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# SOLAR IRRADIATION MODELING IN VALE SÃO FRANCISCO DA BAHIA USING THE WRF-SOLAR MESOSCALE MODEL

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**Abstract.** *The installed capacity in centralized solar photovoltaic generation in Brazil corresponds to 4.5 GW, according to ANEEL data from December 2021. The Northeast region is home to around 72% of the centralized photovoltaic projects in the country, due to its high potential. In this region, Bahia (28.5%) and Piauí (22.5%) stand out. However, for the development of solar projects, it is necessary the study the resource in multiple sites that make it possible to know its regional availability and temporal variability to enhance the performance of the installed technology, since the technical and economic feasibility of a system for harnessing solar energy depends on these factors. In this context, the present work aims to estimate the global solar irradiation (GHI) and direct normal (DNI) in the region of Vale São Francisco da Bahia using the WRF-Solar model. The horizontal spatial resolution of the model was 1 km, and the simulation period was the month of October 2016. The performance of the model was evaluated with hourly data of GHI and DNI estimated by satellite images from the GOES series (Geostationary Operational Environmental Satellites) from the INPE database. The simulations were satisfactory through statistical analysis between simulated and observed hourly data for GHI and DNI. The results showed that the model is able to represent the series with an hourly average, as well as the GHI estimates had better results. Finally, the results allow us to conclude that the WRF-Solar model, which represents the state of the art in mesoscale modeling, presented good performance in the simulation of solar irradiation and presents great potential for operational, research and technological development purposes.*

**Keywords:** *Solar Irradiation Modeling, WRF-Solar, Vale São Francisco of the Bahia.*

## 1. INTRODUCTION

The installed capacity in centralized solar photovoltaic generation in Brazil corresponds to 4.7 GW, according to ANEEL data from March 2022. The Northeast region is home to around 72% of the centralized photovoltaic projects in the country, due to its high potential. In this region, Bahia (28.5%) and Piauí (21.7%) stand out. The high levels of solar irradiation are one of the factors responsible for Bahia's prominence in energy generation, totaling 1.4 GW of installed capacity supervised by the end of March 2022, as well as more than 1000 power plant projects under study, totaling 49 GW of power, which demonstrates a promising scenario for the generation of energy from the solar source.

However, for the development of solar projects, reference magnitudes are essential for adequate characterization of the existing solar resource, since the knowledge of regional availability and temporal variability of solar irradiation are of great importance to assist in the implementation of solar parks. This spatial distribution of solar radiation can be achieved using numerical weather forecast models. The main model of this type, WRF-Solar (Weather Research and Forecasting Model), has been the subject of studies and optimizations with the aim of providing an improved numerical tool for research and the specific needs of the solar energy sector.



and Bom Jesus da Lapa. In addition to activities related to agriculture and commerce, the main hydroelectric plants that represent the energy supply base of the Northeast are also located in this region (ANA, 2020). The Solar Atlas of Bahia (2018) highlights the predominance of solar incidence in the region along the São Francisco River Valley, which is the most privileged in Bahia. As shown in the maps, the average hourly irradiation varies approximately between 700 and 1,100Wh/m<sup>2</sup>, which highlights the promising potential of the region in the use of solar energy.

## 2.2 WRF-Solar simulation details

The simulations were carried out using a specific configuration of the WRF model, suitable for the solar meteorological forecast/simulation, called WRF-Solar version 1.2. October 31, 2016, for the four micro-regions under study. The first 24 hours of simulations were considered as “spin-up” model adjustment time and excluded from the evaluations. The initial and boundary conditions used in the simulations come from the NCEP (National Center for Environmental Prediction) global atmospheric model GFS (Global Forecast System), with a horizontal resolution of 0.25° x 0.25° and a temporal resolution of 6 hours. Topography and land use and occupation data are provided by the United States Geological Survey (USGS) with 5', 2' and 30 s resolution.

The model was configured with six nested grids with a resolution of 9 km (D01), 3 km (D02) and 1 km (D03; D04; D05; D06), with the last four domains referring to each micro-region of the Valley (Figure 2). An overview of the spatial configurations for each micro-region is shown in Table 1. The domains of interest have a horizontal resolution of 1 km and 35 vertical levels with pressure at the top of the model set at 50 hPa.

Table 1. Details of the model configuration

Region	Domain	Horizontal resolution	Domain size (km)	Cell numbers	Number of levels $\eta$
Bahia	D01	9 km	1035x981	115x109	35
Bahia	D02	3 km	831x786	277x262	
Paulo Afonso	D03	1 km	183x174	183x174	
Juazeiro	D04	1 km	393x156	393x156	
Barra	D05	1 km	138x147	138x147	
Bom Jesus da Lapa	D06	1 km	99x162	99x162	

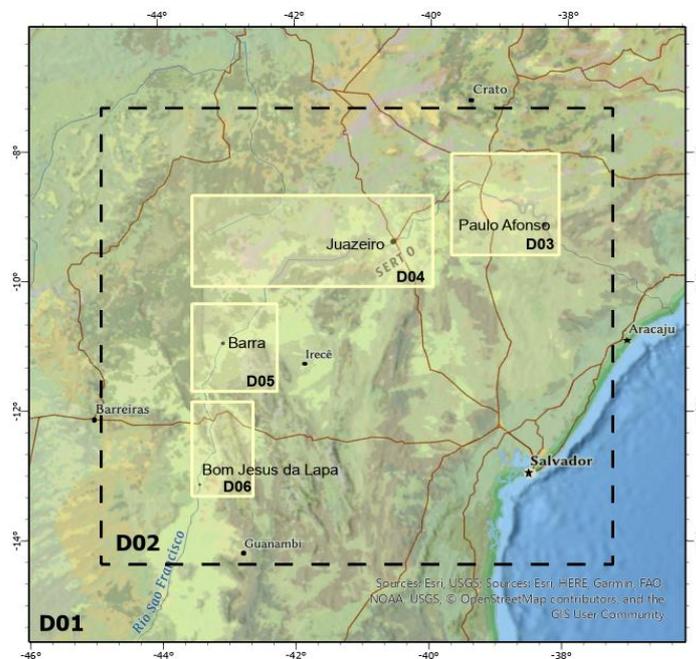


Figure 2. Location of the nested domains  
Source: Author, 2022.

The physics options adopted and, left unchanged for all simulations, were: Thompson aerosol-aware microphysics (Thompson and Eidhammer, 2014), cumulus Grell 3D (Grell, 1993), shortwave radiation RRTMG (Iacono et al., 2008), longwave radiation RRTMG (Iacono et al., 2008) and Noah-MP (multi-physics) Land Surface Model for the year 2016.

For all domains that were run with a spatial resolution of 3 km and 1 km, the cumulus option was turned off, following the model's indications of not using convection schemes for domains less than 10 km of spatial resolution. The parameterization of aerosol interactions with radiation follows Ruiz-Arias et al. (2014), activating this option allows considering constant values of aerosol properties, such as aerosol optical depth, angstrom exponent, single scattering albedo, asymmetry parameter and aerosol type. These properties are included in the RRTMG radiation scheme. An overview of the physical parameterizations of the simulations is shown in Table 2. The physical parameterization schemes were selected according to the conclusions of the study by Lima (2015) and the WRF-Solar User Manual.

Table 2. Simulation details specifying physical options

Parameterizations	Physical options	References
Microphysics	Thompson aerosol aware	Thompson e Eidhammer (2014)
Longwave radiation	RRTMG shortwave	Iacono <i>et al.</i> (2008)
Shortwave radiation	RRTMG shortwave	Iacono <i>et al.</i> (2008)
Aerosols	Ruiz-Arias aer_opt=2	Ruiz-Arias <i>et al.</i> (2014)
Cumulus	Grell 3D	Grell (1993)
Surface layer	Eta similarity	Monin-Obukhov (1954)
Planetary boundary layer	Mellor-Yamada-Janjic	Janjić (1994)
Land surface model	Noah-MP	Niu <i>et al.</i> (2011)

### 3. NUMERICAL RESULTS

Figure 3 presents the hourly average behavior of the Global Solar Irradiation (GHI) simulated by WRF-Solar and estimated by satellite images for the four microregions of the VSF. For the hourly analysis of the GHI and, later, of the Direct Normal Irradiation (DNI), the average was calculated for each hour of the day in the period from October 1 to October 31, 2016.

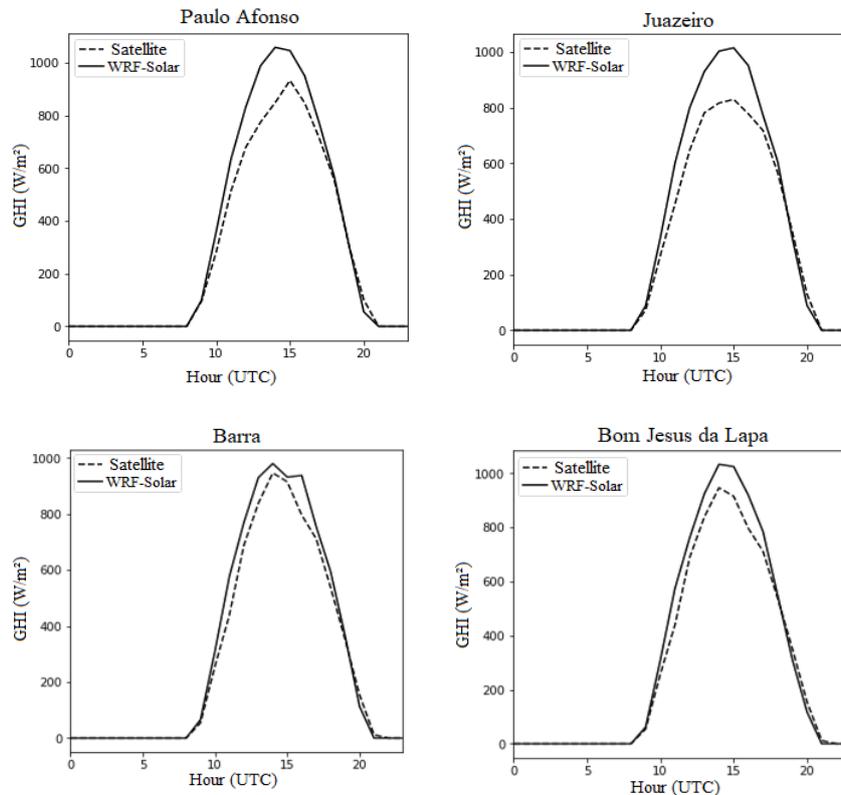


Figure 3 - Average hourly behavior of simulated and estimated GHI with satellite data.

It is noticeable in Figure 3 that, generally, the greatest differences between the WRF-Solar curves and the satellite data occur at peak times of solar irradiation. At other times, there is a better similarity between the curves, with better conformity for the micro-regions of Barra and Bom Jesus da Lapa. The WRF-Solar data is always superior to the

satellite data, demonstrating an overestimation of the GHI peak in the WRF-Solar model. For the Barra microregion, the overestimation was lower.

Furthermore, it can be observed that the highest GHI values occur between 2:00 pm (UTC) and 4:00 pm (UTC) in all regions, with the average GHI at that time in Paulo Afonso varying between 850 W/m<sup>2</sup> - Satellite and 1050 W/m<sup>2</sup> - WRF-Solar, Juazeiro 830 W/m<sup>2</sup> - Satellite and 1010 W/m<sup>2</sup> - WRF-Solar, Bar 980 W/m<sup>2</sup> - Satellite and 1000 W/m<sup>2</sup> - WRF-Solar and Bom Jesus da Lapa 950 W/m<sup>2</sup> - Satellite and 1030 W/m<sup>2</sup> - WRF-Solar.

Figure 4 shows the average hourly behavior of the simulated and estimated DNI by satellite in the four microregions of the VSF in the study period (October 2016).

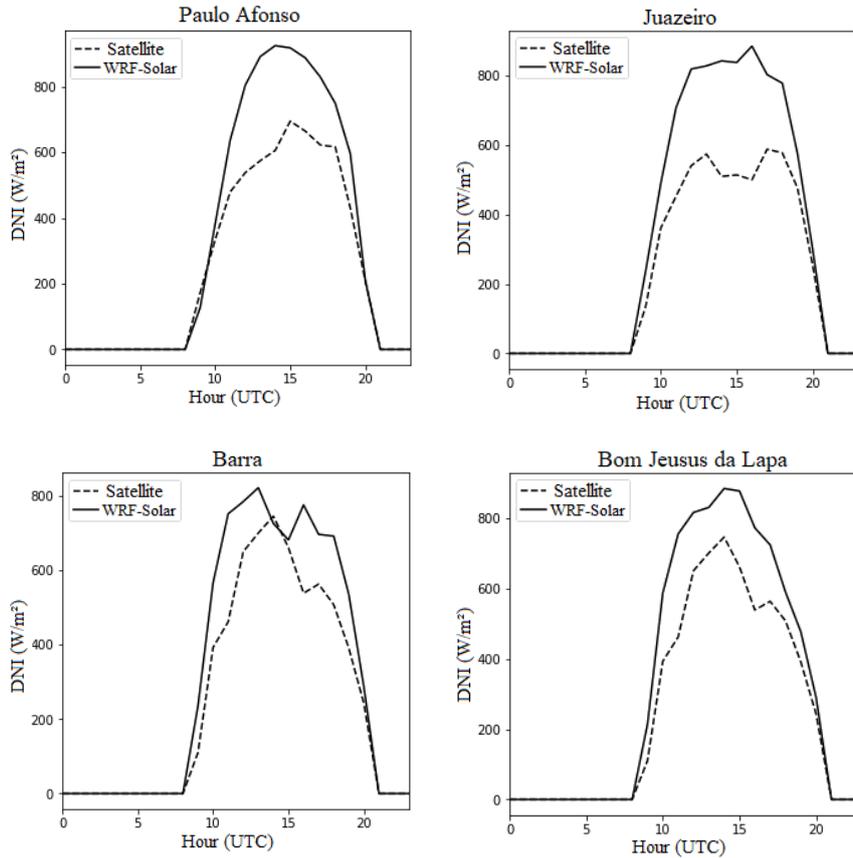


Figure 4 - Average hourly behavior of simulated and estimated DNI with satellite data.

The DNI plots in Figure 4 from simulations data also suggest that the daily distribution of cloudiness is razoavelmente symmetric in Paulo Afonso, and more asymmetric in Juazeiro, Barra e Bom Jesus da Lapa, with more cloudiness occurring from the time of 12 hours UTC. It can be seen that, for the Barra region, the model was able to better follow the behavior of the DNI variation.

In general, it is possible to observe a large difference between the values simulated by the model and those estimated by satellite.

To better evaluate the performance of the WRF-Solar model, a statistical evaluation was used, wherein the indices described below Eq. (1, 2, 3 and 4), o and p refer to the measures observed and predicted by the model, respectively. The bar indicates the mean and “σ” the standard deviation (Hanna, 1989).

$$\text{Normalized mean square error (NMSE)} = \overline{(C_o - C_p)^2} / \overline{C_o C_p} \quad (1)$$

$$\text{Fraction of data for (FAT2)} = 0.5 \leq (C_p / C_o) \leq 2.0 \quad (2)$$

$$\text{Correlation coefficient (COR)} = \overline{(C_o - \bar{C}_o)(C_p - \bar{C}_p)} / \sigma_o \sigma_p \quad (3)$$

$$\text{Fractional bias (Fb)} = \bar{C}_o - \bar{C}_p / 0.5(\bar{C}_o + \bar{C}_p) \quad (4)$$

The Fb statistical index says whether the expected quantities underestimate or overestimate those observed. The statistical index NMSE represents the dispersion of the values of the model in relation to the dispersion of data. The best results are expected to be close to zero for the NMSE, Fb, and Fs indexes, and close to 1 on the COR and FAT2 indices.

Table 3 shows the statistical indices NMSE, Fb, COR and FAT2, when comparing the simulated and satellite estimated data of GHI and DNI in the micro-regions under study.

Table 3: Statistical metrics results

Region/Station	Solar Irradiation	NMSE	Fb	COR	FAT2
Paulo Afonso	GHI	0.10	-0.17	0.89	0.90
	DNI	0.50	-0.35	0.08	0.58
Juazeiro	GHI	0.13	-0.15	0.84	0.86
	DNI	0.59	-0.38	-0.14	0.50
Barra	GHI	0.41	-0.12	0.40	0.49
	DNI	0.63	-0.34	-0.17	0.52
Bom Jesus da Lapa	GHI	0.19	-0.22	0.80	0.79
	DNI	0.60	-0.49	0.19	0.54

In Table 3, analyzing the GHI results, one can see a good correlation between 0.80 and 0.89 and a Factor of 2 between 0.79 and 0.90 for all regions, with the exception of the Barra region with 0.40 and 0.49, respectively. When checking the results of COR and FAT2 for the DNI, they showed less concordant values, ranging from -0.17 to 0.19 for COR and 0.50 to 0.58 for FAT2. In general, the NMSE presented similar values for the regions of Paulo Afonso, Juazeiro and Bom Jesus da Lapa, ranging from 0.10 to 0.19 for GHI and 0.50 to 0.60 for DNI. For this index, the region of Barra obtained the worst result (0.41 and 0.63), respectively for GHI and DNI. It is observed that the Fb was always negative, indicating the model's tendency to overestimate the solar irradiation for both GHI and DNI. The best results for this indicator appear for Barra with -0.12 (GHI) and -0.34 (DNI). In general, the indices for the GHI were better in all regions.

#### 4. CONCLUSION

In this study, it was possible to compare the GHI and DNI data estimated by satellite provided by the National Institute for Space Research (INPE) with data simulated by the WRF-Solar model in the Vale São Francisco region of Bahia. The results show high levels of irradiation in all regions of the VSF, with values between 850 W/m<sup>2</sup> and 1050 W/m<sup>2</sup>.

The evaluations showed that the WRF-Solar model overestimates the global solar irradiance and the normal direct irradiance in all VSF microregions, a trend shown in previous studies. However, the features of the average hourly behavior were represented by the model. In addition, the results showed that the model is able to represent the series with an hourly average, as well as the GHI estimates had better results.

It is important to emphasize that the model uses global data and makes some approximations of the topographic characteristics of the region of interest, a condition that could interfere with the model results, compromising the performance of the simulations. In this way, the WRF-Solar model proves to be an effective and important computational tool in carrying out surveys of this type, proving the methodology in the region.

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