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Climate change impact on Northwestern African offshore wind energy resources

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Abstract

Offshore wind is one of the most important sources of renewable energy. Therefore, it is crucial to assess how this resource will evolve over the 21st century in the context of a changing climate. The North African Coastal Low-Level Jet (CLLJ) region, which encompasses offshore areas from Northwest Morocco to Senegal, has an enormous wind-harvesting potential, as it provides a strong, persistent alongshore flow. In the current study, the present climate wind energy potential is featured for two heights (100 and 250 m). More importantly, the climate change impact on the wind energy density in the region is also depicted. For this purpose, the newest and highest-resolution regional climate simulations available are used, which include two ROM simulations (uncoupled and coupled) at 25 km resolution and 19 CORDEX-Africa runs at 50 km resolution. Historical and future (under the RCP4.5 and RCP8.5 scenarios) simulations are used for the periods 1976–2005 and 2070–2099, respectively. Overall, the results show that the annual wind energy density is projected to increase slightly in the northern offshore areas ($< +10\%$) and decrease in the southern ones ($> -10\%$). In close connection to the projected changes for the seasonal changes of the CLLJ system, in the further north regions (downwind Cap Ghir), the spring season shows the largest increases of wind energy, up to $+20\%$, while in the offshore western Sahara, an increase of wind energy is projected in all seasons. A decrease of wind energy is expected for the southern areas.

1. Introduction

The last Intergovernmental Panel on Climate Change special report on the 1.5 global warming target is very clear about the dramatic impact that an increase of 1.5 °C and 2 °C in the global average temperature will have for society as a whole (IPCC 2018). This report calls in a dramatic manner for society to urgently reduce greenhouse gas emissions and accelerate the transition from fuel fossils to renewable energy. Worldwide, the major renewable energy resources are hydro, wind, and solar; however, these resources are also affected by climate change through modifications

of water availability and wind and cloud patterns (Pryor *et al* 2006, van Vliet *et al* 2013, Wild *et al* 2015, Huber *et al* 2016, Soares *et al* 2017b). However, to achieve a sustainable transition to renewable energy it is necessary to understand how they will evolve in the future at global and regional scales, in the context of a changing climate (Tobin *et al* 2015, Reyers *et al* 2016, Wohland *et al* 2017, Karnauskas *et al* 2018), and also investigate the costs associated with its implementation (Creutzig *et al* 2017, Schlott *et al* 2018). Nevertheless, the variability and non-dispatchability of renewables can play an important role in this transition (Heide *et al* 2010, Grams *et al* 2017, Bloomfield

et al 2018). Different weather regimes are associated with variability of renewables, leading to the need for a balance between different renewable power generation methods. In a climate change context, changes in the synoptic patterns can modify this variability or lead to more frequent unavailability of renewables in some locations.

Countries in the western limit of the Mediterranean basin and in the Canary Upwelling System (Mauritania, Morocco, Portugal, Spain, and Senegal) are considered climate-change hotspots, and amongst the most vulnerable to global warming (Turco *et al* 2015). Cumulatively, Morocco, Portugal, and Spain are amongst the international leaders in renewable energy production: Morocco in solar, Portugal and Spain in wind and hydropower (Wiser and *et al* 2018). In Morocco, around 33% of the total electricity production is from renewable energy resources. In Portugal and Spain, the renewable energy share is about 28% and 33%, respectively (RED 2017, DGEG 2019). Moreover, these three countries have set the demanding target of decarbonization of the electricity sector, that is, to switch to 100% renewable energy resources by 2050. Nevertheless, in this region, it is now clear that anthropogenic-driven climate changes are already present and are projected to profoundly alter precipitation patterns (Seager *et al* 2010, Soares *et al* 2017a), regional to local wind circulations (Soares *et al* 2017b, Nogueira *et al* 2019, Soares *et al* 2019), and irradiation at the surface and, subsequently, also lead to changes in the available renewable energy resources.

Within the development plans for renewable energy, it is believed that hydro and onshore wind energy have arrived at a point where is difficult to largely increase the installed capacity (e.g. Europe) (Wiser *et al* 2011, EIA 2019, GWEC 2019) due to lack of suitable locations and to the human-related and ecosystem impacts (Kaldellis and Kapsali 2013). For that matter, solar and offshore wind energy are believed to be the renewable resources with the greater potential for development in the forthcoming decades. For Portugal, the projections regarding onshore wind resources show a decrease between -5% and -15% for winter and spring seasons, and decreases of up to -35% in autumn (Nogueira *et al* 2019). Only for the summer season is an increase (of around $+5\%$) projected for Portugal. Projections for solar resources indicate an increase in the range of $+5$ to $+10\%$ for large areas of Portugal, Spain, and Morocco towards the end-of-the-century (Jerez *et al* 2015). For the Western Sahara, Mauritania, and Senegal, a small decrease between -2 and -5% is projected (Soares *et al* 2019b).

The offshore wind technologies are advancing at a fast pace. It is projected that offshore wind will become the main source of electricity production in the next decades due to the high capacity factors and lower variability of offshore winds (IEA 2019). Globally, the installed capacity increased from 2.1 to 23 GW from 2009 to 2018 (GWEC 2010, 2019), and turbine heights

are going to higher levels, allowing for important increases of wind harvesting. Currently, offshore floating wind turbines have hub-heights of around 70 to 100 m; however, the development of these technologies is at an early stage. The improvement of floating technologies allows the expansion of turbines to areas with large ocean depths and higher wind energy availability, enlarging substantially the regions for potential exploration when compared with the limited spots in shallow waters. This is important in coastal regions with a narrow continental shelf, which limits the use of platform wind turbines. The regions where coastal low-level wind jets (CLLJs) occur are an example of these kinds of areas (Semedo *et al* 2016, Soares *et al* 2017c, Lima *et al* 2018, Lima *et al* 2019a, Lima *et al* 2019b, Soares *et al* 2019a, Soares *et al* 2019b). These regions, called the Eastern Boundary Current Systems (EBCSs), are characterized by persistent alongshore winds, connected to the presence of high-pressure systems over the ocean and low thermal pressure systems inland (Winant *et al* 1988, Ranjha *et al* 2013, 2015). The CLLJs develop within these along coastal EBCS wind systems, driven by sharp pressure gradients intensified by the land–sea thermal contrast, with maximum speeds at heights within the first 1000 m.

The Canary EBCS includes the offshore regions where the Iberian (Soares *et al* 2014) and North African (Soares *et al* 2019a) CLLJs occur, revealing a wind structure with wind speed maxima within the first 500 m of the marine atmospheric boundary layer (MABL). The Iberian CLLJ is more prevalent in summer, but is projected to become more frequent with global warming (Cardoso *et al* 2016, Soares *et al* 2017c). For the Iberia offshore region, Soares *et al* (2017b) identified significant changes in the offshore wind resource, namely an increase of about 20% in wind power density on the northwest coast during summer. The North Africa CLLJ (NACLJ) extends in a broad offshore area, from the north of Morocco to Senegal, and has maxima frequencies of occurrence in summer above 60% in the offshore areas of Western Sahara, and in spring of $\sim 45\%$ in the offshore areas of Senegal (Soares *et al* 2019a). Analogously, future projections of the NACLJ point to significant increases of the frequency of occurrence in all seasons (Soares *et al* 2019b). Subsequently, it is of vital importance to understand how the offshore wind resource will evolve in response to global warming in the broad North African portion of the EBCS region.

The main goal of the present study is to characterize the present and future climates of the offshore wind resource in the Northwest African region. The newest and highest-resolution climate simulations available are used: two ROM model set of simulations (Sein *et al* 2015) in coupled and uncoupled modes, and the full CORDEX-Africa ensemble for the historical and future periods, in agreement with two greenhouse gas emission scenarios: the RCP4.5 and RCP8.5 (Riahi *et al* 2011). In this way, the projected changes of the

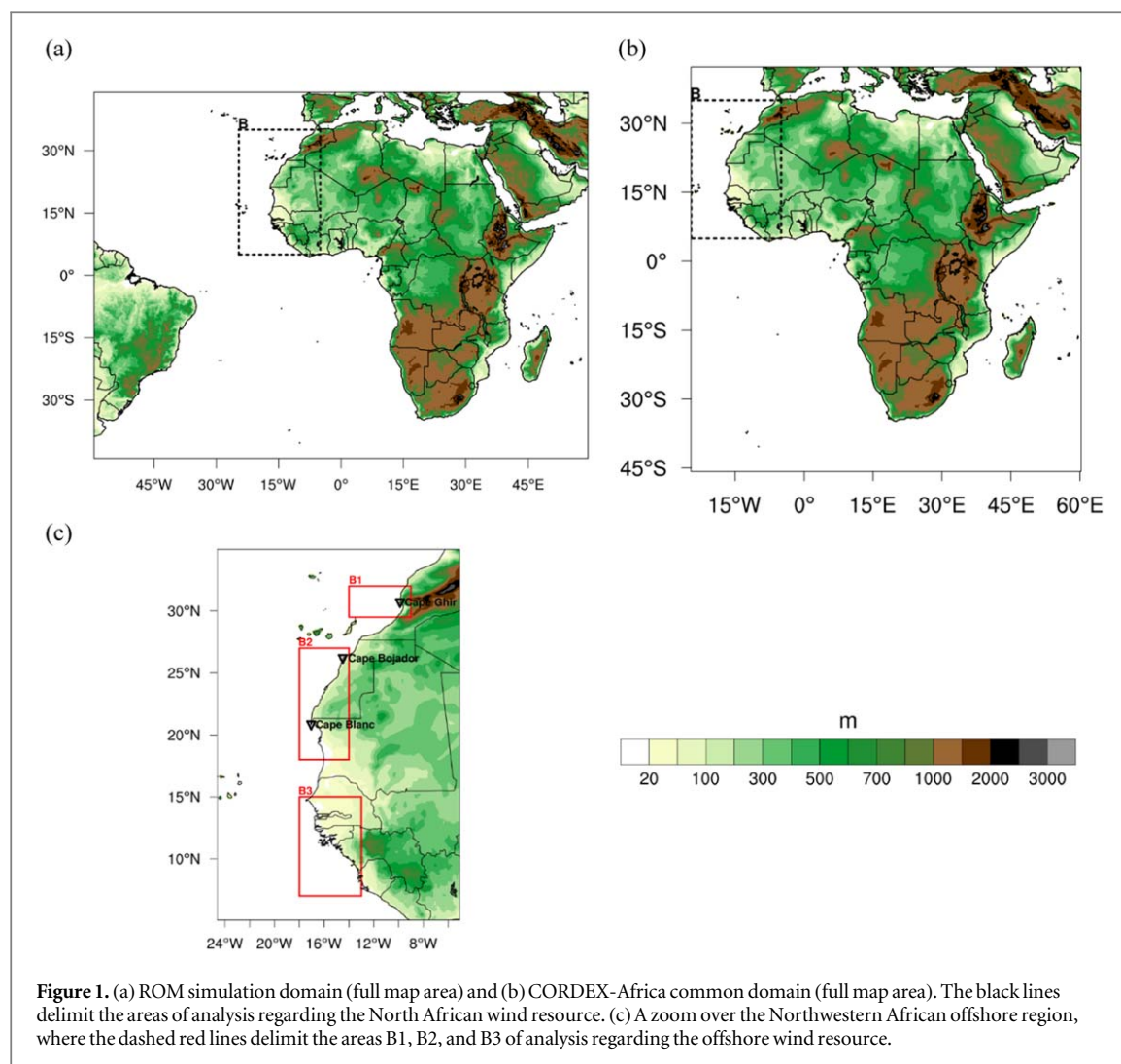


Figure 1. (a) ROM simulation domain (full map area) and (b) CORDEX-Africa common domain (full map area). The black lines delimit the areas of analysis regarding the North African wind resource. (c) A zoom over the Northwestern African offshore region, where the dashed red lines delimit the areas B1, B2, and B3 of analysis regarding the offshore wind resource.

offshore wind resource and the uncertainty associated can be assessed better, giving robustness to the study.

2. Material and methods

2.1. Regional climate simulations

The ROM model (REMO-OASIS-MPIOM) was used to produced four simulations, in stand-alone atmosphere (ROM_U) and in atmosphere–ocean coupled modes (ROM_C), for two time slices: a historical climate run encompassing the 1976–2005 period, and a future climate simulation spanning the period between 2070–2099 under the RCP8.5 scenario (Riahi *et al* 2011). Lateral boundary conditions were taken from a CMIP5 simulation with the Max-Planck Institute Earth System Model (Giorgetta *et al* 2013). The ROM domain, common for all simulations, covers the African continent, the Mediterranean region, and a large part of the Atlantic and Indian Ocean (figure 1(a)). The atmospheric resolution is 0.22°, with 31 hybrid vertical levels and three-hourly output. The vertical levels information allows us to feature the wind at upper atmospheric levels by interpolation.

Additionally, 19 RCM simulations from the Coordinated Regional Climate Downscaling experiment (Giorgi *et al* 2009) over Africa (CORDEX-Africa) (Hewitson *et al* 2012), with a horizontal resolution of 0.44°, are used in this study (table 1). The 10 m daily mean wind speeds are considered for the historical climate (1976–2005) and for the RCP4.5 and RCP8.5 future climate scenarios (Moss *et al* 2010, van Vuuren *et al* 2011), for the mid-21st century (2040–2069) and end-21st century (2070–2099). Within the first hundred meters of the atmosphere, only this data is available. The unavailability of vertical level information requires the use of an extrapolation method to feature the wind at upper levels, as explained further.

2.2. Multi-model ensemble building

Soares *et al* (2019b) performed a qualitative and quantitative evaluation of the near-surface wind speed from the uncoupled and coupled ROM simulations, and from the CORDEX-Africa RCMs, comparing their results against the Cross-Calibrated Multi-Platform (CCMP) dataset (Atlas *et al* 2011). In Soares *et al* (2019b), in order to assess the performance of the different RCMs, a set of statistical metrics were

Table 1. CORDEX-Africa regional climate models considered in the present study, along with the respective forcing global climate models and the acronym for each model combination (RCM-GCM).

Global Climate Model (forcing models)	CORDEX-Africa Regional Climate Model	Institution	References
ICHEC-EC-EARTH MOHC-HadGEM2-ES CNRM-CERFACS- CNRM-CM5 MPI-M-MPI-ESM-LR ICHEC-EC-EARTH	CCLM4-8-17	Climate Limited-area Modelling Community	Rockel <i>et al</i> (2008)
ICHEC-EC-EARTH	HIRHAM5	Danish Meteorological Institute	Christensen <i>et al</i> (2007)
ICHEC-EC-EARTH	RACMO22E	Koninklijk Nederlands	Van Meijgaard <i>et al</i> (2008)
MOHC-HadGEM2-ES ICHEC-EC-EARTH	REMO2009	Meteorologisch Instituut Helmholtz-Zentrum Geesthacht, Climate Service Center, Max-Planck Institute for Meteorology	Jacob <i>et al</i> (2001)
MPI-M-MPI-ESM-LR ICHEC-EC-EARTH	RCA4	Swedish Meteorological and Hydrological Institute	Samuelsson <i>et al</i> (2011)
MOHC-HadGEM2-ES CNRM-CERFACS- CNRM-CM5 MPI-M-MPI-ESM-LR IPSL-IPSL-CM5A-MR CCCma-CanESM2 CSIRO-QCCCE-CSIRO- Mk3-6-0 MIROC-MIROC5 NCC-NorESM1-M NOAA-GFDL-GFDL- ESM2M			

computed for each grid point and time scale (monthly, seasonal, and yearly) such as, bias, mean absolute error, root mean square error, normalized standard deviation, spatial correlation, and the Willmott-D score. These metrics allowed the analysis of mean values at the different timescales. Additionally, to measure the differences between distributions, analysis of the probability density function (PDF) between model and observations was done through a PDF matching score and the Yule–Kendall skewness measure.

To perform a robust assessment of the projected changes of the wind resource, a CORDEX-Africa multi-model ensemble was built considering the relative performance of each CORDEX-Africa RCM. All the above-mentioned metrics were included in the ensemble-building process, allowing the ranking of the models and the attribution of weights for the multi-model ensemble building (a detailed description of the evaluation process and ensemble building can be found in Soares *et al* (2019b)). This CORDEX-Africa multi-model ensemble (MME) is used in the current study to obtain a more robust description of the regional surface atmospheric flow and its climate change signal. The validation of the near-surface wind showed that ROM_C presents the best performance in reproducing the surface wind in the present climate,

and that the CORDEX-Africa MME outperforms most of the individual RCMs, giving confidence for us to perform the climate change assessment in this paper.

2.3. Wind turbines and wind energy computation

In agreement with Pryor and Barthelmie (2011), the instantaneous wind energy density E can be computed as the power per square meter (P/A), and is given by

$$E = \frac{P}{A} = \frac{1}{2} \rho v_z^3 \quad (1)$$

where v_z is the wind speed at a height z and ρ is the air density, here considered constant and equal to 1.2 kg m^{-3} according to a standard atmosphere from the International Organization for Standardization. In general, the wind turbines do not produce electrical power for wind speeds below 3 ms^{-1} and above 25 ms^{-1} . To characterize the present and future climates of the offshore wind resource, the wind energy density is computed at 100 and 250 m heights for wind speeds between 3 and 25 ms^{-1} , but the rated regime is not considered (ignoring the rated regime implies that the results can be strongly impacted by individual windy events). Since the wind speeds at 100 and 250 m are not available for any of the models, an interpolation or extrapolation of this variable is needed. For ROM simulations, the wind speed is

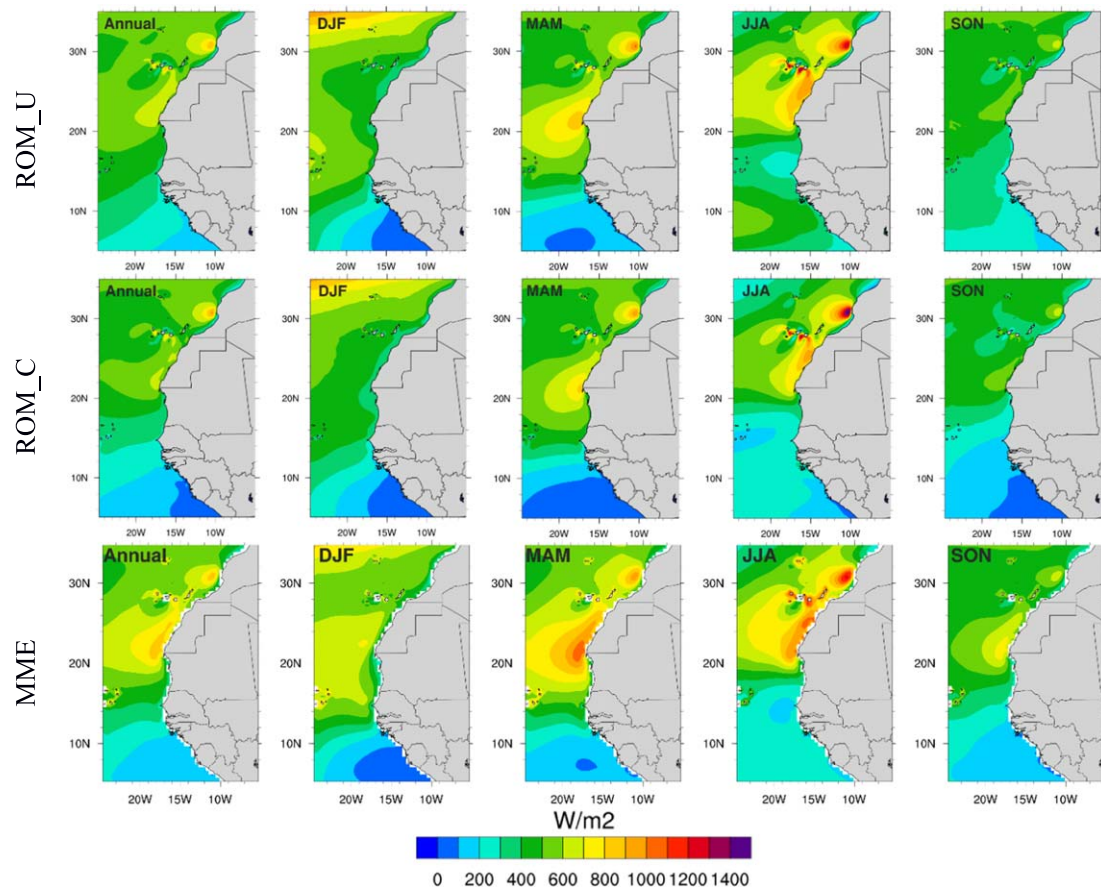


Figure 2. Annual and seasonal mean power density (Wm^{-2}) at 100 m height from ROM simulations, and from the CORDEX-Africa multi-model ensemble (for the historical period 1976–2005). DJF, December–February; MAM, March–May; JJA, June–August; SON, September–November.

interpolated from the model-levels output. For CORDEX-Africa simulations, the 100 and 250 m wind speed is calculated from the wind speed at 10 m height, using the logarithm wind profile extrapolation (equation (2); Yamada and Mellor 1975):

$$v_z = v_{z_m} \ln\left(\frac{z}{z_0}\right) / \ln\left(\frac{z_m}{z_0}\right) \quad (2)$$

Here, v_{z_m} corresponds to the 10 m wind speed and the z_0 is the local roughness length with a constant value of 1.52×10^{-4} m over the ocean surface (Carvalho *et al* 2014).

The wind energy density is calculated at a daily scale since it is the time scale available in all ROM and CORDEX-Africa models. However, for both ROM simulations, it is also calculated at a sub-daily scale (three-hourly).

3. Results

3.1. Present climate wind resource

At the annual and seasonal scales, the present climate wind energy density at 100 m height, given by the two ROM runs (uncoupled and coupled) and by the CORDEX-Africa MME are in general similar (figure 2). The annual energy density pattern and its seasonal

cycle clearly show the imprint of the persistent north-easterly alongshore flow (Lima *et al* 2018, Soares *et al* 2019a), where the larger amount of available resource is present in the coastal regions, downstream of Cape Ghir and between Cape Bojador and Cape Blanc. The annual energy density at those locations can amount up to 800 Wm^{-2} , and then decrease to around 400 Wm^{-2} in offshore areas and less than 200 Wm^{-2} in the southern regions. The ROM uncoupled and coupled results of annual wind energy are quite similar, but the CORDEX-Africa MME presents larger values in the coastal regions offshore Western Sahara.

The wind energy density seasonal cycle in coastal regions is sharp and closely linked to the CLLJ seasonal cycle. In winter, the CLLJ is almost completely absent, increasing its frequency of occurrence in spring and further in summer, when it reaches values above 70% of the time, and decreases in autumn to $\sim 40\%$ (Soares *et al* 2019a). Correspondingly, the winter wind energy density in the coastal regions of Western Sahara shows values below 400 Wm^{-2} , increasing to 900 Wm^{-2} in spring and reaching values up to 1400 Wm^{-2} during summer. In autumn, the wind energy density is reduced to 600 Wm^{-2} for the ROM runs and 800 Wm^{-2} for the CORDEX-Africa MME. The seasonal maximum values occur in summer, downstream

of Cape Ghir, where the coastal jet is more persistent, and in the Canary Islands shading vortices.

The higher horizontal resolution of ROM simulations provides a better representation of the along-shore flow when compared with the CORDEX-Africa results. Furthermore, coupling atmosphere and ocean leads to an improved representation of the surface wind. It should be kept in mind that the surface wind speeds from the RCMs analyzed here are usually stronger than the CCMP winds, especially closer to the shore (Soares *et al* 2019b). Despite this, these authors highlight the good agreement with observations of the ROM runs and of the CORDEX-Africa MME. Importantly, it was also mentioned that there are known problems of the CCMP in representing the near-surface wind close to shore due to pixel land contamination (Tang *et al* 2004). Another important issue refers to the impact of the logarithm extrapolation. Figure S1 (supplementary material), available online at stacks.iop.org/ERL/14/124065/mmedia, shows the wind energy given by the ROM simulations but extrapolating the 10 m wind speed to 100 m height, which display similar wind energy values with the CORDEX-Africa MME. In general, the logarithmic extrapolation results in an overestimation of wind energy density in broader areas, except to the conspicuous offshore areas and seasons where the CLLJ is more intense, such as Cape Ghir in summer. Finally, the impact of computing the wind energy at a daily scale is addressed in figure S2 through the relative difference between the computation of the wind energy density at a sub-daily scale (three hourly) and at a daily scale. There is an increase of the available wind energy density over all the domains, which are larger closer to the coast. The differences do not exceed 9% at the annual scale and 16% at the seasonal, but these occur in very limited areas where the wind energy density shows large values. For example, at the annual scale, the energy density in those areas can reach values of $800 \pm 120 \text{ Wm}^{-2}$ downstream of Cape Ghir, and $400 \pm 70 \text{ Wm}^{-2}$ between Cape Bojador and Cape Blanc; at the seasonal cycle, the higher values are found in coastal regions of Western Sahara during summer ($1400 \pm 150 \text{ Wm}^{-2}$). This issue reveals the significance of the model's higher output sampling for wind energy assessment.

3.2. Future climate wind resource

The future projections for the 100 m offshore wind density, from the RCP4.5 and RCP8.5 scenarios, and their changes, compared with the historical climate, are portrayed in figures 3 and 4. A Student's *t* statistical significance test was applied for all the changes projected by the ROM simulations, CORDEX-Africa MME, and individual CORDEX-Africa models (shaded areas are non-statistically significant at a 90% confidence level). To better understand the regional climate change signal and its coherence among the

different simulations, three areas (B1, B2, and B3) were defined (figure 1(c)). The selected areas are linked to the regions of maxima NACLLJ frequency of occurrence and where larger gains of wind resource are projected (areas B1 and B2), and the region where significant future reductions are foreseen (area B3). The figure S3 shows the seasonal relative changes for the 100 m wind energy density between the RCP8.5 future climate (2070–2099) and the historical climate (1976–2005) for each area indicated in figure 1(c).

The annual and seasonal future spatial wind energy patterns are unchanged for both climate changes scenarios, displaying the same locations of higher availability of energy (figure 3). Nevertheless, there are some changes in wind energy values (figure 4). Both ROM simulations and the CORDEX-Africa MME project a decrease of the annual wind energy in the southern offshore regions. This reduction is especially large in the case of the uncoupled ROM simulation, reaching -30% for the RCP8.5. The CORDEX-Africa MME and the coupled ROM run project a decrease of $\sim -15\%$ for the RCP8.5, and for the RCP4.5, the CORDEX-Africa MME points to $\sim -8\%$. Also, in coastal regions of Morocco, both ROM simulations project an increase in annual wind energy density up to $+12\%$. Seasonally, the future wind energy patterns reveal a larger degree of change, especially in the ROM simulations. All models (ROM and CORDEX-Africa MME) project winter increases of wind energy for the offshore areas of Western Sahara, also for spring offshore Cape Ghir (up to $+16\%$ in winter and $+30\%$ in spring, for the ROM runs). Common to all simulations is a relevant reduction in the wind energy in southern areas for all seasons. The ROM uncoupled run points to a decrease higher than -30% in large southern areas offshore of Guineas in summer and autumn, although the ROM coupled and the CORDEX-Africa MME reveal smaller reductions that may still reach ~ -20 to -25% . Finally, the ROM simulations also point to relevant increases of wind energy in summer and autumn, yet confined to smaller offshore areas, offshore Senegal and Western Sahara, respectively.

Regarding the individual performance of the CORDEX-Africa models (figure S3), at least 2/3 of the CORDEX-Africa individual models agree as to the projected signal in all areas and the changes are statistically significant, giving likelihood and robustness to the CORDEX-Africa MME projections. In area B2, the 100 m wind energy density winter changes projected by the individual models reveal high agreement in the projected signal, resulting also in a robust result. Here, 68% of the individual models agree as to the positive signal projected for spring season (likely change). In the southern area, 90% of the individual models agree as to the projected decrease of the wind energy (very likely change), decreasing this likelihood to 73%, 68%, and 63% in spring, autumn, and summer, respectively.

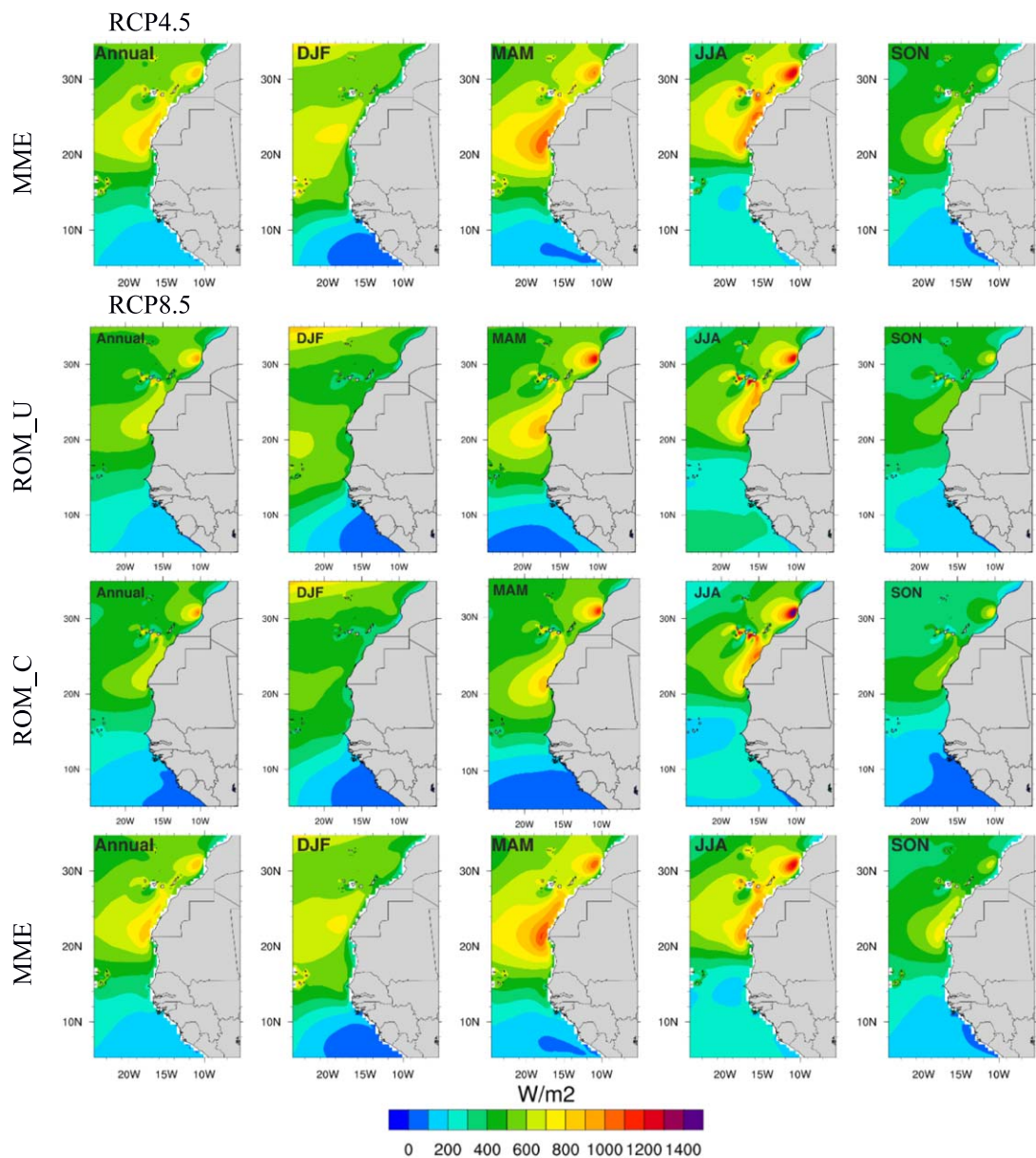


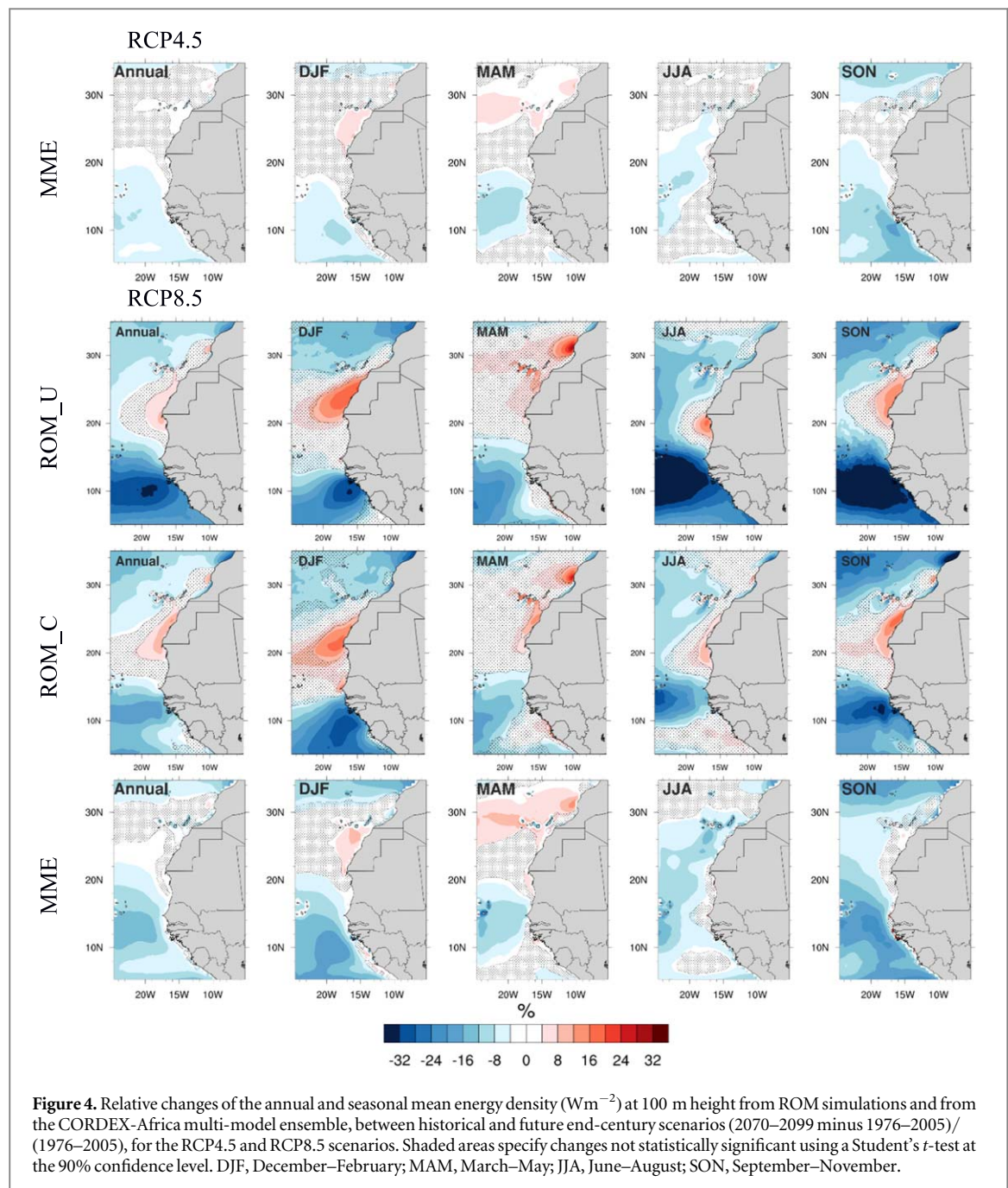
Figure 3. Annual and seasonal mean energy density (Wm^{-2}) at 100 m height from ROM simulations and the CORDEX-Africa multi-model ensemble for the future end-century period (2070–2099), for the RCP4.5 and RCP8.5 scenarios. DJF, December–February; MAM, March–May; JJA, June–August; SON, September–November.

The future relative changes of the energy density computed at a sub-daily scale (figure S4) reveal rather similar values to the ones at a daily scale, therefore ensuring consistency to the presented results. Furthermore, the sharper future changes given by the ROM runs, when compared with the CORDEX-Africa MME, are out of the scope of this paper but may be due to a number of reasons: ROM GCM forcing, the higher resolution used, the smoothing effect of the MME averaging procedure, etc.

For the RCP4.5 scenario, CORDEX-Africa MME projects minor changes for the seasonal wind energy, with statistically significant increases of up to +8% in offshore areas of Western Sahara in winter and in the vicinity of Cape Ghir in spring. The projected decrease in the southern regions include a vast region

southward of Senegal occurrences in all seasons, reaching maxima reductions of $\sim -20\%$ in Guinea in autumn.

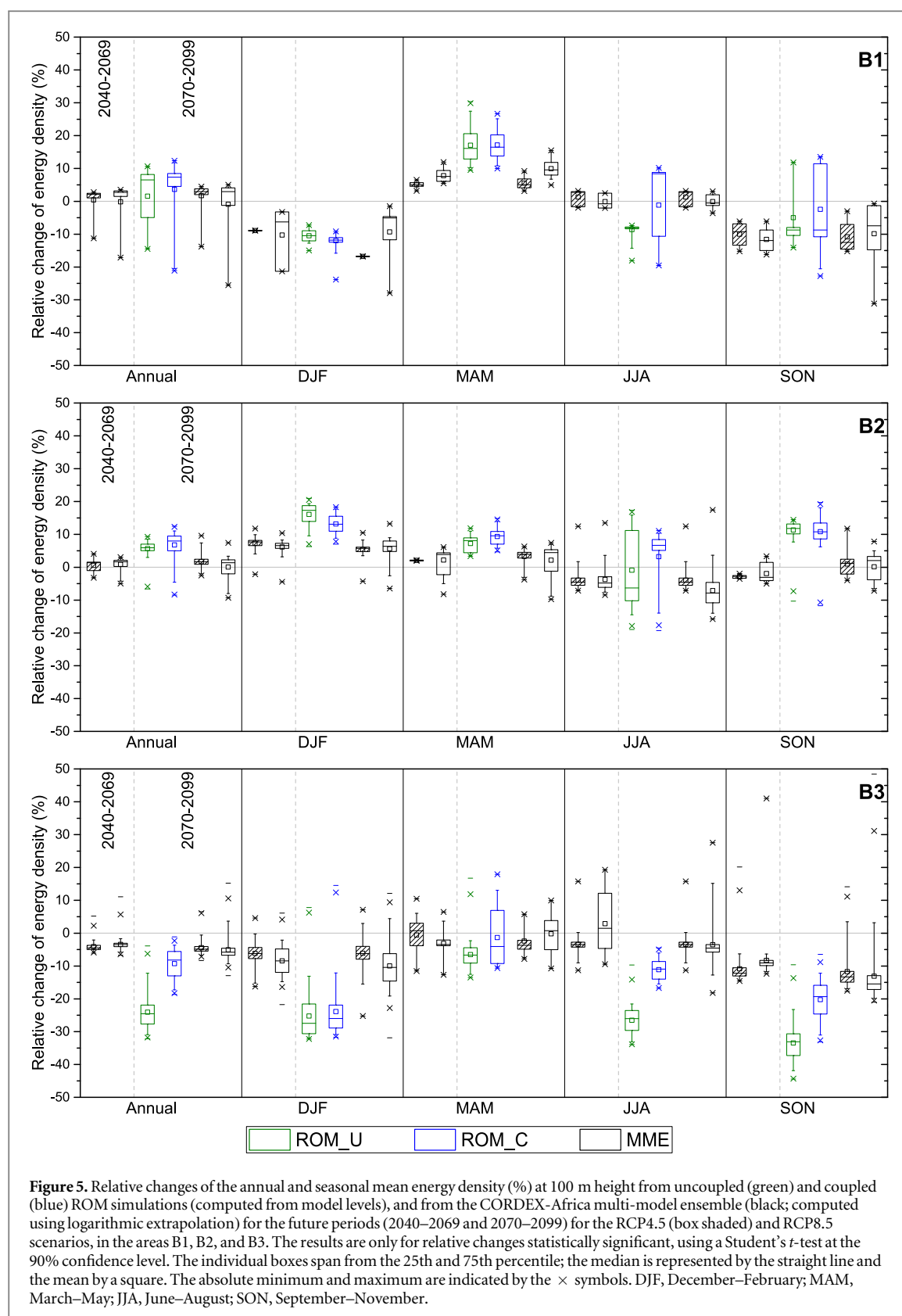
As expected, when looking at the wind energy density at 250 m height (annual and seasonal) in the future climate (figure S5 for RCP8.5), much larger values are projected to arise when compared with the ones at 100 m height. Annual wind energy is expected to reach values above 1000 Wm^{-2} along the NACLLJ region. In accordance with the future increase of NACLLJ frequency of occurrence in spring and summer (Soares *et al* 2019b), the wind energy is projected to peak up to 1700 Wm^{-2} in a significant stretch of coastal areas in the area of study. Accordingly, the wind energy relative future changes at 250 m (figure S6) are larger than at 100 m. For the ROM runs, this may amount up to



+30% in spring in the vicinities of Cape Ghir, and values above +15% cover wide offshore regions.

Figure 5 depict the boxplots of the relative changes (RCP4.5 and RCP8.5 scenarios) of wind energy for 2040–2069 and 2070–2099, compared with to the present climate for each area. For the area B1, the annual wind resource is projected to slightly increase, (under $\sim +7\%$) throughout the 21st century due to a strong spring increase of wind energy, which may reach values of $\sim +20\%$ for the ROM runs and values below $\sim +10\%$ for the CORDEX-Africa MME. This is in line with Soares *et al* (2019), who showed that during spring, the surface wind speed and frequency of NACLLJ occurrence is projected to increase. In winter and autumn, the wind energy is projected to be reduced in the B1 area.

Similarly, the annual wind energy is projected to increase in area B2 by the ROM runs ($<10\%$), and remain practically unchanged throughout the 21st century by the CORDEX-Africa MME. However, the seasonal cycle of relative changes is quite different. The projections of future increasing NACLLJ frequency of occurrence by the ROM runs (Soares *et al* 2019b) in all seasons impact positively the future wind energy in area B2. Particularly in spring and autumn, the wind energy is projected to increase in the range of +10 to +20%, in close relation with the temporal expand of the NACLLJ annual cycle. The CORDEX-Africa MME is overall in line with these changes, although with much smaller projected change values. Finally, for the area B3, the results show a relevant loss of wind energy resource at the annual and seasonal scales. The



projected decreases are more severe across winter and autumn, when the seasonal values are projected to decrease $\sim -30\%$ by the ROM simulations and $\sim -15\%$ by the CORDEX-Africa MME.

Based on the occurrence of the NACLLJ results from Soares *et al* (2019b) for area B1, the relationship

between the energy density at 100 and 250 m heights was computed by model level interpolation and using the logarithmic extrapolation (figure 6), for present and future periods, when NACLLJ occur and when there is no NACLLJ occurrence. The black and red dots represent the maximum value of the daily mean

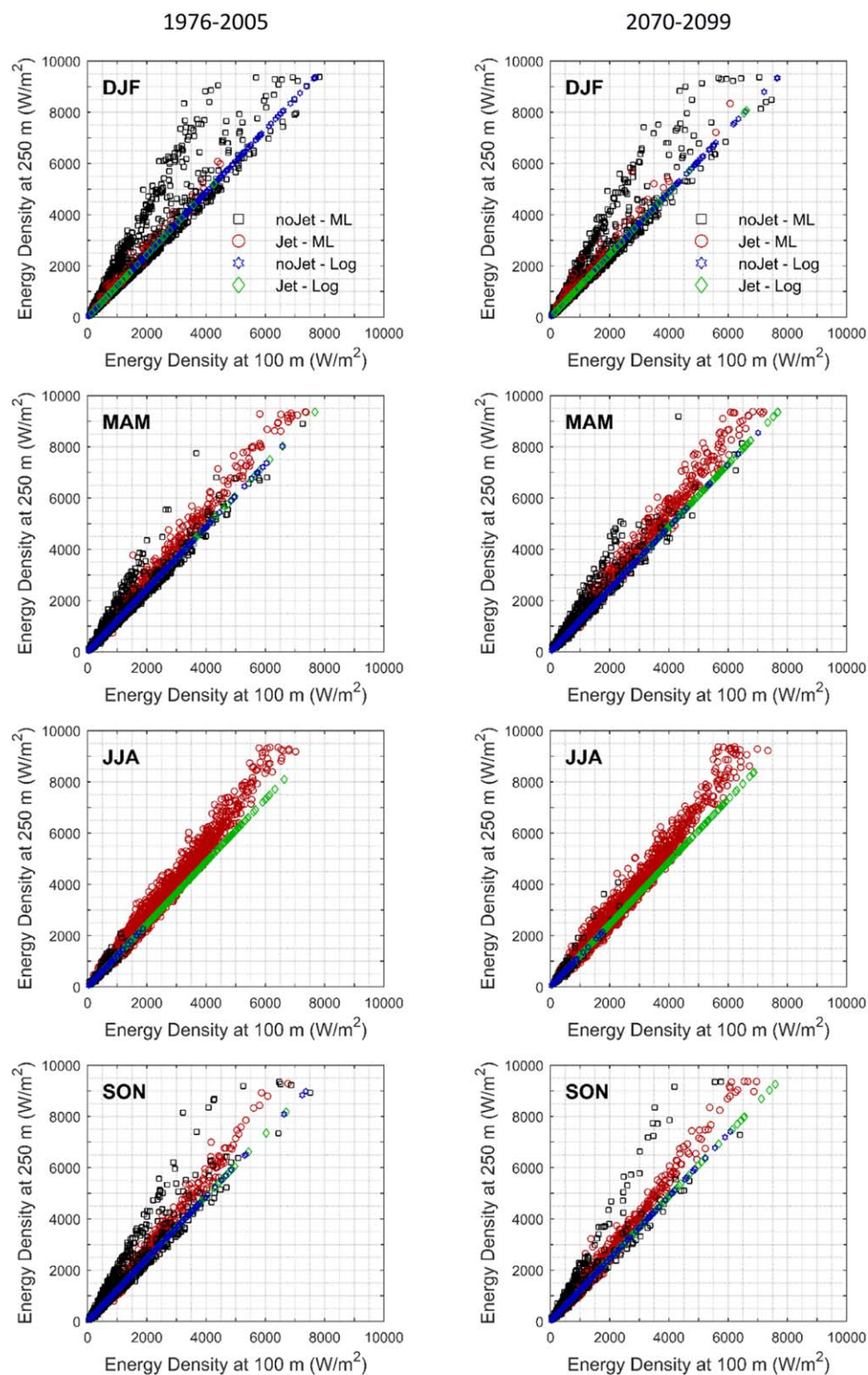


Figure 6. Scatter plot of height gain of seasonal mean energy density (Wm^{-2}) at 100 and 250 m height for the area B1 from coupled ROM simulation for the historical period (1976–2005) and future end-century period (2070–2099) for the RCP8.5 scenarios. The black and red dots represent the maximum value of the daily mean energy density of the area when there is no jet occurrence at all times of the day (eight times) and when there is jet at all times of the day, respectively. The blue and green dots are the same but for the logarithmic extrapolation. DJF, December–February; MAM, March–May; JJA, June–August; SON, September–November.

energy density of the area when there is no jet occurrence at all times of the day (eight times) and when there is jet at all times of the day, respectively (computed by model-level interpolation). The blue and green dots refer to the daily mean wind energy density

for the same grid point, but are computed by logarithmic extrapolation. These results are given by the coupled ROM run. For all seasons, with or without NACLLJ occurrence, it is clear from figure 6 that the logarithm extrapolation leads to a general

underestimation of the relationship between the wind energy density at 100 and 250 m. In spring, the increase in the frequency of the coastal jet (in area B1) is clear and determines higher values of wind energy density, particularly at 250 m, linked to the median height of NACLLJ occurrence of ~ 350 m (Soares *et al* 2019b).

4. Discussion and conclusions

In a climate-change context, the development of and investment in renewable energies has been increasing fast. The main renewables resources are hydro, wind, and solar, but in many regions of the world there is a limited potential for the growth of hydro and onshore wind capacity. Solar and offshore wind energy are the renewable energy production technologies that are increasing quickest in Europe, the United States, and China, and it is believed they will keep this rank in the forthcoming years (EIA 2019, GWEC 2019, WindEurope 2019). However, global warming is also changing surface irradiance and wind patterns, and therefore it is crucial to assess how these resources will evolve within the 21st century in the context of a changing climate.

A comprehensive analysis of the impact of the climate change on wind resources throughout the 21st century in the Northwestern African offshore region was presented for the first time, to our knowledge, in the current study. The analysis of the offshore wind resource was performed with higher-resolution regional climate model output. To give robustness to the study, two ROM simulations in uncoupled atmosphere and coupled atmosphere–ocean modes, at 0.22° resolution, and a CORDEX-Africa multi-model ensemble, at 0.44° resolution, were used to investigate the climate change signal in the offshore wind resource.

Along western North Africa, the Azores high-pressure system with thermal low over North Africa gives persistent equatorward alongshore winds, enhanced by the thermal contrast between land and ocean. The effect of the persistent winds on the present climate's annual and seasonal energy density patterns can be clearly identified by both ROM simulations and the CORDEX-Africa MME. Larger amounts of annual available wind energy resources can be found downstream of Cape Ghir, and further south between Cape Bojador and Cape Blanc, reaching 800 Wm^{-2} . This effect is in close connection with the NACLLJ seasonal cycle: higher in spring and summer, and lower in autumn and winter. The regions where the wind energy density has higher values coincide well with the regions where the NACLLJ occurs with higher frequency. The coastal regions of the Western Sahara showed higher wind energy resource availability during summer, reaching values of around 1400 Wm^{-2} ,

and less potential in winter with values below 400 Wm^{-2} .

The projections showed that annual and seasonal wind energy patterns remain unchanged overall, but with some significant changes in the available wind resource. The analyzed simulations project a decrease of the annual wind energy in the southern offshore area at 100 m height. For the RCP8.5 scenario, the decrease is higher in uncoupled ROM simulation than in the CORDEX-Africa MME and coupled ROM run. An increase of the annual wind energy density in the coastal regions of Morocco ($+12\%$) was also projected from both ROM simulations. Projected seasonal changes are expected to be larger, with relevant increases in winter wind energy offshore Western Sahara, and also in spring offshore Cape Ghir, as shown by both ROM runs, for the RCP8.5 scenario. The ROM simulations also projected increases of wind energy in summer and autumn in limited areas: offshore Senegal and Western Sahara, respectively. The CORDEX-Africa MME projects minor changes in the seasonal wind energy for the RCP4.5 scenario, with lower increases offshore Western Sahara (winter) and in the vicinity of Cape Ghir (spring). The future enhancement of wind energy density closer to the coast is related to a strengthening of the regional forcing. The thermal contrast between land and ocean is projected to be enhanced in the future, since the increase in the land temperature is higher than the SST rise. Southward of Senegal, decreases in the wind energy resource are expected to occur in all seasons.

The interest in developing offshore floating hub turbines to increase the energy production and future plans to place them at higher altitudes (e.g. 250 m) may be relevant in the EBCS regions such as Northwestern Africa. The wind energy resource at 250 m height, for the RCP8.5 scenario showed values that are considerably higher than at 100 m height. The projected changes of the 250 m wind potential can reach $+30\%$ in spring in the area of Cape Ghir. These high values of wind energy are closely related to the higher future frequency of occurrence of the NACLLJ in spring and summer (Soares *et al* 2019b). The difference between model level interpolation and logarithmic extrapolation wind speed results from the ROM runs shows the relevance of having available model-level data for wind energy applications.

The computation of wind energy generation in the Northwestern offshore Africa region will require us to consider specific turbines and the use of output at a sub-daily scale, which is revealed to have a significant impact on wind energy assessment and may require a follow-up investigation. Additionally, a more comprehensive study on the effect of wind model level interpolation and wind logarithmic extrapolation as to energy density is a promising line of research and will be addressed in a future paper.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The CORDEX-Africa model output is available in the Portal Earth System Grid Federation (<http://esg-dn1.nsc.liu.se/esgf-web-fe/live>).

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