Effect of Climate Change on Solar Radiation over a Tropical Region

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Abstract – This study investigates the contribution of climate change to solar radiation variability over a tropical region taking the four climate regions in Nigeria as a case study. Three solar radiation components (diffuse, direct, and global solar radiation) were obtained from the database of Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) spanning the periods of 40 years (1980 – 2020) were used for the study. The seasonal trend and change-point analyses were quantified using the Mann-Kendall test, Pettitt test, and linear regression Panalysis. Mann-Kendall trend test revealed that there were increasing trends in diffuse radiation (DF) with a maximum strength of 3.63 per year in Rainforest and Coastal regions. Meanwhile, absolute decreasing trends were detected in direct (DR) and global solar radiation (GSR) respectively across the four regions in Nigeria. Also, based on the Pettitt test, DF had a predominant change point in 1999, DR in 2005, and GSR in 2001. The maximum observable changes of 0.701 W/m^2 for DF, -3.076 W/m^2 for DR, and -1.487 W/m^2 for GSR annually over Nigeria using the slopes of linear regression. Finally, the climate was observed to contribute a maximum of 50.30% to increase in DF, 67.80% to decrease in DR, and 65.00% to decrease in GSR using the coefficient of determination. It can be inferred from this study that the current variability in solar radiation across the climate regions in Nigeria is largely caused by climate change.

Keywords: solar radiation, MERRA-2, Mann-Kendall test, Pettitt test, trends, change point, Nigeria

I. INTRODUCTION

Anthropogenic activities such as indiscriminate burning of fossil fuel from industrial sites and transportation have contributed immensely to the emission of greenhouse gases and aerosols. They have caused the increase in air pollution which in turn has acted like a blanket that covers the atmosphere in addition to clouds. One of the major consequences may have been attenuation of solar radiation destined for the earth's surface either in the increase or decrease form since the atmosphere is the medium of its transmission [1, 2]. Solar radiation is the radiant energy emanating from the sun which serves as key elements of the total energy exchange between the atmosphere and the Earth's surface [3, 4]. It is essential for the global energy balance of the earth-atmosphere system [5, 6], clean decarbonized energy for domestic and industrial energy sources [7] [8], plant metabolisms such as photosynthesis [9, 10], and examination of climate change and global warming [3] [11]. This radiant energy from the sun can be classified as the direct radiation if it is reaching the earth surface unmodified by atmospheric constituents; the diffuse radiation if it has been scattered and modified by air molecules, aerosols, water vapour, ozone, and the clouds and global solar radiation if both the direct and diffuse radiation fall together on a horizontal surface [12]. Many studies have reported the decrease in global solar radiation in several parts of the world especially between 1960 and 1990 as global dimming while few have equally reported an increase in global solar radiation especially after 1990 as global brightening [13–15]. However, these studies have not paid kin attention to the quantitative extent of changes in the three types of solar radiation, the particular years of change point, and the level of contribution of climate change on this very important energy from the sun that drives all atmospheric processes and oceanic circulations. This present study paid special attention to the changes in direct, diffuse, and global solar radiation quantitatively in the four climate regions over Nigeria, a tropical country. It also examined and evaluated the seasonal change points and their significance in the different atmospheric conditions. Finally, this study analyzed the contributions of seasonal and annual changes to the intensity of solar radiation in these regions. This study uses reanalyzed products from the MERRA-2 database of NASA products being regional because there is no ground measurement gridded data that can effectively capture the entire surface in the study area. The result of this study will be useful for the energy conversion engineers, agricultural agencies, weather forecasting, and airspace agencies as well as other relevant stakeholders to make balance policies with precisions.

II. STUDY AREA

Nigeria is a tropical country situated within latitudes 4ºN – 14ºN and longitudes 4ºE – 14ºE with two main seasons – rainy dry seasons. It is bounded by the Niger Republic northward, Chad and Cameroon eastward, the Benin Republic westward, and the Atlantic Ocean southward. The two seasons in Nigeria are controlled by two trade winds which include maritime trade wind (mT) and continental trade wind (cT) distinguished by the movement of intertropical discontinuity (ITD). The wet season is due to the African monsoon occurs when ITD is at the maximum position in the North. Nigeria is divided into four main climatic regions including the Sahel, Guinea Savannah, Rainforest, and Coastal Regions as shown in Figure 1 along with the latitudinal range based on annual rainfall distribution. Annual precipitation is below 500 mm in the Sahel region, ranges from 1000 mm to 1500 mm in the Guinea Savannah region, above 2000 mm in the Rainforest, and above 3000 mm in the Coastal region.

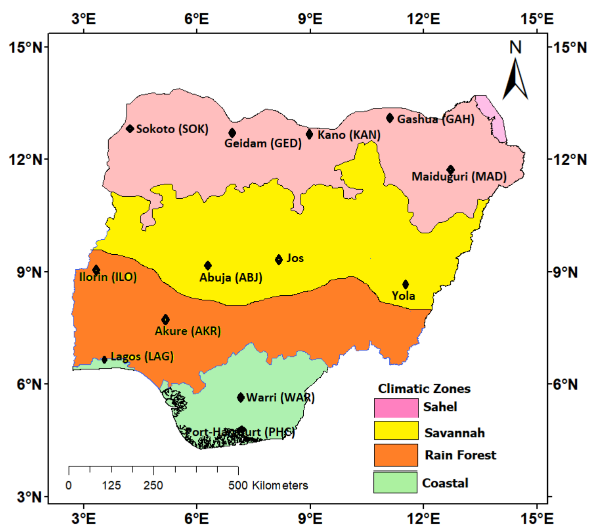

Figure 1: A Map of Nigeria showing the Showing the Study Area

III. MATERIALS AND METHODS

A. Data Acquisition

Surface data of direct, diffuse, and global solar radiation were obtained from the MERRA-2 database of NASA on daily basis for the period of forty (40) years (1980 – 2020) over the entire Nigeria. The detailed description and reliability of MERRA-2 reanalysis for the quality atmospheric research work can be found in [17] and [18]. The data were average annually into four climate regions along with the latitudinal ranges as shown in Figure 1.

B. Data Analysis

The non-parametric tests such as trend test and homogeneity test as well as linear regression were used to quantify the extent of changes in the time series of direct, diffuse, and global solar radiation. Firstly, the Mann-Kendall trend test was employed to ascertain the presence of a monotonic increasing or decreasing trend in the three types of solar radiation denoted as S between 1980 and 2020. The variance of S was computed using Equation (1) which takes the presence of ties into account:

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{a} t_p\left(t_p-1\right)\left(2t_p+5\right)\right] \qquad (1)$$

where p is the number of tied groups and t_p is the number of data values in the pth group.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \qquad (2)$$

Z-value shows the strength of increase or decrease in the time series. That is, the time series shows an increasing trend if the z-value is positive but it is decreasing trend if the z-value is negative. The significance of the trends was detected using the value of a Boolean quantity (h) whose value is either 0 or 1. The value of h = 1 if the trend value is significant but it is non-significant if h = 0. Also, p-value (p) was used to detect the significant of Z values at the 0.05 p-value of significance. Secondly, Pettitt homogeneity test was utilized to detect the exact change point (CP) year using two hypotheses based on Mann-Whitney statistic, U_t given as [10]:

$$U_t = U_{t-1} + \sum_{t}^{N} sgn\left(x_i - x_j\right)\ for\ t = 2, \ldots N \qquad (3)$$

The test returns H0 if the period of change point is homogeneous (the rate of change is constant along the years). It returns Ha if the time series have different patterns after the change point. A significant change was detected at a p-value of 0.05 alpha level. The percentage changes were evaluated using:

$$\% \, Change = \frac{Actual \, Change}{Initial \, value \, before \, Change \, point} \times 100\% \qquad (4)$$

Furthermore, the trends and extent of changes in the solar radiation were established using linear regression taking each of the solar radiation data as dependent variable (Q) and the forty (40) years series served as the independent variable (T):

$$Q = \beta T + \alpha \qquad (5)$$

where β and α are the slope and intercept of the linear regression respectively. The slope gives the value of change in the time series annually. The contribution of the annual variations on the solar radiation trends was evaluated using the coefficient of determination (R^2).

IV. RESULTS AND DISCUSSION

Tables 1 - 2 show the seasonal trend and change point values of solar radiation with linear regression in the Sahel, Guinea Savannah, Rainforest, and Coastal regions over Nigeria between 1980 and 2020. It can be observed in the tables firstly that diffuse radiation (DF) showed increasing trends during both the dry and wet seasons as well as in the annual time scale except in Sahel where a non-significant decreasing trend of DF was detected across the four regions. The increasing trends were significant at 0.05 alpha level with h = 1 during wet season only in Sahel region, dry season in Guinea Savannah region, both dry and wet seasons in Rainforest region and dry season in Coastal region. The strength of the increasing trends of DF increased along with increasing latitudes with the strongest strength in the Coastal region where the Z-value is 3.628. This may be attributed to higher humidity; higher moisture contents and cloud cover due to high precipitation as well as higher concentration greenhouse gases and aerosols arising from the prevalence of anthropogenic activities that are predominant in the Coastal area of Nigeria compared to other regions. Meanwhile, direct (DR) and global solar radiation (GSR) showed decreasing trends during dry and wet seasons as well as in annual time scale across all the regions in Nigeria. These observed decreasing trends were significant for both DR and GSR during wet season in Sahel region, both dry and wet seasons as well as in annual time scale in Guinea Savannah region, Rainforest region, and Coastal region respectively at 0.05 alpha level of significance. The strongest decreasing trends in both DR and GSR were discernible in Sahel regions with Z-values of -4.639 and -4.729 respectively. Therefore, it can be inferred that high humidity, cloudiness, and anthropogenic activities contributed to an increase in the diffuse component of solar radiation but they contributed to a decrease in the direct and global solar radiation.

Table 1: Trend and change-point analyses of solar radiation with the linear region in the Sahel and Guinea Savannah region

CLIMATE REGION	TIME SERIES TEST		DRY SEASON			WET SEASON			ANNUAL		
			DF	DR	GSR	DF	DR	GSR	DF	DR	GSR
Sahel Region	Trend Test	Z	1.247	-0.729	-0.865	2.774	-4.639	-4.729	-1.139	-0.775	-1.247
		H	0	0	0	1	1	1	0	0	0
		p	0.212	0.466	0.387	0.006	0.000	0.000	0.255	0.438	0.212
	Homogeneity Test	CP	1999	2001	2012	2007	2005	2005	1997	2015	2008
		HM	H0	H0	H0	Ha	Ha	Ha	H0	H0	H0
		%C	0.00	0.00	0.00	4.28	-11.91	-6.39	-	-	-
		p	0.378	0.828	0.966	0.041	<0.0001	<0.0001	0.459	0.853	0.347
	Linear Regression	β	0.080	-0.182	-0.102	0.180	-0.972	-0.792	-0.046	-0.122	-0.169
		α	-49.47	701.49	652.02	-250.43	2164.3	1913.9	202.16	527.97	730.13
		R^2	0.022	0.025	0.017	0.193	0.445	0.456	0.026	0.017	0.053
Guinea Savannah Region	Trend Test	Z	3.381	-5.121	-3.516	1.426	-3.740	-3.830	1.426	-3.987	-4.279
		h	1	1	1	0	1	1	0	1	1
		p	0.001	0.000	0.000	0.154	0.000	0.000	0.154	0.000	0.000
	Homogeneity Test	CP	1999	2002	2002	2004	2002	2002	2001	2002	2002
		HM	Ha	Ha	Ha	H0	Ha	Ha	H0	Ha	Ha
		%C	8.18	-14.53	-7.14	0.00	-10.33	-5.62	0.00	-8.21	-4.74
		p	0.000	<0.0001	0.000	0.120	0.000	0.000	0.244	<0.0001	<0.0001
	Linear Regression	β	0.355	-1.285	-0.930	0.068	-0.654	-0.586	-0.053	-0.598	-0.545
		α	-591.8	2839.3	2247.5	-32.4	1486.1	1452.8	3.1	1413.8	1417.0
		R^2	0.295	0.354	0.297	0.062	0.319	0.359	0.052	0.375	0.417

Secondly, the change points and the possible percentage change at these points were deduced using homogeneity test analysis for direct, diffuse, and global solar radiation during the dry season, wet season, and annual time scale at their respective p-value as are shown in the tables between 1980 and 2020. The test returned change point (CP), p-value (p), H0 for change point that is non-significant (p-value greater than 0.05 ($p > 0.05$)), Ha for change point that is significant (p-value less than 0.05 ($p < 0.05$)) and percentage change (%C) at significant change point. The observations showed that the significant change points were detected for DF in 2007 with a 4.28% increase, for DR in 2005 at a -11.91% decrease, for GSR in 2005 at -6.39% decrease during the wet season in the Sahel region. Also, in the Guinea savannah region, significant change points were detected in 1999 for DF at 8.18% increase during, in 2002 for DR at -14.53% decrease, and 2002 for GSR at -7.14 decrease during the dry season. Meanwhile, during the wet season, significant change points were observed in 2002 for DR at a -10.33 decrease and in 2002 for GSR at a -5.62% decrease. In the annual time scale, significant change points were observed in 2002 for DR at a -8.21% decrease (Figure 2b) and in 2002 for GSR at a -4.74% decrease (Figure 3b). Also, in the Rainforest region, significant change points are discernible in two seasons and annual time scale for all the studied variables. That is, DF had change points in 1999 at 13.92% increase during the dry season, 2005 at 4.60% increase during the wet season, and 1999 at 6.90% increase in annual time series (Figure 1c). DR had change points in 1998 at a -44.99% decrease during the dry season, 1998 at -13.26% decrease during the wet season, and 1998 at a -25.01% increase in annual time series (Figure 2c). GSR had change points in 1998 at a -20.01% decrease during the dry season, 1998 at a -7.38% decrease during the wet season, and 1998 at a -12.69% increase in annual time series (Figure 3c). In addition, all the discernible change points were significant ($p < 0.05$) except for DF in the wet season in the Coastal region. That is, DF had change points in 1999 at 7.59% increase during the dry season, 2005 during the wet season, and 2001 at 3.85% increase in annual time series (Figure 1d). DR had change points in 1998 at a -34.69 decrease during the dry season, 1998 at a -12.99% decrease during the wet season, and 1998 at a -25.01% increase in annual time series (Figure 2d). GSR had change points in 1998 at a -20.01% decrease during the dry season, 1998 at a -7.38% decrease during the wet season, and 1998 at a -12.69% increase in annual time series (Figure 3d). Hence, it can be inferred that the observable significant ($p < 0.05$) change points may be attributed to the fluctuation of the characteristics caused by interannual changes in the solar radiation components as a result of climate change (Figures 1 – 3).

Table 2: Trend and change-point analyses of solar radiation with the linear region in the Rainforest and Coastal region

CLIMATE REGION	TIME SERIES TEST		DRY SEASON			WET SEASON			ANNUAL		
			DF	DR	GSR	DF	DR	GSR	DF	DR	GSR
Rainforest Region	Trend Test	Z	3.627	-4.729	-4.616	2.392	-6.178	-4.279	4.796	-5.133	-5.290
		h	1	1	1	1	1	1	1	1	1
		p	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000
	Homogeneity Test	CP	1999	1998	1998	2005	1998	1998	1999	1998	1998
		HM	Ha	Ha	Ha	Ha	Ha	Ha	Ha	Ha	Ha
		%C	13.92	-44.99	-20.01	4.60	-13.26	-7.38	6.90	-25.01	-12.69
		p	<0.0001	<0.0001	<0.0001	0.02	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Linear Regression	β	0.701	-3.076	-2.375	0.157	-1.042	-0.885	0.316	-1.803	-1.487
		α	-1277	6371.40	5094.4	-212.5	2285.4	2072.9	-519.58	3809.9	3290.4
		R^2	0.497	0.552	0.503	0.136	0.383	0.400	0.503	0.678	0.650
Coastal Region	Trend Test	Z	3.628	-4.594	-4.302	1.179	-3.516	-3.695	4.401	-5.335	-5.088
		h	1	1	1	0	1	1	1	1	1
		p	0.000	0.000	0.000	0.238	0.000	0.000	0.000	0.000	0.000
	Homogeneity Test	CP	1999	1998	1998	2005	2001	2001	2001	1998	1998
		HM	Ha	Ha	Ha	H0	Ha	Ha	Ha	Ha	Ha
		%C	7.59	-34.69	-17.21	-	-12.99	-7.28	3.85	-19.09	-10.13
		p	0.000	<0.0001	<0.0001	0.589	0.001	0.000	0.002	<0.0001	<0.0001
	Linear Regression	β	0.377	-2.313	-1.937	0.095	-0.890	-0.795	0.177	-1.277	-1.100
		α	-632.49	4830.60	4198.1	-89.54	1961.3	1871	-246.68	2738	2491.4
		R^2	0.342	0.486	0.437	0.054	0.269	0.309	0.321	0.661	0.646

Furthermore, the contribution of climate change to solar radiation variability was quantified using the slope of linear regression (β) and coefficient of determination (R^2) across the four climatic regions in Nigeria for the dry season, wet season, and annual time scale as shown in Tables 1-2 and Figures 2-4. The analyses showed that among the four climate regions DF was increased maximumly by 0.701 W/m^2 in the Rainforest region during the dry season, 0.180 W/m^2 in the Sahel region during the wet season, and 0.316 for annual time scale in the rainforest region but only showed a decrease by 0.046 in Sahel region during the wet season. Meanwhile, DR and GSR only decrease trends across all the regions. DR showed a maximum decrease of -3.076 W/m^2 in the Rainforest region during the dry season; -1.042 W/m^2 in the Rainforest region during the wet season; and -1.083 W/m^2 in the Rainforest region during the annual time scale.

Also, GSR decreased by -2.375 W/m^2 in the Rainforest region during the dry season; -0.885 W/m^2 in the Rainforest region during the wet season; -1.487 W/m^2 in the Rainforest region during the annual time scale. Therefore, based on the R^2 value, it can be inferred that climate change contributed 0.497 (49.70%) maximumly to increase in DF during the dry season, 0.193 (19.30%) maximumly to increase of DF during the wet season, and 0.503 (50.3%) to increase of DF on an annual scale.

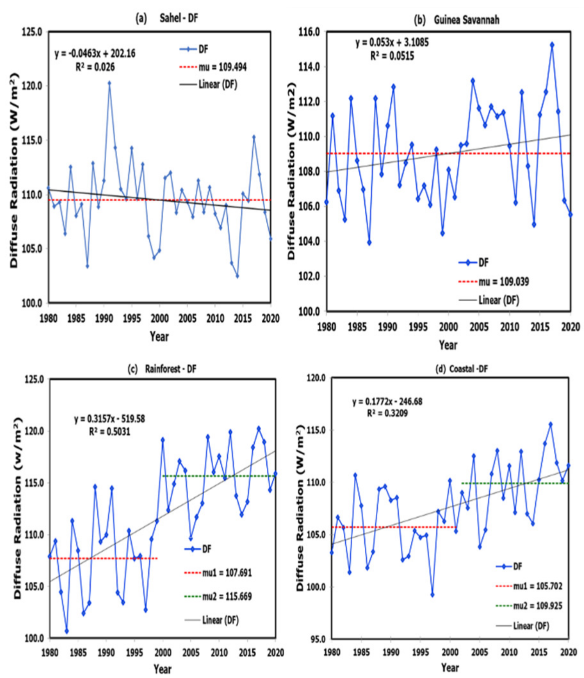

Figure 2: Interannual Variations of Diffuse Radiation Showing the Change Points over Four Climate Regions in Nigeria.

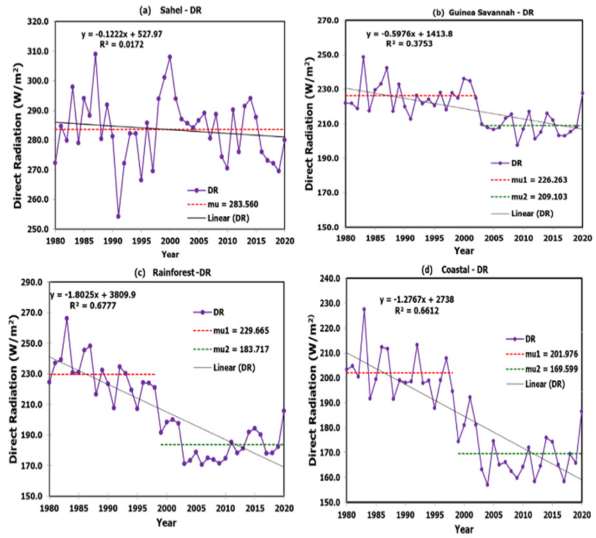

Figure 3: Interannual Variations of Direct Radiation Showing the Change Points over Four Climate Regions in Nigeria.

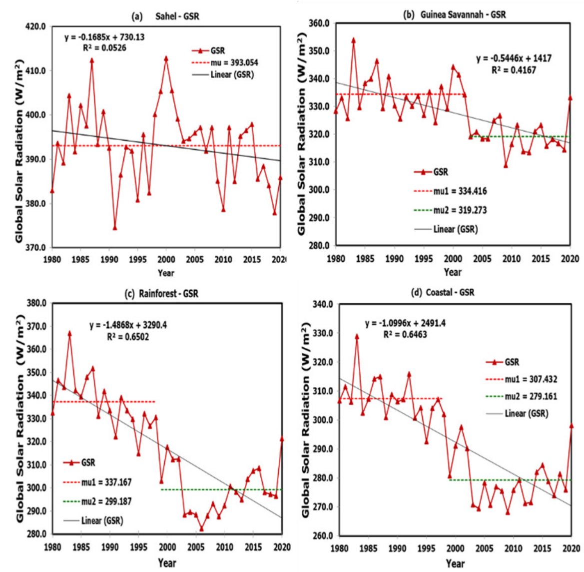

Figure 4: Interannual Variations of Global Solar Radiation Showing the Change Points over Four Climate Regions in Nigeria.

It contributed 0.552 (55.20%) to decrease in DR during the dry season, 0.383 (38.30%) maximumly to decrease in DR during the wet season, and 0.678 (65.00%) to increase in DR on an annual scale. Climate change contributed 0.503 (50.3 %) to a decrease in GSR during the dry season, 0.400 (40.00%) maximumly to decrease of GDR during the wet season, and 0.678 (67.80%) to decrease of GSR on an annual scale.

V. CONCLUSION

The impact of climate change on diffuse, direct, and global solar radiation have been studied from the data obtained from the MERRA-2 database of NASA using the Mann-Kendall trend test, Pettitt test, and linear regression analysis. Trend analyses showed that diffuse radiation had increasing trends but DR and GSR showed decreasing trends in all regions during dry and wet seasons. Also, change points were detected in the three components of solar radiation across the climate regions during both dry and wet seasons as well as in annual time scales. Some of the change points are significant ($p < 0.05$) but a few of the change points are homogeneous. Meanwhile, the slopes of linear regression analysis showed the magnitude of the changes in DF, DR, and GSR respectively with greater changes in the wet season than in the dry season at different change points. Finally, the climate change was observed to have contributed a maximum of 50.30% to increase in DF, 67.80% to decrease in DR, and 65.00% to decrease in GSR on annual timescales. Ground measured solar radiation can be used to validate the results obtained in this study where they are available especially in locations within the study regions.

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REFERENCES

[1] F. Perera, “Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist,” International Journal of environmental research and public health, vol. 15, no. 1, 2017, doi: 10.3390/ijerph15010016.

[2] V. Ramanathan and Y. Feng, “Air pollution, greenhouse gases, and climate change: Global and regional perspectives,” Atmospheric Environment, vol. 43, no. 1, pp. 37–50, 2009, doi: 10.1016/j.atmosenv.2008.09.063.

[3] J. C. Antuña-Sánchez et al., “Solar Radiation Climatology in Camagüey, Cuba (1981–2016),” Remote Sensing, vol. 13, no. 2, p. 169, 2021, doi: 10.3390/rs13020169.

[4] H. Jiang, Y. Yang, H. Wang, Y. Bai, and Y. Bai, “Surface Diffuse Solar Radiation Determined by Reanalysis and Satellite over East Asia: Evaluation and Comparison,” Remote Sensing, vol. 12, no. 9, p. 1387, 2020, doi: 10.3390/rs12091387.

[5] V. M. Fedorov and D. M. Frolov, “Spatial and Temporal Variability of Solar Radiation Arriving at the Top of the Atmosphere,” Cosmic Res, vol. 57, no. 3, pp. 156–162, 2019, doi: 10.1134/S0010952519030043.

[6] J. Bai, A. Heikkilä, and X. Zong, “Long-Term Variations of Global Solar Radiation and Atmospheric Constituents at Sodankylä in the Arctic,” Atmosphere, vol. 12, no. 6, p. 749, 2021, doi: 10.3390/atmos12060749.

[7] T. Burandt, B. Xiong, K. Löffler, and P.-Y. Oei, “Decarbonizing China’s energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors,” Applied Energy, vol. 255, p. 113820, 2019, doi: 10.1016/j.apenergy.2019.113820.

[8] Z. Feng, B. Guo, H. Xu, L. Zhang, J. Xu, and Y. Xu, “A new view on the trend of solar radiation in mainland China — based on the optimized empirical model,” Theor Appl Climatol, vol. 145, 1-2, pp. 519–532, 2021, doi: 10.1007/s00704-021-03643-8.

[9] G. LIU et al., “Reducing maize yield gap by matching plant density and solar radiation,” Journal of Integrative Agriculture, vol. 20, no. 2, pp. 363–370, 2021, doi: 10.1016/S2095-3119(20)63363-9.

[10] Z. Huo, X. Dai, S. Feng, S. Kang, and G. Huang, “Effect of climate change on reference evapotranspiration and aridity index in the arid region of China,” Journal of Hydrology, vol. 492, pp. 24–34, 2013, doi: 10.1016/j.jhydrol.2013.04.011.

[11] O. O. Apeh, O. K. Overen, and E. L. Meyer, “Monthly, Seasonal and Yearly Assessments of Global Solar Radiation, Clearness Index and Diffuse Fractions in Alice, South Africa,” Sustainability, vol. 13, no. 4, p. 2135, 2021, doi: 10.3390/su13042135.

[12] Y. Qian, W. Wang, L. R. Leung, and D. P. Kaiser, “Variability of solar radiation under cloud-free skies in China: The role of aerosols,” Geophys. Res. Lett., vol. 34, no. 12, 2007, doi: 10.1029/2006GL028800.

[13] X. Yang, W. Qin, L. Wang, M. Zhang, and Z. Niu, “Long-term variations of surface solar radiation in China from routine meteorological observations,” Atmospheric Research, vol. 260, p. 105715, 2021, doi: 10.1016/j.atmosres.2021.105715.

[14] H. Xie, J. Zhao, K. Wang, and H. Peng, “Long-term variations in solar radiation, diffuse radiation, and diffuse radiation fraction caused by aerosols in China during 1961-2016,” PloS one, vol. 16, no. 5, e0250376, 2021, doi: 10.1371/journal.pone.0250376.

[15] Z. Wang et al., “Long-term evolution of clear-sky surface solar radiation and its driving factors over East Asia,” Atmospheric Environment, vol. 262, p. 118661, 2021, doi: 10.1016/j.atmosenv.2021.118661.

[16] M. G. Bosilovich et al., “MERRA-2: Initial Evaluation of the Climate,” Goddard Space Flight Center Greenbelt, Maryland 20771, vol. 43, pp. 3–26, 2015.

[17] O. S. Ojo, I. Emmanuel, B. Adeyemi, and E. O. Ogolo, “Effect of the radiation balance on warming occurrence over West Africa,” Scientific African, vol. 11, e00700, 2021, doi: 10.1016/j.sciaf.2021.e00700.