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Investigation of the Near Future Solar Energy Changes Using a Regional Climate Model over Istanbul, Türkiye

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Abstract: This study aims to assess potential changes in radiation values at the solar power plant facility in Istanbul using the RegCM. This analysis seeks to estimate the extent of the solar radiation changes and evaluate the production capacity of solar power in Istanbul in the future. The research involved installing an off-grid rooftop solar energy system. Meteorological parameters (temperature, etc.) and the system's outputs were monitored to evaluate the energy production and its relationship with these parameters. The performance of the Regional Climate Model version 5.0 (RegCMv5) in accurately representing surface solar radiation and temperature patterns was assessed by comparing it with measured monocrystalline solar panel output data. The impact of different cumulus convection schemes was examined on the sensitivity of the RegCM by analyzing surface solar radiation data over the initial three months. Long-term simulations were conducted with the representational concentration path (RCP) scenarios of 2.6, 4.5, and 8.5 spanning from 2023 to 2050 with convection schemes yielding the best results. All scenarios project a slight decrease in incoming surface radiation.

Keywords: photovoltaic power plant; insolation; cumulus convection schemes; RegCM; solar energy



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1. Introduction

Driven by the rapid growth of population and industrialization worldwide, there has been an increase in the consumption of natural resources and the emission of greenhouse gases from burning fossil fuels, which contribute to global warming. Unplanned resource management and disregard for the environment are causing damage to ecosystems. Given these challenges, industrial enterprises must prioritize energy efficiency and invest in renewable energy sources to mitigate environmental pollution.

As of the end of July 2023, the installed power of Türkiye has reached 105,135 MW. The distribution by resources includes 30% hydraulic energy, 24.1% natural gas, 20.7% coal, 11% wind, 9.9% solar, 1.6% geothermal, and 2.6% other sources [1]. Additionally, the number of electrical power generation plants in Türkiye has increased to 12,251 (including unlicensed power plants) as of the end of July 2023 [1]. Of the existing power plants, 751 are hydroelectric, 68 are coal, 362 are wind, 63 are geothermal, 346 are natural gas, 10,169 are solar, and 492 are other types [1]. According to the Turkish Solar Energy Potential Atlas, the average annual cumulative duration of sunshine is 2741 h, the average daily sunshine is 7.5 h, annual mean total radiation intensity equals 1527 kWh/m², and the daily mean total radiation intensity is 4.1 kWh/m². In addition, due to the length of daylight hours, its location for generating electricity is superior to that of other European countries [1]. According to the Turkish Solar Energy Potential Atlas, which specifically has available data for Istanbul, an average annual total sunshine duration of approximately 6.7 h and an average annual total radiation value of 4.4 kWh/m²-day were reported [1]. There are significant fluctuations in the intensity of solar radiation, which varies significantly

between regions. Cloud cover, a key meteorological parameter, significantly impacts solar radiation reaching the Earth's surface. These conditions include atmospheric aerosols and geographic location apart from cloud cover [2]. Consideration of these factors is essential for an accurate prediction and estimation of the combined effects on solar energy production and potential environmental impacts.

Numerous studies have been conducted to assess the solar energy potential of several geographical regions utilizing different models. Niu et al. [3] examined the possible influence of climate change on photovoltaic (PV) power generation from the year 2023 to 2100 using the Coupled Model Intercomparison Project Phase 6 (CMIP6) model. They stated that the rise in temperature associated with the Shared Socioeconomic Pathway 5-8.5 (SSP585) and SSP370 scenarios will lead to a decrease in photovoltaic (PV) power generation potential. Alexandri et al. [4] assessed the performance of the RegCM for the simulation of the surface solar energy trends over Europe between 2000 and 2009. They stated that the model slightly overestimates the patterns compared to satellite-based observations. Şenkal [5] used remote sensing and artificial neural networks (ANNs) to investigate the solar radiation. They found that the generalized regression neural network (GRNN) tool can effectively be used to predict the solar radiation in Türkiye. Ndiaye et al. [6] investigated solar energy potential in Western Africa and reported that the RegCM represents annual and monthly patterns quite well. They highlighted the importance of the RegCM with its superior performance for solar radiation modeling among regional climate models (RCMs). Zuluaga et al. [7] evaluated Brazil's photovoltaic power potential (PPV) under two climate scenarios, SSP2-4.5 and SSP5-8.5 using CMIP6 modeling. The results demonstrated improvements in the potential for photovoltaic power generation in the future. The projected growth in solar power capacity is estimated to reach 3%. Dutta et al. [8] studied impact of climate change on global solar energy potential by running general circulation models (GCMs) using simulations from Shared Socioeconomic Pathways. The findings revealed that there is a reduction of 6–10% in the photovoltaic capacity in India and China, likely due in part to increased cloud cover. Ghanim and Farhan [9] examined the projected effects of radiation and temperature values on future photovoltaic energy using the CMIP5. They found that the average temperature across the country is expected to increase by 1.5 °C and 2.4 °C under RCP4.5 and RCP8.5, respectively. The study also revealed that the change in solar PV potential will be 0.3% to 8.1% under RCP4.5 and 5.1% to 6.3% under RCP8.5, with the highest potential in the western parts. Wild et al. [10] reported photovoltaic energy production is decreasing in large regions of the world due to rising temperatures and decreasing surface solar radiation. Whereas increasing solar radiation is unlikely in most of Europe, the US, Australia, and southeastern China using the CMIP5 model. Gaetani et al. [11] studied the future productivity of photovoltaic energy in Europe and Africa using the ECHAM5-HAM model. Their studies indicate a decline in Eastern Europe and North Africa, while an increase in Western Europe and the Eastern Mediterranean. They also highlighted the use of climate modeling for understanding the future changes in photovoltaic energy productivity. Müller et al. [12] used surface solar radiation and temperature projections from 23 CMIP5 global climate models to predict the average change in photovoltaic electricity production from 2007–2027 to 2060–2080. The data showed −6% to +3% and −25% to +10% annual and monthly average changes in PV potential, respectively. In their study, Wu et al. [13] applied the RegCM4 to a specific region to project annual changes in photovoltaic potential (PVP) under the RCP2.6 and RCP8.5 scenarios. Notably, the model demonstrated reasonable accuracy in capturing the observed spatial distribution of surface air temperature and surface downwelling shortwave radiation in China. Gurel et al. [14] emphasize the importance of accurate solar irradiance calculations for financial planning, variable power generation forecasting, and improved power grid integration.

This study aims to investigate the solar energy changes in Istanbul using a regional climate model, RegCM, under different scenarios between 2023 and 2050. This study investigates the potential impacts of climate change on solar energy production in a megacity,

particularly whether it will enhance or diminish solar energy output. To reach this aim, a two-step study is conducted. First, model physical schemes are calibrated according to insolation recordings. The model is then run using the configuration identified as most effective for future simulations.

2. Materials and Method

2.1. Study Area

In this study, we selected Istanbul as the study area due to its significant role in Türkiye's energy landscape as a major metropolitan hub. With a population of 16 million and its major role as an energy consumer, Istanbul was chosen as a prime case study to assess the feasibility of transitioning to solar energy [15]. The research was conducted at Yıldız Technical University's Davutpaşa Campus in Istanbul's Esenler district. Figure 1 provides a detailed map highlighting the position of the study area within the campus.



Figure 1. The location of the study area.

An off-grid solar energy system was installed on the rooftop of the Civil Engineering Faculty waste storage facility to provide electricity to the composting unit and other lighting fixtures within the storage area (Figure 2). The installed capacity of the solar energy system is 6.6 kilowatt peak (kWp).

The system has a hybrid inverter that can operate in both grid-connected and off-grid ways. The flowchart of the solar energy system is given in Figure 3. It consists of a monocrystalline solar panel (330 Wp), a lithium iron phosphate battery, an inverter, a direct current (DC) cable, an alternating current (AC) cable, an aluminum construction, a connector, and a radiation sensor. The monocrystalline solar panel is used to convert sunlight into electricity, which is then stored in the lithium iron phosphate battery. The hybrid inverter enables seamless switching between grid-connected and off-grid operations. In an off-grid solar system, the DC cable connects the solar panel to the inverter. The inverter charges a battery bank with DC electricity. The inverter can then convert the DC battery power to AC to power lighting fixtures in the storage area. The aluminum construction provides a sturdy framework for mounting the solar panel and other components. The connector ensures a secure and reliable connection between the different parts of the system.

The radiation sensor measures the amount of radiation for optimal system performance. The sensor possesses dimensions of 142 mm × 110 mm × 40 mm (width × length × height) and weighs 0.3 kg. The irradiance sensor features an analog 4–20 mA output and measures irradiance between 0 and 1500 W/m². The solar energy system materials are listed in detail in Supplementary Materials.



Figure 2. An off-grid solar energy system with 6.6 kWp installed capacity.

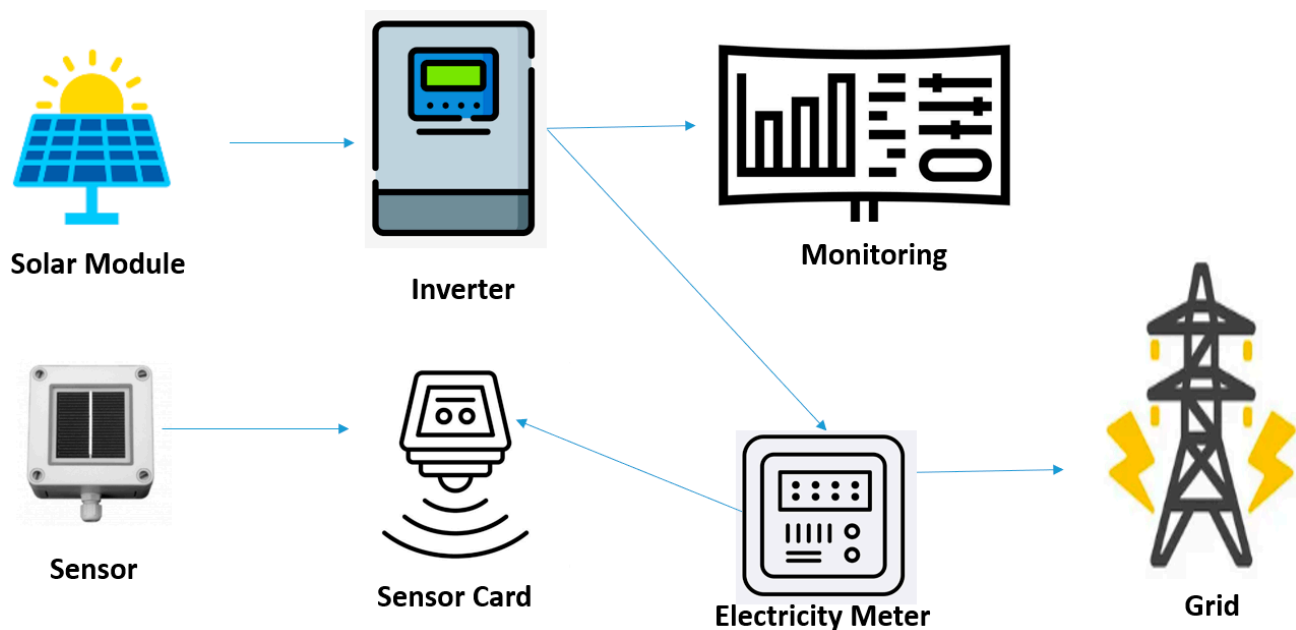


Figure 3. The flowchart of the solar energy system.

The direct current (DC) power output of a PV panel is determined by analyzing its current–voltage (I–V) curve in conjunction with the actual irradiance it receives. The I–V curve illustrates the behavior of the panel under varying irradiance and temperature conditions. Typically, this curve exhibits a characteristic shape with a knee point, which corresponds to the maximum power point (MPP). The MPP represents the specific point on the I–V curve where the panel generates the highest power output. To calculate the DC power output of the PV panel, we utilize the MPP values expressed in Equation (1).

$$\text{DC Power Output (PV Panel)} = I_{\text{MPP}} \cdot V_{\text{MPP}} \quad (1)$$

where I_{MPP} is the MPP current, and V_{MPP} is the MPP voltage.

2.2. Solar Energy System Output Data

This study acquired hourly solar radiation and ambient temperature data from the solar energy system throughout 2023. Figure 4 shows the daily and monthly average radiation sensor readings between January and December 2023. The radiation data exhibited an increasing pattern from January to June and a decreasing pattern from July to December, which is expected in the Northern Hemisphere. The monthly average measurement value started at 71.07 W/m^2 in January. By June, it had significantly increased by 272.13%, reaching 264.47 W/m^2 . The daily average temperature measurements are illustrated in Figure 5. It shows the average temperature sensor readings between January and December 2023. In January, the monthly average measurement value was 8.2°C . With the successive increase in temperature, it was observed that the average temperature in July increased to 30.5°C .

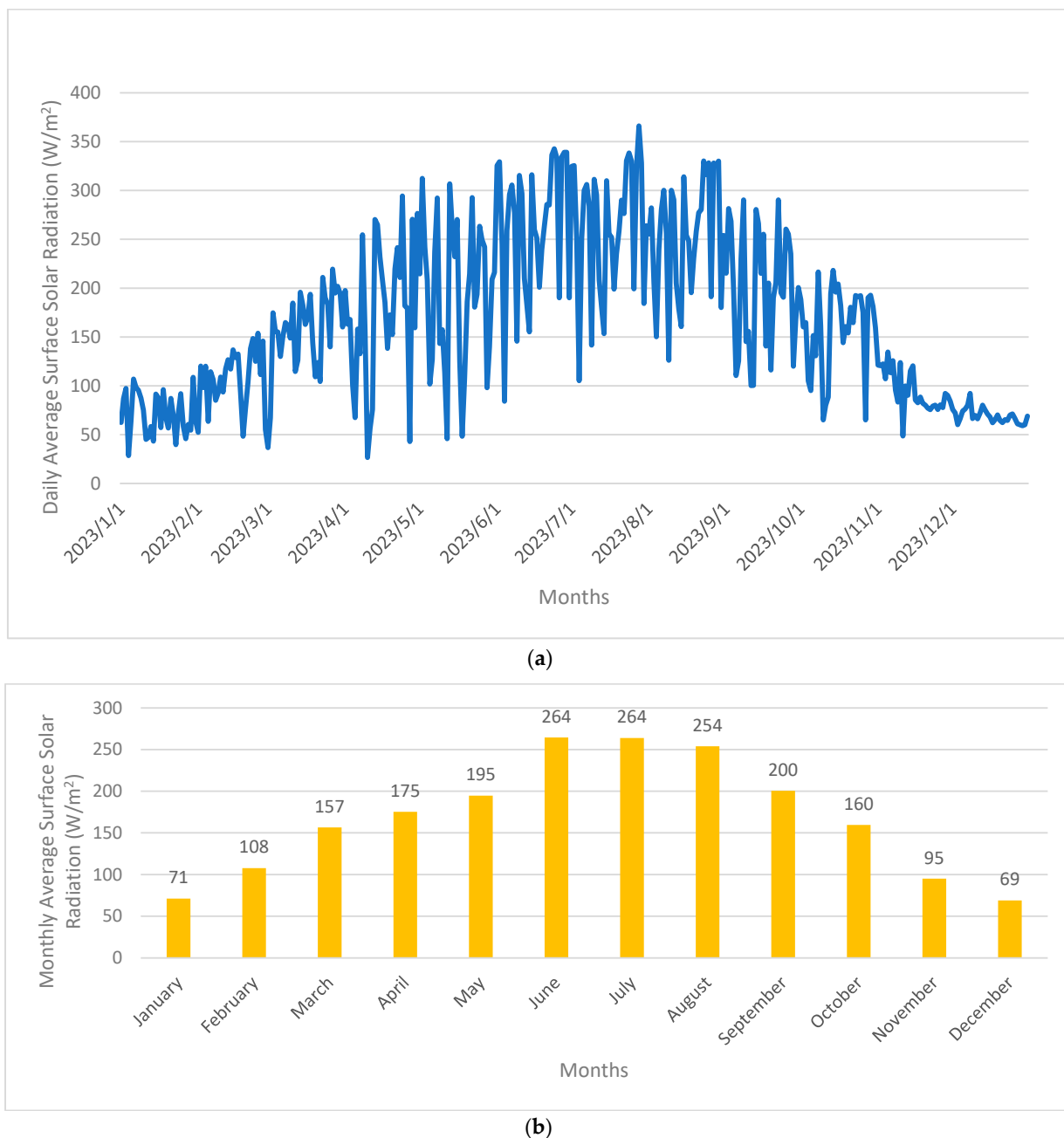


Figure 4. (a) The daily and (b) monthly average surface solar radiation readings between January and December 2023.

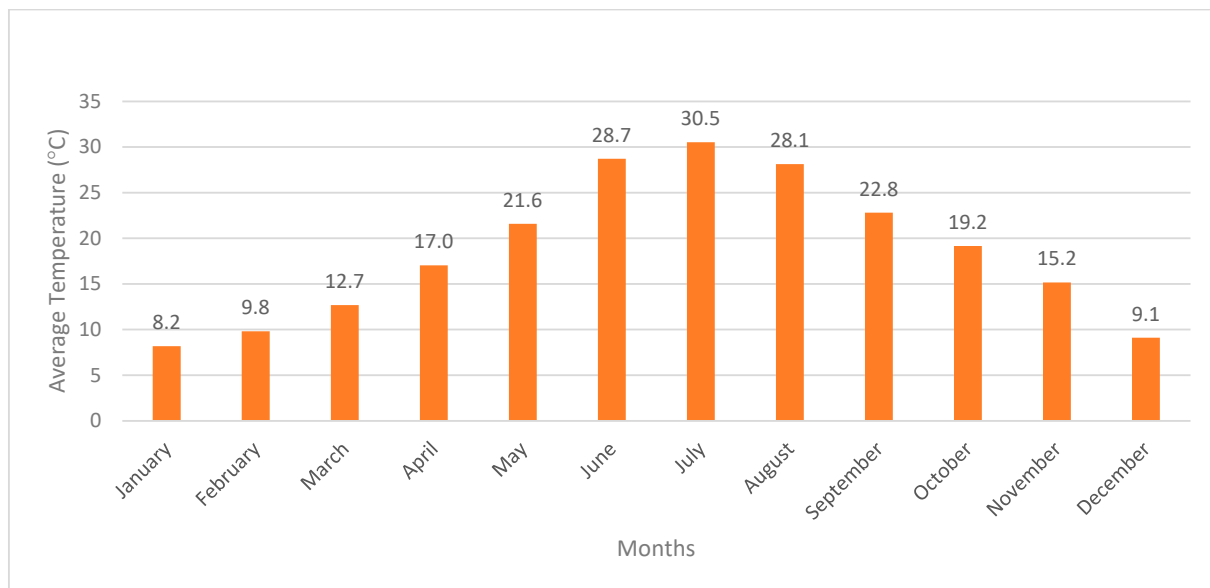


Figure 5. The average temperature measurements between January and December 2023.

2.3. RegCM Setup

In the study, the solar radiation variations were analyzed by the International Center for Theoretical Physics (ICTP) using the Regional Climate Model version 5.0 (RegCM5.0). The model dynamics are based on the National Center for Atmospheric Research (NCAR)-Pennsylvania State University (PSU) Fifth Generation Mesoscale Model (MM5) [16]. The calculation procedure of the model is available elsewhere in detail [17]. RegCM principally contains five physical schemes. These are land surface scheme, planetary boundary layer (PBL) scheme, cumulus convection scheme (CCS), moisture, and ocean flow scheme. Six CCSs are available over land and ocean. These include the modified Kuo scheme [18], the Grell scheme [19], the MIT-Emanuel scheme [20,21], the Tiedtke scheme [22], the Kain-Fritsch scheme [23], and the MM5 Shallow scheme. In the Kuo-type parameterization scheme, precipitation begins when the moisture convergence in the column exceeds a certain threshold. Vertical sounding is convective unstable. The Grell scheme uses a single cloud scheme with updraft and downdraft fluxes, and there is no direct mixing between cloudy weather and ambient air except at the bottom and top of the circulation. The MIT-Emanuel scheme assumes that the mixing in the clouds is highly episodic and non-homogeneous. This scheme includes an automatic conversion threshold that is temperature dependent, so ice processes are roughly described. It also adds a single hydrostatic, unsaturated downdraft that carries sediment, heat, and water. The Kain-Fritsch (KF) scheme is a mass flux parameterization that uses the Lagrangian parcel method. This method considers vertical momentum dynamics [24] to estimate several factors related to cloud formation. These factors include whether atmospheric conditions favor instability, whether existing instability can trigger cloud growth, and the properties of any resulting convective clouds. For the sake of this discussion, it is convenient to divide the KF scheme into three parts: (i) the convective trigger function, (ii) the mass flux formulation, and (iii) the closure assumptions [25]. MM5 is a previously used weather modeling system. This model can be utilized to predict meteorological events and weather features in smaller-scale regions. The term “shallow” can often refer to a particular parameterization or computational approach included within the model. This approach simplifies the incorporation of surface effects and processes in the lower atmospheric layers into the model. The MM5 is a regional mid-size model that is used to generate weather forecasts and climate projections. It is an ensemble model maintained by Penn State University and the National Center for Atmospheric Research. The MM5 is a limited-area, terrain-tracking sigma coordinate model used to reproduce or predict mid-scale and regional-scale atmospheric circulation. It was updated

several times since the 1970s to fix bugs, adapt to new technologies, and work on different types of computers and software.

In this study, several optimization studies were carried out to determine the performance and sensitivity of climatic factors affecting the solar power plants planned to be installed in Istanbul using the RegCM5.0. Optimization studies involved fine-tuning and improving the solar energy system's performance. Specifically, we compared the measurement data obtained from the surface solar radiation sensor with the simulation data generated by the RegCM5.0. Optimization, in this context, refers to maximizing efficiency, accuracy, and other relevant performance metrics by altering physical schemes. For this purpose, twenty-six RegCM simulations were performed using different cumulus convection schemes over land and ocean (Table 1).

Table 1. The RegCM experiments utilizing different cumulus convection schemes.

Experiment Number	Cumulus Scheme over Land	Cumulus Scheme over Ocean	Experiment Number	Cumulus Scheme over Land	Cumulus Scheme over Ocean
1	The Grell Scheme	The MIT-Emanuel Scheme	14	MM5 Shallow Scheme	The Kain–Fritsch Scheme
2	The MIT-Emanuel Scheme	The MIT-Emanuel Scheme	15	MM5 Shallow Scheme	The Tiedtke Scheme
3	The Grell Scheme	The Tiedtke Scheme	16	The Kain–Fritsch Scheme	The Tiedtke Scheme
4	The Grell Scheme	The Grell Scheme	17	The Kain–Fritsch Scheme	The MIT-Emanuel Scheme
5	The Grell Scheme	The Kain–Fritsch Scheme	18	MM5 Shallow Scheme	The Grell Scheme
6	The MIT-Emanuel Scheme	The Kain–Fritsch Scheme	19	The MIT-Emanuel Scheme	MM5 Shallow Scheme
7	The Tiedtke Scheme	The Grell Scheme	20	The Grell Scheme	MM5 Shallow Scheme
8	The Tiedtke Scheme	The MIT-Emanuel Scheme	21	The Kain–Fritsch Scheme	MM5 Shallow Scheme
9	The MIT-Emanuel Scheme	The Tiedtke Scheme	22	The Tiedtke Scheme	MM5 Shallow Scheme
10	The Tiedtke Scheme	The Tiedtke Scheme	23	MM5 Shallow Scheme	The MIT-Emanuel Scheme
11	The MIT-Emanuel Scheme	The Grell Scheme	24	MM5 Shallow Scheme	MM5 Shallow Scheme
12	The Tiedtke Scheme	The Kain–Fritsch Scheme	25	The Kain–Fritsch Scheme	The Kain–Fritsch Scheme
13	The Kain–Fritsch Scheme	The Grell Scheme	26	The Kuo Scheme	The Kuo Scheme

The RegCM domain that extends from 39.11° N to 43.04° N and 25.45° E to 30.79° E is shown in Figure 6, including its topography. The model configuration was applied in Lambert conformal projection with different horizontal resolutions of 10, 20, and 50 km. The simulation extent was 500 km for the north–south and east–west directions. It used an upper pressure of 5 hPa and a pressure level of 18 vertical sigma. The land surface processes were represented using Community Land Model version 4.5 (CLM45). The physical parameters of the model used in the study were: the Holtslag PBL scheme [26], cumulus convection schemes including the modified Kuo scheme [18], the Grell scheme [19] the MIT-Emanuel scheme [20,21], the Tiedtke scheme [22], the Kain–Fritsch scheme [23], the MM5 Shallow scheme over land and ocean, SUBEX moisture scheme [27], and NCAR CCSM atmospheric radiation scheme and ocean flow scheme [28] (Table 2).

Table 2. The physical parameters of the RegCM.

Physical Parameter	Scheme
Planetary boundary layer (PBL) scheme	Holtslag PBL scheme [26]
Moisture scheme	SUBEX moisture scheme [27]
Radiation scheme	NCAR CCSM atmospheric radiation scheme and ocean flow scheme [28]
Cumulus convection schemes	The modified Kuo scheme [18]
	The Grell scheme [19]
	The MIT-Emanuel scheme [20,21]
	The Tiedtke scheme [22]
	The Kain–Fritsch scheme [23]
	The MM5 Shallow scheme

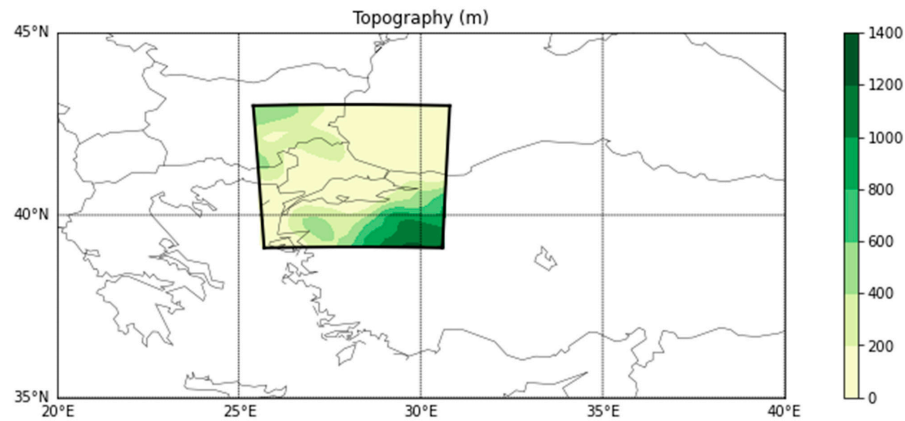


Figure 6. The RegCM domain with topography.

HadGEM2-ES (a second-generation global model developed by the Hadley Centre, a research agency of the UK Meteorological Service) was used for initial and boundary conditions. The HadGEM2-ES, which is a part of the Coupled Model Inter-comparison Project Phase 5 (CMIP5), employs a horizontal grid spacing of $1.25^\circ \times 1.875^\circ$ and 38 vertical levels for the atmospheric component. On the other hand, the oceanic component utilizes a horizontal grid of 1° and 40 vertical levels [29]. The dataset was acquired from a website (<http://clima-dods.ictp.it/regcm4/>, accessed on 20 May 2024). The temporal resolution of the input dataset was 6 h. The entire model was executed to produce hourly data. The simulations used for optimization were carried out using different cumulus schemes in 2023. In simulations of the near future, the optimal configuration was used, which was determined by the optimization study. The initial and boundary conditions of the RegCM global climate model were utilized using the RCP2.6, RCP4.5, and RCP8.5 scenario outputs which imply that the total radiative forcing will reach 2.6 W/m^2 , 4.5 W/m^2 , and 8.5 W/m^2 by 2100, respectively. The near future simulation period spans from 2023 to 2050.

2.4. Validation

Verification and validation of data among selected different schemes are the most important part of the deterministic calculations. An accurate model has to be chosen and used for the forecast processes. Ian Sosa-Tinoco et al. [30] used mean bias error in their studies as skill factors. Rakesh et al. [31] preferred utilizing mean bias and root mean square error as skill factors. The performance of the RegCMv5 model in simulating surface solar radiation was evaluated by comparing its results with measured output data from a monocrystalline solar panel system. A validation study was conducted for the measured and simulated surface solar radiation using the mean absolute error (MAE), root mean square error (RMSE), and R-square (R^2) performance metrics, shown in the following Equations (2)–(4):

$$\text{MAE} = N^{-1} \sum_{i=1}^N (P_i - O_i) \quad (2)$$

$$\text{RMSE} = \left[N^{-1} \sum_{i=1}^N (P_i - O_i)^2 \right]^{0.5} \quad (3)$$

$$R^2 = \frac{(\sum_{i=1}^n (O_i - O_m)(P_i - P_m))^2}{\sum_{i=1}^n (O_i - O_m)^2 \sum_{i=1}^n (P_i - P_m)^2} \quad (4)$$

Here N is the number of data, P is the predicted data, and O is the observed data.

3. Results and Discussion

3.1. The RegCM Optimization Results

Actual measurements from the solar energy system's surface solar radiation sensor were compared with simulated data generated by the RegCM5.0 to assess the model's performance. The optimization experiments conducted in the simulation focused on the

cumulus convection schemes over land and ocean. Table 3 displays the results of an optimization study conducted for twenty-six different cases to determine the cumulus scheme that provides the best results over the land and ocean. As a consequence of optimizing the model designated to operate on the RCP4.5 scenario outputs generated by the global climate RegCM5.0, which projects a total radiative forcing of 4.5 W/m^2 by 2050, the selection of initial and boundary conditions was based on the determination that the Grell scheme for land and the MIT-Emanuel scheme for ocean were the most suitable physical parameters for the cumulus scheme. The lowest mean absolute error value (MAE) was found to be 0.08 for the Kain–Fristch scheme, while the MIT-Emanuel scheme and the Tiedtke scheme demonstrated the highest MAE value of 8.8 for land and ocean, respectively. The validation analysis indicated that the Grell scheme over the land and the MIT-Emanuel scheme over the ocean resulted a very high R^2 of 0.95, along with a very low MAE of 0.01 and the lowest RMSE of 39.81.

The RegCM was used to investigate the impact of different horizontal resolutions on simulations. Simulations were run using the Grell scheme over land and the MIT-Emanuel scheme over the ocean, with varying horizontal resolutions. Figure 7 compares observed and predicted solar data at 10 km, 20 km, and 50 km horizontal resolutions utilizing the Grell and the MIT-Emanuel cumulus convection schemes. It was determined that the optimal horizontal resolution was 50 km with an R^2 value of 0.97, an MAE value of 0.84, and an RMSE value of 27.3.

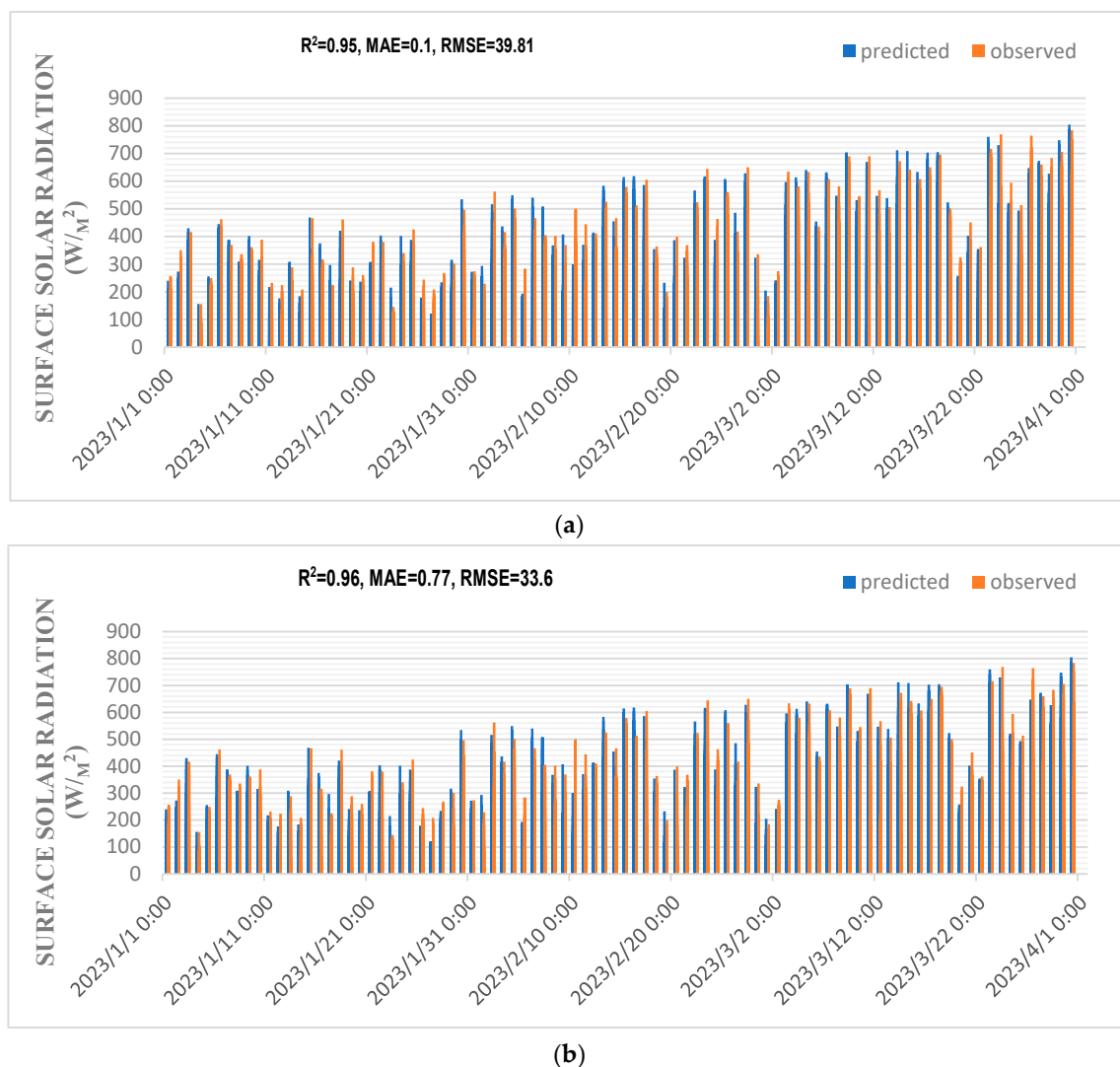


Figure 7. Cont.

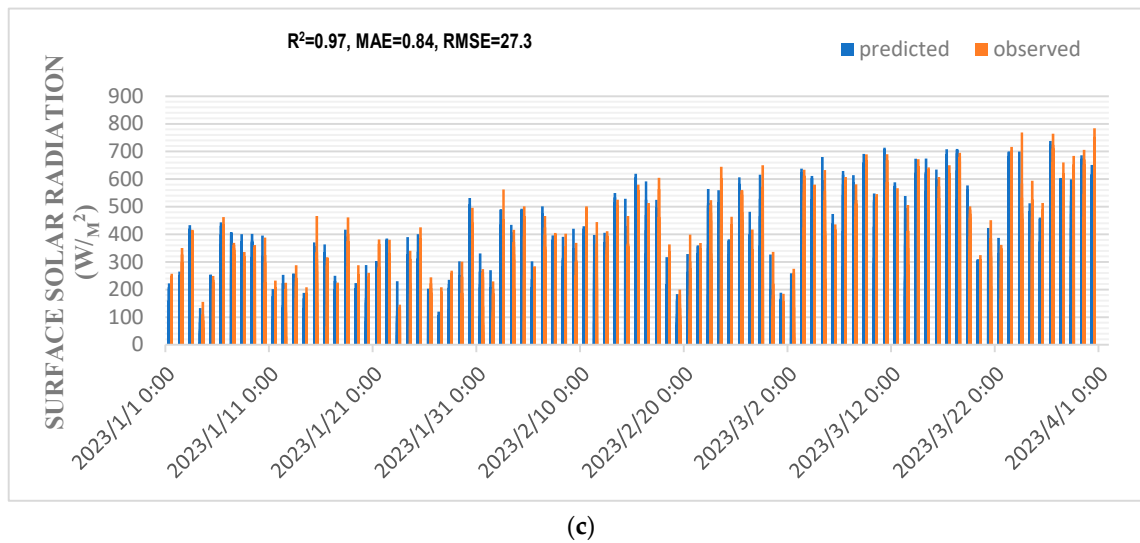


Figure 7. The observed and predicted solar data at (a) 10 km, (b) 20 km, and (c) 50 km horizontal resolutions utilizing the Grell and the MIT-Emanuel cumulus convection schemes.

Table 3. The RegCM optimization study performance metrics.

Experiment Number	R ²	MAE	RMSE	Experiment Number	R ²	MAE	RMSE
1	0.95	0.10	39.81	14	0.87	2.56	66.51
2	0.93	3.94	46.43	15	0.87	2.30	66.43
3	0.89	0.70	60.70	16	0.86	6.98	65.03
4	0.89	0.87	61.57	17	0.86	6.29	65.37
5	0.89	0.60	61.78	18	0.86	2.78	66.66
6	0.88	8.37	60.63	19	0.86	3.63	66.60
7	0.88	0.71	63.61	20	0.86	3.17	67.00
8	0.88	1.63	63.76	21	0.86	2.17	67.48
9	0.88	8.83	61.04	22	0.86	3.17	67.25
10	0.83	0.09	75.24	23	0.86	2.24	68.16
11	0.88	7.94	61.71	24	0.81	4.70	78.13
12	0.88	0.71	64.63	25	0.81	8.04	77.77
13	0.87	6.33	64.41	26	0.75	2.50	90.89

3.2. Near Future Solar Simulation Results

Based on the optimization studies, the best-performing horizontal resolution was 50 km by the Grell scheme on land and the MIT-Emanuel scheme on the ocean. To assess future climate conditions, the RegCM was applied to conduct long-term simulations using various RCP scenarios. The monthly average radiation results derived from RegCM simulations, employing different RCP scenarios, between 2023 and 2050 are represented in Figure 8.

The solar radiation values increased from RCP2.6 to RCP8. The highest irradiation is expected to be observed during June with 353.9 W/m², 358.3 W/m², and 365.2 W/m² for RCP2.6, RCP4.5, and RCP8.5, respectively. The lowest irradiation is projected to be observed in December with 72.5 W/m², 84.9 W/m², and 87.03 W/m² for RCP2.6, RCP4.5, and RCP8.5, respectively.

Figure 9 illustrates the annual variation of surface solar radiation between 2023 and 2050 under the RCP2.6, RCP4.5, and RCP8.5 scenarios. Several factors, including cloudiness, air pollution, and the albedo can influence these variations. Considering Figure 9a, the RCP2.6 scenario is expected to have the most fluctuating solar radiation pattern among the three scenarios. The year 2041 is expected to have the lowest radiation value, which is estimated to be 208.5 W/m². The year with the highest radiation value will be 2025 with a value of 221.2 W/m². According to Figure 9b the lowest radiation was in 2023 with 220.15 W/m² for the RCP4.5 scenario. The year with the highest radiation value is 2047

with a value of 229.0 W/m^2 . The fluctuation solar radiation of RCP4.5 was less than that of RCP2.6. Standard deviation (STD) values confirm this. STDs are 2.9 and 2.7 for RCP2.6 and RCP4.5, respectively. Figure 9c indicates that the RCP8.5 scenario had the lowest radiation value in 2023 as did the RCP4.5 scenario. The radiation value was 224.4 W/m^2 . The year with the highest radiation value is estimated as 2032 with 232.4 W/m^2 . RCP8.5 has the least solar radiation fluctuation among the three scenarios. The STD of solar radiation value is 2.2.

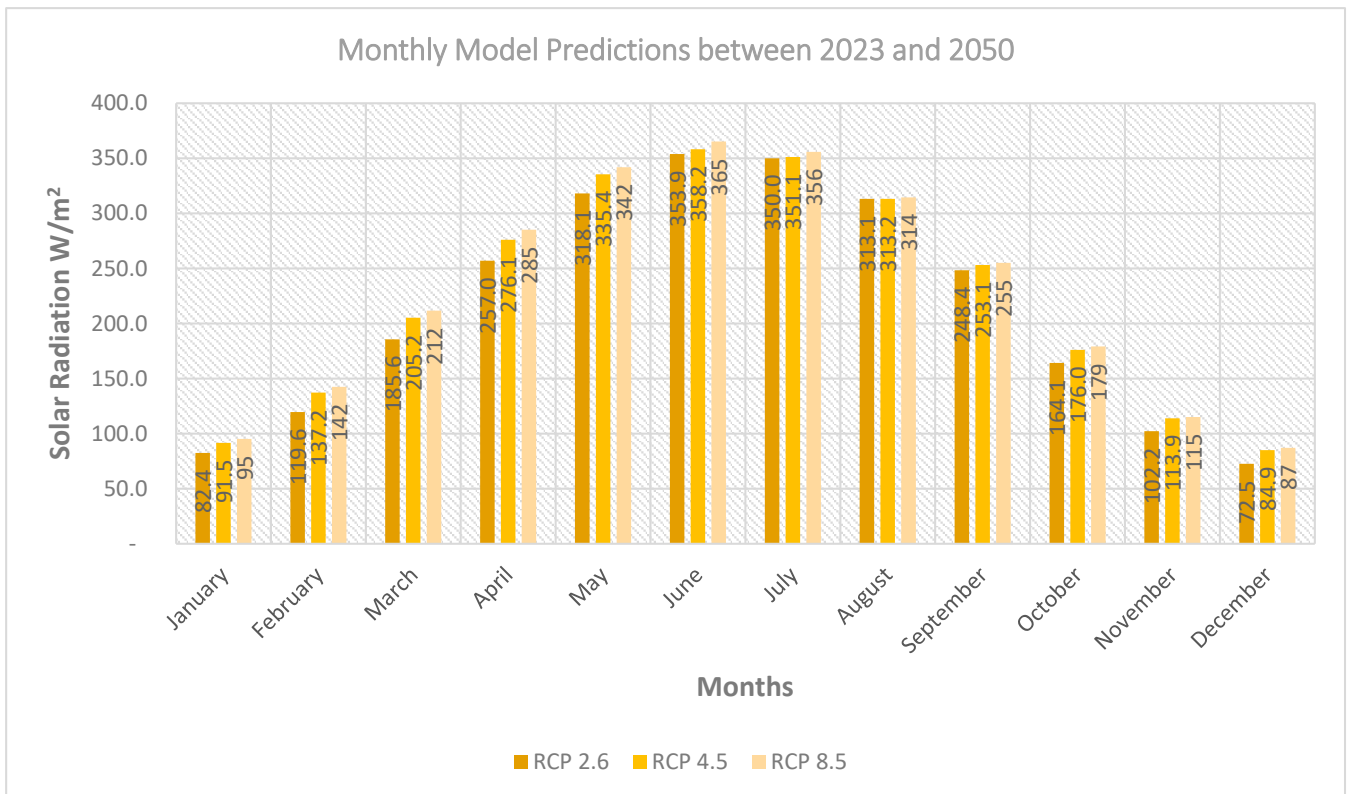
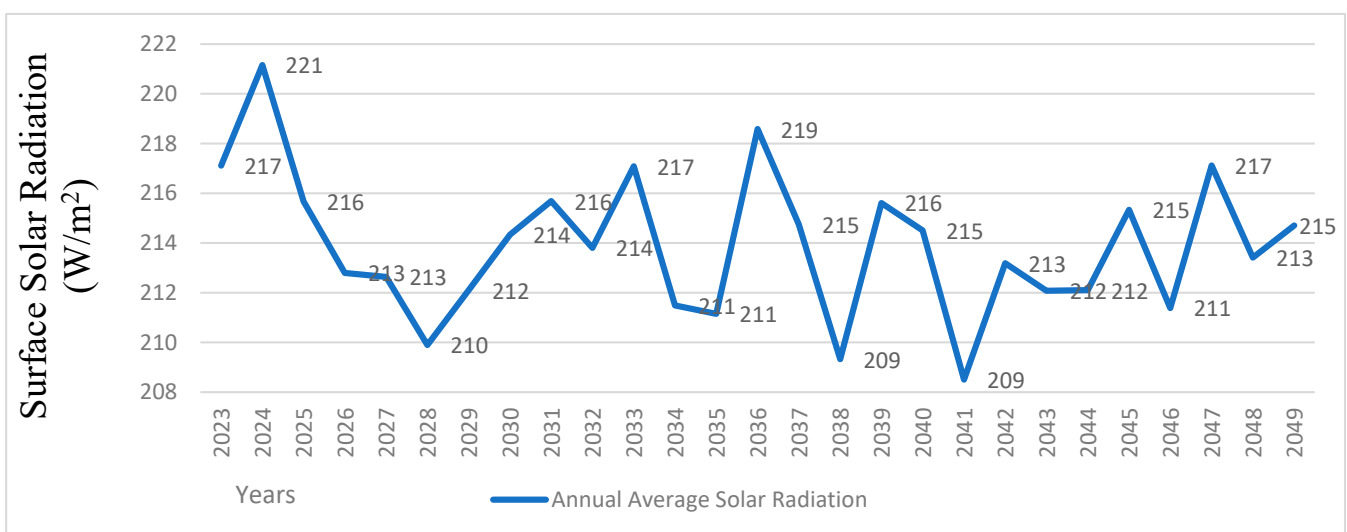


Figure 8. The monthly average surface solar radiation results (W/m^2) from RegCM simulations using various RCP scenarios for 2023–2050.



(a)

Figure 9. Cont.

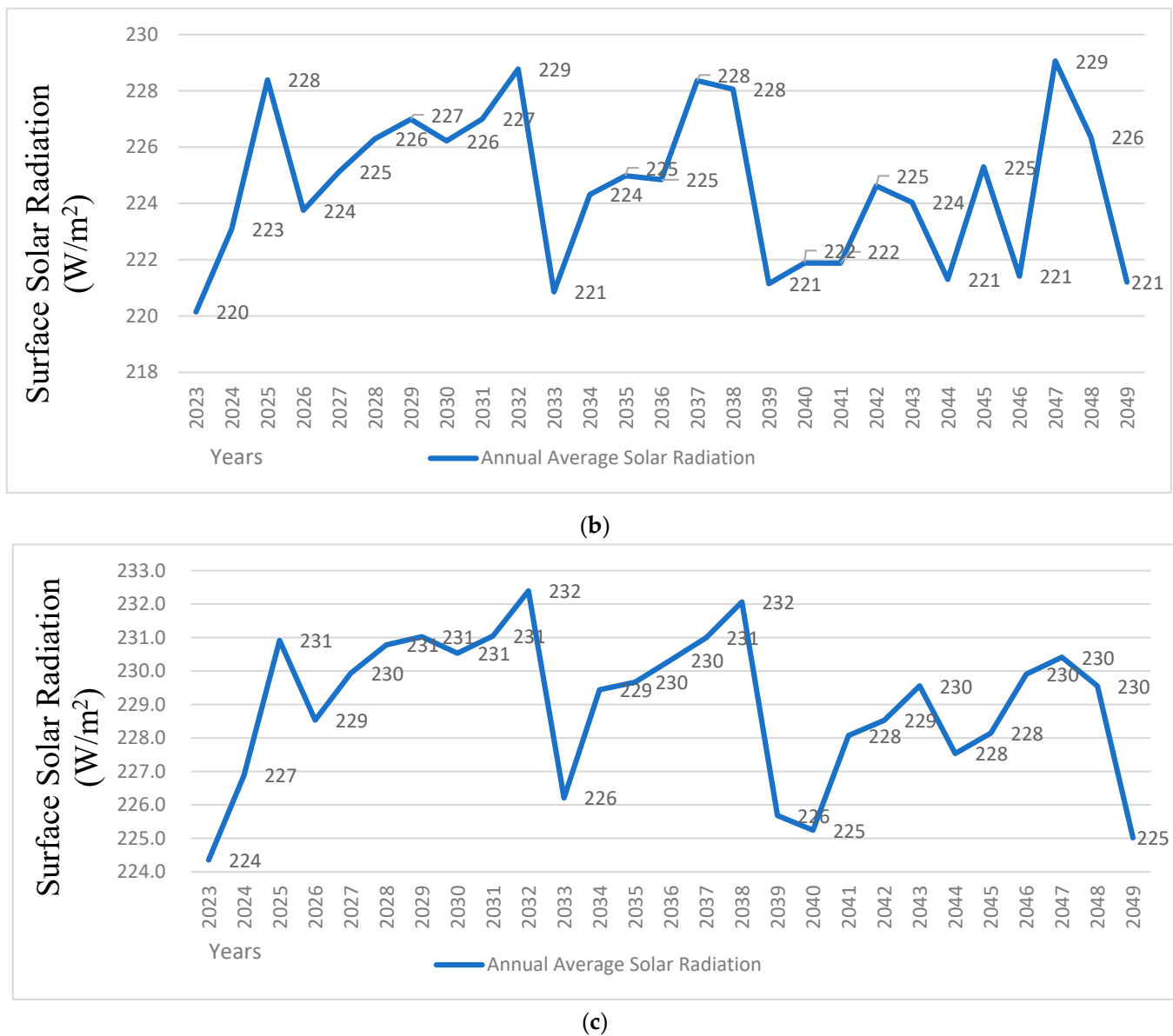


Figure 9. The variation of annual average surface solar radiation (W/m^2) between 2023 and 2050 using (a) RCP2.6, (b) RCP4.5, (c) RCP8.5 scenarios.

The average solar radiation values across three future periods (2023–2030, 2031–2040, and 2041–2050) show an increase with RCP scenarios. For RCP2.6, the averages are 214.4, 214.2, and 213.1 W/m^2 , respectively. Similarly, the averages for RCP4.5 are 225.0, 225.0, and 223.9 W/m^2 , and for RCP8.5, they are 229.1, 229.3, and 228.5 W/m^2 , respectively. While the global trend suggests increasing solar radiation, some regions might experience decreases. Therefore, regional climate downscaling is important in understanding the trend of solar radiation. Müller et al. [12] indicated that there is an increase in the photovoltaic output in Southern Europe and, controversially, a decrease in Northern Europe. An increase in the photovoltaic output was reported by Crook et al. [32], who ran the SRES A1B scenario with the Hadley general circulation model. According to their findings, an increase in PV output was reported for Europe and China towards 2080. It was also stated that little change will occur in Algeria and Australia. A decrease of a few percent is possible in the western United States and Saudi Arabia. Unlike North America, an increase in PV output is expected in South America (northeast of Brazil) by 3.6% [33]. Bazyomo et al. [34] evidenced a PV output decrease in most countries in Africa except for Liberia and Sierra

Leone. Danso et al. [35] predicted a PV output decrease in the 21st century by executing the SSP-5-8.5 emission scenario. Available dust in the atmosphere is a factor that affects radiative forcing and according to regional climate models, the intensity and number of dust transport events are going to change.

Figure 10 shows the seasonal variation of mean surface solar radiation (W/m^2) between 2023 and 2050 using the RCP2.6, RCP4.5, and RCP8.5 scenarios. The graph shows the average solar radiation values of winter, spring, summer, and autumn. Across all seasons, RCP8.5 exhibited the highest values, followed by RCP4.5 and then RCP2.6.

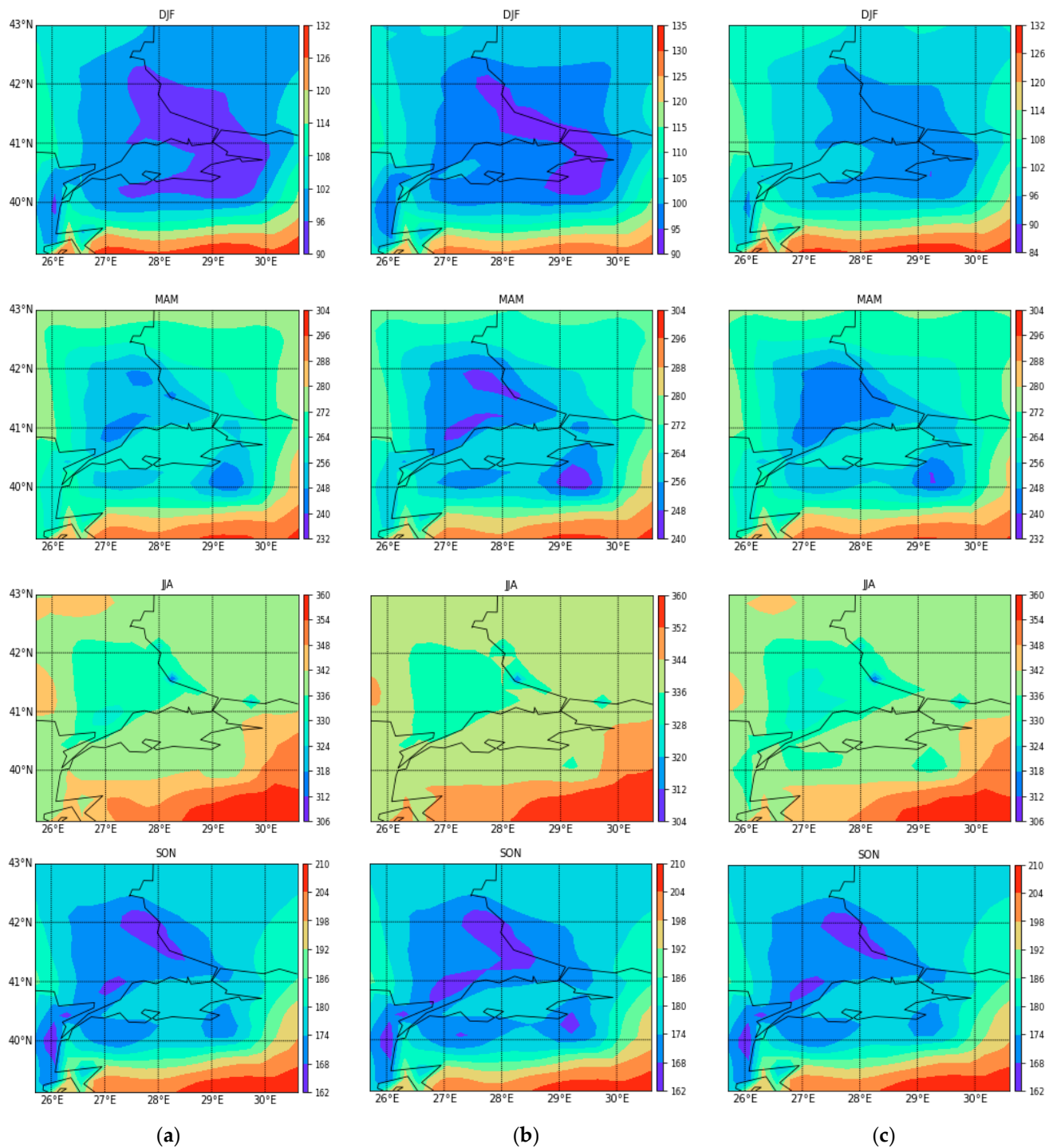


Figure 10. The seasonal variation of average surface solar radiation (W/m^2) between 2023 and 2050 using RCP8.5, (a) RCP4.5, (b) RCP2.6 (c) scenarios.

4. Conclusions

In this study, we investigated the near future solar energy changes in Istanbul, Türkiye using a regional climate model. Addressing the inherent limitations of RegCMs related to spatial resolution and parameterization schemes, we conducted a sensitivity analysis by varying spatial resolutions and utilizing six different cumulus convection schemes to understand their impact on solar energy simulations. Additionally, future climate projections include uncertainties arising from emission scenarios and model sensitivity. To address uncertainties in future climate projections related to emission scenarios and model sensitivity, we considered multiple emission scenario pathways, including RCP2.6, RCP4.5, and RCP8.5. We assessed the model's capability to simulate solar radiation patterns by examining hourly seasonal trends over one year. The results showed that when the Grell scheme on land and the MIT-Emanuel scheme on the ocean were used, the model accurately captured the diurnal variations in solar energy, indicating its suitability for predicting future solar energy patterns in Istanbul. Fluctuation was present in all three scenarios with the highest being in RCP2.6 and lowest being in RCP8.5. When the time until 2050 is divided into three periods, which are 2023–2030, 2031–2040, and 2041–2050, in all three scenarios a slight decrease in solar radiation is expected. This study's findings will aid in the comprehension of the effect of solar radiation on regional climates and enhance climate models and forecasting. In addition, they will provide vital insights for the development of effective renewable energy planning and management strategies. The findings will assist policymakers in making well-informed decisions regarding the deployment of solar energy technologies and their potential contribution to climate change mitigation. Overall, this research will play a crucial role in advancing our knowledge of solar radiation's role in shaping regional climates and its implications for sustainable development. The model simulation without chemistry option, which did not enable dust transport, is one of the limitations of this study. It can be improved by simulating the presence of dust, which affects solar radiation. On the other hand, Shared Socioeconomic Pathways (SSPs) were released along with AR6 instead of RCPs. The model can be run with the new climate change scenarios.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en17112644/s1>, Table S1: Solar Energy System Materials.

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