Examination of potential impacts of future climate change on solar radiation in Togo, West Africa

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Abstract

This study investigates the potential impacts of future warming on Global Solar Radiation (GSR) in different parts of Togo, West Africa. It used regional climate simulations of the International Centre for Theoretical Physics version 4.7 (RegCM4) driven by HadGEM-ES and NorESM-M GCM for three different time-slice periods: baseline (1976–2005), near future (2031–2060) and far future (2070–2099). The models produced realistic simulations of GSR and temperature characteristics over the stations and the simulations spread are within the observation uncertainty. The simulations compared fairly well with the NASA observations. Biases in both the GSR ($10\text{--}37\text{ Wm}^{-2}$ or $5\text{--}17\%$) and temperature ($0.1\text{--}2.0\text{ }^{\circ}\text{C}$ or $0.5\text{--}7.3\%$) were found to be insignificant at $p < 0.05$ across all the stations under investigation. The results revealed increasing but insignificant trends ($0.025\text{--}0.043\text{ }^{\circ}\text{C year}^{-1}$) in observed temperature but decreasing ($0.225\text{--}0.567\text{ Wm}^{-2}\text{ year}^{-1}$) in GSR during the baseline period. The estimated increasing trends ($0.004\text{--}0.035\%\text{ year}^{-1}$) in cloud cover were partly attributed to the observed variations in surface GSR. All models projected increase in temperature ($0.2\text{--}4.6\text{ }^{\circ}\text{C}$) but decrease in GSR ($0.5\text{--}5.8\%$) over the entire country at both annual and seasonal time-scales. The simulated future changes in temperatures and GSR were expected to increase further and decrease, respectively, by the end of the century. The study has noteworthy implication in solar photovoltaic power production under warmer climate. It suggests a need for improved technology with the least climate change impacts over the republic of Togo, West Africa.

Keywords Climate change · Warming · Global solar radiation · Regional climate model · Togo

1 Introduction

The need to meet the energy demand of developing countries in a manner which fosters economic development without environmental degradation is one of the world's foremost challenges [1]. Greenhouse Gas Emission (GHG) is well reported as the challenge of non-renewable sources, the fossil-based energy (such as coal, natural gas and oil) which constitute the supply of a vast majority of the world's energy demand [2, 3]. Caineng, et al. [4] reported that with the persistent increase in the economic and social demand for energy and the advent of low-carbon

society, the third major transformation from traditional fossil fuel to non-fossil new energy (renewable energy) will become inevitable. This assertion was corroborated in the work of [5]. In the submission of the authors [5], part of the main strategies to reduce GHG emissions and transit to low carbon cum green economy is to decommission carbon intensive electricity production while increasing the deployment of renewable energy technologies—such as wind and solar power generation [6]. Therefore, renewable energy is growing rapidly as a source of alternative energy to fossil fuels, not just because of the adaptability and variety of technologies but because of their economic

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viability [7]. Although a clear consensus within the international community that traditional fossil fuel-based energy production systems are key contributors to global climate change, has been reported [6, 8–10], the impacts of climate change and in particular, weather variability on the energy production sector have been underestimated. The generation capacity, availability, and intermittency of these renewable energy sources have been reported to be strongly climate dependent [6, 11].

The world's climate is changing and may continue to experience enormous alteration into the next century at an unprecedented rate [12–14]. With changing climate and air pollution levels, solar resources may no longer be stable over time and undergo substantial decadal changes [15]. It has been shown that climate conditions relevant for the productivity of solar power plants may change in the due to anthropogenic climate change [8, 15]. However, our current understanding of the potential impact of climate change on global solar radiation using climate projections with their associated high uncertainty is still inadequate, particularly over West African region [16]. The importance of data on future effect of climate variations on global solar radiations for photovoltaic systems cannot be overemphasized in the renewable energy resource forecasting and future planning. Some of the few reported literature on the influence of climate change on global solar radiation in respect of energy production from solar photovoltaic (PV) are mentioned in the subsequent paragraphs of this paper.

Wild, et al. [17] investigated the effects of climate change on the projections of long-term changes on global solar radiation and the resultant influence on energy yields from solar photovoltaic (PV) systems. The authors explored the latest generation of climate models that are used for predicting potential changes in surface global solar radiation over the coming decades. They were also explored to study how the expected greenhouse warming can alter solar power output from PV systems. The authors found that a significant decrease in PV energy outputs in large parts of the world, but noteworthy exceptions with positive trends in large parts of Europe, South-East of North America and the South-East of China. The study obtained 1%/decade projected changes in energy yields for a period between 2006 and 2049 under the RCP8.5 scenarios. In a study implemented by [18], the effect of projected changes in irradiance and temperature on the performance of photovoltaic systems in Greece was examined. The spatiotemporal analysis shows significant increase in mean annual temperature and mean total radiation (about 5 W/m^2) for Greece, in the year 2100. In the work of [15], projection based on prevailing changing climate and air pollution levels up to the mid-twenty-first century revealed potential future increases in concentrated solar

power production in many parts of the globe, with few exceptions in places such as the North of India.

Africa is considered as one of the most vulnerable continents to climate change and climate variability, a situation aggravated by the interaction of 'multiple stresses', occurring at various levels, and low adaptive capacity [8]. Therefore, it is crucial to consider couple of reported studies on this subject matter with special focus on Africa. The effects of climate change on solar PV output in the fifteen countries of the Economic Community of West African States (ECOWAS) was studied in the work of [19]. Using eight climate models, the trends of global solar radiation and temperature within 2006–2100 were considered by the authors. Except for Sierra Leone with maximum increase of 0.013%/year, climate change was found to lead to a decreasing trend of PV output in the rest of the ECOWAS countries with a minimum of 0.032%/year in Niger. Analysis of seasonal trend of solar irradiation from 2006–2100 was carried out by [20]. The authors estimated solar PV system outputs power changes up to the mid-twenty-first century. Findings obtained by the authors revealed a significant reduction in PV power output in all the parts of West-Africa. The outcome of the study showed that from 2006–2100, the maximum of $0.05 \text{ Wm}^{-2} \text{ year}^{-1}$ was found for Gambia over the period JJA (June–July–August) season, whereas the strongest negative change was found for the Cape Verde with $0.15 \text{ Wm}^{-2} \text{ year}^{-1}$ over the period DJF (December–January–February) season. In [21], authors in their independent and comprehensive work predicted a reduction in future global solar radiation across different parts of Nigeria using data outputs from a regional climate model.

From the foregoing literature findings, it can be deduced that the future effects of climate change on global solar radiation in respect of energy production from solar PV varies across seasons and different parts of the globe. While the future influence of climate change is generally observed to increase global solar radiation for PV applications in Europe and some other parts of the world, the effects of the climate change is largely unfavourable for global solar radiation energy yields in Africa. This trend for Africa is in line with the earlier submission of IPCC [8] that the continent remains one of the most susceptible continents to climate change and climate variability. Sequel to this, rigorous research efforts are required on the impacts of climate changes on global solar radiation in African countries (most especially Sub-Sahara countries such as Togo) where energy generation from renewable technologies is gaining more acceptance as part of energy-mix solution to the general energy crisis in the continent.

Although it has been shown that climatic changes in Togo have impacts on agriculture, crop production, and

aquatic ecosystem among others [22], there is paucity of information on the effects of climate change on the variations in global solar radiation over different parts of Togo. This study, therefore, examined the potential impacts of the climate change on global solar radiation in different climatic regions of Togo using multi-regional climate model simulations.

2 Materials and methods

2.1 Methods

The study used Global Solar Radiation (GSR) and temperature datasets obtained from MOHC-HadGEM2-ES and NorESM1-M GCMs-driven high-resolution CORDEX (Coordinated Regional Downscaling Experiment) CORE simulations over the entire Africa domain (AFR-22) with a spatial resolution of 0.22° by 0.22° ($\sim 25 \text{ km} \times 25 \text{ km}$). In this study, the historical runs from 1976 to 2005 were considered for the baseline period. Future climate projections for two RCPs (Representative Concentration Pathways, i.e. RCP2.6 and RCP8.5) for 2031–2060 and 2070–2099 time slices were considered as 'Future 1' and 'Future 2' periods, respectively. Then, historical simulations of GSR and temperature for HadGEM and NorESM models were validated by comparing them with the observational data obtained from the Prediction

of Worldwide Energy Resource (POWER) project data supported by NASA and Langley Research Center, LaRC (<https://power.larc.nasa.gov/>) with a spatial horizontal resolution of $0.5^\circ \times 0.5^\circ$ [23, 24]. The appropriate grid-data were extracted for five different locations (Lomé, Atakpamé, Sokodé, Kara and Mango) scattered over Togo, West Africa (Fig. 1). The raw daily datasets were statistically analysed to obtain monthly, annual and seasonal means of the weather parameters. In this study, the seasonal variations were considered over four seasons, i.e. DJF (December to February), MAM (March to May), JJA (June to August), and SON (September to November). As widely used in the literature (e.g. [25, 26].), linear regression was then used to determine possible linear trends of the indices while a Mann–Kendall test, a nonparametric statistics [27, 28], was used to estimate the statistical significance of the observed trend at 90% level of confidence. Parameters used for model performance evaluation include mean bias (BIAS) and percentage bias (PBIAS) defined as:

$$\text{BIAS} = \frac{1}{N} \sum_{t=1}^N (\text{SIM}_t - \text{OBS}_t) \quad (1)$$

$$\text{PBIAS} = \frac{\frac{1}{N} \sum_{t=1}^N (\text{SIM}_t - \text{OBS}_t)}{\frac{1}{N} \sum_{t=1}^N (\text{OBS}_t)} \times 100\% \quad (2)$$

Fig. 1 Map of Togo and geographical locations of the five meteorological stations used in this study

where, t is the time scale, OBS is the NASA observations, SIM is the simulation (HadGEM and NorESM) while N is the total number of years.

Monthly observations of cloud cover of the Climate Research Unit (CRU) version 4.0 of resolution $0.5^\circ \times 0.5^\circ$ [29] were also used to explain the observed variations in the global solar radiation over the country. The difference between the historical and future simulations were obtained and analysed with a view to assessing the potential impacts of climate change on global solar radiation in the country.

2.2 Model description and simulations

Within the CORDEX framework, regional climate model (RegCM) version 4.7 developed at the Earth System Physics (ESP) section of the Abdus Salam International Centre for Theoretical Physics (ICTP) was deployed to downscale the selected GCMs (MOHC-HadGEM-ES, developed by the Met Office Hadley Center [30, 31] and NorESM-M of the Norwegian Climate Centre [32, 33]. The grid of all the AFR-22 simulations have 3 km grid-spacing with 41 vertical sigma levels [34].

The oceanic boundary conditions for the simulations were taken from the driven GCM with the choice of shallow convection scheme and MM5 Non-Hydrostatic core without large-scale option [34–36]. The Lake Coupling described in [39] with modification after [40] were adopted. Detailed descriptions of the configuration, initial and lateral boundary conditions as well as various improved schemes adopted in the CORDEX models have been well documented in the literature [34–40]. The future climate projections were carried out for two emission scenarios: RCP 2.6 and RCP8.5 of low and high range mitigation scenarios, respectively [41]. This choice of two extreme scenarios enabled us to effectively capture and describe the spread of the models' simulations and their prediction uncertainties over the study area.

3 Results and discussion

3.1 Mean monthly climatology of global solar radiation (GSR) and temperature

Figure 2 describes mean monthly statistics of observed (NASA) and model simulations of GSR and temperature from 1976 to 2005 in selected five meteorological stations in Togo, respectively. The box-and-whisker plots show the spread of the GSR simulations as an indication of agreements amongst the model projections. The lower part of the box/whisker represents the 25th percentile (or the lower quartile), the line that divides the box into

Fig. 2 Box-and-whisker of monthly **a** global solar radiation and **b** temperature for NASA, HadGEM2 and NorSEM datasets in selected five meteorological stations in Togo, West Africa (1976–2005)

two parts is the 50th percentile (or the median) while the upper part of the box is the 75th percentile (or the upper quartile). The interquartile range is the difference between the lower and upper quartiles. A vertical (dotted black) line goes through the box to the minimum and maximum values while the data points that are located outside the whiskers of the box plot (red plus sign) are called the outliers *i.e.* observations that are numerically distant from the rest of the data.

The models produced realistic simulations of GSR and temperature characteristics over the stations, and in virtually all cases, the simulations spread are within the observation uncertainty (Fig. 2). The estimated median for GSR observations were 227 Wm^{-2} (Lomé), 225 Wm^{-2} (Atakpamé and Sokodé), 220 Wm^{-2} (Kara) and 221 Wm^{-2} (Mango; Fig. 2a). Maximum values of about 250 Wm^{-2} were obtained over the stations in the north (e.g. Sokodé, Kara and Mango) but less (242 Wm^{-2}) in

the south, e.g. Lomé and Atakpamé. This is an indication that, in some months, GSR could be higher in the north than the southern parts of the country. Similarly, estimated median for temperature observations were 26.1 °C (Lomé and Atakpamé) 25.9 °C (Sokodé), 25.7 °C (Kara and Mango; Fig. 2b). The maximum values could reach about 26.9 °C in the northern stations. The obtained spatial patterns of GSR and temperature are indications of increased surface warming due to higher solar insolation reaching the ground surface. The closest agreement between model simulations of GSR and the observations were found in HadGEM over Lomé and Atakpamé. Almost all the simulated temperatures, fall within the observed values and the closest agreements were found in both HadGEM and NorSEM over Sokodé and Kara. Over other locations, model simulations of both GSR and temperature were found to be

relatively higher than those of the observations. In addition, NorSEM simulations were found to be higher than those of HadGEM.

3.2 Comparison between NASA observations and RegCM simulations

Results in Fig. 3 suggested that the models' simulations slightly overestimated both the GSR and temperature across all the stations. In addition, NorSEM generally produced higher biases (BIAS) and percentage bias (PBIAS) than HadGEM as earlier suspected. The range of computed biases in GSR were 17–37 Wm⁻² (Lomé), 10–34 Wm⁻² (Atakpamé), 15–35 (Sokodé), 16–34 Wm⁻² (Kara) and 18–33 Wm⁻² (Mango). PBIAS were 8–17% (Lomé), 5–15% (Atakpamé), 7–15% (Sokodé and Kara) and 8–13.5% (Mango). Similarly, the BIAS (PBIAS) in monthly temperatures ranged

Fig. 3 Comparisons between NASA and model (HadGEM2 and NorSEM) monthly simulations of global solar radiation (upper panel; **a, b**) and temperature (lower panel; **c, d**) over selected sta-

tions in Togo, West Africa from 1987 to 2016 (I and II are bias, BIAS and percentage bias, PBIAS respectively)

between 0.1 °C (0.5%) and 2.0 °C or 7.3% (Fig. 3). Generally, the simulations compared fairly well with the NASA observations as *t* test results showed no significant difference at $p < 0.05$ except for GSR simulations by NorSEM at Lomé and Atakpamé. The overall implication is that the RegCM model simulations are good data resources for climate change impact study as explored in this present work. It can also be deduced that the model performance varied across the stations with the least BIAS/PBIAS in GSR and temperature simulations at Atakpamé and Sokodé, respectively. On the other hand, the highest BIAS in GSR simulation was obtained at Lomé while those of temperature was at Mango.

3.3 Annual trends of historical GSR and temperature

Results of annual trends and variations in temperature and GSR are presented in Table 1. The results suggested increasing trends in temperature observations across all the investigated stations during the baseline period (1976–2005). The temperature observation was found to increase by 0.028 °C year⁻¹ over Lomé, 0.025 °C year⁻¹ over Atakpamé and Kara, 0.032 °C year⁻¹ over Sokodé and 0.043 °C year⁻¹ over Mango. The trends in observed temperatures were found to be insignificant at $p < 0.05$. In the same manner, model simulations suggested rise in temperature trends over all stations and the variations were found to be insignificant except for NorSEM simulations over Sokodé and Kara. This might not be unconnected with the relatively large positive biases in NorSEM simulations of temperature as reported in Sect. 3.2. On the other hand, the results showed decreasing trends in GSR simulations over the entire the country. For example, observed GSR was found to decrease in trends by 0.567 Wm⁻² year⁻¹ (Lomé), 0.326 Wm⁻² year⁻¹ (Atakpamé), 0.225 Wm⁻² year⁻¹ (Sokodé), 0.275 Wm⁻² year⁻¹ (Kara) and 0.483 Wm⁻² year⁻¹ (Mango). In other words, GSR had decreased by 17.0 Wm⁻² (Lomé), 9.78 Wm⁻² (Atakpamé), 6.75 Wm⁻² (Sokodé) 8.25 Wm⁻² (Kara) and 12.9 Wm⁻² (Mango) between 1976 and 2005. The highest reduction (17.0 Wm⁻²) was over Lomé in the south and the least (6.75 Wm⁻²) over Sokodé in the middle belt. Model simulations also suggested decrease in GSR trends over all stations during the 30-year period. However, the variations were found to be insignificant in all stations. The estimated increasing trends in cloud cover during the historical period justified the observed variations in GSR in the study area. Specifically, cloud cover was observed to have increased per year by 0.017% over Lomé, 0.020% over Atakpamé, 0.035% over Sokodé, 0.024% over Kara and 0.004% over Mango. These suggested that increased or decreased cloud cover could results in decreasing or increasing trends in GSR [21]. Thus, the

results obtained are in agreement with range of increasing ambient temperature and GSR as documented in [19, 20].

Furthermore, literature suggested that variations in GSR could not be 100% attributed to changes in cloud cover. For example, increase in atmospheric aerosols could also contribute to reduction in GSR reaching the ground surface [42, 43].

3.4 Future changes in temperature and GSR

Figure 4 describes the projected future changes [2031–2060 (future 1) and 2070–2099 (future 2)] in annual mean temperature relative to the historical period (1976–2005) in the five selected meteorological stations in Togo. All models generally projected increase in temperature over the entire country. As expected, RCP8.5 of high range mitigation scenario produced relatively higher increase in temperature than RCP 2.6 of low range mitigation scenario. The range of increment projected for RCP 2.6 and RCP 8.5 scenarios by the models during 2031–2060 period was 0.2–3.6 °C (Lomé), 0.5–4.2 °C (Atakpamé), 0.6–4.6 °C (Sokodé, and Mango; Fig. 4a). Results also revealed that HadGEM-driven model for both scenarios generally projected higher temperatures over the entire country. These projected rise in temperatures were expected to increase further till the end of the century (2070–2099; Fig. 4b). Our results support previous studies on the well published warmer climate in the future over West Africa like every other region of the world due to increasing atmospheric greenhouse gases as a result of exponential rise in global population, industrialization and the use of fossil fuel [44]. Projected changes and variations in seasonal mean temperature are illustrated in Fig. 5. The results revealed future rise (warming) in temperature in all seasons across stations. A more warming in DJF than other seasons during both future 1 and 2 was obtained. On the other hand, projected changes in GSR are presented in Fig. 6. The models generally suggested decline in GSR over Togo. All models unanimously projected range of declines in GSR of 2.5–5.8% (Lomé), 1.5–4.5% (Atakpamé), 0.5–4.3% (Sokodé), 0.5–4.0% (Kara) and 0.8–3.8% (Mango) during future 1 (Fig. 6a). Similar patterns of decline in GSR were projected for the end of the century (future 2) but with lower magnitudes ranging between 0.2 and 3.8%, except for HadGEM of RCP 2.6 which projected slight increase (0.2 and 0.5%,) in GSR over the northern stations (e.g. Sokodé, Kara and Mango; Fig. 6b). Furthermore, Fig. 7 illustrates future changes in seasonal GSR (in percentage) over the selected stations. In general, the models projected decrease in GSR during different seasons ranging from 0.1 to 5.2% during 2031–2060 period (Fig. 6a). However, one or two of the models (specifically HadGEM RCP 2.6 or/and RCP 8.5) suggested possible rise (0.2–2.1%) in GSR;

Table 1 Results of the statistical trend analysis of the historical data using the nonparametric Mann–Kendall (M–K) method

Variable	Statistics	Meteorological Station											
		Lomé			Atakpamé			Sokodé			Kara		
		Had	Nor	Obs	Had	Nor	Obs	Had	Nor	Obs	Had	Nor	Obs
TMP	Trend	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	β -slope	0.009	0.019	0.028	0.000	0.022	0.025	0.006	0.021	0.032	0.006	0.023	0.025
	Z-score	0.957	1.701	1.570	0.169	1.970	0.642	0.957	2.120	0.428	0.807	2.270	0.000
	p value	0.339	0.088	0.116	0.866	0.049	0.527	0.339	0.034	0.669	0.420	0.023	1.000
GSR	Sig	–	–	–	–	–	–	–	*	–	–	*	–
	Trend	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
	β -slope	–0.217	–0.056	–0.567	–0.362	–0.130	–0.326	–0.397	–0.150	–0.225	–0.472	–0.164	–0.275
	Z-score	–1.257	–0.019	–1.963	–2.232	–0.469	–0.821	–2.082	–0.694	–0.749	–2.607	–0.544	–0.571
CLD	p value	0.209	0.985	0.050	0.026	0.639	0.412	0.037	0.4877	0.454	0.009	0.587	0.568
	Sig	–	–	–	–	–	–	*	–	–	–	–	–
	Trend	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	β -slope	0.042	0.031	0.017	0.012	0.019	0.020	0.039	0.065	0.035	0.009	0.017	0.024
	Z-score	2.308	0.927	0.131	1.390	0.807	0.807	1.000	2.391	0.807	1.505	0.564	0.807
	p value	0.655	0.708	0.896	0.600	0.421	0.420	0.620	0.880	0.420	0.420	0.770	0.420
	Sig	–	–	–	–	–	–	–	–	–	–	–	–

TMP: Temperature (°C)

GSR: Global solar radiation (Wm^{-2})

CLD: Cloud cover (%)

Had: HadGEM-driven RegCM model

Nor: NorSEM-driven RegCM model

Obs: Observations (NASA or CRU)

Z: standardized M–K score;

 β -slope: Sen's trend line slope;

↑: increasing trend;

↓: decreasing trend

p value: statistical p values

Sig.: Significant status: * means significant at $p < 0.05$

Fig. 4 Projected future changes in annual mean temperature relative to the historical period (1976–2005) in the five selected meteorological stations over selected stations in Togo, West Africa: **a** future 1 (2031–2060) and **b** future 2 (2070–2099)

particularly in a few stations in JJA season. Declines in seasonal variations in GSR were also found during 2070–2099 period but with reduced magnitudes ranging between 0.1 and 4.0% over the study area.

In all, the projected general declines in future GSR could be a good signal for enhanced precipitation and relative humidity over Togo. Togo has been reported to be rapidly expanding economically and thereby increases her potential to emit anthropogenic pollution into the atmosphere [45]. High atmospheric pollution or aerosol loading could affect the atmospheric transmission under clear-sky conditions to decrease rapidly [21]. Thus, the anticipated decrease in the surface GSR could be an indication of enhanced future aerosol loading/pollution (as reported by [46] over China), cloud cover and precipitation. Further research should assess the impacts of variations in aerosol loading/pollution on GSR in Togo. Reduction in GSR is a

serious threat to solar photovoltaic (PV) power production and thus there is a need to work on enhanced technology with the least climate change impacts over West Africa [47].

4 Conclusion

The potential impacts of future climate change on global solar radiation in Togo using RegCM4.7 driven by HadGEM-ES and NorESM-M GCM for RCP2.6 and RCP8.5 future scenarios, provided by the CORDEX (Coordinated Regional Downscaling Experiment) framework have been examined in this study. Simulations of the baseline (1976–2005) climatology of surface Global Solar Radiation (GSR) and temperature were validated by comparing them with the National Aeronautics and Space Administration (NASA) observation datasets. In addition, the potential impacts of future warming on global solar radiation in different parts of Togo during two different time-slices [near future (2031–2060) and far future (2070–2099)] were investigated. The models produced realistic simulations of GSR and temperature characteristics over the stations, and in virtually all cases, the simulations spread are within the observation uncertainty. However, the models' simulations slightly overestimated both the GSR ($10\text{--}37\text{ Wm}^{-2}$ or $5\text{--}17\%$) and temperature ($0.1\text{--}2.0\text{ }^{\circ}\text{C}$ or $0.5\text{--}7.3\%$) across all the stations. Generally, the simulations compared fairly well with the NASA observations as t test results showed no significant difference at $p < 0.05$. There were indications that both GSR and temperatures could be higher in the north than the southern parts of the country. The obtained spatial patterns of GSR and temperature are indications of increased surface warming due to higher solar insolation reaching the ground surface. Both observations and models' simulations showed similar patterns of annual trends of GSR, temperature and cloud cover. The results suggested increasing trends ($0.025\text{--}0.043\text{ }^{\circ}\text{C year}^{-1}$) in observed temperature but decreasing ($0.225\text{--}0.567\text{ Wm}^{-2}\text{ year}^{-1}$) in GSR across all the investigated stations during the baseline period. The trends in temperatures and GSR were found to be insignificant at $p < 0.05$. The estimated increasing trends in cloud cover during the historical period justified the observed variations in GSR in the study area. Specifically, cloud cover was observed to have increased per year by 0.017% over Lomé, 0.020% over Atakpamé, 0.035% over Sokodé, 0.024% over Kara and 0.004% over Mango. These suggested that increased or decreased cloud cover could result in decreasing or increasing trends in GSR. Furthermore, literature suggested that variations in GSR could not be 100% attributed to changes in cloud cover. For example, increase in atmospheric aerosols could also contribute to reduction in GSR reaching the ground surface. All

Fig. 5 Projected future changes in seasonal temperature in selected five meteorological stations in Togo, West Africa: **a** DJF=December to February, **b** MAM=March to May, **c** JJA=June

to August and **d** SON=September to November). **(I and II are for future 1 (2031–2060) and future 2 (2070–2099), respectively)**

Fig. 6 Projected future changes in annual mean global solar radiation relative to the historical period (1976–2005) over selected five meteorological stations in Togo, West Africa: **a** future 1 (2031–2060) and **b** future 2 (2070–2099)

models generally projected increase in temperature over the entire country at both annual and seasonal time-scales. The range of increment projected for RCP 2.6 and RCP 8.5 scenarios by the models during 2031–2060 period was 0.2–3.6 °C (Lomé), 0.5–4.2 °C (Atakpamé), 0.6–4.6 °C (Sokodé, and Mango). These projected rise in temperatures were expected to increase further during future 2 (2070–2099). On the contrary, the models unanimously suggested decline in GSR over Togo. The range of declines in GSR were 2.5–5.8% (Lomé), 1.5–4.5% (Atakpamé), 0.5–4.3% (Sokodé), 0.5–4.0% (Kara) and 0.8–3.8% (Mango) during future1. Similar patterns of decline in GSR were projected for future 2 but with lower magnitudes ranging between 0.2 and 3.8%. Thus, the anticipated decrease in the surface GSR was attributed to enhanced future aerosol loading, cloud cover and higher precipitation. The findings have implications in solar photovoltaic (PV) power production and the need to work on a guide for improved technology with the least climate change impacts in Togo and West Africa at large. As a follow up work to the present paper, further research endeavour is proposed to assess the impacts of variations in aerosol loading/pollution on GSR in the study area.

Fig. 7 Projected future changes in seasonal global solar radiation in selected five meteorological stations in Togo, West Africa: **a** DJF=December to February, **b** MAM=March to May, **c** JJA=June

to August and **d** SON=September to November). 1 (2031–2060) and future 2 (2070–2099). (I and II are for future 1 (2031–2060) and future 2 (2070–2099), respectively)

Author contributions All the authors contributed greatly in various capacities to this work.

Availability of data and materials The authors declared that the data and materials for this work were available.

Compliance with ethical standards

Conflict of interest The authors declared that there is no conflict of interest among them. All the authors read and approved the manuscript.

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