracy of this kind of assessments is certainly worth being pursued. Among other ways of improvement, the wind speed at the turbine hub height (~100 m) could be made available as a standard model output in next RCM coordinated experiments because wind vertical extrapolation methods employed so far do not account for variations in atmospheric stability conditions and surface roughness. Further increased resolution will also help better accounting for complex terrain and breeze flows. In addition, for a full assessment of wind energy resource evolution, climate change-induced effects on surface roughness and aerosols should be accounted for along with effects

related to human-induced surface roughness changes and wind turbines massive deployment. All these effects are not or only partially included in the state-of-the-art regional climate simulations. This may be why climate models are currently not capable of reproducing the historical 10 m wind speed trends reported in previous studies (Pryor *et al* 2009 and supp section 2–4 figure S18 of the present study to compare with Vautard *et al* 2010, Bichet *et al* 2012, Tobin *et al* 2014).

Acknowledgments

This research work has received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under the project IMPACT2C: grant agreement n° 282746.

Results also used the methodology and expertise developed within the CLIMIX DSM-Energy project from the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA). The authors gratefully acknowledge the computing time granted on the supercomputer JUROPA at Jülich Supercomputing Centre (JSC).

We thank the reviewers for helping improve the manuscript.

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