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REVIEW OF SURFACE SOLAR RADIATION PROJECTIONS IN BIAS-CORRECTED EURO-CORDEX REGIONAL CLIMATE MODELS

Blanka Bartók[1,2]

[1]*Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA/CNRS/UVSQ, Gif-sur-Yvette 91191, France*

[2]*Hungarian Department of Geography, Babes-Bolyai University, Clinicilor 5-7, Cluj-Napoca 400006, Romania*

Article Info	Abstract
Received: 27.03.2018 *Accepted: 14.06.2018* **Keywords:** surface solar radiation, EURO-CORDEX regional climate model.	Regional climate models (RCMs) are used in a wide range of climate applications as they can provide high resolution (up to 10 to 20 km or less) and multi-decadal simulations of the climate system describing climate feedback mechanisms acting at the regional scale. However due to different forcing data and physics parametrisations regional climate models might produce different results. This study aims to achieve a state-of-the-art knowledge of bias-corrected surface solar radiation projections coming from 11 EURO-CORDEX regional climate models. First a comparison against 63 GEBA observations is elaborated indicating a general overestimation of surface solar radiation (SSR) in the RCMs by 6.12 W/m^2 (4.4%). Next changes in surface radiation between the period of 2031-2060 and 1971-2000 are presented on annual and seasonal time scale. The model projections indicate robust increase in SSR mainly in the western part of the Mediterranean region, while the northern part of the continent is characterised by decreases in SSR till the middle of this century. The study emphasis the need of an overall validation of different climate models before introducing them in impact studies in order to have an overview regarding the uncertainties.

1. Introduction

The spatial and temporal distribution of surface solar radiation can be considered not only the main factor of the environmental physical processes, but also as a main aspect of the subsistence of the society, such as food production, ecosystems, energy system, etc. In this way the characteristics and variations of solar radiation related processes of the Earth-atmosphere system have social and economic impacts as well. From the atmospheric point of view we consider the shortwave solar radiation (<4μm) reaching the surface (SSR) as the main energy source of our system. Despite of the large climate modelling community, however, studies concerning future projection of SSR are still scarce. Focusing on Europe a limited number of papers describe scenarios of surface solar radiation projections based on global [1], [2], [3] and regional [4] [5] [6] climate models. Even if these type of assessments are substantial, comparing and interpreting their outcomes some controversial conclusions have been found in terms of the magnitude and sign of SSR changes [7]. In general, in the impact studies the validation of applied model data (in the historical periods) and also the intercomparison of climate models are missing which introduces uncertainties into this type of studies.

However, several model validations have been done in the case of temperature and precipitation fields, but very little effort put in the validation of the different component of the energy balance such as SSR. However, the validation of radiation products should be emphasized mainly because these radiation products are parametrized instead of being calculated, and the compensating errors of the model could result in big biases.

On the other hand, the evaluation of the climate system is controlled not only by natural processes, but also by anthropogenic activities [8] difficult to foresee (e.g. greenhouse gas emissions, aerosol loadings). So the uncertainties in climate predictions could originate, on the one hand, from the lack of theoretical knowledge, but, on the other hand, also from the unforeseeable behaviour of the society. Hereafter the present study emphasizes the need of multi-model evaluation of SSR changes before elaborating any impact studies.

The paper is organized as follows. Section 2 describes the regional climate models and observational data used in the study, Section 3 presents the results regarding validation against surface observations, Section 4 includes future changes of surface solar radiation in different regional climate models, and Section 5 includes the conclusions and final remarks regarding review of surface solar radiation changes in EURO-CORDEX regional climate models.

2. Data

2.1 EURO-CORDEX regional climate models

Regional climate models (RCMs) are used in a wide range of climate applications as they can provide high resolution (up to 10 to 20 km or less) and multi-decadal simulations of the climate system describing climate feedback mechanisms acting at the regional scale. RCMs are nested in global climate models (GCMs) deriving initial conditions, time-dependent lateral meteorological conditions and surface boundary conditions from the given GCM.

Embedded into the Coordinated Regional Climate Downscaling Experiment (CORDEX), EURO-CORDEX [9] provides regional climate projections for Europe at grid-spacing of about 12 km (0.11°x0.11° degree resolution). The experiment gathers outputs of different regional climate models developed and maintained in several climate research institutes. Table 1 contains the 11 regional climate models considered in the study where the driving GCM realizations are also listed.

In the study bias corrected simulations have been included, where WFDEI meteorological forcing data set [10] are applied as reference data. The bias-correction has been elaborated in the framework of Clim4Energy project (http://clim4energy.climate.copernicus.eu/) using the Cumulative Distribution Function Transform (CDFT) method [11]. The bias-corrected simulations are published and freely available on the ESGF server.

Table 1 The 11 EURO-CORDEX regional climate model considered in the study

	Institute	**Driving Global Climate Model (realization)**	**Regional Climate Model**
1	Helmotz Centrum Max Plank Institute-Climate Service Center	MPI-ESM-LR (r1i1p1)	REMO2009
2	Swedish Meteorological and Hydrological Institute (SMHI)	MPI-ESM-LR (r1i1p1)	RCA4
3	Swedish Meteorological and Hydrological Institute (SMHI)	HadGEM2-ES (r1i1p1)	RCA4
4	Centre National de la Recherche Météorologique (CNRM)	CNRM-CM5 (r8i1p1)	ARPEGE52
5	Swedish Meteorological and Hydrological Institute (SMHI)	CNRM-CM5 (r1i1p1)	RCA4
6	Danish Meteorological Institute (DMI)	EC-EARTH (r3i1p1)	HIRHAM5
7	The Royal Netherlands Meteorological Institute (KNMI)	EC-EARTH (r1i1p1)	RACMO22-E
8	Swedish Meteorological and Hydrological Institute (SMHI)	EC-EARTH (r12i1p1)	RCA4
9	Institute Pierre Simon Laplace-	IPSL-CM5A-MR (r1i1p1)	WRF331F
10	Swedish Meteorological and	IPSL-CM5A-MR	RCA4

	Hydrological Institute (SMHI)	(r1i1p1)	
11	The Royal Netherlands Meteorological Institute (KNMI)	HadGEM2-ES (r1i1p1)	RACMO22-E

2.2. Observations

The validation has been performed by comparing the SSR simulations with observations coming from the Global Energy Balance Archive (GEBA) [12]. The study area is represented by 63 stations (Fig. 1) for the period of 1971-2010. In order to calculate yearly means the missing monthly observations has been filled using the MASH homogenization method [13].

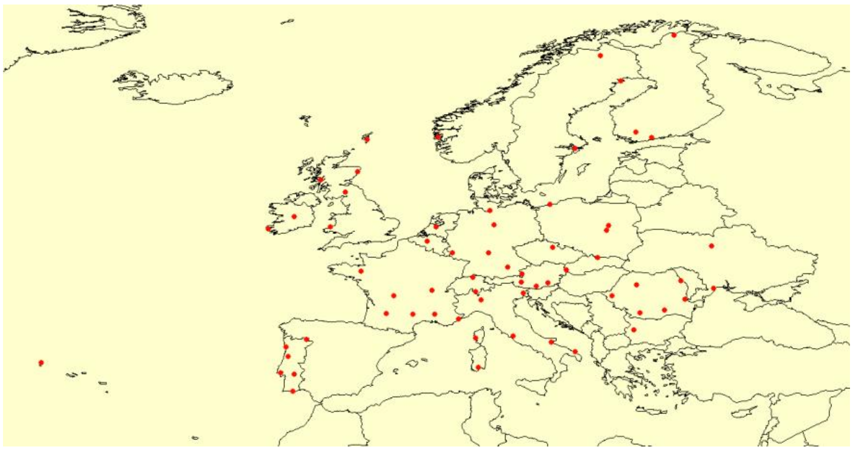

Fig. 1. The 63 surface solar radiation GEBA stations considered in the study

3. Validation of SSR simulations

Before using RCM simulations in impact studies consideration needs to be given to the limitations of such products. First RCMs could inherit systematic errors from the fields provided by the driving GCM, on the other hand the inner parametrization, model domain size and resolution, technique for assimilation of large-scale meteorological conditions, and internal variability could produce biases as well. In this way validation of simulated fields against observations in the historical period give a very useful overview regarding the uncertainty associated to future projections. The most common index to quantify the differences is the BIAS calculated as the difference between modelled data and observations. As Fig. 2 shows the regional climate models overestimate the surface solar radiation by 6.12 W/m^2. However there are differences among the models due to the different driving GCM but also due to the different parametrisations. Regarding the extremes the multi-model Q05 absolute bias is 5.37 W/m^2, and the Q95 absolute bias is 6.94 W/m^2. This fact indicates that the models give higher values on the low extremes and also on the high extremes which is the result of the shift of the whole distribution towards high values.

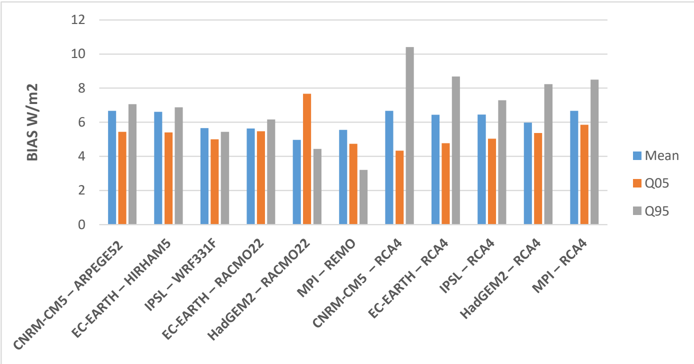

Fig. 2. BIAS (W/m^2) of surface solar radiation simulations in the 11 EURO-CORDEX models (first name driving GCM, second name of the RCM)

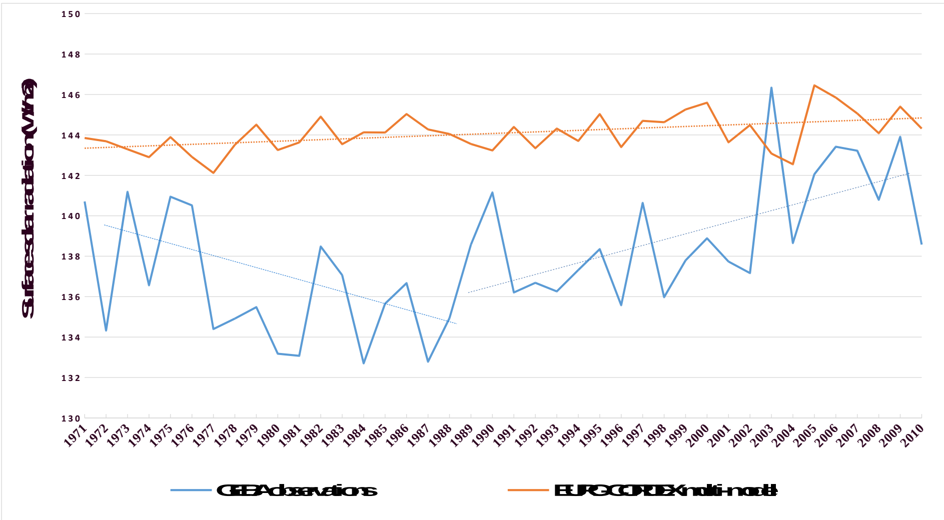

Fig. 3. Surface solar radiation time series over Europe in the period of 1971-2010 in GEBA observations - mean of 63 station data (blue curve) and in the 11 EURO-CORDEX simulations - multi-model mean (orange curve).

In terms of trends significant bias can be detected between the trend in observations and in multi-model mean of RCMs (Fig. 3). GEBA observations (mean of 63 station) indicate a decrease of SSR in the period of 1971-1990 by 1.09 W/m^2 per decades called “global dimming” period [14], while starting from 1991 reproduce the brightening period [15] by 3.45 W/m^2 per decades. In case of model simulations this change in trends cannot be detected, where we have a continuous slight increase by 0.38 W/m^2 per decades. However it should be mentioned that all RCMs investigated here consider temporally invariant aerosol climatology only, therefore they cannot reproduce the full extent of the decadal SSR variability, which is considered to be mainly caused by changes in the aerosol content over Europe in the last decades [16].

4. Long term changes of surface solar radiation

RCMs simulate future climate based on different Representative Concentration Pathways (RCPs). The four RCPs, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively). In the study only the middle-way RCP4.5 is considered. Changes in SSR can be defined as the difference between multi-year mean projected for the future and means simulated for the historical periods. In this case two periods are compared, namely 1971-2000 and 2031-2060. Fig. 4 presents the annual changes of surface solar radiation in case of the 11 regional climate simulations. Using different boundary conditions RCMs give a general decrease in SSR, the multi-model change is -0.64 W/m^2. Similar changes have been reported in [7]. However, opposite sign in changes can be observed among the models. Obviously, the SSR changes in the RCMs are mainly controlled by internal processes of the model and little influenced by the boundary forcings as we have different trends in regional climate models driven by the same GCM (e.g. CNRM – ARPEGE51 and CNRM – RCA4).

Fig. 5 shows the multi-model seasonal changes for the 2031–2060 vs. 1971–2000 period. The multi-model mean of the 11 RCMs included in the study gives SSR relative changes (reference period 1971-2000) between -6.0% and +5.1% in wintertime, between -8.3% and +7.1% in spring, between -7.0% and +6.2% in summer and between -3.7% and 7.5% in autumn over the whole European domain. The results show that spring exhibits the strongest negative changes while autumn has the strongest relative increase in SSR.

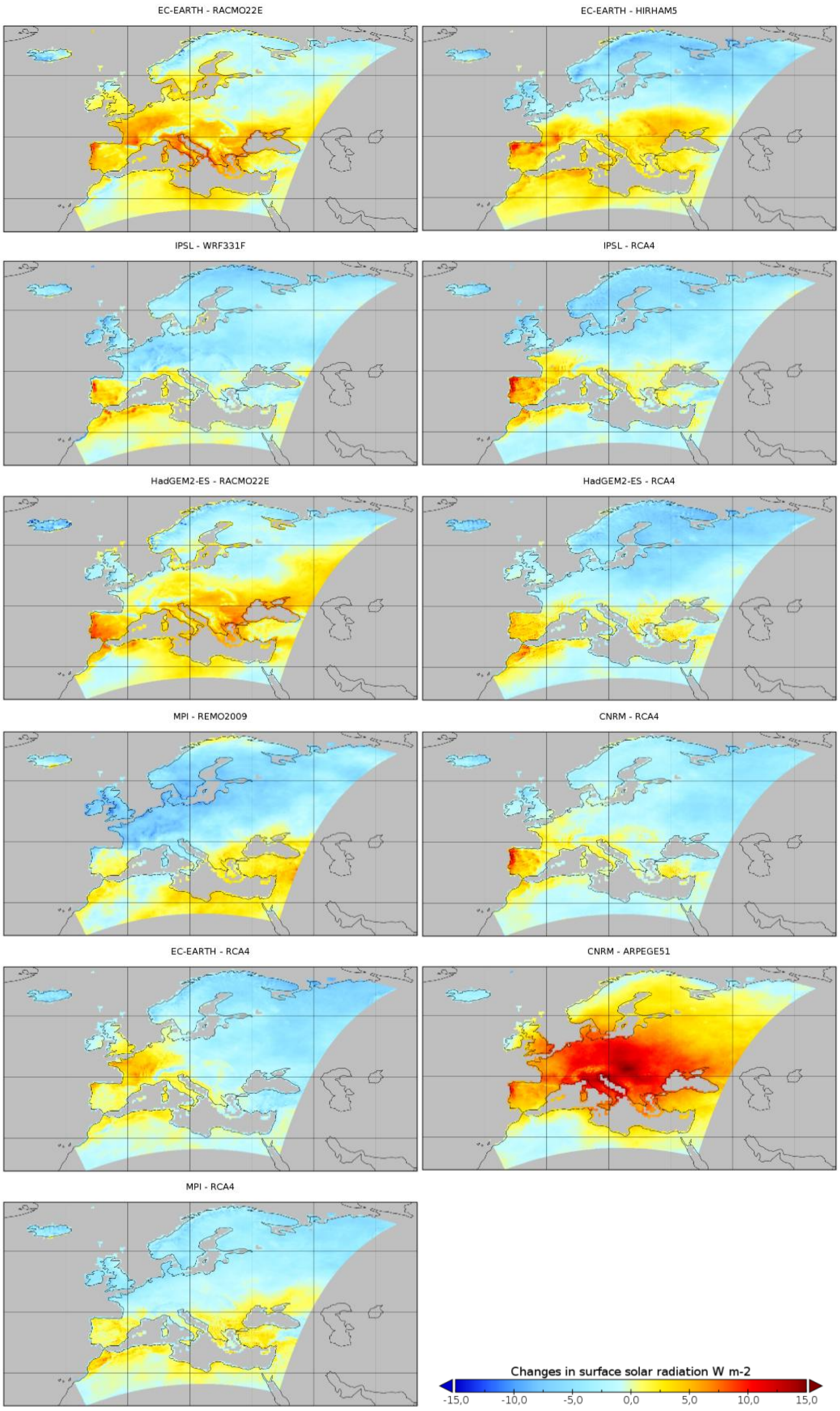

Fig. 4. Projected changes in surface solar radiation in the 11 EURO-CORDEX bias-corrected simulations (first name is the driving GCM, second name the RCM). The changes are calculated as the difference between the future projections for RCP4.5 (2031–2060) and the historical simulation (1971–2000). The scale at the bottom right is to be applied for each map.

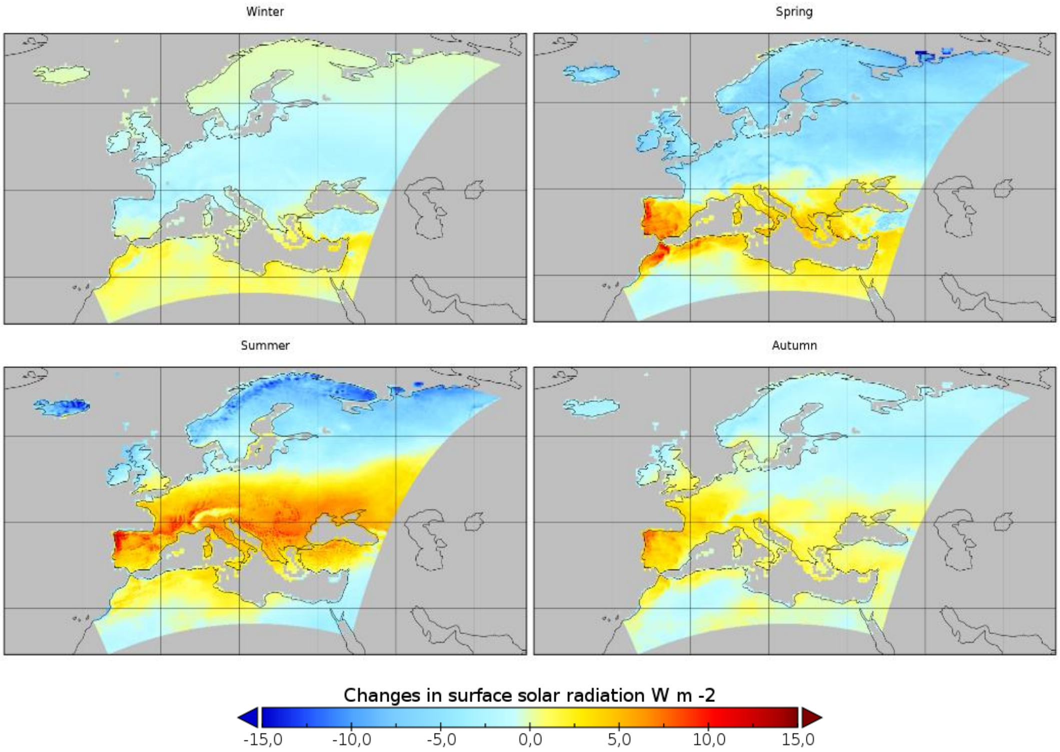

Fig. 5. Seasonal changes in surface solar radiation in 11 EURO-CORDEX bias-corrected simulation – multimodel-mean. The changes are calculated as the difference between the future projections for RCP4.5 (2031–2060) and the historical simulation (1971–2000). The scale at the bottom is to be applied for each map.

In spite of opposite changes in singular models, however, RCMs future projections can be used in impact studies taking into account the agreement among the models. In case of high agreement (>80%, here more than 9 out of the 11 models) the uncertainties became very low. Fig 6 shows the agreement among the 11 simulations, where negative changes are set to 0, positive changes are set to 1. That means that regions having values less than 3 show a significant decrease in surface solar radiation (more than 80% of the simulations), while regions showing values higher than 9 indicate significant increase in surface solar radiation (more than 80% of the simulations). Over the European domain robust increases in SSR can be detected mainly in the western part of the Mediterranean region, while the northern part of the continent is characterised by decreases in SSR till the middle of this century.

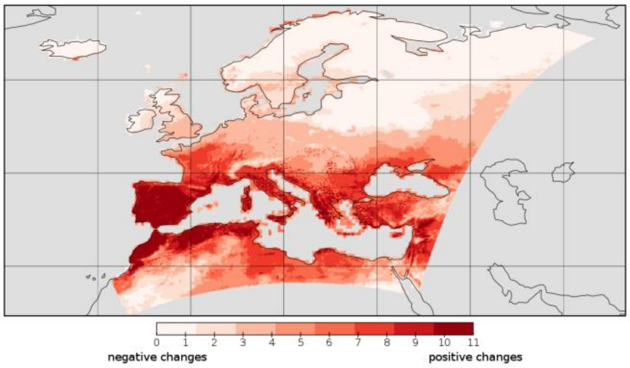

Fig. 6. Agreement in sign of SSR changes among the 11 EURO-CORDEX simulations, negative changes are set to 0, positive changes are set to 1.

5. Conclusions and remarks

The study gives a general review of long-term projections SSR assessing 11 bias-corrected EURO-CORDEX simulations. The point-wise comparison with GEBA station data reveals an overall overestimation of SSR in regional climate models by 6.12 W/m^2 (4.4 %). The whole distribution of simulated data also presents a shift towards high values. In terms of trends in the historical period model simulations cannot reproduce the global dimming and global brightening periods mainly because no time variant aerosol data are included in the simulations [7]. Future projections of SSR indicate a slight decrease for the European domain, however regional differences should be considered. The projections are robust (>80% agreement among the models) in the western part of the Mediterranean region indicating increase in SSR, while the northern part of the continent is characterised by less SSR till the middle of the century.

The results of the study on spatial variation and multi-annual changes in SSR are essential in many applications field, such as solar energy applications, studies related to the change of terrestrial ecosystems, as well as in the analysis of problems related to water supply and agriculture. In any cases the study highlights the importance of evaluating the SSR future projections from different climate models and suggest to analyse not singular realisations but multi-model ensembles.

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