

CHANGES IN SOLAR RADIATION EXTREMES AND THEIR IMPACT ON THE SOLAR POWER GENERATION IN EUROPE

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Abstract. Changes in solar radiation extremes and their impact on the solar power generation in Europe. Present study focuses on distribution of low surface solar radiation (overcast situation) and high surface solar radiation (clear sky situation), since, the frequencies of these situations have high impact on the electricity generation. The results show a shift in the distributions projected for the period of 2065-2100 based on 56 high-resolution EURO-CORDEX simulations (RCP8.5). In the northern countries a shift towards lower values is detected. The changes are more accentuated in wintertime, when the low extremes are becoming lower by 16%, the high extremes decrease with 8%. These tendencies are detected in the central part of the continent as well, however, the changes are smaller, -10% in case of low values, and 5% for high values. In the southern part of the continent the shift of distribution has opposite direction. In these countries, the low surface solar radiation values are becoming higher by 4% in summertime; on the other hand, there is no significant change in high extremes (+1%). The shift of extreme values might have serious impact on solar power generation, since it could induce even 20-25 extra days with low radiation in the northern regions, while in the southern regions 15-20 extra days with high radiation are projected.

Keyword: surface solar radiation, EURO-CORDEX simulations, low extremes, high extremes, solar power generation

1. INTRODUCTION

Solar energy is one of the most strategic renewable energy in Europe given by the abundance of the solar resource, especially in the southern part of the continent. The Renewable Energy in Europe 2020 report published by the European Environment Agency (European Environment Agency 2020)

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highlights that solar PV electricity production reached 9.5 Mtoe in 2018, exceeding by more than 38 % (2.6 Mtoe) the level that was expected for 2020, according to the NREAPs (6.9 Mtoe). For 2005-2018, the increase was the highest for solar PV systems (+573%), after the slower growth in 2017 and 2018 (+8%). Müller et al. (2019) suggested that PV is a no-regrets investment in Europe, especially for Spain, France, Italy, and Germany. In the same time, concentrated solar power (CSP) technology is also applicable in southern Europe, CSP provided 0.4 Mtoe of renewable energy in 2018, and further new installations are planned. Furthermore, the production of renewable heat from solar thermal technology realised an increase of 18% per year, on average, over the period 2005-2018, growing from 0.7 Mtoe in 2005 to 2.4 Mtoe in 2018.

The increased interest on solar energy applications in the context of achieving a carbon-free future makes a major challenge to introduce this type of renewable energy into the energy system supply at both national and global level. This assumes not only the implementation of new technologies, but also detailed information regarding the availability of surface solar radiation together with other environmental conditions. The entire planning processes of solar energy production including the location of solar parks, feeding into the national electricity grid (or into a small stand-alone grid system), energy storage and also grid regulation have to consider the long-term variability of surface solar radiation.

Focusing on Europe several papers describe scenarios of surface solar radiation future projections based on general circulation models or GCMs (Hou et al. 2021; Müller et al. 2019; Wild et al. 2015; Gaetani 2014) and regional climate model simulations (Coppola et al. 2021; Boe et al. 2020; Gutiérrez et al. 2020; Bartok et al. 2017; Jerez et al. 2015; Gunderson et al. 2015). These climate information are necessary for the solar energy sector, but in the practice the use of climate projections has remained limited so far for a number of reasons such the lack of consistency among different climate projections in terms of the magnitude and sign of surface solar radiation changes. The majority of the regional climate models indicates slight decrease, while the associated global climate models gives an increase in surface solar radiation over Europe. This fact suggests that the one of the greatest uncertainty in climate modelling remains in the changes in surface solar radiation (Bartok et al. 2017). One reason could be the different behaviour of simulated cloud cover. In the global models cloudiness

shows a significant decrease over Europe and despite the fact that the atmospheric absorption is increasing there is still a surplus of energy at the surface indicated by the positive trends in surface solar radiation. In RCMs no significant changes in cloud cover can be detected, thus clouds are not expected to induce changes in surface solar radiation. At the same time regional models simulate an increase in atmospheric absorption (with similar magnitude as in GCMs), which is not compensated by an increase of surface solar radiation due to the less cloudiness, finally causing a decrease in surface solar radiation. Recent studies show that the different signs of projected changes are mainly attributed to the weak representation of aerosol radiative forcing in RCMs (Boe et al. 2020; Gutiérrez et al. 2020; Nabat et al. 2020). It should be mentioned that the evaluation of the climate system is controlled not only by natural processes, but also by anthropogenic activities difficult to foresee (e.g. greenhouse gas emissions, aerosol loadings). The uncertainties in climate projections originating on the one hand from the lack of theoretical knowledge, on the other hand from unforeseeable behaviour of the society inevitably should be taken into account during the interpretations of impact studies, such as of solar energy applications.

Jerez et al. (2015) evaluated the vulnerability of the PV production in Europe to the climate change projected for the XXI century based on 10 different regional climate simulations and found the conclusion that climate change would not affect significantly the European PV production but there exist worth mentioning nuances. For example, PV production in northern countries presents a reduction of up to 10% by the end of the century under the most extreme climate change scenarios. Contrary, in southern countries, the richest in terms of solar resource, the impact of climate change on the average production would be negligible despite of the projected increase of surface solar radiation (because the simultaneous increases of temperature), but the temporal stability of the supply would increase, especially with regard to the daily variability. Taking into account that solar energy applications are all space dependent the Jerez et al. (2015) study draws our attention to the importance of such assessments in local scales.

In the line with Jerez et al. (2015) further recent studies (Gutiérrez et al. 2020) analysed the impact of climate change on the solar energy sector in Europe, however, their results are focusing mainly on the changes of the mean surface solar radiation. Present study, therefore, focuses on extreme values,

namely on the changes in low surface solar radiation (5th percentile) representing overcast situations, and on the changes in high surface solar radiation (95th percentile) representing the clear sky situations. The projected changes in the frequencies of these situations have high impact on the solar electricity generation mainly in the operational phase. In this work, new results for solar energy practitioners and decision-makers was provided in order to facilitate the use of climate information in operation and planning.

The paper is organized in the following way: in Section 2 the regional models considered in the study are presented and observational data are described. Furthermore, this section contains the validation of modelled surface solar radiation data against ground-based observations. In Section 3 the main results regarding the projected surface solar radiation changes in RCMs over Europe are detailed. Section 4 includes analyse regarding the impact of surface solar radiation extremes on solar energy availability, and finally Section 6 contains the wider discussion of the results and the general conclusions of the study are summarized.

2. DATA

2.1 EURO-CORDEX model outputs

The paper includes the full set of the high-resolution (0.11 deg) regional climate models from Coordinated Downscaling Experiment - European Domain (EURO-CORDEX) (Jacob et al. 2014; Jacob et al. 2020) available at the time of publication of this article (56 simulations). An comprehensive presentation and validation of the entire dataset van be found in Vautard et al. (2021). The database represents the state of the art in terms of climate change experiments and allow to robustly characterize and narrow the uncertainty associated to future climate projections. The full list of the simulations is presented in Table S1. For the future changes the high-emissions RCP8.5 scenario was considered, which is frequently referred to as “business as usual”, suggesting that is a likely outcome if society does not make concerted efforts to cut greenhouse gas emissions. The outputs of this scenario show the wider range of possible changes to what any future solar energy application could face to. All the simulations are freely available on the Earth System Grid Federation (ESGF) portals.

2.2 Observational data

Annual surface solar radiation observations for the period of 1975-2005 are used for model validation. The observations are coming from the World Radiation Data Centre (WRDC), which is one of recognised World Data Centres sponsored by the World Meteorological Organization. WRDC centrally collects and archives radiometric data from the world, all the data are accessible at the website of World Radiation Data Centre. Daily sums, monthly sums and means of global radiation are available for European station, however, the length of the time series do not cover the full period of 1975-2005 in each cases. For this reason, only 50 European stations are considered in the study, the list of these stations are listed in Table S2. First, the missing monthly surface solar radiation data were filled, then and the whole dataset was homogenised using the MASH homogenization method (Szentimrey 2003).

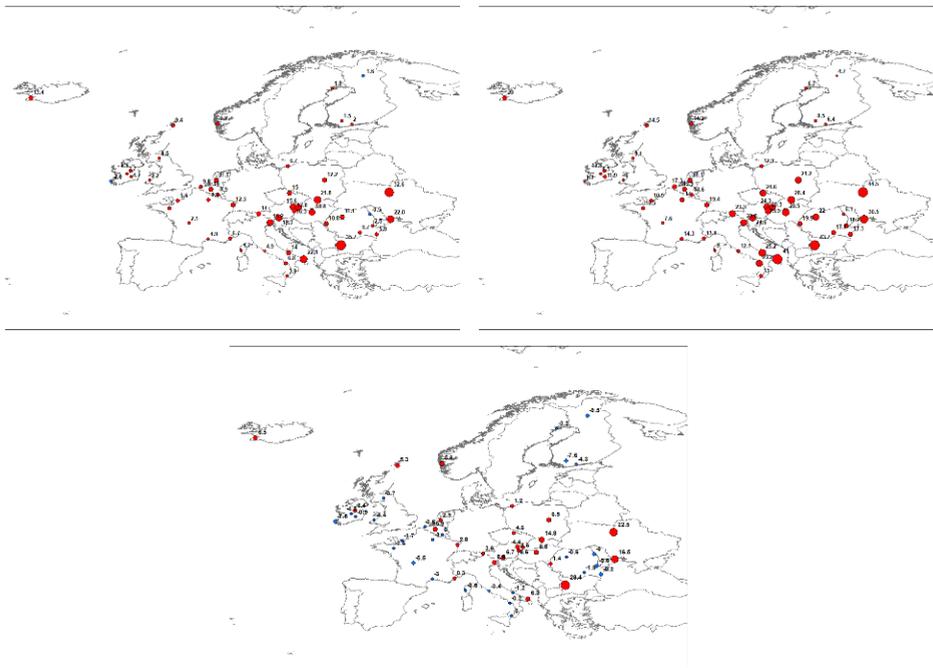


Fig. 1 Biases in annual mean (left), annual 05th percentile (middle) and annual 95th percentile (right) in the 56 EURO-CORDEX simulations against WRDC observations, 1975-2005.

2.3 Validation of RCM model outputs

In the study, first, the evaluation of EURO-CORDEX simulations against WRDC ground-based measurements was elaborated. The annual surface solar radiation data from 60 stations are compared with the modelled values extracted from the same location for the period of 1975-2005. Fig. 1 presents the biases for annual means, annual 5th percentiles and annual 95th percentiles. Overall, the RCMs overestimates the annual means of surface solar radiation by +10.4 W/m², however, spatial differences can be detected. The highest biases are detected in the central and southeastern part of the continent. Similar spatial pattern can be found in the case of biases in low surface solar radiation values, namely in the case of 5th percentiles. Here the overestimation of the models are more accentuated with a bias of +18.2 W/m² for the whole area. In the case of high surface solar radiation values (95th percentiles) the mean bias is 2.05 W/m², however, the sign of biases turns over indicating an underestimation in surface solar radiation at the most stations. The higher positive biases in case of low surface solar radiation values, as well as the lower negative biases in case of high surface solar radiation can be seen on Fig. 3 where the shifts of frequency distribution in Euro-CORDEX historical simulations (blue colour) vs. observations (pink colour) are presented.

In terms of means, the results are in line with the validation of Vautard et al. (2021) elaborated for the same EURO-CORDEX ensembles. On the other hand, the biases in the case of extremes differs even in sign. It should be mentioned, that in Vautard et al. (2021) the model data were evaluated against the Surface Solar Radiation Data Set - HELIOSAT (Müller et al. 2015), which is a remote-sensed surface radiation dataset having a 5.5 W/m² mean absolute bias for monthly means.

3. RESULTS

3.1 Annual changes of surface solar radiation in EURO-CORDEX simulations

In the study the changes of surface solar radiation was investigated based on 56 EURO-CORDEX simulations. The changes were calculated for the end of the century, namely for the period of 2065-2100. The reference period was 1971-2005. In the following the changes for the RCP8.5 scenario are presented. Fig. 2 presents the relative changes (%) of multi-model mean surface solar radiation

(left), multi-model 5th percentile (middle) and multi-model 95th percentile (right) calculating as a simple mean of the changes obtained in the case of single models. Changes in extreme surface solar radiation show similar spatial patterns as the changes of mean values, namely a general decrease in the northern part of the continent, and increases in the southern regions. Significant decreases also can be found on the altitudes (e.g. Alps, Pyrenees). Regarding the magnitudes, the widest spread in changes can be found in the case of the 5th percentile (min. -17.8%, max. 10.8%, mean -2,5%), which means that situations with low surface solar radiation are going to change in the greater extend in the future. The magnitude of changes in the case of high surface solar radiation (95th percentile) are smaller (min. -11.1%, max. 3,1%, mean -1,6%), while the changes in mean annual surface solar radiation are in between (min. -13,7%, max. 5,6%, mean -2%).

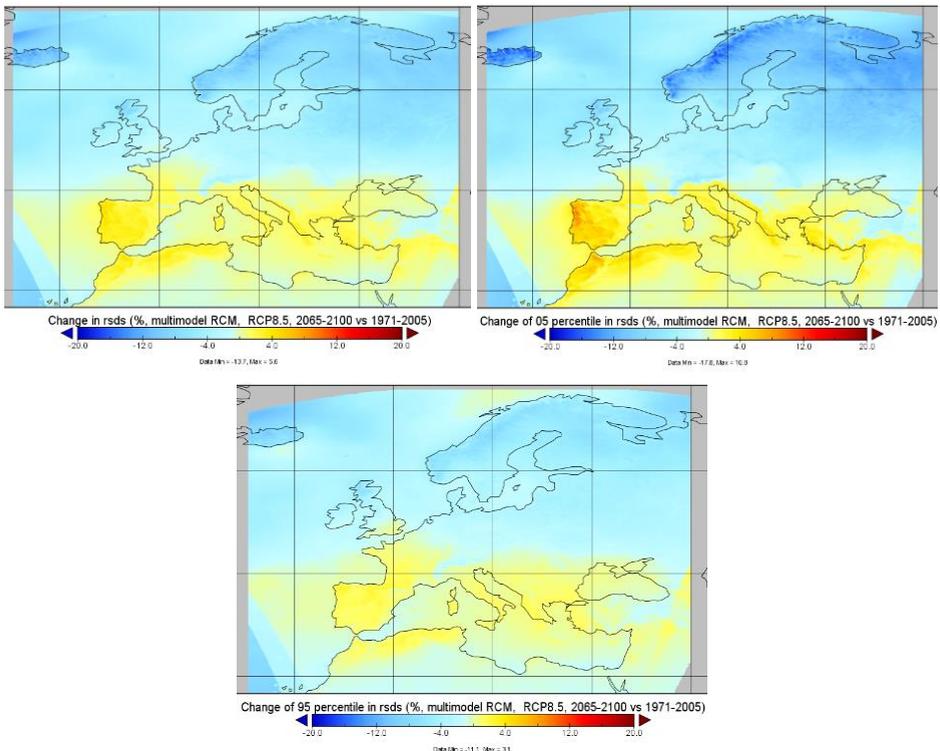


Fig. 2 Relative changes (%) of multi-model mean surface solar radiation (left), multi-model 5th percentile (middle) and multi-model 95th percentile (right) in 56 EURO-CORDEX simulations, 2065-2100 vs. 1971-2005

The detected changes in extremes imply the shift of the full surface solar radiation distribution, which also presents regional differences. In Fig. 3 the frequency distributions of the EURO-CORDEX historical simulations (blue colour) and future runs of RCP8.5 (green colour) are presented in case of several European station. The stations are grouped based on latitudes representing Northern Europe (55-65 lat), Central Europe (45-55 lat) and Southern Europe (35-45 lat). In the norther part of the continent a clear shift towards the low values is detected, while in the southern part a shift towards the high values can be see. In the central regions of the continent the shift is not so obvious. The chances in case of each WRDC stations can be found in Fig. 1S. It should be mentioned that the distribution of surface solar radiation is highly affected by local factors, thus the variability of surface solar radiation of stations belonging to the same sub-region could also differ.

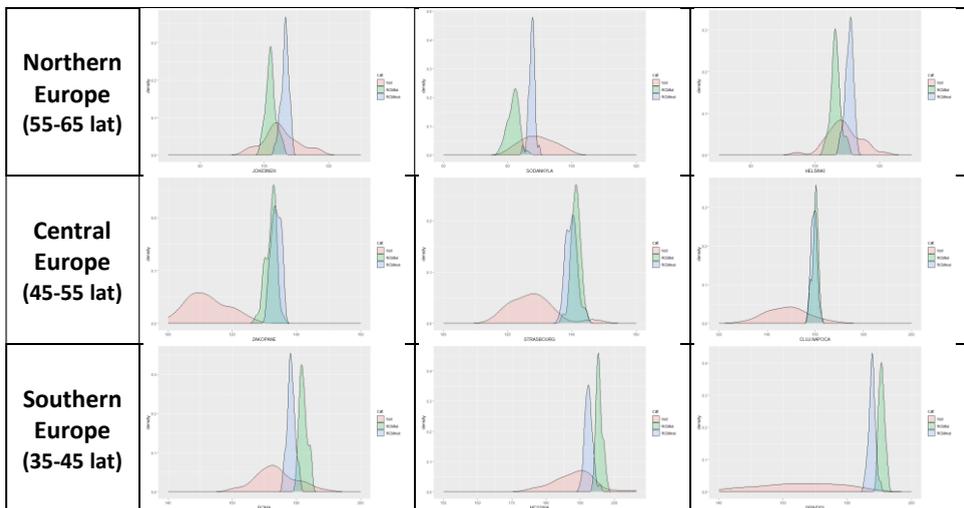


Fig. 3 Frequency distributions of EURO-CORDEX historical simulations 1971-2005 (blue colour), future projection 2065-2100 based on RCP8.5 (green colour), and in WRDC observations 1975-2006 (pink colour) at different stations over Europe.

3.2 Monthly changes of surface solar radiation in RCM simulations changes

In solar energy applications, the seasonal variability of surface solar radiation is a very important factor since in there is a significant difference in solar energy availability in the cold season and warm season. In this way, the changes surface solar radiation at monthly scale is also investigated in the study.

Fig. 4 presents the changes of surface solar radiation extremes in January and in July. In wintertime, both extremes are decreasing almost in the whole continent in average by -4.8% (minimum -28.9%) in case of low surface solar radiation, and by -2.9% (minimum -17.8%) in case of high extremes. These tendencies mean less energy available for PV production in this season, with higher values in the inner parts of continent. In summertime, both extremes are increasing excepting the norther part of the continent. Even if the overall average changes are -0,7% in case of 5th percentiles and -0,6% in case of 95th percentile, the greatest effect on the PV production can be found in the central end western part of the continent with changes even 16% in case of 5th percentiles, and 8% in case of 95th percentile, respectively.

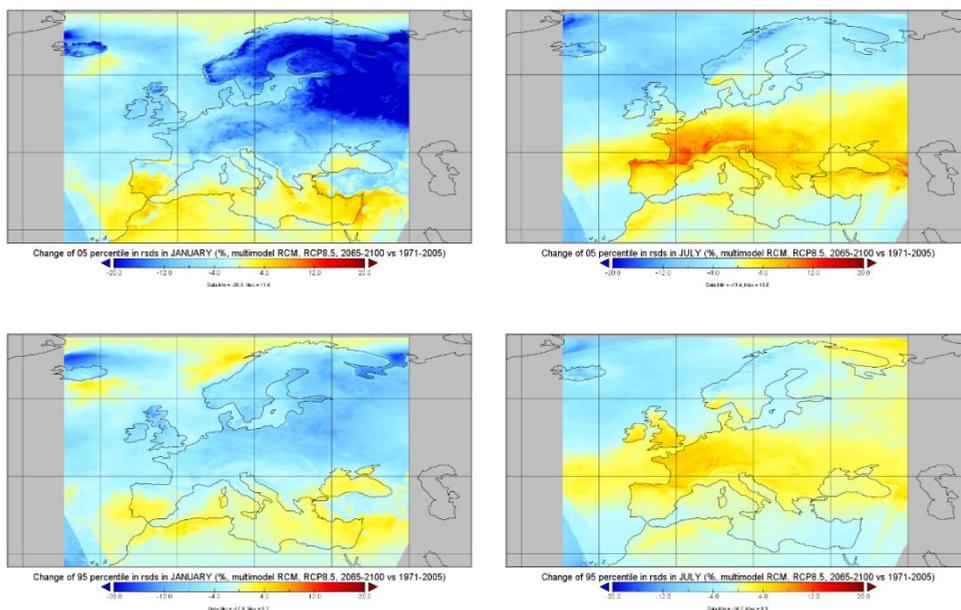


Fig. 4 Monthly surface solar radiation relative changes (%) in case of 5th percentile in January (upper left) and in July (upper right) and 95th percentile in January (bottom left) and in July (bottom right) in 56 EURO-CORDEX simulations, 2065-2100 vs. 1971-2005

Fig. 5 presents the relative changes of surface solar radiation extremes in each months in the three european sub-regions. The differences are more accentuated in case of low values (Fig. 5 left). In the winter months no significant changes was found in the southern part of the continent, in contrast, in the center

and northern part a decrease by 10% or more can be detected. In summer low values are increasing in the central and southern regions, but the magnitude of changes are less than 5%. In the case of 95th percentiles a difference between the changes in winter and summer can also be detected, but with smaller magnitudes.

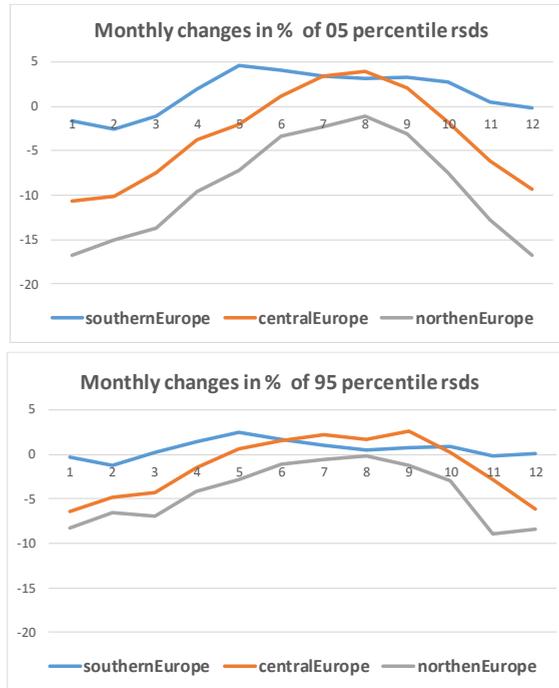


Fig. 5 Monthly surface solar radiation relative changes (%) in the sub-regions of Northern Europe (55-65 lat), Central Europe (45-55 lat) and Southern Europe (35-45 lat) of 5th percentile (left) and 95th percentile (right), multi-model mean of 56 EURO-CORDEX simulations, 2065-2100 vs. 1971-2005

4. IMPACT OF SURFACE SOLAR RADIATION CHANGES ON SOLAR POWER GENERATION

In the operational phase, the number of days when the surface solar radiation is below 5th percentile or exceeds the value of 95th percentile could be a key information. In the study, first the number of days in both cases was calculated for the historical period and for each month. Next, since these values are shifted in the future projections, the number of days below the 5th percentile and above the 95th percentile was also calculated for the period of 2065-2100.

The differences (in days) between the two periods are presented in Fig. 6. The results show that in the northern part of the continent the number of the days having surface solar radiation below the present-day 5th percentile will increase. In some regions, this could mean even 20-25 extra days with low radiation during the year. In case of high extremes, positive shifts are detected in the central part and southern part of the continent. In the south and southeastern regions, it could mean 15-20 extra days during the year having surface solar radiation above the present-day 95th percentile. It is not valid for the high altitudes in the region (Alps, Carpathians, Dinara, Apennine) where the changes are not so significant.

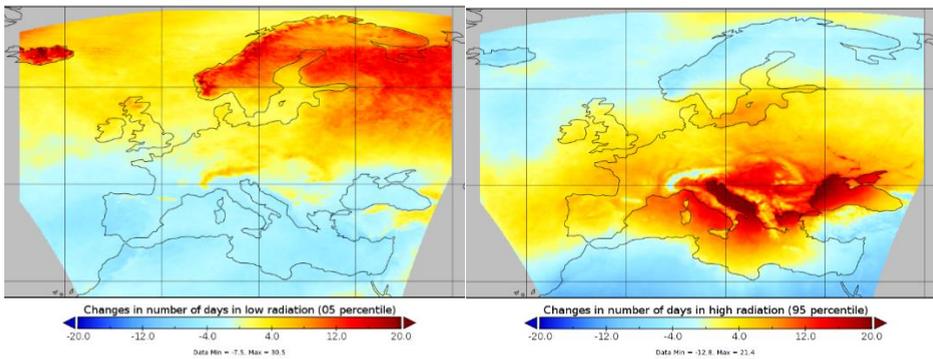


Fig. 6 Shift in number of days having surface solar radiation below the 5th percentile (left) and above the 95th percentile (right) based on the multi-model mean of 56 EURO-CORDEX simulations, 2065-2100 vs. 1971-2005

5. DISCUSSION AND CONCLUSIONS

In the study, the changes of low and high extremes of surface solar radiation are analysed since these situations have high impact on the solar power generation. The magnitude of changes was calculated based on 56 high-resolution (0.11°) EURO-CORDEX simulations taking into account a high radiation forcing in the future (RCP8.5). These RCMs differ in sense of structure, physical background, parametrisation, on the other hand they use different lateral conditions coming from 6 different General Circulation Models (GCM) (Table 2S). Several studies investigate the discrepancies between single model outputs (Coppola et al. 2021; Boe et al. 2020; Gutiérrez et al. 2020; Bartok et al. 2017) which contribute significantly to understand our climate system and to developing climate modelling, however, this is beyond the objectives of this

study. In impact studies, the full range of future climate responses should be taken into account, for this reason the use of multi-model means or sub-ensemble selection is recommended instead of single runs (Bartok et al. 2019). In our case, the high number of simulations considered in the study allows the use multi-model means, where the possible outliers are cancelled by averaging. In the study, a validation of model outputs against point-wise measurements was elaborated in order to check the magnitude of errors in modelled climate data. In general, the results indicate more narrow distributions (smaller standard deviation) in model simulations, furthermore, a shift of the full distribution towards low or high values are detected in several cases. On the other hand, spatial differences in the magnitude of errors also can be detected, which are determined by local-scale processes not captured by the model but still affecting the radiative budget, e.g. aerosol content. For this reason, first a bias-correction of modelled values with observations should be applied, in order to correct the model errors and then introduce them in impact studies. Several bias-corrected surface solar radiation runs are available, however the number of these runs are very limited (Bartok et al. 2019). It should be mentioned, however, that these type of model errors have effect of the absolute surface solar radiation values but do not have effect on the magnitude of their changes in the future. For this reason, and because in the study the full set of available row model data are analysed, only the relative changes are presented (in %) instead of the absolute values (W/m^2).

First, the annual surface solar radiation values was investigated and the projected changes of mean, 5th percentile and 95th percentile was calculated for the end of this century (2065-2100) using 1971-2005 as reference period. In the case of all three variables, the changes show similar spatial differences, obvious differences between the northern and southern part of the continent. In terms of sign and magnitude, these changes are in line with the results of other studies in the literature (Coppola et al.; 2020, Bartok et al. 2017; Jerez et al. 2015), however, these studies are mainly focusing on the evaluation of means, no surface solar radiation extremes are included. Indeed, in long-term solar energy applications planning the change of annual means consists the starting point, however, in the operational phase the changes in low solar energy availability or high solar energy availability became more important.

Base on the more pessimistic emission scenario (RCP8.5) the multi-model mean of EURO-CORDEX simulations shows that in the central and

northern part of Europe low surface solar radiation are becoming more frequent. The decrease of the 5th percentile can exceed even 10% in north and 4% in the countries located in the central region. These tendencies are even more accentuated in the cold period of the year, with -16% in northern part, and -10% in the central part of the continent, respectively. The significant reduction of solar energy availability negatively affect the PV generation and could cause severe shortage in energy supply in this season when, on the other hand, throughout the year the energy demand is the highest. The shift towards the lower surface solar radiation values in the future could mean even 25 extra days with lower radiation during the year in the northern part of the continent, and around 10 extra days with low radiation (less than the actual 5th percentile) in the central regions. Regarding changes in low surface solar radiation in the southern part of the continent, here positive changes are detected, but the magnitude of these changes are smaller (less than 5%) and characterizes the warm period of the year. A very slight negative changes can be found during the winter months (-1.5%), which indicate an extra 7 days with less radiation than the actual 5th percentile.

In terms of high extremes, the multi-model RCM means shows smaller changes. In the central and northern part of Europe high surface solar radiation values (95th percentiles) are decreasing mainly during wintertime, but this decrease do not exceed 10 % in these areas. On the other hand, in the southern part of the continent, no remarkable changes are detected throughout the whole year. Overall, in case of high radiation we have around 15 extra days in southern and centre part of Europe with higher radiation than the actual 95th percentile, while in the northern region this number is only 9.

In the study, a large set of RCM simulations was included in order to capture the whole range of climate response to the radiative forcing. However, single models can give very different surface solar radiation changes in terms of magnitude, and also in terms of sign. On the other hand, further inconsistency was detected between the regional climate models and the forcing global climate models or General Circulation Models (GCM). In general, GCMs give increases in surface solar radiation all over Europe (Hou et al. 2021; Boe et al. 2020; Bartok et al. 2017). In recent studies, the main factor causing these inconsistencies are attributed to the invariable aerosol representation in most RCMs (Boe et al. 2020; Nabat et al. 2020; Gutiérrez et al. 2020). Gutiérrez et al. (2020) found that RCMs including time-varying aerosols simulate an increase, especially in summer for

Central and Eastern Europe, with maximum values reaching +10% in some cases. All these studies suggests that it is important to be very careful when using the multi-model EURO-CORDEX projections for solar radiation and argues for the inclusion of aerosol forcing evolution in the next generation of CORDEX simulations.

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