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Analysis of the accuracy of daily series of global solar radiation simulated by the weather generator PGECLIMA-R, in the State of Parana, Brazil

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ABSTRACT

This study aimed to analyze the accuracy of daily series of global solar radiation, simulated by the weather generator PGECLIMA_R, in the State of Parana, Brazil. For this purpose, there were used historical series of 30 years from 28 different localities, spatially well distributed, so as to represent the entire State. There were five replications for each locality, allowing to compare the monthly average observed and simulated data to test the accuracy of the generator PGECLIMA_R through statistical analysis of the coefficients of Pearson correlation index "r", Willmott agreement index "d", confidence index "c", the mean bias error (MBE), the root mean square error (RMSE) and the mean absolute error (MAE). The comparison between data generated by PGECLIMA_R and historical data demonstrated a very satisfactory performance of this weather generator for estimating global solar radiation in almost all studied localities.

Keywords: global solar radiation, weather generator, PGECLIMA_R.

Análise da exatidão de séries diárias de radiação solar global simuladas pelo gerador de dados climáticos PGECLIMA-R, no estado do Paraná, Brasil

RESUMO

Este trabalho teve por objetivo analisar a exatidão das séries diárias de radiação solar global, simuladas pelo gerador de dados climáticos PGECLIMA_R, no estado do Paraná, Brasil. Para tanto, foram utilizadas séries históricas de 30 anos de 28 localidades diferentes, espacialmente bem distribuídas, de forma a representar todo o Estado. Foram realizadas cinco replicações para cada localidade, possibilitando comparar as médias mensais observadas e simuladas para testar a exatidão do gerador PGECLIMA_R por meio da análise dos coeficientes estatísticos índice de correlação de Pearson "r", índice de concordância de Willmott "d", índice de confiança "c", o erro viés médio (MBE), a raiz quadrada do quadrado médio do erro (RMSE) e o erro absoluto médio (MAE). A comparação entre dados gerados pelo PGECLIMA_R e dados históricos, demonstrou um desempenho bastante satisfatório deste gerador climático para a estimativa da radiação solar global nas localidades avaliadas.

Palavras-chave: radiação solar global, gerador de dados climáticos, PGECLIMA_R

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Introduction

The weather generators are computational tools, which are mathematical simulation models designed to generate synthetic series of climate data with the same statistical characteristics of the historical series. These, in turn, have been used in various areas of human activity, as they allow the analysis of information on local climate, and from simulations, makes it possible to evaluate the influence of climate on natural or human-induced processes.

Weather generators have also been important in the modeling and analysis of ecosystems. Kittel et al. (1995) used this feature to build a bioclimatic database, enabling the analysis of the sensitivity of an ecosystem to climate change.

According to Zanetti (2003) the use of weather generators in the construction of future climate scenarios, aimed at predicting events that might occur at some time in a location of interest, is an alternative of great interest due to the lack of observed data series in the future, allowing thus the use of simulated data.

Today, there are several weather generators developed, and some better known may be cited as example: CLIGEN – Climate Generator (Nicks et al., 1995), LARS-WG (Semenov & Barrow, 1997), SEDAC_R - Stochastic Simulator of Climatic Data (Virgens Filho, 2001), and ClimaBR (Zanetti, 2003).

It stands currently the PGECLIMA_R – Stochastic Generator of Climate Scenarios (Virgens Filho et al., 2011a; Virgens Filho et al., 2011b), which can be considered an evolution of SEDAC-R, with the difference that in addition to simulate weather data, it is also capable of generating climate scenarios from future statistics disturbance in climate variables. This model simulates daily weather data series of rainfall, air temperature (minimum and maximum), relative humidity and global solar radiation, and can also fill the remaining gaps in historical series, parameterize the existing data and simulate the missing data.

Among the climatic variables, the solar radiation can be identified as the main element related to the meteorological phenomena, due to the fundamental character of his direct intervention of life on Earth. According to Valiati (2005), solar radiation is a primary climatological variable, responsible for the distribution of fauna and flora on the planet, directly influencing the physiological activity of living beings and the elements of weather, so plant and animal production depend directly on availability of solar energy. Pereira et al. (2002), also argue that solar radiation is the primary source of all atmospheric phenomena and physical, chemical and biological processes observed in ecosystems.

It can also be used in various forms, such as the capture by the biomass, heating

ventilation and water for domestic and industrial purposes, photoelectricity for small potential and sources for thermodynamic cycles.

In this context, this study aimed to analyze the accuracy of daily series of global solar radiation simulated by the weather generator PGECLIMA_R in the State of Parana, Brazil.

Material and methods

The historical series of global solar radiation, measured in langley.day^{-1} (ly), referring to the twenty-eight locations in the State of Parana, Brazil (Figure 1 and Table 1) were obtained from meteorological stations belonging to the Agronomical Institute of Parana – IAPAR.

Source: The author

Figure 1. Selected locations in the State of Parana, Brazil.

Table 1. Geographical coordinates of the meteorological stations.

Localities	Latitude (S)	Longitude (W)	Altitude (m)
Apucarana	23° 30' S	51° 32' W	746m
Bandeirantes	23° 06' S	50° 21' W	440m
Bela Vista do Paraíso	22° 57' S	51° 12' W	600m
Cambará	23° 00' S	50° 2' W	450m
Cascavel	24° 26' S	53° 26' W	760m
Cerro Azul	24° 49' S	49° 15' W	360m
Cianorte	23° 40' S	52° 35' W	530m
Clevelândia	26° 25' S	52° 21' W	930m
Fernandes Pinheiro	25° 27' S	50° 35' W	893m
Francisco Beltrão	26° 05' S	53° 4' W	650m
Guarapuava	25° 21' S	51° 30' W	1058m
Guarapuã	25° 16' S	48° 32' W	40m
Ibiporã	23° 16' S	51° 1' W	484m
Joaquim Távora	23°30' S	49° 57' W	512m
Laranjeiras do Sul	25° 25' S	52° 25' W	880m
Londrina	23° 22' S	51° 10' W	585m
Morretes	25° 30' S	48° 49' W	59m
Nova Cantú	24° 40' S	52° 34' W	540m
Palmas	26° 29' S	51° 59' W	1100m
Palotina	24° 18' S	53° 55' W	310m
Paranavaí	23° 05' S	52° 26' W	480m
Pato Branco	26° 07' S	52° 41' W	700m
Pinhais	25° 25' S	49° 8' W	930m
Planalto	25° 42' S	53° 47' W	400m
Ponta Grossa	25° 13' S	50° 1' W	880m
Quedas do Iguaçu	25° 31' S	53° 1' W	513m
Telêmaco Borba	24° 20' S	50° 37' W	768m
Umuarama	24° 44' S	53° 17' W	480m

Thus, the accuracy of PGECLIMA_R was obtained by statistical comparison between different coefficients, by starting confidence index “c” (equation 1), proposed by Camargo & Sentelhas (1997), whose criteria are shown in Table 2.

$$c = r * d \quad (1)$$

In more detail, to calculate the confidence index “c”, it was used the Pearson correlation coefficient “r”, precision indicator, which measures the degree of dispersion among the observed and simulated and the coefficient of agreement “d” proposed by Willmott (1981), regarding the accuracy. The latter indicates the distance between estimated and observed data, ranging from the 0 (no

correlation) to 1 (perfect agreement), and is described by the following equation:

$$d = 1 - \left[\frac{\sum (P_i - O_i)^2}{\sum (|P_i - O| + |O_i - O|)^2} \right] \quad (2)$$

where P_i represents the monthly averages of the series simulated by weather generators, O_i the monthly averages of the observed historical series and O represents the mean values of historical monthly averages.

Table 2. Criteria for interpretation of performance PGECLIMA_R, by the index "c" (Camargo & Sentelhas, 1997).

Value of "c"	Performance
> 0,85	Excellent
0,76 a 0,85	Very good
0,66 a 0,75	Good
0,61 a 0,65	Median
0,51 a 0,60	Tolerable
0,41 a 0,50	Poor
< 0,40	Very Poor

It was used MBE (Mean Bias Error), which represents the deviation of the mean. This is an indicator that provides information on the performance of a long-term model. Can be represented by negative values ($MBE < 0$) or positive values ($MBE > 0$), indicating an underestimation or overestimation, respectively, represented by equation 3:

$$MBE = \frac{\sum_{i=1}^N (P_i - O_i)}{N} \quad (3)$$

To analyze the dispersion between the observed and simulated values due to non-systematic errors, were used RMSE (Root Mean Square Error) (equation 4), which is related to the real value of the error produced by the model. This index provides information about the performance of the

model in the short term, and the lower its value, the lower the data dispersion. Its disadvantage is that just a few outliers are enough to a significant increase in its results (Stone, 1993).

$$RMSE = \left[\frac{\sum_{i=1}^N (P_i - O_i)^2}{N} \right]^{\frac{1}{2}} \quad (4)$$

It was also used mean absolute error, MAE (Mean Absolute Error), which according to Willmott (2005) (equation 5), is a more natural measure of average error, and (unlike RMSE) is unequivocal.

$$MAE = \frac{\sum_{i=1}^N |P_i - O_i|}{N} \quad (5)$$

For the application of equations 3, 4 and 5, it is considered that P_i represents the

monthly averages of the series simulated by weather generator, *O_i* the monthly averages of the observed historical series, and N is the number of observed values, of historical series.

To complement the study it was also carried out a visual comparison of the

observed averages with the averages of the simulated data through the analysis of graphs.

Results and discussion

In Table 3 are represented the values of statistical indexes r, d, c, MBE, RMSE and MAE for the global solar radiation on dry days in the twenty-eight evaluated localities.

Table 3. Statistical index for evaluating the performance of PGECLIMA_R in the simulation of global solar radiation on dry days.

Localities	r	d	c	MBE (ly)	RMSE (ly)	MAE (ly)
Apucarana	0.9995	0.9993	0.9987	3.0870	4.5165	3.3386
Bandeirantes	0.9995	0.9986	0.9981	4.3850	6.2100	4.9850
Bela Vista do Paraíso	0.9998	0.9996	0.9994	2.7317	3.4395	2.8054
Cambará	0.9905	0.9879	0.9785	11.8991	16.6745	11.8991
Cascavel	0.9995	0.9997	0.9992	1.2362	2.5438	2.1413
Cerro Azul	0.9997	0.9994	0.9991	3.4593	4.2591	3.6394
Cianorte	0.9997	0.9998	0.9995	0.2046	2.0828	1.5654
Clevelândia	0.9996	0.9994	0.9990	3.3006	4.3384	3.4094
Fernandes Pinheiro	0.9994	0.9987	0.9981	5.3716	6.8060	5.4823
Francisco Beltrão	0.9995	0.9994	0.9989	3.2397	4.6024	3.5144
Guarapuava	0.9982	0.9967	0.9949	7.2004	9.1845	7.2004
Guaraqueçaba	0.9973	0.9942	0.9915	9.8601	11.2401	9.8601
Ibiporã	0.9992	0.9988	0.9980	4.4660	6.1388	4.4660
Joaquim Távora	0.9992	0.9992	0.9984	3.7322	5.2840	4.3842
Laranjeiras do Sul	0.9995	0.9994	0.9990	2.6288	3.7924	2.9275
Londrina	0.9992	0.9986	0.9978	4.2449	6.3963	4.5723
Morretes	0.9969	0.9964	0.9934	6.1479	8.5662	6.6432
Nova Cantú	0.9993	0.8232	0.8226	-60.5208	61.5374	60.5208
Palmas	0.9969	0.9879	0.9848	16.9914	18.5740	16.9914
Palotina	0.9656	0.9567	0.9238	24.3327	32.7292	24.3327
Paranavaí	0.9970	0.8045	0.8021	-69.0428	70.2511	69.0428
Pato Branco	0.9988	0.9978	0.9966	7.6332	8.8640	7.6332
Pinhais	0.9924	0.8623	0.8557	-54.7765	57.0923	54.7765
Planalto	0.9991	0.8592	0.8584	-68.1853	70.4884	68.1853
Ponta Grossa	0.9998	0.9998	0.9996	1.5434	2.1587	1.6298
Quedas do Iguaçu	0.9958	0.9968	0.9926	6.0811	10.9064	6.3812
Telêmaco Borba	0.9995	0.9993	0.9988	2.5954	3.9030	2.9222
Umuarama	0.9999	0.9998	0.9997	1.9310	2.3923	2.2937

The occurrence of values greater than 0.99 for the index "r" in almost all localities, allowed establishing a high correlation between predicted and observed data, which can be considered an excellent performance for the index. Baena (2004), testing the model ClimaBR to generate synthetic series of precipitation in Brazil and analyzing the solar radiation, also used the correlation coefficient, concordance rates and confidence and found values above 0.98, considering this a great performance.

In the analysis of the concordance coefficient "d" regarding the accuracy, there were few observed values, ranging from 0.80 to 0.86, linked to the cities of Nova Cantu, Paranavai, Pinhais and Planalto, indicating a greater distance between the simulated and observed values, while in most locations the values were above 0.99, corresponding to a minimum distance between the simulated and observed data.

When interpreted the results of the concordance coefficient, according to the performance criteria proposed by Camargo & Sentelhas (1997), were observed that the values obtained for the index "c", confidence, were above 0.86 for most cities, which can be considered "Excellent", except Nova Cantu and Paranavai, which had values between 0.80 and 0.82, considered "Very good". It can be seen the relationship between the index "d"

and index "c", by the fact that in cities where there was a less satisfactory performance in one of these indexes, the other in turn, showed very similar results, also lower than the others.

As proposed by Stone (1993), which states that the smaller the values of MBE and RMSE, the better the agreement between the observed and simulated data, and also considering the fact that these indexes are measured dimensional, i.e. depend on the unit so that the data presented in the variable of interest, to determine if the index value indicates compliance or non of simulated and observed values (Willmott, 2006), it is possible then, when were performed the analysis of the MBE index, to observe the occurrence of small deviations in comparison with the variable values (ly) in question, both for overestimation as to underestimation, indicating a greater agreement of the observed and simulated values, i.e. a lower incidence of errors or deviations.

The only places where the values were more distinct, representing larger deviations between simulated and observed data, were the cities of Nova Cantu, Paranavai, Pinhais and Planalto, which, in turn, presented in the same way, less performance considered satisfactory when analyzed the indexes "c" and "d".

The same occurs with indexes RMSE and MAE, which values were small for most locations, citing as an example, Cianorte, which showed RMSE of 2.08 ly, and a MAE of 1.57 ly, evidencing then small deviations between observed and simulated data.

Figure 2 shows the annual trend of the series of global solar radiation on dry days to the twenty-eight sites studied, which allows to check-out the close similarity between observed and simulated data in most places, even in cases where there was an underestimation for the towns of Nova Cantu, Paranavaí, Pinhais and Planalto, and this was quantified by the indexes MBE, RMSE and MAE.

In Table 4 are represented the values of statistical indexes r, d, c, MBE, RMSE and MAE for the global solar radiation on wet days in the twenty-eight locations.

It was observed that the simulated values have high correlation with the observed, because the index "r" in all regions showed values greater than 0.98, which can be considered excellent.

When analyzed the concordance index "d" values were above 0.97, demonstrating an excellent result, which showed to be consistent with the data obtained by Pereira et al. (2002), in monitoring the full potential of global solar radiation in the city of Ponta Grossa, where it was obtained high accuracy "d" with a value of 0.98. As noted previously for dry days in Nova Cantu, Paranavaí,

Pinhais and Planalto, the values of the index "d" indicated a greater deviation between predicted and observed data, these being, values ranging from 0.86 to 0.89.

The values obtained for the index "c" occurred all above 0.86, thus, according to the classification proposed by Camargo & Sentelhas (1997), being considered "Excellent".

Similarly to what occurred during dry periods, the index for MBE in wet periods, showed high values underestimated, which range from -42.21 ly to -50,39 ly, representing a greater spacing between the observed and simulated data in the localities, showing underestimates in the cities of Nova Cantu, Paranavaí, Pinhais and Planalto.

It indicates a greater error according to Stone (1993), which states that the lower the index value MBE, the better the model. But in most localities, the index values for MBE were very satisfactory, for example, in the city of Cerro Azul, which had a value of 0.64 ly for MBE, indicating strong agreement between the observed and simulated data, representing a very small error.

Likewise, the MAE and RMSE indexes showed the most significant deviations also in these four localities, representing a larger distance between the observed and simulated data, but in other places the values obtained were much lower.

For example, the city of Fernandes Pinheiro, which showed an RMSE of 3.61 ly,

and a MAE of 2.97 ly, indicates smaller deviations between series of synthetic data and historical data, representing in turn, reduced errors, and satisfactory results on the

performance of PGECLIMA_R in the generation of series of global solar radiation on wet days in these localities.

Source: The author

Figure 2. Annual trend of the series of global solar radiation on dry days to evaluate the performance of PGECLIMA_R.

Table 4. Statistical indexes for evaluating the performance of PGECLIMA_R in the simulation of global solar radiation on wet days.

Localities	r	d	c	MBE (ly)	RMSE (ly)	MAE (ly)
Apucarana	0.9993	0.9986	0.9979	-4.6793	5.5093	4.9917
Bandeirantes	0.9939	0.9953	0.9893	4.0708	10.2248	7.9739
Bela Vista do Paraíso	0.9983	0.9975	0.9958	-5.8948	8.1644	6.9937
Cambará	0.9889	0.9864	0.9755	10.6936	16.0648	11.2659
Cascavel	0.9802	0.9788	0.9594	11.6631	18.4846	12.8969
Cerro Azul	0.9972	0.9983	0.9955	-0.6404	5.4210	4.1843
Cianorte	0.9837	0.9890	0.9729	5.7624	15.4240	9.8368
Clevelândia	0.9854	0.9878	0.9734	9.4445	18.4525	14.5962
Fernandes Pinheiro	0.9991	0.9995	0.9986	-0.0192	3.6188	2.9726
Francisco Beltrão	0.9990	0.9989	0.9979	-3.5193	5.8053	4.8895
Guarapuava	0.9859	0.9834	0.9695	11.0073	16.8282	14.3139
Guaraqueçaba	0.9988	0.9986	0.9974	2.7600	4.0297	3.0963
Ibiporã	0.9977	0.9974	0.9951	-3.8902	7.8435	6.5197
Joaquim Távora	0.9978	0.9970	0.9949	-6.6439	8.8725	8.0369
Laranjeiras do Sul	0.9931	0.9943	0.9874	5.7093	12.2789	8.7454
Londrina	0.9890	0.9938	0.9829	0.6007	11.4513	8.2942
Morretes	0.9813	0.9776	0.9593	11.6285	17.3657	12.0910
Nova Cantú	0.9976	0.8564	0.8543	-50.0880	52.0690	50.0880
Palmas	0.9991	0.9993	0.9984	-2.0059	3.9981	2.6474
Palotina	0.9660	0.9679	0.9349	17.9581	26.3017	20.2941
Paranavaí	0.9914	0.8704	0.8630	-49.4991	53.2758	49.4991
Pato Branco	0.9987	0.9988	0.9976	-3.5905	5.8356	4.8343
Pinhais	0.9881	0.8696	0.8593	-42.2098	46.0275	42.2098
Planalto	0.9838	0.8980	0.8834	-50.3901	55.3173	50.3901
Ponta Grossa	0.9937	0.9945	0.9882	5.5332	10.6711	7.6111
Quedas do Iguaçu	0.9950	0.9945	0.9895	8.9461	12.6159	9.6038
Telêmaco Borba	0.9925	0.9909	0.9835	5.0837	11.0127	7.4930
Umuarama	0.9971	0.9979	0.9950	-4.4972	8.3355	5.9531

The Figure 3 represents the behavior of the series of annual global solar radiation on wet days to the twenty-eight localities studied, from which one can see the close similarity between observed and simulated global solar radiation data in most cities, thus leading to a very good result.

Importantly, on wet days, the averages of simulated global solar radiation, in the evaluated localities, sometimes overestimated and sometimes underestimated the historical monthly averages. On the other hand, this was not observed in dry days, since only four localities (Nova Cantu, Paranavaí, Pinhais and Planalto), presented a clear underestimation,

while the other locations showed only small

deviations around the mean.

Source: The author

Figure 3. Annual trend of the series of global solar radiation on wet days to evaluate the performance of PGECLIMA_R.

Conclusions

Considering the results obtained from the use of the statistical coefficients r , d , c , MBE, MAE and RMSE to evaluate the

accuracy of the daily series of global solar radiation simulated by the weather generator PGECLIMA_R, in the State of Paraná, Brazil, it is concluded that it had a very good

performance in simulating the daily global solar radiation, in almost all of the twenty-eight localities, getting very satisfactory values for both conditions, wet and dry days, for all the analyzed coefficients.

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