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LETTER

Persistence of the high solar potential in Africa in a changing climate

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Abstract

The African continent faces several challenges and threats: high vulnerability to climate change, the fastest population increase, the lowest degree of electrification and the need for an energy transition towards renewable energies. Solar energy constitutes a viable option for addressing these issues. In a changing climate the efficient implementation of solar capacity should rely on comprehensive information about the solar resource. Here, the newest and highest resolution regional climate simulation results are used to project the future photovoltaic and concentrated solar power potentials for Africa. We show that the high potentials for solar energy will not be reduced much throughout Africa with climate change. However, the PV solar potential is projected to decrease up to about −10% in limited areas of eastern central Africa; increases are also projected to the northwest and southern Africa (up to about +5%). These changes are mostly determined by changes in solar irradiance but in certain areas the warming is a critical factor limiting PV potential.

1. Introduction

Africa features the fastest rate of population increase in the world, projected to reach four billion by 2100 (Desa 2015). This growing population has the lowest degree of electrification in the world, and in widespread regions, when available, the only source of energy relies upon hydrocarbons and/or wood. Moreover, climate change is increasingly seen as the major threat that humankind faces, and Africa is identified as the most vulnerable continent to its impacts (Barros *et al* 2014, Carabine *et al* 2014, de Sherbinin 2014, Desa 2015), although it is a minor historical contributor to greenhouse gas emissions (Hannah and Max 2018). A new energy paradigm based on local renewable energies is needed, which may lead to a reduction of greenhouse gas emissions and to climate change mitigation, responding to a critical increase of energy demand in African cities and supplying electricity to remote regions. This emergency was recently emphasized by the IPCC special report on the 1.5 °C threshold (IPCC 2018).

Solar energy technologies, solar photovoltaics (PV) and concentrated solar power (CSP), offer a promising path for addressing these issues. PV in particular is characterized by its easy deployment, modularity, low maintenance and, mostly, its competitive cost and fast learning curve (Baurzhan and Jenkins 2016). An efficient implementation of solar capacity requires a thorough characterization of the solar resource for present and future climates. For the present climate, observations, ground-based or retrieved by remote sensing, are the key tools to study and portray the solar incoming radiation. In Africa, ground-based observations are rather scarce and therefore remote sensing measurements are the most valuable data available (Huld *et al* 2012). However, remote sensing still encompasses a relatively short period to portray climatological properties, especially in a transient climate, and feature challenges in cloudy conditions (Ruiz-Arias *et al* 2015). Climate models, from global to regional scales, are an additional tool to characterize the solar radiation for present climate, but more importantly, they are the only means to assess how this resource may evolve in the context of global warming.

Solar radiation measurements from the satellite data of the Climate Monitoring Satellite Application Facility (CM-SAF) allowed building a database and characterize the solar resource and performance of PV systems in Europe and Africa in present climate (PVGIS, Ruiz-Arias *et al* 2015). This led to overall gains for the space and temporal description of the solar resource in Africa. The PVGIS dataset has become the reference for PV and CSP in the continent, for the present climate.

In recent years, a number of studies investigated the impact of climate change on solar resources and PV power generation, at the global scale using Global Climate Models (GCM) results (Crook *et al* 2011, Wild *et al* 2015, Huber *et al* 2016), at a continental scale using Regional Climate Models (RCMs) results (Jerez *et al* 2015) and also at smaller regional scales (Burnett *et al* 2014, Bazyomo *et al* 2016, Fant *et al* 2016). The standard approach to compute the PV potential from climate model data has been to consider its proportionality to the global horizontal irradiation, with a correction for the effect of temperature on the modules' efficiency (Wild *et al* 2015).

The goal of this paper is to assess the solar power potential in present and future climates based on the combination of state-of-the-art RCM results and bias correction. The CORDEX-Africa (Nikulin *et al* 2012) runs for the historical and future climates of Africa are used to build a mean multi-model ensemble. Its performance is assessed, and a delta change bias correction technique is used to remove present climate biases, offering higher confidence to climate projections. These projections are then used to estimate PV potential for optimally tilted PV modules, which is shown to be significantly different from previous estimates for horizontal irradiation. This procedure enables the characterization of the impact of climate change on solar resource and generation output for Africa, with high resolution, accuracy, and likelihood.

2. Methods

2.1. Observations

The surface downwelling shortwave radiation was retrieved from the Satellite Application Facility on Climate Monitoring (CM-SAF, Pfeifroth *et al* 2017). CM-SAF has developed climate data records (CDR) of surface incoming solar irradiance (SIS), surface direct irradiance (SID) and effective cloud albedo (CAL), derived from the METEOSAT Visible and Infrared Imager (MVIRI) instruments on-board Meteosat First Generation (MFG) satellites (Meteosat-2 to Meteosat-7) (Posselt *et al* 2012). A 23 year old (1983–2005) CDRs is available at monthly, daily and hourly means at a spatial resolution of 0.03°. According to Huld *et al* (2012), CM-SAF solar radiation dataset shows good accuracy for the African continent. As discussed in (Zelenka *et al* 1999), solar surface irradiance derived from satellite data is more accurate than that using interpolated ground-based data. In Africa, ground-based observations are rather scarce and therefore remote sensing measurements are the most valuable data available. Huld *et al* (2012) have validated CM-SAF global horizontal irradiation against data from 20 ground stations, showing an overall +2% mean bias with deviation of individual station bias values of the order of 5%.

Surface temperatures were retrieved from the UDEL dataset (Willmott and Matsuura 2001). This dataset was built from a large number of stations from the Global Historical Climate Network (Menne *et al* 2012), providing precipitation and surface air temperature at a spatial resolution of 0.5° and a temporal coverage from 1900 until 2017, depending on the version. A great advantage of this dataset is the accuracy in representing spatial variability when comparing to gridded average simulated data, such as in reanalysis. In fact, in UDEL dataset each grid value is a local point estimate (Willmott and Matsuura 2001). However, as for all other ground-based observational datasets, UDEL also depends on the spatial coverage of station data, which is scarce within the African domain. It should be kept in mind that to identify the best dataset for model evaluation remains an open matter in areas with poor observational coverage, like Africa (Nikulin *et al* 2012, Hernández-Díaz *et al* 2013, Panitz *et al* 2014).

2.2. CORDEX-Africa simulations

Global circulation models (GCMs) can reproduce the main features of the synoptic-scale atmospheric circulations in present climate (IPCC Intergovernmental Panel on Climate Change 2013), although revealing deficiencies in capturing regional to local atmospheric phenomena, such as circulations thermally driven and convective-cloud processes induced by land-ocean-atmosphere interactions (Rummukainen 2010, Soares *et al* 2012, 2014). To overcome these shortcomings, downscaling techniques were developed, from regional climate models (RCMs) to statistical downscaling methods (SDMs). RCMs are forced by GCMs and improve importantly the representation of regional to local climates (Giorgi and Mearns 1999, Laprise 2008, Soares *et al* 2012, Lucas-Picher *et al* 2017). Statistical downscaling creates empirical relationships between large-scale atmospheric predictors and observed local scale predictands representing in an improved way local climate (Wilby and Wigley 1997, Fowler *et al* 2007, Maraun *et al* 2010). The differences between model results and observations, the biases, may be alleviated introducing a SDMs, more precisely a bias correction technique, for example, a delta change bias correction or quantile mapping (Gutiérrez *et al* 2018, Maraun and Widmann 2018, Soares *et al* 2018). Subsequently, the errors in the present climate may be used to correct the future climate model results (Maraun *et al* 2017).

The World Climate Research Program—CORDEX—is a coordinated effort for creating a large RCM ensemble for all continents, where a set of regional

Table 1. CORDEX-Africa regional climate models used in the current study.

Institution	References	RCM	Forcing model	Acronym
Climate Limited-area Modelling Community	Rockel *et al* (2008)	CCLM4-8-17	ICHEC-EC-EARTH	CLM1
			MPI-ESM-LR	CLM2
			MOHC-HadGEM2-ES	CLM3
			CNRM-CM5	CLM4
Swedish meteorological and hydrological institute	Samuelsson *et al* (2011)	RCA4	ICHEC-EC-EARTH	SMHI1
			MPI-ESM-LR	SMHI2
			MOHC-HadGEM2-ES	SMHI3
			CNRM-CM5	SMHI4
			MIROC-MIROC5	SMHI5
			IPSL-CM5A-MR	SMHI6
			CCCma-CanESM2	SMHI7
			CSIRO-Mk3-6-0	SMHI8
			GFDL-ESM2M	SMHI9
Koninklijk Nederlands meteorologisch instituut	Van Meijgaard (2008)	RACMO22T	ICHEC-EC-EARTH	KNMI1
			MOHC-HadGEM2-ES	KNMI2
Institute for meteorology helmholtz-zentrum geesthacht, climate service center, max planck	Jacob *et al* (2012)	REMO2009	MPI-ESM-LR	MPI
			ICHEC-EC-EARTH	MPI1
Canadian Centre for Climate Modelling and Analysis	Scinocca *et al* (2016)	CanRCM4	CCCmaCanESM2	CCCma
Danish Meteorological Institute	Christensen *et al* (2007)	HIRHAM5	ICHEC-EC-EARTH	DMI

climate models (RCMs) share a common domain (Giorgi *et al* 2009). The CORDEX-Africa initiative (Giorgi *et al* 2009, Hewitson *et al* 2012) constitutes the latest and highest resolution (~50 km) multi-model dataset covering Africa, which allows the characterization of the present and future climates in this continent. In the context of CORDEX-Africa, several simulations were produced, including hindcast runs forced by ERA-Interim (Dee *et al* 2011), historical present climate simulations for the 1971–2000 period, and future simulations for different RCPs scenarios of greenhouse gas emissions for the 21st century. Most of the model evaluation studies focused on the hindcast simulations and analysed fundamental meteorological variables like precipitation (Nikulin *et al* 2012, Kim *et al* 2014, Careto *et al* 2018). These studies showed significant biases in some sub-regions and seasons but supported the added value of this set of simulations for climate assessment studies over Africa. In fact, Soares *et al* (2019) also scrutinized the CORDEX-Africa historical simulations and featured the main climate projections for Africa, based in the building of a multi-model ensemble. Noteworthy is the outperformance of the multi-model ensemble mean relative to the individual models for most statistical errors and variables considered.

To perform the solar resource climate change assessment study, two sets of simulations are considered: a set of Historical runs, where the RCMs are forced by different CMIP5 GCMs (table 1), for the present climate period 1971–2000 and a set of future simulations, which features the same RCMs-GCMs pairs for the period 2071–2100. These future runs were performed for different greenhouse gas concentration scenarios according to the Intergovernmental Panel on Climate Change Representative Concentration Pathways (IPCC RCP) scenarios. In this study, two scenarios are considered: the RCP4.5 and the RCP8.5 which are respectively characterized by a radiative forcing value of 4.5 and 8.5 W m^{-2} by the year of 2100 (Riahi *et al* 2011, van Vuuren *et al* 2011). It is important to mention that global emissions of aerosols and their precursors are projected to decrease up to 80% by 2100, according to the RCPs, but the projected global radiative forcing and climate response due to aerosol reductions do not differ significantly across RCPs (Westervelt *et al* 2015). The RCMs output variables considered in the current study are the daily surface downwelling shortwave radiation or solar radiation expressed in W m^{-2}, and the daily near surface mean air temperatures in °C.

2.3. CORDEX-Africa results evaluation

The surface downwelling shortwave radiation output from the historical simulations is evaluated against the remote sensing observations from CM-SAF, and the surface air mean temperature is assessed against the UDEL dataset. To match the coarser resolution of UDEL dataset, all simulated variables used and data from CM-SAF were first conservatively interpolated (Schulzweida *et al* 2019), from their original resolutions to 0.5°. For surface mean air temperature, first an adiabatic heating (+6.5 °C km^{-1}) from the original height to sea level was performed, by considering each model's orography. After the interpolation, the temperatures were brought back to their original height, through adiabatic cooling, by considering a common topography: ETOPO1 (Amante and Eakins 2018), at 0.5° for all models. The surface incoming solar irradiance in W m^{-2}, taken from CM-SAF, is analyzed for the African continent for the period of 1983–2000 and compared to the CORDEX-Africa model's solar radiation. Whereas the CORDEX-Africa surface mean air temperature is compared against the UDEL dataset for the full historical period (1971–2000). From the annual and seasonal means (DJF: December, January and February, MAM: March, April and May, JJA: June, July and August, SON: September October and November), a multi-model ensemble mean (MMEM) was built by simple averaging the model's mean results. An MMEM using equal weighting for all models has been shown to outperform individual models (Knutti *et al* 2010). The allocation of higher weights to better performing models has also been used to decrease uncertainties (Giorgi and Mearns 2002, Tebaldi and Knutti 2007). Although, Christensen *et al* (2010) found that, in comparison with equal weighting schemes, the use of weights in ensemble building did not improve the description of the mean climate. Since the observational datasets in Africa have clear shortcomings, a MMEM with equal weights is built in order to improve the mean climate description for temperature and solar radiation (Soares *et al* 2015, 2017a, 2017b, Cardoso *et al* 2019, Nogueira *et al* 2019). Subsequently, the MMEM is evaluated in a similar manner as the individual models.

2.4. Bias-correction

To overcome the model's biases, climate model output may be adjusted by the so-called bias correction methods (Maraun *et al* 2010, 2017, Teutschbein and Seibert 2012, Huber *et al* 2016, Maraun and Widmann 2018). A wide range of methods is in use (Gutiérrez *et al* 2018, Hertig *et al* 2018, Soares *et al* 2018), from additive or multiplicative (scaling) corrections (Durman *et al* 2006, Casanueva *et al* 2013) to more flexible distributional bias correction, often named by quantile mapping (Déqué 2007, Piani *et al* 2010, Iizumi *et al* 2011, Lavaysse *et al* 2012). Subsequently, the model's projections are produced by correcting the future results in agreement with model biases known in a historical reference period (Teutschbein and Seibert 2012, Maraun *et al* 2017). Here, we apply a simple delta change method, at the seasonal scale, by subtracting the seasonal biases to each individual model seasonal results. Thus, assuming that each model biases are the same for present and future climates. This assumption is widely used in climate impact studies to reduce climate model biases (Christensen *et al* 2008, Teutschbein and Seibert 2012, Maraun 2016, Maraun *et al* 2017). The limited confidence on the observations led to the selection of the simple delta change bias correction method.

2.5. PV performance model

The PV potential, expressed in KWh m^{-2}yr^{-1}, is roughly proportional to the incident irradiation. However, one must consider that the efficiency of PV modules depends on their temperature. Furthermore, for potential assessment for the tilted plane, one needs to consider the global irradiation on the tilted plane (H), which depends on the contribution of both beam (H_b) and diffuse irradiation (H_d), which may be determined from the fraction of diffuse radiation (k_D). Reflected irradiation is strongly conditioned by site conditions (e.g. ground albedo) and it is, therefore, difficult to model at the continent level, in a meaningful way. Nevertheless, for this range of latitudes, it is expected to not have a very significant impact on the results.

2.5.1. Diffuse irradiation

The diffuse fraction k_D may be estimated using empirical fits to observed values. There are many regression models to determine the diffuse fraction from global irradiation. Most are based on the Liu and Jordan (Liu and Jordan 1960) seminal idea of determining an empirical fit between k_D and k_T (the clearness index, the ratio between the global horizontal irradiation on the surface and the extra-terrestrial irradiation). The fit is dependent on the location and there are many models for many places, including in the African continent (Nwokolo and Ogbulezie 2018). For modelling a continental region, as in this work, it is more adequate to use a globally valid model, albeit perhaps less accurate for specific regions. Erbs *et al* (1982) is a well-established and often used empirical model developed for five locations in North America, across very different climates, which is perhaps one of those more widely tested around the globe. It estimates k_D for three different ranges of k_T:

$$k_T \leqslant 0.22\colon k_D = 1 - 0.09\, k_T \quad (1)$$

$$0.22 < k_T \leqslant 0.80\colon k_D = 1 - 0.9511 - 0.1604\, k_T + 4.39\, k_T{}^2 - 16.64\, k_T{}^3 + 1.23\, k_T{}^4 \quad (2)$$

$$k_T > 0.80\colon k_D = 0.165. \quad (3)$$

Diffuse irradiation is modelled considering the isotropic model for diffuse irradiation. Assuming tilt is equal to latitude one has

$$H_d = \frac{1 + \cos\phi}{2} k_D\, H_0. \quad (4)$$

2.5.2. Beam irradiation

The beam irradiation can be determined from the global irradiation on the horizontal plane by geometric factors considering the position of the Sun in the sky. This is usually done by defining $R_{b\beta}$, the ratio of the radiation on the inclined plane to that on a horizontal plane. The beam irradiation can be computed as:

$$H_{b\beta} = R_{b\beta}\, H_{b0} \quad (5)$$

$$= R_{b\beta}\,(1 - k_D)\,H_0. \tag{6}$$

$R_{b\beta}$ is an hourly varying function of the latitude (ϕ), day of the year (i.e. declination, δ) and inclination (β) given by

$$R_{b\beta} = \frac{\omega_s{}'\sin\delta\,\sin(\phi - \beta) + \cos\delta\,\cos(\phi - \beta)\sin\omega_s{}'}{\omega_s\sin\delta\,\sin\phi + \cos\delta\,\cos\phi\,\sin\omega_s}, \tag{7}$$

where ω_s and $\omega_s{}'$ are the Sunrise hour angle for the horizontal and the tilted surface, respectively (Iqbal 2012). For the case of a surface whose inclination is equal to the latitude, it becomes

$$R_{b\beta} = \frac{\cos\delta\,\sin\omega_s{}'}{\omega_s\sin\delta\,\sin\phi + \cos\delta\,\cos\phi\,\sin\omega_s}. \tag{8}$$

Beam irradiation was calculated for each month of the year, considering the characteristic day of each month, which is defined as the day with declination identical to the average declination for that month. CSP potential is estimated directly from beam irradiation estimates.

2.5.3. PV power

The efficiency of a PV system depends on the operating temperature through a power temperature coefficient (β). Its daily average value ($\bar{\eta}$) may be modelled by equation (9) where η_{STC} is the nominal efficiency at Standard Test Conditions (including $T_{STC} = 25$ °C, low wind, etc), NOCT is normal operation cell temperature ($G_{NOCT} = 800$ W m^2 and 20 °C), a parameter specified in the module data sheet (assumed 48 °C), the daily solar radiation ($\bar{H}$) and the mean ambient temperature $\bar{T_a}$.

$$\bar{\eta} = \eta_{STC}\left(1 - \beta\,(\bar{T_a} - T_{STC}) - \beta\frac{\text{NOCT} - 20}{G_{NOCT}}\bar{H}\right). \tag{9}$$

PV potential results are presented in kWh/kWp, which is calculated from the solar energy produced during the period ($\bar{\eta} \times H$, in kWh) divided by the installed power ($\eta_{STC} \times 1$ kWp). This approach makes results independent on technology developments since increased conversion efficiency leads to lower areas for the same power output but same kWh/kWp. Calculations are performed for each month of the year and then added for seasonal or annual values.

It ought to be underlined that it would be more accurate to use daytime mean temperature instead of daily mean temperature since the effect of the temperature on the conversion efficiency of PV modules is only relevant when there is solar electricity generation. This approach is not feasible in the present study as it would severely limit the amount of climate models to be considered. The error introduced by this approximation is below 4 °C which does not have a relevant impact on the PV generation efficiency, below 2% underestimation.

3. Present climate

CORDEX-Africa offers a set of state-of-the-art climate change assessment simulations using a common horizontal grid at 50 km resolution covering the full African continent. The simulations have been evaluated extensively for temperature, precipitation and surface fluxes (Nikulin *et al* 2012, Kim *et al* 2014, Careto *et al* 2018, Soares *et al* 2019), showing significant biases. In general, a multi-model ensemble strategy mitigates these errors (Careto *et al* 2018). The multi-model ensemble mean (MMEM) results for solar radiation and temperature, at both annual and seasonal timescales, here computed by simple averaging, outperform individual RCMs, when are compared with CM-SAF and UDEL datasets, respectively The observed climatology, the statistical errors between models and observations, the degree of agreement between RCMs and their spread are shown in figures S1–S4 of the supplementary material is available online at stacks.iop.org/ERL/14/124036/mmedia. In general, the MMEM captures the annual and seasonal means of solar radiation and temperature. However, substantial biases remain in some areas, especially in the case of temperature (figure 1). For solar radiation, the annual biases are in the range of −45 W m^{-2}, in some coastal regions of western Africa, and +25 W m^{-2} in small areas in eastern Africa. These errors correspond to relative biases in the range of −25% to +8%. The biases show a seasonal different spatial pattern, more pronounced in boreal summer in the Gulf of Guinea countries (up to −40%) and in localized areas of Central Africa (up to +25%). For temperature, the MMEM show annual biases between −3 °C, in the Sahara, and +2 °C in limited coastal regions. Seasonally, the cold bias covers larger areas of the Sahara and Sahel in boreal winter, while the overestimations reach +3 °C in coastal areas of the northwest and of the southwest.

The magnitude of the MMEM errors requires a bias adjustment in such a way that the present and future projections for solar radiation and temperature, both at the annual and seasonal scales, are corrected considering present climate biases (Maraun *et al* 2017, Gutiérrez *et al* 2018, Soares *et al* 2018).

4. Projections for future climate

After bias correction, the MMEM projected future changes for the annual and seasonal solar radiation and temperature are shown in figure 2 (in percentage for solar radiation in figure S5), in agreement with two future climate scenarios, RCP8.5 and RCP4.5. For the RCP8.5 at the annual scale, a decrease of available solar radiation is projected for broad regions of the north and central-eastern Africa, which can attain values up to ∼−10 W m^{-2}. Exceptions to this decrease are projected to occur in the northwest coastal regions and

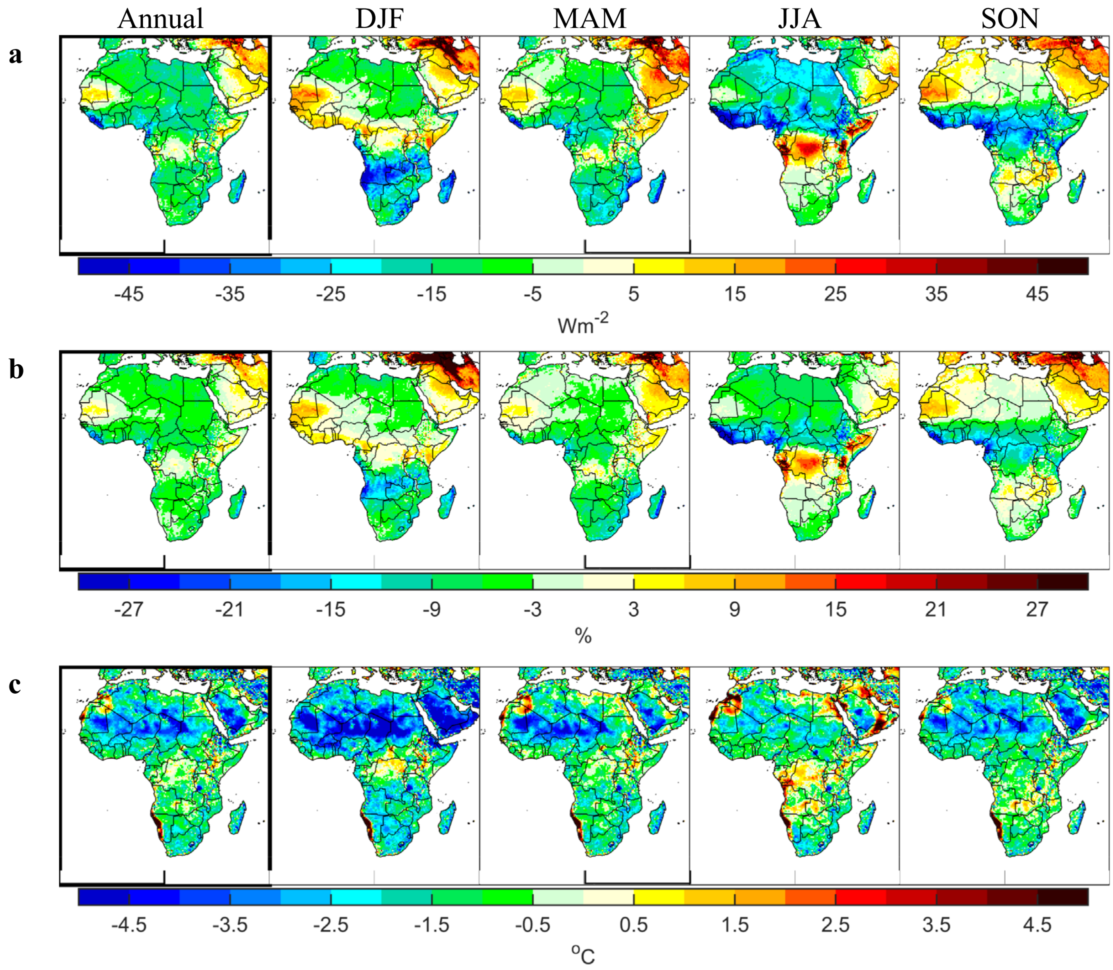

Figure 1. Annual and seasonal biases of the CORDEX-Africa MMEM for solar radiation against the CM-SAF dataset and near surface mean air temperature against the UDEL dataset for the historical period (1971–2000). (a) absolute solar radiation values, (b) relative solar radiation values and (c), absolute surface mean air temperature values.

larger extensions of the South African regions. These projected increases are up to +12 W m^{-2} in areas of Angola, Zambia, and Zimbabwe. At the seasonal scale, in austral summer, this pattern of change is accentuated, with a dipole of larger projected increases, in southern Africa (Angola) (>+15 W m^{-2}; >+5%), and reductions, in Kenya and Tanzania (∼−15 W m^{-2}; ∼−10%). In boreal spring, for the northwest region, solar radiation is projected to grow over +15 W m^{-2}, as well in Sierra Leone and Liberia. In boreal summer, the changing pattern is rather different, with a stripe along the south Sahel, from Guinea to Ethiopia, with a noteworthy increase of solar radiation up to +15 W m^{-2} (∼8%). Changes in austral spring are as in austral autumn, but with larger increases of solar radiation in southeastern Africa, including Mozambique, Madagascar, Zimbabwe and Tanzania, and solar radiation decrease in Somalia and northern Kenya. These changes are closely linked to the projections of future cloud cover and precipitation modifications, pointing to decreases in precipitation in southern Africa and significant increases in Ethiopia and neighbouring countries (Weber *et al* 2018, Soares *et al* 2019). When looking to the projections according to RCP4.5 analogous patterns appear but with changes in the magnitude of the order of half of those of RCP8.5 (figure S6), except to the areas where changes are small such as in central western Africa.

Projections for temperature represent widespread warming (figures 2(c) and (d)). At the annual scale, the temperature change is projected to be over 5 °C in much of the continent, reaching 6 °C in Mali for the RCP8.5 scenario. Seasonally, the warming is accentuated regionally, e.g. in boreal summer, in Sudan areas, the projected warming is over 7 °C. For the RCP4.5 scenario, both at the annual and seasonal scale, the temperature changes are in the range of 2 °C–3 °C in most of the African continent.

Although the MMEM reveals a relevant spread of solar radiation, especially in the Sahel region during boreal summer (figures S7 and S8), there is a widespread agreement in the solar radiation change signal between the RCMs. It is noteworthy that these results are of opposite signal to anomalies projected by Huber *et al* (2016), based in one GCM, which suggested a decrease in surface irradiances in southern Africa, when comparing the 1995–1999 and 2035–2039 periods.

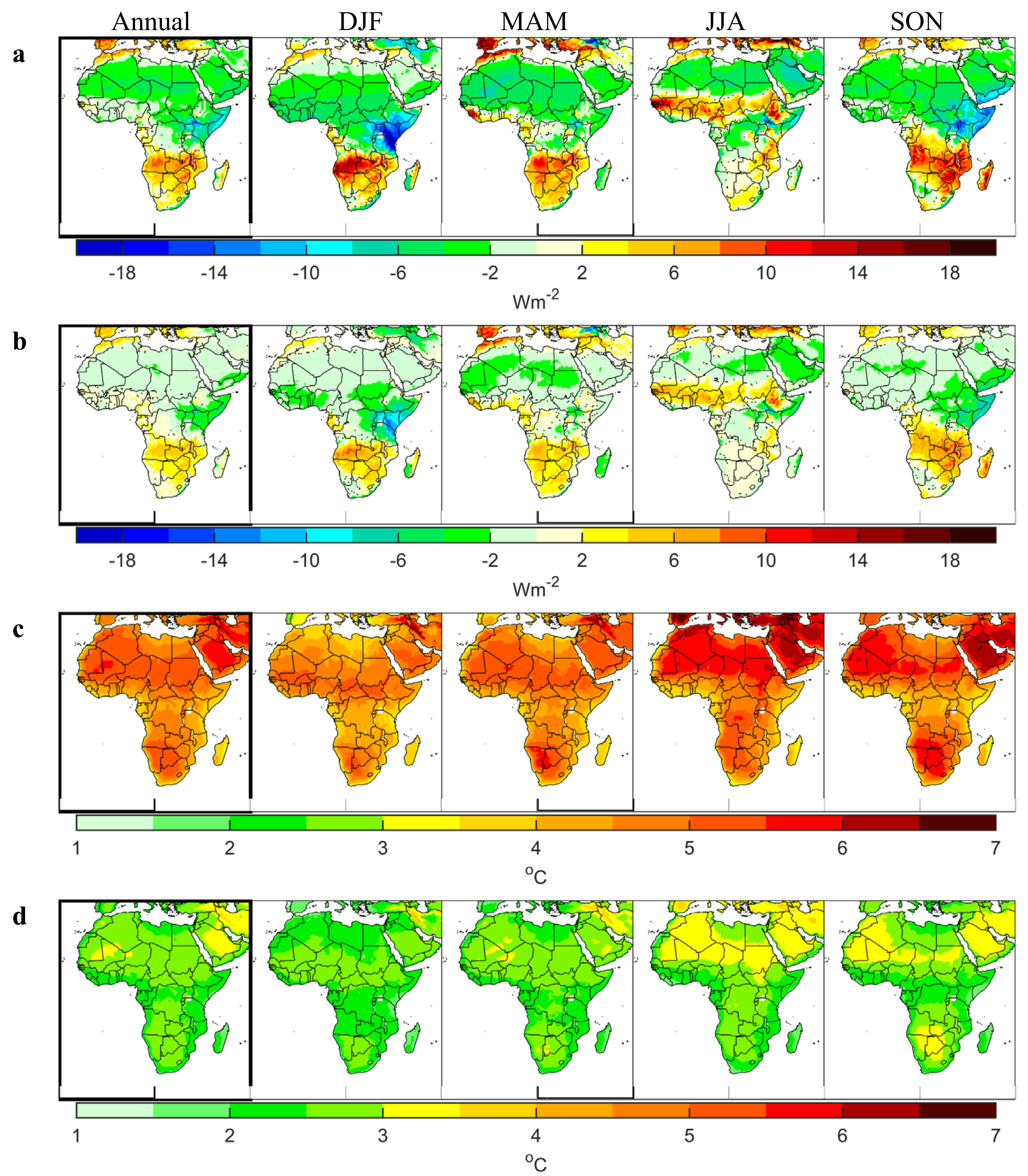

Figure 2. Annual and seasonal future changes of solar radiation (a) for the RCP 8.5 scenario and (b) for the RCP 4.5 scenarios. Also shown is the annual and seasonal future changes of the near surface mean air temperature for (c) RCP 8.5 scenario and (d) RCP 4.5 scenario. These changes are given by comparing the future MMEM against the historical MMEM (2071–2100 minus 1971–2000). Dotted where the differences are not statistically significant at the 95% confidence level.

5. Projections for future solar power potential

PV power potential is determined for optimum tilted angle and orientation, which differs from PV power estimated from global horizontal irradiation not only due to the different position of the Sun in the sky, hence different angle of incidence, but also because it requires separated consideration for beam and diffuse irradiation. Figure 3(a) shows the estimated PV potential for the present climate. One can observe that, in general, the whole continent has very favorable conditions for solar energy harvesting, especially in the northern and southwest regions, notwithstanding high ambient temperatures. Solar potential in equatorial regions is hindered by cloudy skies, associated with the intertropical convergence zone, which leads to lower levels of irradiation throughout the whole year.

Regarding the future climate, figures 3(b)–(e) display the projected future PV potential and the corresponding relative changes, in agreement with the RCP8.5 and RCP4.5 scenarios, respectively. In general, results show that solar potential will increase in confined areas of southern and north-western areas of Africa, while decreasing in most of the continent. These change patterns are in most areas determined by projected changes in solar irradiance, despite the

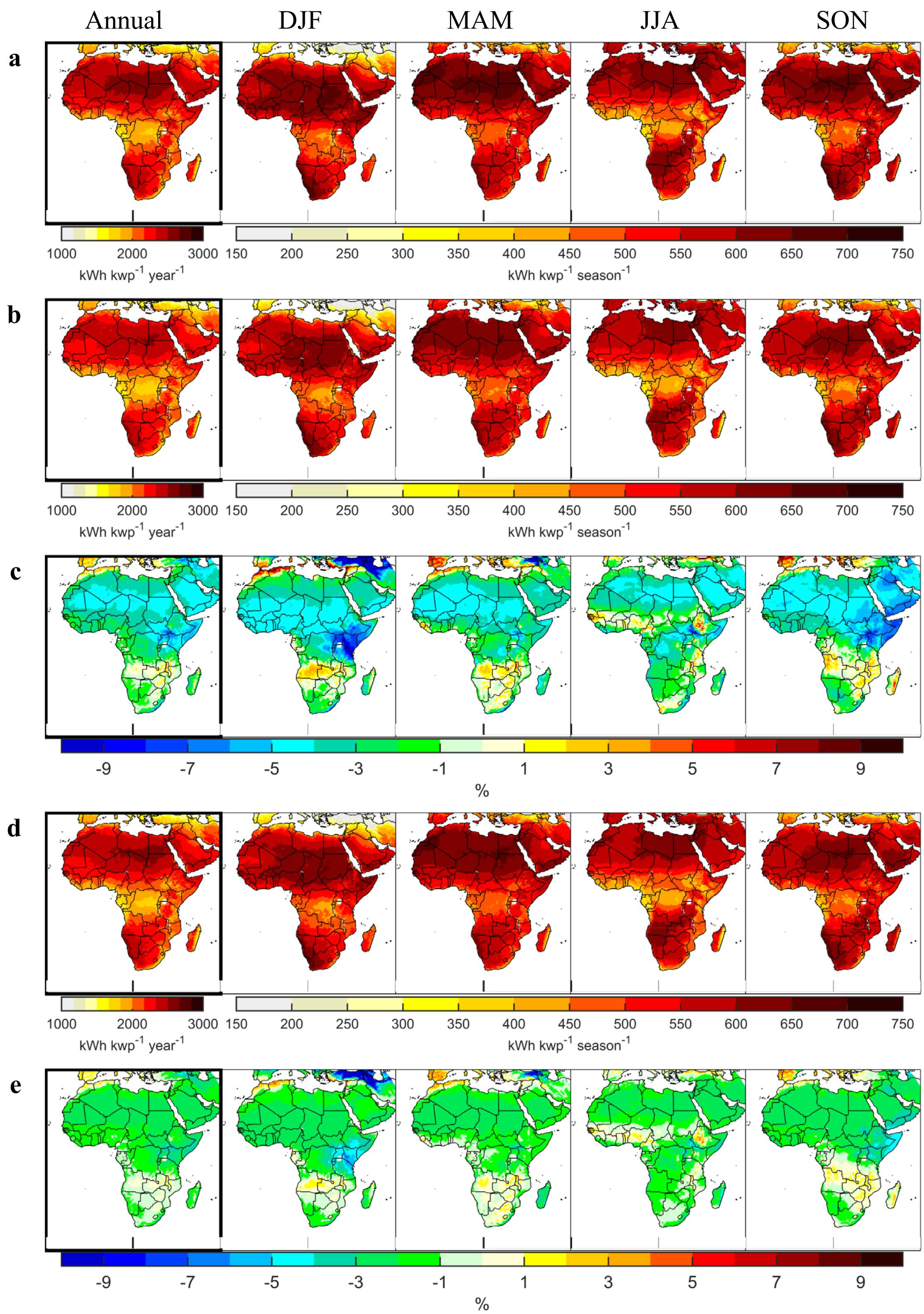

Figure 3. Annual and seasonal photovoltaic production of a tilted module, with inclination equal to the latitude given by the CORDEX-Africa MMEM. For the (a) historical period (1971–2000), (b) future RCP 8.5 scenario (2071–2100), (c) relative changes for the RCP 8.5 scenario, (d) future RCP 4.5 scenario and (e), relative changes for the RCP 4.5 scenario. The relative changes are given by comparing the future MMEMs against the historical MMEM (2071–2100 minus 1971–2000/1971–2000).

opposing effect of changes in ambient temperature. It is noteworthy the decrease in solar potential in the region north to Lake Victoria, including Uganda, Kenya, most of Ethiopia and South Sudan, with declining PV potential which, in some locations, can reach −10% for the more extreme scenario. On the other hand, there is a significant increase in solar potential in the region around Lake Malawi, extending westwards to Zambia and Angola and southerly to Zimbabwe, and Mozambique in austral spring. In those regions, the increase in PV potential may be over +5% for the RCP8.5 scenario. This is associated with a northerly and eastwardly growth of the high solar potential region of Namibia. Overall, the continental projected changes for PV, in agreement with RCP8.5, are at the annual scale ∼−2.4%, and for boreal winter, spring, summer and autumn are −3%, −1.9%, −2.2% and −2.4%, respectively. The ensemble standard deviations are shown in figure S9 of the supplementary material, revealing a rather small RCM spread with percentage values below 5%.

It is interesting to note that for some areas of the southern part of the continent, solar power potential is projected to decrease, despite increased irradiation (figure 2). This suggests that, unlike what was proposed by Crook *et al* (2011) and Wild *et al* (2015), based on CMIP5 GCMs, regional PV power is not fully determined by irradiation anomalies, but the increasing temperature is a critical factor limiting the PV potential. For the west Africa region, the signals of projected anomalies are in line with the work of Bazyomo *et al* (2016), with climate models running until 2045, also using CORDEX-Africa RCM simulations. The magnitude of anomalies in the present work is higher, mainly due to the longer period range considered and the impact of considering tilted modules.

The relevance of the assumption of tilted modules has a strong positive impact on the solar power potential across the continent, in particular at the seasonal scale, as expected. For the present climate, it increases annual solar potential in a range of about 2%–6% for vast areas, with higher impact in Morocco and South Africa, where the assumed tilt is higher (figure S10). One may observe the awaited seasonal effect, with decreased potential in the boreal summer compensated by increasing potential in the boreal winter, when the Sun is lower in the sky. Its impact on the solar potential in future climate is magnifying or reducing projected changes by a factor of more than two showing that it is a critical assumption to consider when assessing changes in solar power potential (figures S11–S13).

The CSP potential is determined by the available beam irradiation. For the RCP8.5 scenario, the MMEM future change results indicate a strong variation of beam irradiation, in the range of ±10%, with a severe decrease in the eastern region, a moderate decrease in North Africa, and a steep improvement in the southern part of the continent, mostly driven by changes in irradiation from September to February (figure 4). Unlike PV, CSP conversion efficiency is not negatively affected by increasing ambient temperature, as CSP potential in southern Africa is projected to increase in the coming decades. Despite these changes, the most favourable locations for CSP systems will still be the western part of southern Africa and North Africa. The latter features an overall moderate decline in potential below 5% and an increase in coastal regions of the same order of magnitude. Again, it is visible the north and easterly expansion of the Namibian desert good conditions for solar CSP harvesting. The spread of individual models for CSP is limited in magnitude (<5%) but extends to wider regions of central Africa when compared with PV potential (figure S14).

6. Conclusions and discussion

It is urgent to take action towards a combination of challenges that the African continent is facing: a fast increase of electricity demand, limited electrification rates and climate change with its impacts. We believe solar technologies, such as solar PV and CSP, will play a major role in this context, due to its easy deployment, modularity, low maintenance and, mostly, its competitive cost and fast learning curve.

In this study, we assess the future evolution of the solar potential (PV and CSP) in the context of climate change and in agreement with the scenarios RCP4.5 and RCP8.5. This assessment relies on a multi-model ensemble of regional climate simulations performed within CORDEX-Africa. The simulation results are evaluated and then bias corrected, to increase the likelihood of the projections.

Our analysis indicates an overall persistence of the large values of irradiance in Africa. In limited regions solar irradiance reductions are projected, that may reach in the north and central-eastern Africa, values up to about $-10\ \mathrm{W\,m^{-2}}$, for the RCP8.5 scenario. Yet, in some confined areas of the northwest and southern Africa, gains of resource are projected up to $+12\ \mathrm{W\,m^{-2}}$. Seasonally, the patterns of future changes point to an enhancement of the annual signal for austral summer, with a dipole of larger projected increases, in southern Africa (Angola) ($>+15\ \mathrm{W\,m^{-2}}$; $>+5\%$), and reductions in Kenya and Tanzania ($\sim-15\ \mathrm{W\,m^{-2}}$; $\sim-10\%$). Considering tilted PV modules, future projections of PV potential indicate a seasonal decrease for the full continent in the range of −2% to −3%, that regionally is mostly modulated by the mentioned reduction of the solar irradiance. In fact, the decrease in PV potential in the region of Uganda, Kenya, most of Ethiopia and South Sudan is projected to reach, at the end of the century, by about −10%, for the RCP8.5; the projected growth for the northwest and the region of Angola to Zambia may reach values over +5%. This is associated with a northerly and eastwardly growth of the high solar potential region of Namibia. In the southern area, it is interesting to note that solar power potential is projected to decrease despite increased irradiation, due to the projected large increase in temperatures. As expected, the assumption of tilted modules has a strong effect on the PV power potential across the continent, in particular at the seasonal scale. For the future climate, the impact of neglecting tilted modules is projected to increase by a factor of more than two.

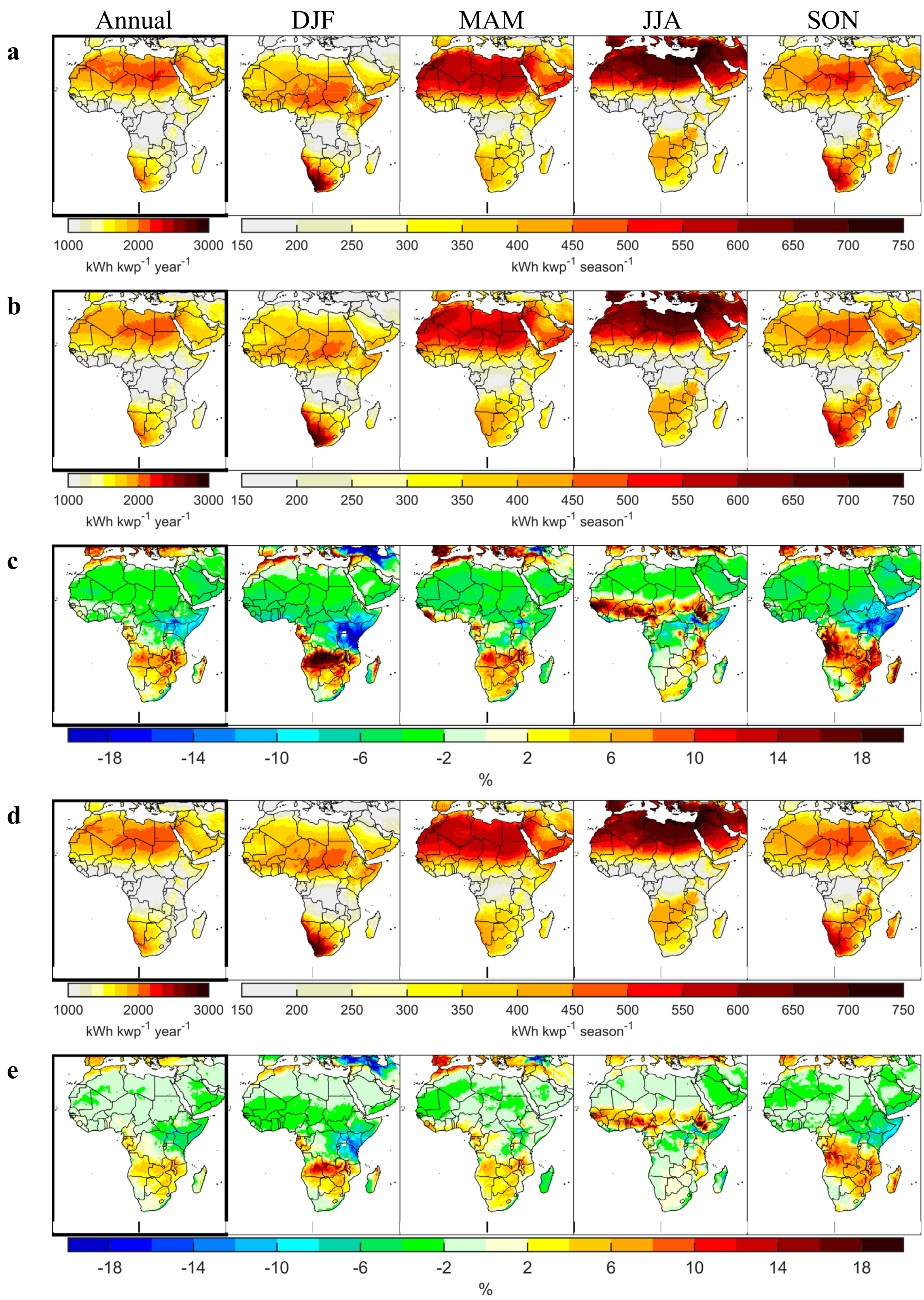

Figure 4. Annual and seasonal CSP over the plane of incidence for the CORDEX-Africa MMEM for the (a) historical period (1971–2000), (b) future RCP 8.5 scenario (2071–2100), (c) relative changes for the RCP 8.5 scenario, (d) future RCP 4.5 scenario and (e), relative changes for the RCP 4.5 scenario. The relative changes are given by comparing the future MMEMs against the historical MMEM (2071–2100 minus 1971–2000/1971–2000).

This study reveals the immense solar potential existing in Africa and its lasting in the future despite climate change, supporting the massive deployment of solar technologies. Moreover, further cost reductions and technology development will surely offset the reduction in solar potential identified. Finally, the shift to solar energy will contribute significantly to mitigate the rampant air pollution from localized burning in Africa. Very importantly, this study wants to contribute to the United Nations Sustainable

Development Goals for 2030, such as Goal 13 (take urgent action to combat climate change and its impacts), Goal 11b (make cities and human settlements inclusive, safe, resilient and sustainable) and Goal 7 (ensure access to affordable, reliable, sustainable and modern energy for all).

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for legal and/or ethical reasons.

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