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Validation and Projections for Solar Radiation up to 2100: HadGEM2-AO Global Circulation Model

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Abstract**—**The objective of this work is to evaluate the results of solar radiation projections between 2006 and 2013 for the state of Rio Grande do Sul, Brazil. The projections are provided by the General Circulation Models (MCGs) belonging to the Coupled Model Intercomparison Phase 5 (CMIP5). In all, the results of the simulation of six models are evaluated, compared to monthly data, measured by a network of thirteen meteorological stations of the National Meteorological Institute (INMET). The performance of the models is evaluated by the Nash coefficient and the Bias. The results are presented in the form of tables, graphs and spatialization maps. The ACCESS1-0 RCP 4.5 model presented the best results for the solar radiation simulations, for the most optimistic scenario, in much of the state. The efficiency coefficients (CEF) were between 0.95 and 0.98. In the most pessimistic scenario, HADGen2-AO RCP 8.5 had the best accuracy among the analyzed models, presenting coefficients of efficiency between 0.94 and 0.98. From this validation, solar radiation projection maps were elaborated, indicating a seasonal increase of this climatic variable in some regions of the Brazilian territory, mainly in the spring.

Keywords**—**Climate Change. Projections. Solar Radiation. Validation.

I. Introduction

THE knowledge of the solar radiation incident on the terrestrial surface plays a fundamental role in diverse human activities like, for example, the agriculture and the architecture. Solar radiation is a clean and renewable option for energy production. In order to better understand the future availability of this energy source and its utilization, it is possible to use computational models that project the amount of solar energy that arrives on the earth's surface and its relation with the climatic changes [1].

There are research centers in different countries that work on the development and improvement of simulation models capable of designing the behavior of climatic variables. The IPCC (Intergovernmental Panel on Climate Change) conducts research to assess and establish links between climate variability and human activities, developing climate change scenarios by the end of the 21st century [2]. It is important to compare the different models, to evaluate if they can underestimate, overestimate or produce in an appropriate way, the results of the projection of a certain climatic variable.

Significant scientific and computational advances have enabled a better understanding of the global climate, contributing significantly to the identification of possible causes and future impacts of climate change. However, some authors consider that the accuracy of climate projections, based on numerical models, still cannot be considered satisfactory [3]. Based on this need for a more adequate reliability check in climate projection models, especially solar radiation, this study is developed.

II. Materials and Methods

A. Description of the Study Area

The state of Rio Grande do Sul (Fig. 1) is located in the extreme south of Brazil, between latitudes 27° and 34° South (S) and longitudes 50° and 57° West (W). The state maintains borders, to the West with Argentina, to the South with Uruguay, to the North with the Brazilian State of Santa Catarina and to the east it is bathed by the Atlantic Ocean. The territorial area of Rio Grande do Sul has 268,781,896 km², and the number of inhabitants per square kilometer is on average 38 hab/km².

1. Global Circulation Models Used

In this work, we used monthly solar radiation series of HadGEM2-AO (Hadley Global Environment Model 2 - Atmosphere) from the UK Research Center MOHC (Met Office Hadley Center) belonging to CMIP5. The Data from this model were collected through the WCRP (World Climate Research Program) website and its resolution is 1.85º x 1.86º latitude-longitude. The period of comparison between the monthly solar radiation data of the meteorological stations and the monthly solar radiation data projected by HadGEM2-AO was between 2006 and 2013.

B. Statistical Methods

In order to compare the solar radiation projections obtained through the climate model with the solar radiation measured in the meteorological stations, the following statistical parameters were used: the bias (Equation 1) that can be defined as the systematic difference between the modeled property and the property [4], and a possible trend of the model data to overestimate or underestimate the observed solar radiation data [5]; and the coefficient of efficiency (EFC) (2) that evaluates the accuracy of the alternative data, and can vary from - infinity to 1, with 1 being the perfect fit. For this coefficient the methodology is considered satisfactory if the value is between 0.50 and 0.65, good if the value is between

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0.65 and 0.75 and very good if the value is above 0.75 [6]. The following equations are used:

$$Bias = \frac{1}{n}\sum_{1}^{n} Y_{proj} - Y_{obs} \quad (1)$$

$$EFC = 1 - \frac{\sum_{1}^{n}\left(Y_{obs} - Y_{proj}\right)^{2}}{\sum_{1}^{n}\left(Y_{obs} - Y_{\acute{o}bs}\right)^{2}} \quad (2)$$

where Yobs is the value of the measured data (observed) in the meteorological stations of period i; Yproj the value of the data projected by the MCG for period i and n the total number of data.

To represent the efficiency coefficient distribution of each MGC, we used the boxplot, a graphic descriptive statistical tool that provides a graphical summary of this distribution [7]. Boxplot graphics display batches of data. Six values of a set of data are conventionally used; the extremes, the lower and upper quartiles and the median, the average, in addition to the outliers that are extreme locations to the central tendency, and therefore do not follow the same process of spatial dependence that most observations, this tool is widely used in exploratory analysis and as a visual statistical resource.

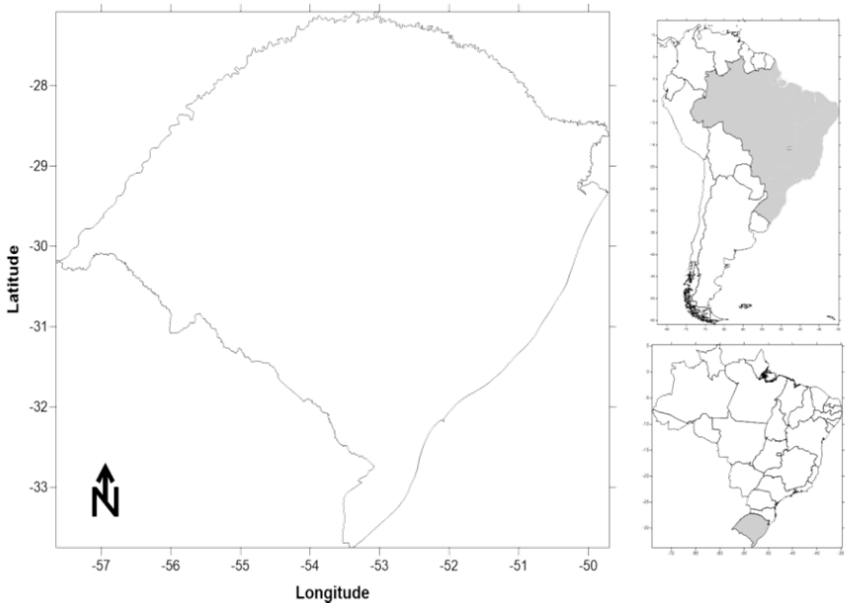

Fig. 1 Map Location of the Study Region

The method and results are validated by comparing the solar radiation values of projections with the actual measurements of meteorological stations, which have historical records in periods where MCGs have already projected data [8]. To date, the mathematical models of the global climate system (GCM), which quantitatively consider the behavior of climate compartments (atmosphere, oceans, cryosphere (areas with ice and snow), vegetation, biogeochemical cycles, etc.) and their interactions. These MCGs enable plausible climate development scenarios to be simulated for various scenarios of greenhouse gas (GHG) emissions. However, there are at least two important sources of uncertainties in using these models. The first is that we do not know exactly the future trajectory of GHG emissions and atmospheric aerosols, which depends on human decisions. The second source of doubt is the fact that mathematical models are imperfect representations of natural occurrences and different climate models differ substantially in their projections for the climate of the future given the same scenario of evolution of GHG concentrations and aerosols in the atmosphere [9].

C. Comparative Analysis

The data model validation process was carried out through a comparison between the results of the Global Circulation Models projections and the values provided by the meteorological stations through the statistical methods already described (Efficiency Coefficient and Bias).

The values of solar radiation were organized by the monthly average in the period of time between 2006 and 2013, since from that period we have both observed data and projected data of the evaluated models, and for this reason it is possible to do the statistical analysis of each GCM, comparing the projection values with real data.

Since MCGs provide their data by points and these points have known geographical coordinates, it was possible to compare the data of each point with the station closest to it.

The observed data of solar radiation come from thirteen meteorological stations of the state of Rio Grande do Sul, are: Weather Station of the city of Bagé, Canguçu, Erechim, Porto Alegre de Quaraí, Rio Pardo, Santa Rosa, São Borja, São Gabriel, São Luís Gonzaga, Soledade and Vacaria.

III. Results

The validation of the models intends to indicate which model presented the best results in the comparison of the projection data with the data observed in meteorological stations in the same period of time.

The validation methods used are the Bias, with results presented in the form of the table and the EFC presented in the form of tables, maps.

According to what is presented in Table II, where the bias of each MCG is presented in the comparison of measured data and projection data, we can verify how much each model tends to overestimate or underestimate the data observed in the different meteorological stations in which the data were collected measurements.

From the visual analysis of Table I, we can see the general tendency of the models to overestimate the radiation data for the southeast region and the metropolitan region of the state, with all values of bias above 0.1 kWh /m² in the comparison of the data of the stations meteorological data from the cities of Rio Grande, Canguçu, Rio Pardo and Porto Alegre, with data from projections of MCGs, which is considered statistically significant.

TABLE I
Bias

City	HADGen2-AO	
	4.5	**8.5**
São Borja	-0.156	-0.183
Quaraí	0.023	-0.057
Santa Rosa	-0.064	-0.038
São Luiz Gonzaga	-0.262	-0.278
São Gabriel	0.019	-0.080
Bagé	-0.074	-0.252
Erechim	0.003	0.020
Soledade	-0.082	-0.136
Rio Pardo	0.120	-0.003
Canguçu	0.188	0.020
Rio Grande	0.253	0.075
Vacaria	0.002	-0.038
Porto Alegre	0.285	0.215

TABLE II
EFC

MCG	HADGen2-AO	
RCP	4.5	8.5
São Borja	0.953	0.960
Quaraí	0.965	0.968
Santa Rosa	0.961	0.977
São Luiz Gonzaga	0.923	0.941
São Gabriel	0.949	0.974
Bagé	0.907	0.969
Erechim	0.949	0.953
Soledade	0.912	0.930
Rio Pardo	0.914	0.947
Canguçu	0.914	0.947
Rio Grande	0.914	0.944
Vacaria	0.935	0.971
Porto Alegre	0.948	0.945
Média	0.934	0.956

A. Results According to the Efficiency Coefficient

The efficiency coefficient compares the performance of the MCG of the atmosphere with the average of the observed data. According to [10], values close to 1 indicate a perfect model, analyzing the results of Table II, we noticed that the HADGen2-AO presented a performance considered very good for all the meteorological stations in both scenarios.

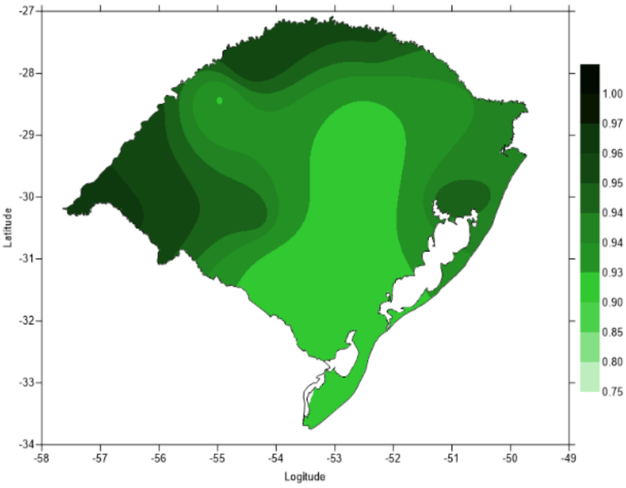

Fig. 2 Efficiency of the HADGen2-AO RCP 4.5

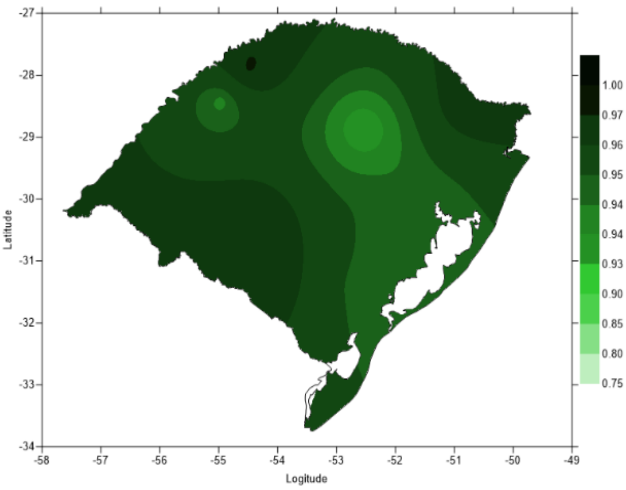

Fig. 3 Efficiency of the HADGen2-AO RCP 8.5

B. Validation Maps

The maps were generated from the isolines of solar radiation, being the lighter green tones where they present less accuracy and in the darker tones the better precisions found.

The model HADGen2-AO had an accuracy considered very good, mainly in RCP 8.5 (Fig. 3), agreeing with [11], who also considered this model among the best for projections of climate change, taking into account the scenario pessimistic, but for the precipitation variable.

C. Projections Maps

Projections were spatialized with the seasonal averages for the period from 2026 to 2100 for scenario 8.5.

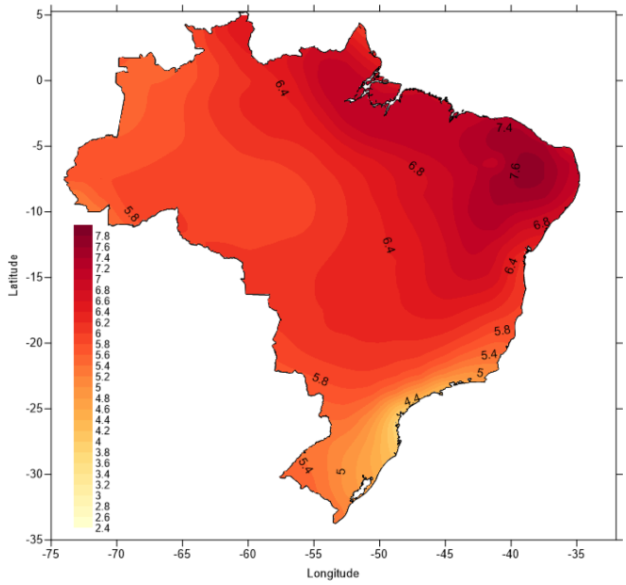

Fig. 4 Solar radiation projections (kWh/m²) spring HADGen2-AO RCP 8.5

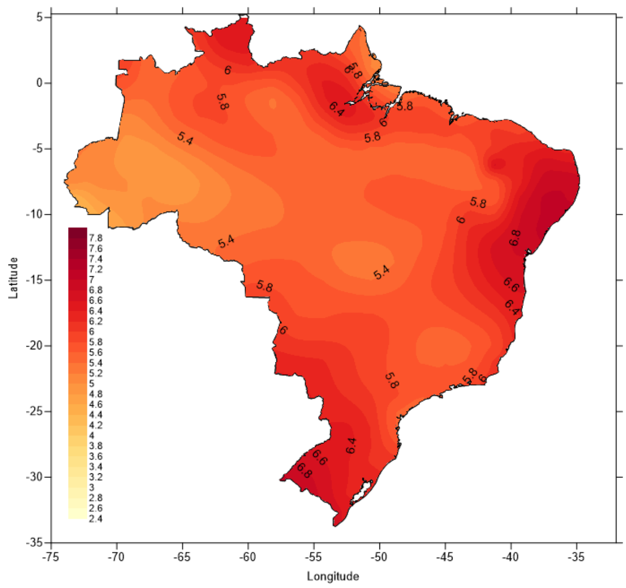

Fig. 5 Solar radiation projections (kWh / m²) summer HADGen2-AO RCP 8.5

Fig. 4 shows the solar radiation projections for the spring, where it can be observed that the values were between 4.4 kWh/m² in the Brazilian Southeast, reaching 7.6 in some places in the Northeastern region of Brazil. In the summer (Fig. 5), it can be observed that in the Northeast region and in southern Brazil the values tend to be closer with values of 6.6 kWh/m² in the west of the state of Rio Grande do Sul and 6.8 kWh/m² in most of the Brazilian northeast. In the autumn (Fig. 6), the results were at most 6 kWh/m² in the northeast and approximately 4 kWh/m² in most of the south and southeast regions. Fig. 7 represents the average of the solar radiation projections in the inverse for the period already mentioned, showing values of approximately 3 kWh/m² in the southern region and 6 kwh/m² in the northeast of Brazil. In agreement with [12], who evaluated the regional model HadRM3P, in simulations of seasonal variability, similar to the ones presented in this paper, of the main climatological patterns on the region of South America, and concluded that the model simulates reasonably well the spatial and temporal pattern of precipitation and temperature. Comparing the projection data obtained with the Brazilian Solar Energy Atlas, there is an increase in global solar radiation, especially in spring, where according to [13], the current seasonal averages at this station are a maximum of 6.87 kWh/m² and the projections of HADGen2-AO RCP 8.5 reach 7.6 kWh/m² in Northeastern Brazil.

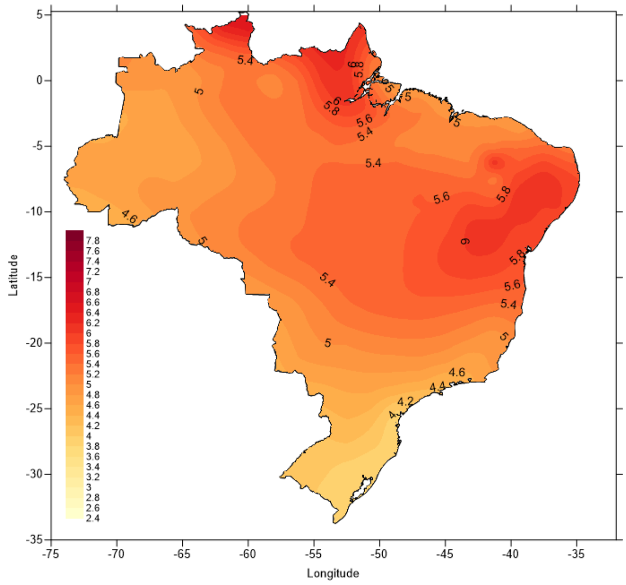

Fig. 6 Solar radiation projections (kWh / m²) autumn HADGen2-AO RCP 8.5

IV. Conclusion

It is well known that the need for a better use of energy resources of renewable origin, among which solar energy stands out; however, in order to better understand the impact of climate change on this variable, MCGs are used to design these effects, however, it is important that the projections presented by these models are validated.

When we evaluated the results, we observed that HadGEM2-AO (Hadley Global Environment Model 2 - Atmosphere) MCG presented the best results for solar radiation projections according to RCP 8.5, with a EFC above 0.93 in all meteorological stations compared.

As HADGen2-AO presented a very good performance in the validations, its data were used to elaborate the seasonal maps of projections of global solar radiation in Brazil from the period 2026 to 2100, noting an increase in solar radiation in some regions of Brazil, especially in the spring.

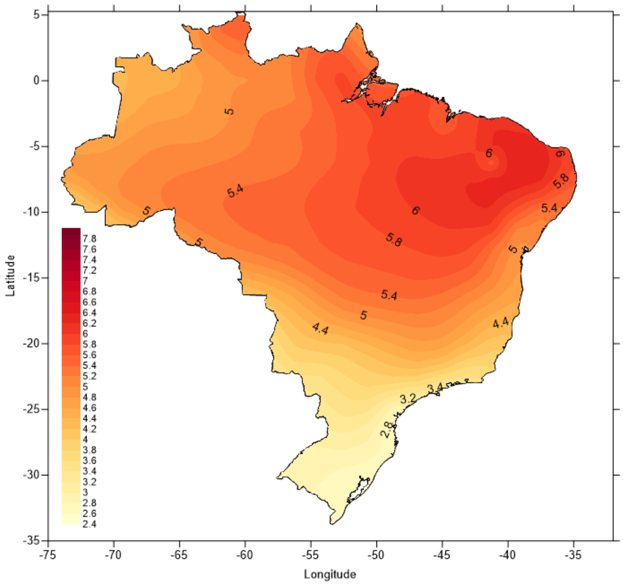

Fig. 7 Solar radiation projections (kWh / m²) winter HADGen2-AO RCP 8.5

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