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Modeling of the Global Solar Radiation Series as a Function of Probability Distribution

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Abstract

The use of probability density functions (pdf) is directly linked to the nature of the data to which they relate. Some have good estimation capacity for small number of data, others require a large number of observations. In this study, the most probability distribution function for modeling the global solar radiation in Campo Grande, MS (Brazil) was determined. The global solar radiation data used for the analysis consists of daily average global solar radiation collected from University of Mato Grosso do Sul which span over the period of one year from January 2016 to December 2016. Various distribution functions were tested in this study and the most suitable one is determined using four different goodness of fit tests. The tested distributions used are Weibull, Rayleigh, Gamma, Lognormal, Rician and Frechet distributions. Four performance indicators; Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and Coefficient of Determination (R^2) were calculated to evaluate the adequacy criteria of the chosen distributions. The best distribution that fits well the global solar radiation observations in Compo Grande region was the Frechet distribution, followed by Weibull and Rician distributions. The worst distributions are given by Rayleigh and Lognormal. This paper is useful as first-hand information in the prediction of future global solar radiation for Campo Grande having known the past behavior and for fixing the missing data.

Keywords

Probabilistic Distribution Function, Cumulative Distribution Function, Global Solar Radiation, Campo Grande

1. Introduction

Climate is a factor of great influence in the control of the growth of plants. Moreover, agricultural productivities can be described as probabilistic elements (random variables), in the sense that they depend on climatic variables, such as temperature and global solar radiation of the region during the growing season of a crop.

The use of probability density functions (pdf) is directly linked to the nature of the data to which they relate. Some have good estimation capacity for small number of data, others require a large number of observations. Due to the number of parameters in the density function, some can take different forms, being framedina greater number of situations, that is, they are more flexible. Since respecting the aspect of data representativeness, the estimates of its parameters for a given region can be established as general purpose, without prejudice to the precision in the estimation of probability [1, 2].

The adjustment of probabilistic models to the daily data of solar radiation, plant growth productivity and as uccinct summary of these data represents an efficient technique for the analysis of this information. Each frequency distribution is presented in a certain way, this can be approximated through the use of probability density functions with some parameters extracted from the sample in question. The use or not of a distribution lies in it sability to estimate the observed data, based on its parameters, and this capacity is measured through the performance indices.

To investigate the characterizations of solar radiation, some probability density functions have been proposed in literature to describe its frequency distribution. Forinstance, Ayodele [3] used seven distributions and some of the main results show that the logistic distribution presents the best probability distribution for global solar radiation model in gof Ibadan, Nigeria. Other distributions have also been applied in this line of research, example of such include the normal function [4], the Boltzmann function [5-8], the gamma function [9], the logistic function [8] and many others.

In particular, Kudish and Ianetz [4] found that the frequency distribution for clear days is more approximate to the normal distribution than that for cloudy days. Babu and Satyamurty [9] found that the probability models available in literature are not applicable for all climates, and proposed new expressions to obtain a family of generalized distribution function. Assuncao *et al*., [10] analyzed the clearness index in Brazil to estimate sky condition based on global irradiation data. De Assis [11] in Brazil, used seven density functions while using the Kolmogorov-Smirnov, Chi-square, Cramer Von Mises, Anderson Darling, Kuiper, and Logarithm of Maximum Likelihood as selection criteria. The superiority of the adjustment of the Gumbel, Weibull and Log-normal distributions were verified when compared with the other competing distributions. The rein the logistic and Weibull functions were used for clear and cloudy sky situations respectively.

In addition, Ettoumi et al. [12] stated that a linear combination of two beta distributions is found properly to fit the monthly frequency distributions of the hourly solar radiation data in Algeria. Moreover, Jurado et al. [13] proposed a mixture of two normal distributions while Soubdhan et al. [14] used a mixture of Dirichlet distributions to analyze solar radiation data. However, a detailed comparison demonstrating how appropriate the probability density functions model the frequency distributions has never been found in literature.

The objective of this research is to evaluate the adjustment of historical hours of global daily/daily radiation (Mj/m^2) using the performance indices to the probability density functions: Weibull, Rayleigh, Gamma, Log-normal, Rician and Frechet in Campo Grande, MS.

2. Materials and Methods

2.1. Studied Area and Data

Campo Grande is the capital city of South Mato Grosso (MS) state. It is located in the southern of Brazil Midwest region and sited in the center of the state. Geographically, the considered city is near to the Brazilian border with Paraguay and Bolivia. It is located at 20°26’34”South and 54°38’47”West. Figure 1 shows the location of Campo Grande in the state of South Mato Grosso.

The city occupies the total area of 8,096.051 km^2 or 3,126m^2, representing 2.26% of the total state area within 860,000 inhabitants in year 2016 and a corresponding HDI of 0.78. The urban area is approximately 154.45km^2 or 60m^2, where tropical climate and dry seasons predominate with two clearly defined seasons: warm and humid in summer, and less rainy and mild temperatures in winter. During the months of winter, the temperature can drop considerably, arriving in certain occasions to the thermal sensation of 0° Cor 32°F with occasional light freezing.

They early average precipitation is estimated at 1,534 millimeters with small lupor down variations.

The main pollution problems in the city are attributed to the traffic of vehicles, the raise of building activities, the presence of dumping grounds, the use of small power generators running on oil to supply electric grids power, and the induced fire out break used to clean up local terrains.

2.2. Meteorology

This study was conducted at the main site in the University of Mato Grosso do Sul, in Campo Grande (MS). A pictorial view is provided in Figure 1.

2.3. Modeling of the Global Solar Radiation Datasets

The probability density functions (Weibull, Rayleigh, Gamma, Lognormal, Frechet and Rician) are used for fitting the observed global solar radiation data sets. They are defined as follow:

2.3.1. Weibull (W) PDF

The probability distribution function (pdf) of two (2) parameters is given as:

$$f_W(x;k,c) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} \exp\left[-\left(\frac{x}{c}\right)^{k}\right] \quad (1)$$

It was obtained from the derivative of its cumulative distribution function (cdf) expressed as:

$$F_W(x;k,c) = 1 - \exp\left[-\left(\frac{x}{c}\right)^{k}\right] \quad (2)$$

Where k and C are the shape and scale parameters respectively derived from the time series of the global solar radiation (Hg) datasets; x is the time series observations from each variable/dataset. Mean while, the shape parameter "k" is obtained from the maximum likelihood estimator (MLE) expressed as:

$$k = \left[\frac{\sum_{i=1}^{N} \ln(x_i)\, x_i^k}{\sum_{i=1}^{N} x_i^k} - \frac{\sum_{i=1}^{N} \ln(x_i)}{N}\right]^{-1} \quad (3)$$

Once the value of k is obtained, the scale parameter can be estimated as:

$$c = \left[\frac{\sum_{i=1}^{N} x_i^k}{N}\right]^{\frac{1}{k}} \quad (4)$$

Where N is the number of time series data points. Mean while, Eq. (3) is applied to each global solar radiation observations and solved iteratively with an initial guess of 2 (that is, k=2) until k values converge after several iterations.

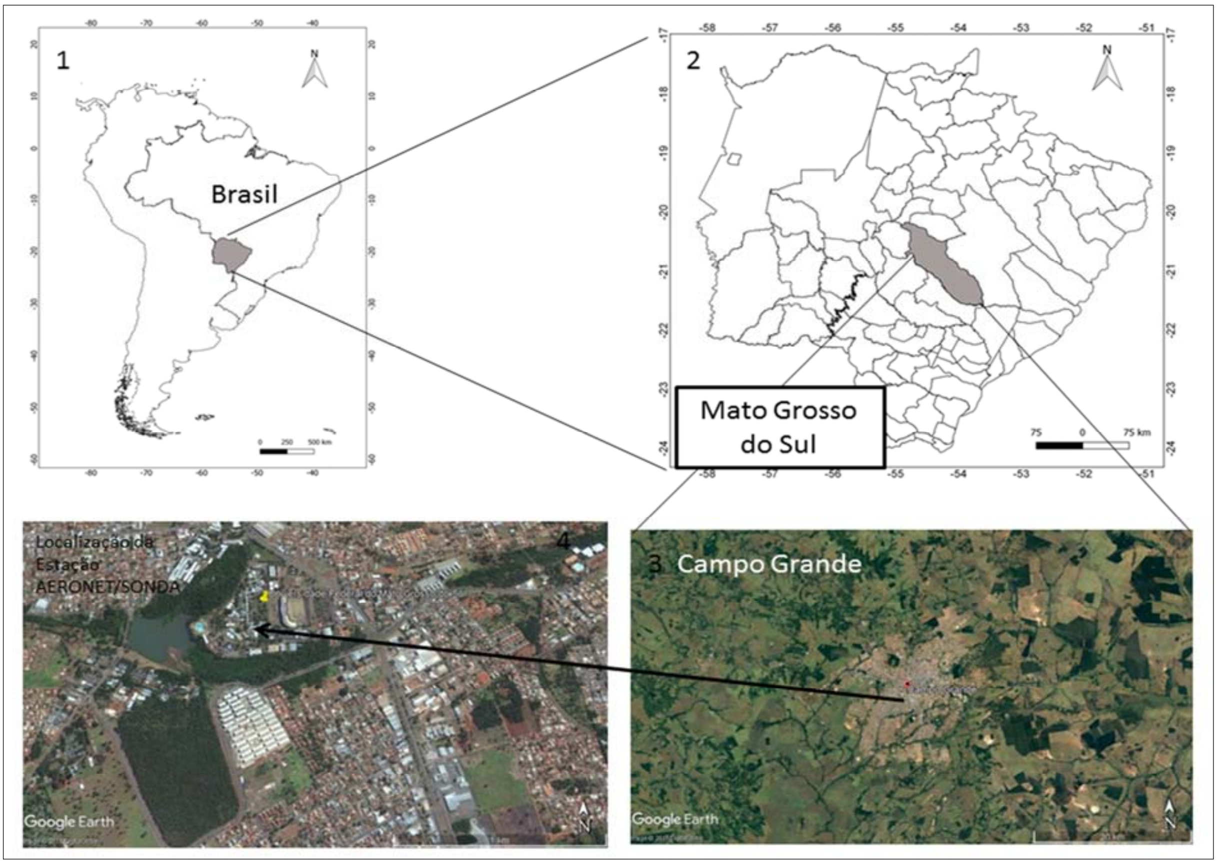


Figure 1. Location of the Municipality of Campo Grande in the State of South Mato Grosso, and the continuous monitoring station located on the campus of the Federal University of South Mato Grosso [15].

2.3.2. Rayleigh (R) PDF

Rayleigh distribution is a special case of the Weibull distribution and its densities are given as:

$$f_R(x;c) = \frac{x}{c^2} e^{-x^2/(2c^2)} \quad (5)$$

and

$$F_R(c) = 1 - e^{-x^2/2c^2} \tag{6}$$

respectively, where ‘c’ is the scale parameter.

2.3.3. Gamma (G) PDF

According to Olaofe and Folly [16], the pdf of Gamma distribution is defined as:

$$f_g(\mathrm{x}; k, C) = \frac{x^{k-1}}{C^k \Gamma(k)} \exp\left[-\left(\frac{x}{C}\right)\right] \tag{7}$$

where f_g and $\Gamma(k)$ are the pdf of gamma distribution and the Gamma function of (k), respectively. k and C are the shape and scale parameters of the Gamma distribution derived from the time series observations.

The cdf of Gamma distribution is defined as:

$$\mathrm{F}_g(\mathrm{x}; k, C) = \frac{1}{C^k \Gamma(k)} \int_0^x t^{k-1} \exp\left(-\left(\frac{t}{C}\right)\right) dt \tag{8}$$

Where F_g is the cumulative density function of Gamma distribution.

2.3.4. Lognormal (L) PDF

Lognormal pdf was used to fit the ozone concentration dataset. The location parameter of the Lognormal distribution is estimated from the expression:

$$\mu = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \log x_i \tag{9}$$

The scale parameter of the Lognormal distribution is estimated as:

$$\sigma = \sqrt{\left(\frac{1}{n-1}\right) \sum_{i=1}^{n} \left[\log\left(x_i - \mu\right)\right]^2} \tag{10}$$

The pdf and cdf of Lognormal distribution are given by:

$$f_l(x; \mu, \sigma) = \frac{1}{\sigma x \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right); x > 0 \tag{11}$$

and

$$F_l(x; \mu, \sigma) = 1 - \mathrm{erfc}\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right) \tag{12}$$

respectively. Details can be found in Oguntunde et al. [17].

where σ, μ, f_l, F_l and erfc (.) are the location parameter, scale parameter, pdf, cdf and error loss function respectively.

2.3.5. Frechet (F) PDF

According to Noor et al. [18], the pdf of the generalized extreme value (GEV) distribution with shape ($k \neq 0$), location (μ) and the scale (δ) parameters is given as:

$$f_f(\mathrm{x}; k, \mu, \delta) = \left(\frac{1}{\delta}\right) \exp\left(-\left(1 + k\frac{(x-\mu)}{\delta}\right)^{-\frac{1}{k}}\right) \left(1 + k\frac{(x-\mu)}{\delta}\right)^{-1-\frac{1}{k}} \tag{13}$$

where f_f is the probability density function of Frechet (GEV) distribution.

2.3.6. Rician (Ri) PDF

In Olaofe [19], the pdf of Rician distribution is given as:

$$f_{ri}(\mathrm{x}; s, \delta) = \mathrm{I}_0\left(\frac{xs}{\delta^2}\right) \frac{x}{\delta^2} \exp\left(-\frac{\left(x^2 - s^2\right)}{2\delta^2}\right) \tag{14}$$

Where $s \geq 0$ and $\delta = 0$ are the non-centrality and scale parameters respectively; I_0 is the zero-order modified Bessel function of the first kind.

The two parameters of Rician distribution are estimated as:

$$s = \frac{1}{N} \prod_{i=1}^{N} x_i \frac{\mathrm{I}_1(z)}{\mathrm{I}_0(z)} \tag{15}$$

$$\delta = \sqrt{0.5\left(\frac{1}{N} \prod_{i=1}^{N} x_i^2 - s^2\right)} \tag{16}$$

Where I_1 (z) is the first-order modified Bessel function of the first kind and $z = (x_i s / \delta^2)$. A good numerical optimization algorithm with a starting value is needed to solve Eq. (15).

2.4. Accuracy Test

The accuracy results are essential for determining the effectiveness of the statistical models. Thus, accuracy check is carried out by comparing the observed climate distributions with the predicted/modeled distributions. The observed dataset is the values from the monitoring systems where as the modelled datasets are obtained from the fitted distributions [20] The various tests for determining the goodness-of-fit of the models are discussed below:

2.4.1. Mean Absolute Error (MAE)

The mean absolute error is used to test the predicted distribution of observed variables (global solar radiation) against the observed distribution. Often, it is defined as the mean of the absolute errors derived from the observed and predicted values. The mathematical equation is defined as:

$$MAE = \frac{\sum_{i=1}^{N} \left| y_i - x_i \right|}{N} \tag{17}$$

where x_i ' s are the observed values of the global solar radiation; y_i is the predicted/modeled values from the Weibull, Rayleigh, Gamma, Lognormal, Rician and Fretchet models.

2.4.2. Root Mean Square Error (RMSE)

The root means square error for the best-fit statistical model is given as:

$$RMSE = \left(\frac{\sum_{i=1}^{N} \left(y_i - x_i \right)^2}{N} \right)^{\frac{1}{2}} \tag{18}$$

It is usually used for comparing the predicted with the observed values.

2.4.3. Mean Absolute Percentage Error (MAPE)

The mean absolute percentage error is calculated as:

$$MAPE = \left[\frac{1}{N} \sum_{i=1}^{N} \left| \left(y_i - x_i \right) \times 100\% \right| \right] \tag{19}$$

3. Results and Discussions

The summary of global solar radiation used in this study is displayed in Table 1. It is described on monthly average for the year of study (2016). The table reveals that the month of September has the highest values of global solar radiation averaging 20,66 MJ/m^2 (rainy season), and from April to August (dry season) lower values of solar radiation were observed with an average of 15.0 MJ/m^2.

Table 1. *Descriptive analysis of global solar radiation (Hg) (Campo Grande, 2016).*

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Av.	18.31	21.63	18.92	16.42	12.72	13.91	15.36	16.61	20.66	18.79	20.96	18.49
SD	4.64	4.21	4.11	4.73	4.97	3.58	3.79	4.46	3.44	6.44	6.61	5.87
Med.	18.55	22.30	19.51	17.39	14.43	15.14	16.74	17.65	21.67	20.29	21.48	17.71
Min	8.77	11.38	9.73	4.26	3.45	2.31	1.86	6.14	5.43	2.22	2.70	9.14
Max	28.51	27.27	25.52	23.35	19.30	17.07	18.09	21.71	23.98	27.46	30.15	29.11
Sk	0.07	-0.96	-0.34	-1.11	-0.69	-2.09	-2.58	-1.28	-3.31	-1.06	-1.15	0.32

In the dry season, despite the difference of latitude in relation to the solar declination, the highest levels of solar radiation were observed (Table 1). On the other hand, in the rainy season although the local declination was almost nil, the levels of solar radiation were at medium. This demonstrates the complexity of the solar radiation estimation, where local declination is important component, but not a determinant of the cosine integral of the angle of incidence. In this context, the highest levels of solar radiation verified in comparison with the other areas can be attributed to the longer duration of the day, which increases in summer as higher latitudes are observed.

It is seen that the frequency distribution of the observed solar radiation variation for a given period are adequately reflect its climatic condition. For example, at the Campo Grande station, the pattern of solar radiation distribution reveals an average level, due to the often rainy days as well as cloud and aerosol attenuation effects.

In order to determine the most likely statistical distribution that can accurately model the global solar radiation of Campo Grande, several statistical distributions have been tested. However, only six of the tested distributions that best approximate global solar radiation data are presented in this paper because of brevity, the statistical analysis results are presented in Table 2.

Table 2. *Statistical analysis of the distribution functions used for Modeling Global Solar Radiation (Campo Grande, 2016).*

Models	Estimates		R^2	MAE	RMSE	MAPE
Weibull	a=19.5521	pdf	0.96606	0.01283	0.01981	21.72613
	b=3.67586	cdf	0.99803	0.01467	0.01848	18.78871
Rayleigh	b=13.0975	pdf	0.49934	0.06163	0.07729	105.58609
		cdf	0.95229	0.08372	0.10758	64.41529
Gamma	a=7.21709	pdf	0.80492	0.03507	0.04768	58.91075
	b=2.45227	cdf	0.98699	0.03978	0.04885	26.63515
Lognormal	μ = 2.80259	pdf	0.65358	0.04457	0.06349	73.70508
	σ =0.43204	cdf	0.97514	0.05564	0.07049	30.14228
Rician	s =16.6969	pdf	0.96278	0.01444	0.02080	25.121810

Models	Estimates		R^2	MAE	RMSE	MAPE
	sigma =5.67018	cdf	0.99781	0.01634	0.01916	17.96359
	k =-0.380687	pdf	0.97439	0.01467	0.01788	26.88717
Frechet	σ = 5.79839	cdf	0.99891	0.01044	0.01362	12.33482
	μ =16.02					

The evolution of solar radiation using the probability distribution functions (Weibull, Rayleigh, Gamma, Lognormal, Rician and Frechet) in Campo Grande, is indicated in Figure 2. They are positively distorted, indicating that most concentrations are within the mean value range. They are narrowed toward the center, indicating that they have lower and lower than average values. The Lognormal distribution indicates that the global solar radiation predicted will have more extreme values, as shown in its longer tail on the right.

Figure 3 shows the cumulative distribution functions for global solar radiation using the same distribution functions. They are plotted and compared with the cumulative observed data.

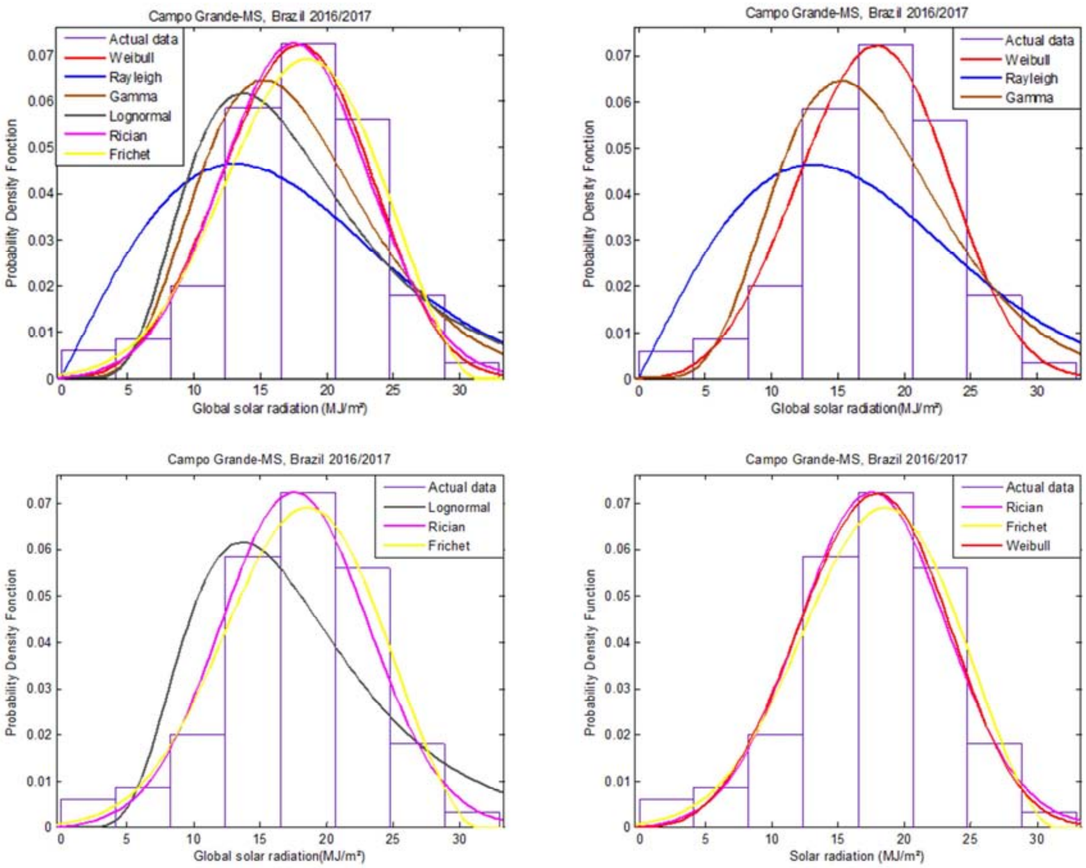
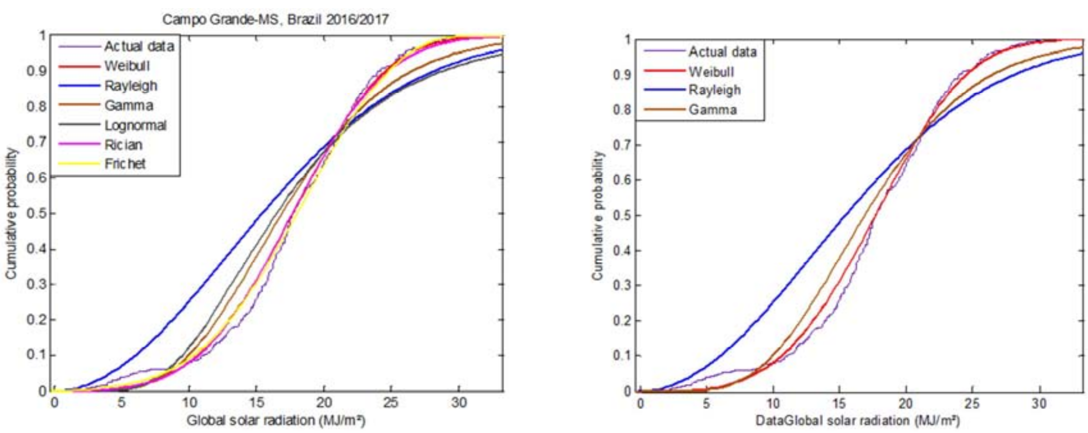
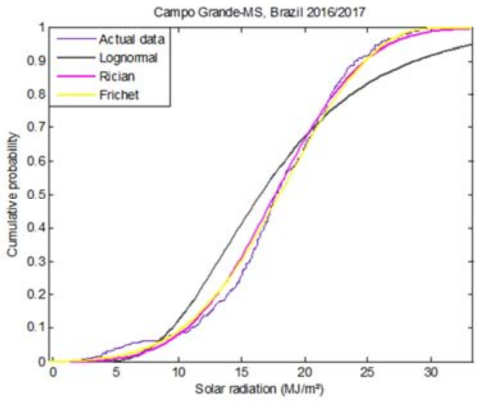


Figure 2. Global solar radiation evaluation using PDF (Campo Grande, 2016).





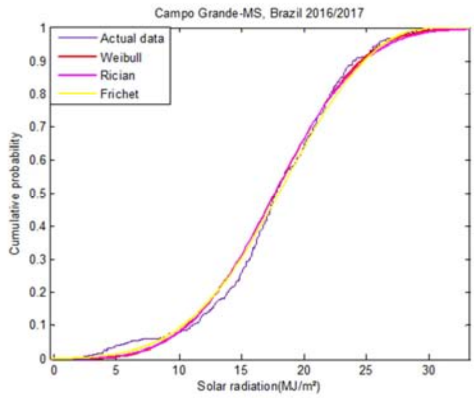


Figure 3. *Global solar radiation evaluation using CDF (Campo Grande, 2016).*

Referring to Figure 3, the graphs show that the Weibull, Rician and Frichet distributions fit very well to the observed distribution compared to Rayleigh, Gamma and Lognormal. The worst distributions are given by the Rayleigh and Lognormal distributions in which the distributions under estimate solar radiation up to 20 MJ/m^2 and over estimate the radiation with values above 20 MJ/m^2 (Figure 3).

4. Conclusion

Based on the statistical characteristics of global solar radiation, it indicates that the mean solar radiation of the monitoring data is smaller than the median values, showing that all observations are left skewed. The Weibull, Rayleigh, Gamma, Lognormal, Rician and Frechet distributions were fitted to the selected datasets. Four performance indicators, that is, mean absolute error (MAE), mean square error (RMSE), Mean Absolute Percentage Error (MAPE) and coefficient of determination (R^2) were obtained to evaluate the adequacy criteria of the distributions.

The best distribution that fits the observations of global solar radiation was the Frechet distribution, followed by Weibull and Rician distributions. The importance of statistical analyses in the field of energy for environmental engineering is shown in this research which gives contribution to the fitness of the global solar radiation datasets with the 'best' probability model (based on the criteria used).

Author Contributions

All the authors contributed equally to the elaboration of this work. All authors will review and approve for publication.

Interest Conflicts

The authors declare no conflict to interest.

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