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Znanstveni časopis *Hrvatski meteorološki časopis* nastavak je znanstvenog časopisa *Rasprave* koji redovito izlazi od 1982. godine do kada je časopis bio stručni pod nazivom *Rasprave i prikazi* (osnovan 1957.). U časopisu se objavljuju znanstveni i stručni radovi iz područja meteorologije i srodnih znanosti.
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SURFACE DOWNWELLING SHORTWAVE RADIATION FLUX PROJECTIONS FOR 2021−2050 IN MOROCCO ACCORDING TO CORDEX-AFRICA REGIONAL CLIMATE MODELS

Projekcije površinskoga dolaznog kratkovalnog zračenja za razdoblje 2021. − 2050. u Maroku prema CORDEX-Afrika regionalnim klimatskim modelima

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Abstract: The article considers the results of an estimation of the shortwave radiation flux at the surface in Morocco from 2021–2050. Average monthly values of shortwave radiation coming to the underlying surface (Surface Downwelling Shortwave Radiation, RSDS), calculated using 11 regional climate models of the CORDEX-Africa project, were used as input data. The model calculation was performed assuming a greenhouse gas concentration scenario of RCP4.5. The aim of the work is to determine the characteristics of the distribution of shortwave radiation over the territory of Morocco from 2021–2050 and to identify areas with favourable conditions for developing solar energy in the near future. The results of an analysis of annual RSDS values in the vicinity of the solar power station in Ouarzazate in 2021–2050 are also presented.

Key words: CORDEX-Africa, Surface Downwelling Shortwave Radiation, RCM, solar energy, Morocco

Sažetak: U članku se razmatraju rezultati procjene površinskoga dolaznog kratkovalnog zračenja (RSDS) za razdoblje 2021. – 2050. godine u Maroku. Kao početni podatci upotrijebljene su prosječne mjesečne vrijednosti RSDS-a izračunane s pomoću 11 regionalnih klimatskih modela CORDEX-Afrika. Izračun modela izveden je uzimajući u obzir scenarij koncentracije stakleničkih plinova RCP4,5. Cilj je rada utvrditi osobine raspodjele RSDS-a preko teritorija Maroka u razdoblju 2021. – 2050. te identificirati područja s povoljnim uvjetima za razvoj solarne energije u bliskoj budućnosti. Također, prikazani su rezultati analize godišnjeg RSDS-a na području solarne elektrane u Ouarzazatu 2021. – 2050.

Ključne riječi: CORDEX-Afrika, površinsko dolazno kratkovalno zračenje, RCM, solarna energija, Maroko

1. INTRODUCTION

Solar radiation is one of the most affordable and energy-intensive of all renewable energy sources. The world's leading economists have come to the conclusion that the modern long-term energy development strategy can no longer be based solely on the fuel and energy complex, and that the way out of this situation is a gradual transition to alternative energy through the use of natural renewable energy sources on a global scale. Today, worldwide energy consumption trends are increasing due to high rates of economic development, demographic growth, and changes in people's living standards. Industrially developing countries see energy security as a national security and sovereignty issue. Additionally, in recent decades, there has been a need for rapid solutions to the urgent environmental problems associated with increased levels of atmospheric greenhouse gas emissions. Climate change, which has been observed worldwide since the mid-1970s, will lead to the redistribution of natural renewable resources. Therefore, a timely assessment of possible changes in the potential of solar energy resources in Morocco is an urgent issue that will ensure its energy security in the future.

Regional changes in the climate system are affecting the socio-economic development of many countries. The instability of the climate system manifests mainly in the formation of abnormal modes of temperature indices, wind characteristics, atmospheric phenomena, etc. In this context, the availability of the most reliable information on the future climate is a strategically important point in the development of Morocco's economy. Today, it is possible to obtain such information by modeling future climate conditions using climatic models.

An assessment of Morocco's thermal solar power potential was carried out in studies by both Moroccan and European scientists. Nfaoui and Sayigh (2013) conducted a study of the solar energy potential of the Ouarzazate region using observations from July 1982 to December 1989. As a result, the Ouarzazate region has been shown to have a high solar power potential: sunshine hours – 3,400 hours per year; daily global radiation: 5.5 $kWhm^{-2}day^{-1}$. Radiation attenuation increases from 30% in June (maximum radiation) to 40% in November. The average monthly value of direct radiation on the normal surface ranges from 5.56 $kWhm^{-2}day^{-1}$ (December) and 8.47 $kWhm^{-2}day^{-1}$ (May). This shows that the Ouarzazate area is suitable for concentrated solar systems for large-scale electricity production.

The study of the impact of climate change on the amount of shortwave radiation entering the underlying surface was conducted by Italian scientists within the framework of the CLIM-RUN project for the Mediterranean region, including the territory of northern and central Morocco (Calmanti and Dell'Aquila, 2014). The work determined the change in the amount of shortwave radiation in the period from 2021–2050 as compared to 1961–1990. As a result, it was concluded that RSDS is expected to increase in Southern Europe in the future. For the territory of northern and central Morocco, RSDS is expected to increase to 5 Wm^{-2} in the northern and northeastern regions of the country in December–February, while minimal or zero change is expected from June–August.

The impact of climate change in Europe (including the northern Morocco region) on solar photovoltaic energy was estimated by analysing the quantity of RSDS calculated by the CORDEX project (Jerez et al., 2015). As a result, it was concluded that RSDS values will increase from 2070–2099 in the southern Mediterranean as compared to 1970–1999. Today, the WRF and ECHAM models calculate shortwave radiation parameterization by interpolating data obtained from calculating all absorption lines, taking into account the actual temperature and pressure. Fourteen spectral intervals are considered separately for shortwave radiation. The calculation error does not exceed 3 Wm^{-2} in the case of clear skies (Tolstyh, 2016). An evaluation of CORDEX-Africa project models shows that a majority of RCMs underestimate overland-mean cloudiness and spatial variability as compared to the gridded surface station data of the Climatic Research Unit, and that simulated cloudiness is not as reliable as precipitation or air temperatures. Simultaneously, most models simulate the annual cycle in the western Mediterranean and western Sahara well (Kim et al., 2014).

The key element in high-accuracy calculation of radiation balance models for top-of-atmosphere

(TOA) and surface radiation budgets is the correct representation of clouds in the models by identifying characteristics such as cloud cover, cloud water mass, and cloud particle size. Most global climate models (GCM) usually represent hydrometeors in suspended state, which generates some discrepancies when comparing model calculations with the results of satellite observations. The multi-model ensemble mean bias of RSDS to CMIP5 is ~2.5 Wm^{-2}, mainly due to positive shifts over the land and negative bias over the ocean. Constant and systematic spatial biases in most models with average values of the multi-model ensemble overestimate RSDS in the strongly convective region of the tropics. GCMs underestimate water content due to errors in precipitation representations and convective cloud core, which in turn leads to an overestimation of RSDS (Li et al., 2013). Total cloud cover is a key component affecting the influx of radiation. Offsets in clouds and RSDS calculations have opposite signs (Katragkou et al., 2015).

A study of the current state of the solar potential of Morocco has shown that solar resources are abundant throughout its territory. The hinterland administrative areas of Souss – Massa Region, Draa – Tafilalet, Laayoune – Sakia El Hamra, Dakhla – Oued Ed-Dahab, and Marrakesh – Safi Region (Fig. 1) have sufficient resources to use Concentrated Solar Power plants (CSP). The western parts have optimal conditions for Photovoltaic (PV). The energy strategy of Morocco includes the commissioning of such solar energy projects by 2020 (Schinke et al., 2016):

- two mixed CSP/PV solar complexes in Ouarzazate (510 MW CSP and 70 MW PV), and Midelt (320 MW CSP and 80 MW PV) contributing around 980 MW;
- two PV projects in Boujdour (80 MW PV) and Laayoune (20 MW PV);
- three regional PV complexes – with singular projects in the range of 10–30 MW – in the central provinces (100 MW PV Noor Tafilalt, 200 MW PV Noor Atlas and 100 MW Noor Argana);
- private PV projects with a planned installed capacity of 470 MW.

The aim of the work is to determine the characteristics of shortwave radiation distribution over the territory of Morocco from 2021–2050 and to identify areas with favourable conditions for the development of solar energy in the near future.

2. STUDY AREA

Morocco is located in the northwest of Africa at a latitude of 20ºN to 35ºN. The area of the territory is 446,550 km² (Fig. 1). It is bordered by the Mediterranean Sea in the north and the Atlantic Ocean in the west with a coastline of 1835 km. Morocco is separated from Europe by the Strait of Gibraltar. The Eastern borders are within the continent. The territory of the country can be divided into four physical and geographical regions: the Rif (mountain region), located parallel to the Mediterranean coast, with an altitude not exceeding 1500 m; the Atlas Mountains run from southwest to northeast and are divided into three main ridges: the Anti-Atlas (2360 m), the High Atlas, whose peaks exceed 3700 m, and the Middle Atlas, the northern part of which is a plateau at an altitude of roughly 1800 m; the coastal plains region lying on the Atlantic coast; the valleys, located south of the Atlas Mountains, which pass into the desert. The Fes-Taza corridor stretches between the Rif and the Middle Atlas.

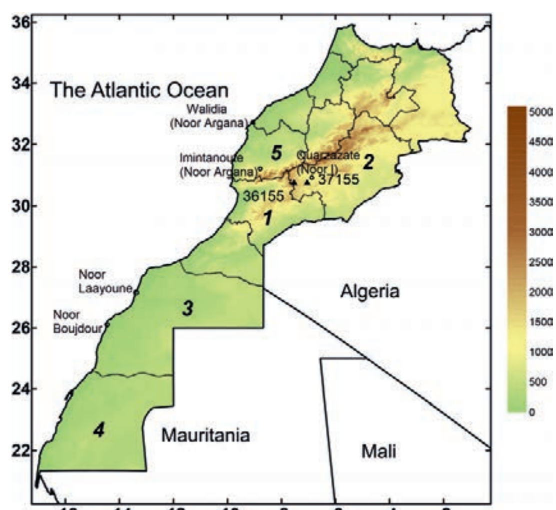


Figure 1. Map of Morocco (black triangles – model grid nodes No 36155 and 37155, for which the annual RSDS and TC cycle is provided; 1 – Souss – Massa, 2 – Draa – Tafilalet, 3 – Laayoune – Sakia El Hamra, 4 – Dakhla – Oued Ed-Dahab, 5 – Marrakesh – Safi).

Slika 1. Karta Maroka (crni trokuti – točke mreže broj 36155 i 37155 za koje je dan godišnji ciklus RSDS i TC; 1 – Souss – Massa, 2 – Draa – Tafilalet, 3 – Laayoune – Sakia El Hamra, 4 – Dakhla – Oued Ed-Dahab, 5 – Marrakesh – Safi).

The Atlas range passes through the centre of the country, forming a dividing line between the two main climatic zones – the Mediterranean northern coastal region, and the southern, inner region lying on the edge of the hot Sahara desert.

3. DATA AND METHODS

The CORDEX-Africa project's regional climate modelling data with high spatial resolution were used to study future climate change in Morocco (Kim et al., 2014; Dosio and Painitz., 2016; IS-ENES, 2018). The CORDEX climate data were obtained from observational data analysis (1988–2010) or global climate models (1950–2100) (CORDEX-Africa, 2019). RCM modelling was carried out for the region of Africa, with a spatial resolution of ~44 km. The model calculation was performed assuming a greenhouse gas concentration scenario of RCP4.5. Eleven combinations of regional and global climate models developed at leading research institutes and meteorological centres around the world were used for the calculation. A brief description of the models used is provided in Table 1.

Modelling for the period from 2021–2050 provided average monthly surface downwelling shortwave radiation RSDS (Wm^{-2}) values; for more detailed analysis, the average monthly total cloud cover TC (%) values for this period were also calculated. The values for the territory of Morocco were then extracted from the modelling data.

As a rule, averaging across the ensemble of models shows the most successful reproduction of average climatic characteristics as compared to observational data. This is due to the fact that the systematic errors inherent in each model individually are often random in relation to the ensemble of models; averaging across the ensemble compensates for these errors (Pavlova et al., 2014).

To estimate the RSDS change from 2021–2050 as compared to the recent climatic period, the average monthly RSDS values for 1971–2000 were obtained from the historical run of CORDEX-Africa RCMs. The satellite observation data of CERES_EBAF-Surface_Ed4.0 data for the period from 2005–2015 (average monthly RSDS values) were additionally considered (Electronic database, 2018).

4. RESULTS AND DISCUSSION

The analysis of average RSDS value for 2021–2050 shows a latitudinal distribution, with some deviations in the mountainous and coastal Atlantic ocean areas (Fig. 2a). The largest RSDS values are simulated in the inner regions of the southern part of Morocco and in the Anti-Atlas (250 to 290 Wm^{-2}). The lowest RSDS values are simulated in the north of the country in the areas of Tanger – Tetouan – Al Hoceima region and the Oriental region, as well as in the Middle Atlas in the Fes – Meknes Region (200 to 220 Wm^{-2}), which is a consequence of the increased total cloudiness in these areas (Fig. 2b).

Table 1. Regional climate models used for the calculations.

Tablica 1. Regionalni klimatski modeli koji su upotrijebljeni za proračune.

Nº of model	RCM Model Name and Version ID	Driving GCM	Data Centre
1	KNMI-RACMO22T_v1	ICHEC-EC-EARTH	CNRM, France
2	SMHI-RCA4_v1	CCCma-CanESM2	CCCMA, Canada
3	SMHI-RCA4_v1	CNRM-CERFACS-CNRM-CM5	CNRM/CERFACS, France
4	SMHI-RCA4_v1	ICHEC-EC-EARTH	CNRM, France
5	SMHI-RCA4_v1	CSIRO-QCCCE-CSIRO-Mk3-6-0	CSIRO, Australia
6	SMHI-RCA4_v1	IPSL-IPSL-CM5A-MR	IPSL, France
7	SMHI-RCA4_v1	MIROC-MIROC5	AORI/NIES/JAME S&T, Japan
8	SMHI-RCA4_v1	MOHC-HadGEM2-ES	Hadley Centre, UK
9	SMHI-RCA4_v1	MPI-M-MPI-ESM-LR	MPI, Germany
10	SMHI-RCA4_v1	NCC-NorESM1-M	NCC, Norway
11	SMHI-RCA4_v1	NOAA-GFDL-GFDL-ESM2M	GFDL, USA

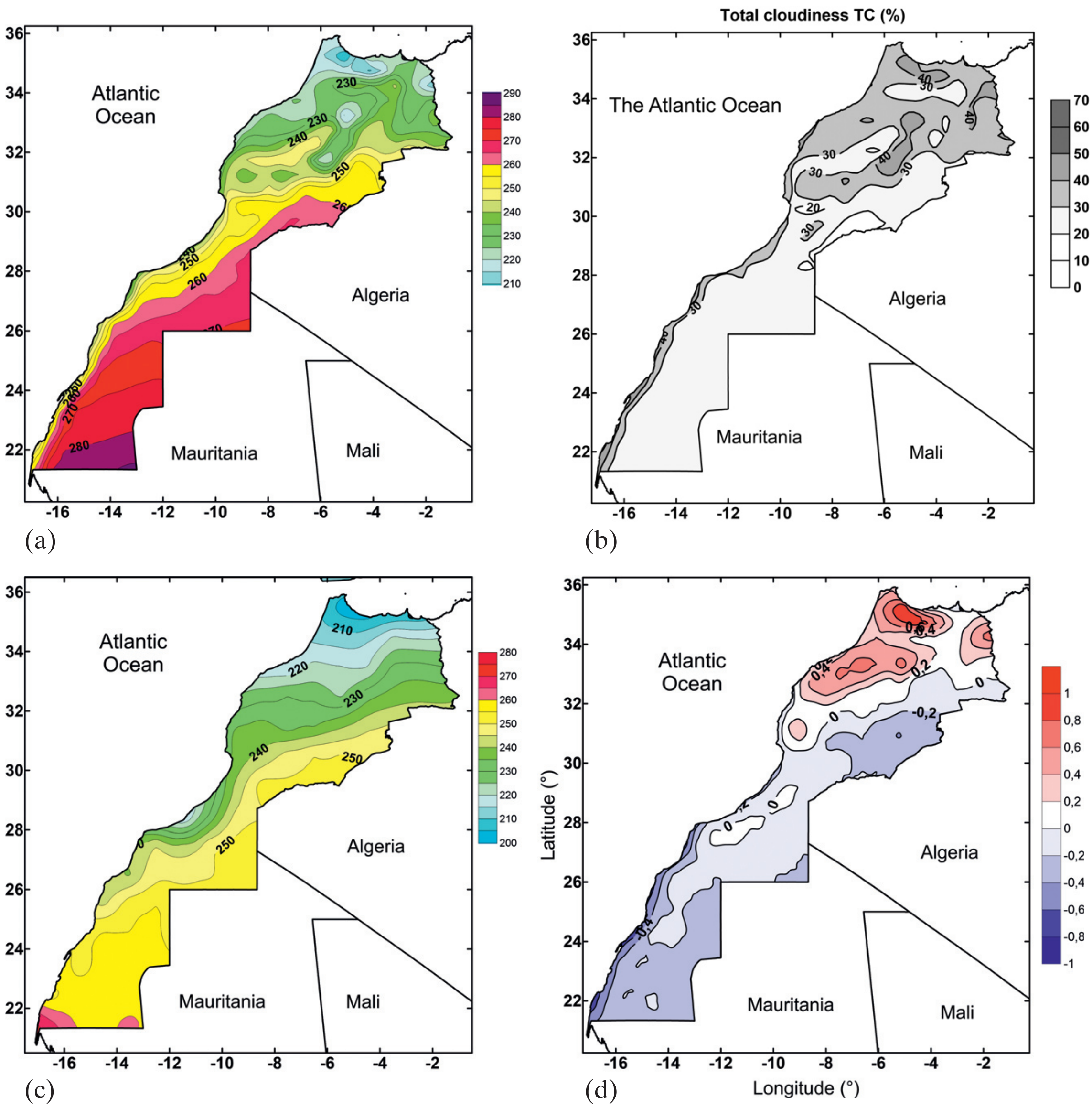


Figure 2. Mean of multi-RCM ensemble RSDS (Wm^{-2}) for 2021–2050 (a); mean of multi-RCM ensemble total cloudiness TC (%) for 2021–2050 (b); satellite observation RSDS (Wm^{-2}) for 2005–2015 (c); RSDS (Wm^{-2}) changes for 2021–2050 versus 1971–2000 (d).

Slika 2. Srednja vrijednost multi-RCM ansambla RSDS (Wm^{-2}) za razdoblje 2021. – 2050. (a); srednja vrijednost ukupne naoblake ansambla multi-RCM-a TC (%) za razdoblje 2021. – 2050. (b); satelitska opažanja RSDS (Wm^{-2}) za razdoblje 2005. – 2015. (c); RSDS (Wm^{-2}) promjene 2021. – 2050. u odnosu na 1971. – 2000. (d).

The analysis of RSDS changes in 2021–2050 as compared to 1971–2000 (Fig. 2a, d) shows that the largest increase is projected in the Rif (0.96 Wm^{-2}). Increases are also expected in the eastern region (up to 0.65 Wm^{-2}) and in the Moroccan Meseta (up to 0.68 Wm^{-2}). Decreases are projected in the southern Atlantic coast (-0.69 Wm^{-2}).

It should be noted that an increase in RSDS from 3 to 5 Wm^{-2} in the winter months in the Tanger – Tetouan – Al Hoceima region, the Oriental region, Fes – Meknes, Rabat – Sale – Kenitra, and Beni Mellal – Khenifra region was shown in model calculations received by Italian scientists as a result of climatic change studies in the Mediterranean basin within the CLIM-RUN program (Calmanti and Dell'Aquila, 2014).

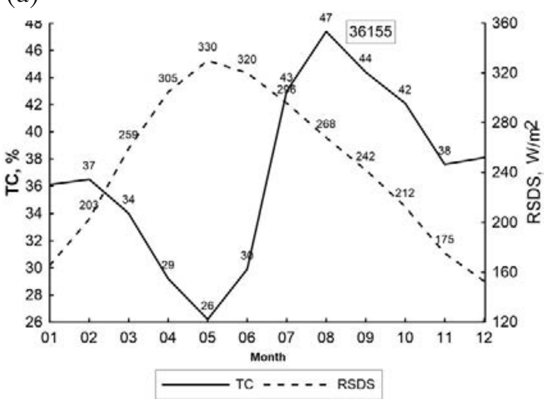
It is interesting to estimate the change in the RSDS value in areas where solar power plants are located. Let us consider what changes can be expected at these sites in greater detail.

1. In the Draa – Tafilalet region, where the largest concentrating and photovoltaic power stations are located (Ouarzazate, Midelt, Noor Tafilalt, Noor Atlas, and Noor Argana plants), the models predict a decrease of RSDS by up to -0.4 Wm^{-2}.

2. In the Laayoune – Sakia El Hamra region, where large stations are located in Boujdour, the RCMs predict a decrease in RSDS of up to -0.6 Wm^{-2}.

3. In Marrakesh – Safi, where a solar photovoltaic power plant (Imintanoute) is under construction as part of the Noor Argana project, an increase of 0.25 Wm^{-2} is expected.

(a)



(b)

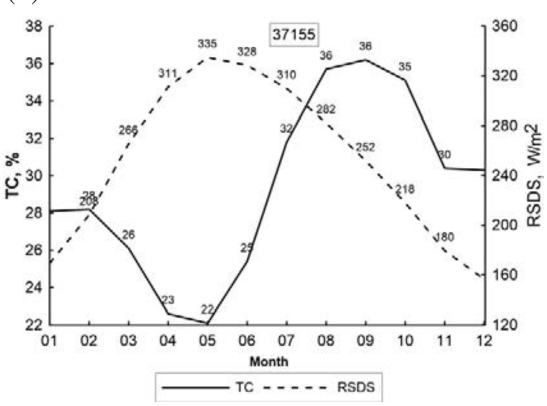


Figure 3. Annual cycle of total cloudiness TC (%) and RSDS (Wm^{-2}) in grid nodes 36155 (coordinates: 30.75 °N, 7.75 °W) – (a) and 37155 (coordinates: 30.75 °N, 7.25 °W) – (b).

Slika 3. Godišnji hodovi ukupne naoblake TC (%) i RSDS (Wm^{-2}) u mrežnim točkama: 36155 (koordinate: 30,75 °N, 7,75 °W) – (a) i 37155 (koordinate: 30,75 °N, 7,25 °W) – (b).

The annual course of RSDS is influenced by the amount of incoming solar radiation due to astronomical factors (the rotation of the Earth around the Sun, the inclination of the Earth's axis of rotation relative to the Earth's orbital plane (ecliptic), the daily rotation of the Earth) and the annual run of total cloud cover. The nature of seasonal changes in the arrival of solar radiation (insolation) is well traced in the change in its daily amounts at TOA, and varies at different latitudes.

In the extratropical latitudes of the Northern Hemisphere, the annual cycle of insolation has one maximum in June and one minimum in December (Alisov, 1974; Matveev, 1984). The amplitude of the seasonal variation of insolation increases with increasing latitude.

For the analysis of seasonal changes in the RSDS, annual flow graphs were constructed in the grid nodes of the model located in the Ouarzazate region (Fig. 3).

As seen in the graphs, the maximum RSDS in the annual cycle is noted in May. This deviation in RSDS and a shift of the maximum in the Anti-Atlas can be explained by the influence of cloudiness, which increases in the mountains in the summer months due to the development of thermal convection on the mountain slopes.

5. CONCLUSION

The results of RCM calculation using the RCP4.5 scenario showed that the distribution of average annual RSDS will be quasi-latitudinal in the future, with some deviations in the mountainous and Atlantic coastal areas. The areas with the greatest solar energy potential will be the inland areas of southern Morocco and the southern slopes of the Anti-Atlas Mountains, where simulations estimate the lowest total cloud cover values in addition to increased shortwave radiation values.

Expected changes in RSDS from 2021–2050 relative to recent climatic conditions have both positive and negative values. The projected decrease in shortwave radiation on the southern Atlantic coast near the city of Dakhla may be related to the influence of total cloud cover in this area. In most parts of

Morocco, RCMs have predicted that RSDS flux values will either increase or remain unchanged. The highest increase is projected in the Rif. The nature of the annual RSDS cycle in the vicinity of solar installations in the Anti-Atlas shows that the maximum will be observed in the month of May.

Thus, potential climate change in Morocco will not significantly affect the arrival of shortwave radiation; expected changes in RSDS in the near future as compared to recent climatic conditions are not large (less than 1%). Conditions for solar electricity generation will thus be relatively stable. However, it must be noted that modelling-related uncertainties have not been addressed in this research.

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