Brazilian database for solar irradiation assessment

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Abstract

Scenarios associated with climate change have highlighted the need for adaptation and mitigation measures, including the planning of low-carbon electric and energy matrices that enhance energy security. In the case of solar energy, there is a clear demand for understanding the resource's availability and variability. LABREN/INPE has provided such information for about 20 years via the satellite-based BRASIL-SR model, which has undergone several upgrades since the last edition of the Brazilian Atlas of Solar Energy (Pereira et al., 2017). This study presents the preliminary outcomes of these improvements, including a recent enhancement in determining effective cloud cover. The results show significant advances, such as reduced bias - even under high aerosol concentrations - and a greater spatial features detail.

Keywords: solar radiation assessment, radiative transfer model, solar irradiation database

1. Introduction

Brazil, being an essentially tropical country, has a high solar energy potential. In recent decades, solar energy - particularly through photovoltaic technology - has been one of the fastest-growing sources in the Brazilian electricity matrix, with exponential growth over the past seven years, leading to an installed capacity expected to exceed 60 GW by 2025. This is an extremely positive development in the context of climate change scenarios, which require increasingly diversified, affordable, and low-carbon energy matrices. Solar energy also helps balance Brazil's strong dependence on hydropower and contributes to enhanced energy security, especially in light of the growing frequency of extreme climate events such as droughts (FERREIRA et al., 2023).

However, such a significant increase in solar capacity requires increasingly accurate information on the resource itself, its potential, and its variability. The Laboratory for Modeling and Studies of Renewable Energy Resources at the National Institute for Space Research (LABREN/INPE) has stood out in recent years by providing such data, using the BRASIL-SR radiative transfer model to publish the two editions of the Brazilian Atlas of Solar Energy (Pereira et al., 2006; Pereira et al., 2017). These publications have been widely disseminated in Brazil and abroad, becoming a reference in terms of the quality and reliability of solar resource data. The datasets have even been used by official institutions of the Brazilian government as the benchmark for energy sector auctions, among other relevant applications.

Nonetheless, some limitations of the BRASIL-SR model still needed to be addressed - particularly those related to tropical atmospheric conditions, such as the high spatial and temporal variability of cloud cover; significant increases in aerosol optical thickness; and the need to model large water bodies due to the growing use of floating photovoltaic technologies, among others. These factors are important sources of bias in the simulations. In recent years, these issues have been individually addressed in studies such as Casagrande et al. (2021), which introduced significant improvements to the clear-sky model and implemented new

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parameterizations for atmospheric aerosols. More recently, Siqueira et al. (2025) presented important findings regarding optimal values for maximum cloud reflectance, which were adjusted in the model to improve estimates of effective cloud cover (C_{eff}).

This study, therefore, presents the simulation results for the period from 2018 to 2024 as a preliminary evaluation of the new solar irradiation database for Brazil, in comparison with the most recent dataset published in the second edition of the Brazilian Solar Energy Atlas.

2. Methods

3.1. BRASIL-SR Model and Data

BRASIL-SR is a physical model developed for estimating surface solar radiation. It employs the "two-stream" method (Meador and Weaver, 1980) to solve the radiative transfer equation (RTE), parameterizing effective cloud cover derived from satellite imagery. In this study, visible channel imagery from the GOES-16 satellite was used for the years 2018 to 2024, with a spatial resolution of 4 km and a temporal resolution of 30 minutes - finer than that used in the estimates of the second edition of the Brazilian Solar Energy Atlas.

By combining this information - modulated by meteorological variables such as temperature, humidity, precipitable water column, ozone, atmospheric aerosols, and albedo - the model is able to estimate surface irradiance. Effective cloud cover (C_{eff}) remains the primary factor controlling atmospheric transmittance and is estimated from geostationary satellite images using Eq. (1):

$$C_{eff} = \frac{\tau - \tau_{clear}}{\tau_{cloud} - \tau_{clear}} \qquad \text{(Eq. 1)}$$

where τ is the reflectance from the visible channel of the geostationary satellite, τ_{clear} is the clear-sky reflectance, and τ_{cloud} is the overcast-sky reflectance. BRASIL-SR performs its simulations over 37 spectral intervals, ranging from 200 to 3500 nm. It accounts for the absorption of solar radiation by water vapor, ozone, CO_2, and oxygen using the methodology proposed by Wiscombe and Evans (1977).

In this new dataset, updated sources for precipitable water and total ozone were implemented, along with the option to use aerosol optical thickness data from the MERRA-2 reanalysis (BRIGHT et al., 2020). The model also incorporates biome classification data (IBGE, 2021) and bidirectional reflectance distribution functions (BRDF) from the MODIS sensor aboard the TERRA and AQUA satellites (BLANC et al., 2018). Further details can be found in Casagrande et al. (2021).

Another important aspect implemented in the model for the parameterization of C_{eff} was based on the findings of Siqueira et al. (2025), where the τ_{cloud} used in the effective cloud cover index can mask errors related to a low-performance clear-sky model. The study demonstrated that a proper combination of the clear-sky model and τ_{cloud} is essential for reducing the all-sky bias in GHI estimates. The paper indicates that the optimal value for τ_{cloud} in Brazil is around 0.8, which is the value adopted in these simulations.

3.2. Model validation - SONDA Network data

For the preliminary validation of these simulations, global horizontal irradiance (GHI) data from the SONDA Network stations were used. These sites are an initiative maintained by INPE to promote the use of renewable energy sources in Brazil. The network's stations are distributed across the country to adequately represent its diverse regions and biomes, providing free, high-quality data to users from public institutions and private companies. These data can be accessed through the website: http://sonda.ccst.inpe.br.

Figure 1 shows the locations of the SONDA Network stations in Brazil, highlighting the 11 sites used for this preliminary assessment: Cachoeira Paulista (CPA), Florianópolis (FLN), Petrolina (PTR), Brasília (BRB), São Martinho da Serra (SMS), Ourinhos (ORN), Caicó (CAI), Palmas (PMA), Florianópolis – Sapiens Park (SPK), Campo Grande – Fazenda (CGR), and Natal (NAT). These datasets were used to calculate the bias and root mean square error (RMSE) of the simulations.

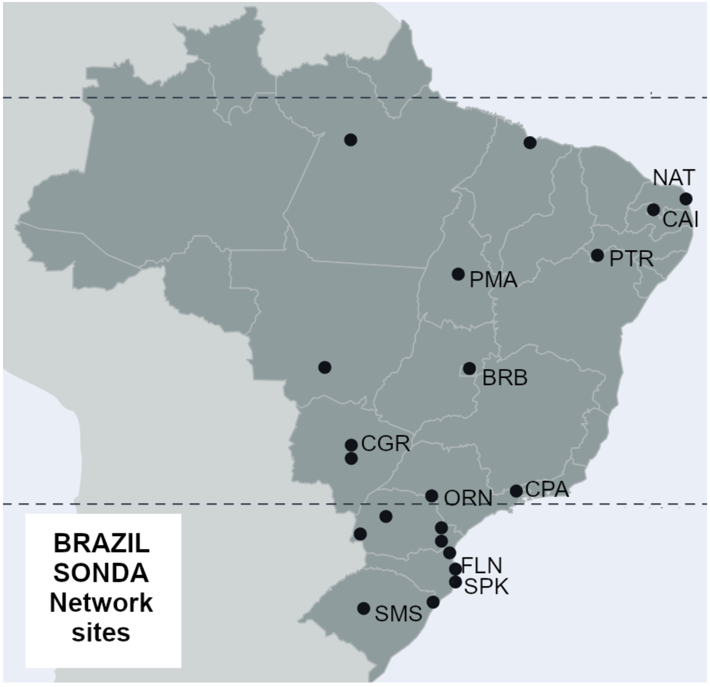

Fig. 1: SONDA Network sites.

3. Results and Discussions

Following the analysis of the simulation results, it was observed that the expected intra-annual variability was preserved, with the annual cycle consistently represented. The implementation of the new C_{eff} parameterization led to significant improvements during the rainy months, which typically exhibit higher effective cloud cover.

In addition, the increase in spatial resolution contributed to a more detailed representation of solar irradiance features and spatial patterns throughout the year, as reflected in the annual mean values. Enhancements achieved in previous versions - such as the inclusion of atmospheric aerosol effects and the reduction of bias over regions with extensive water bodies - were also maintained.

Figure 2 presents the monthly average totals of Global Horizontal Irradiation (GHI) for the 2018-2024 period, as well as the annual mean values derived from the simulations. As mentioned earlier, the new results confirm the BRASIL-SR model’s ability to consistently reproduce intra-annual variability, with the highest average values occurring during the spring and summer months and gradually decreasing toward autumn and winter. A more refined depiction of spatial features is also evident, particularly in northeastern Brazil, where the solar energy potential is greatest. In this region, annual mean daily totals reach up to 6,249 Wh/m², while the lowest values, around 3,789 Wh/m², are observed in the southern part of the country.

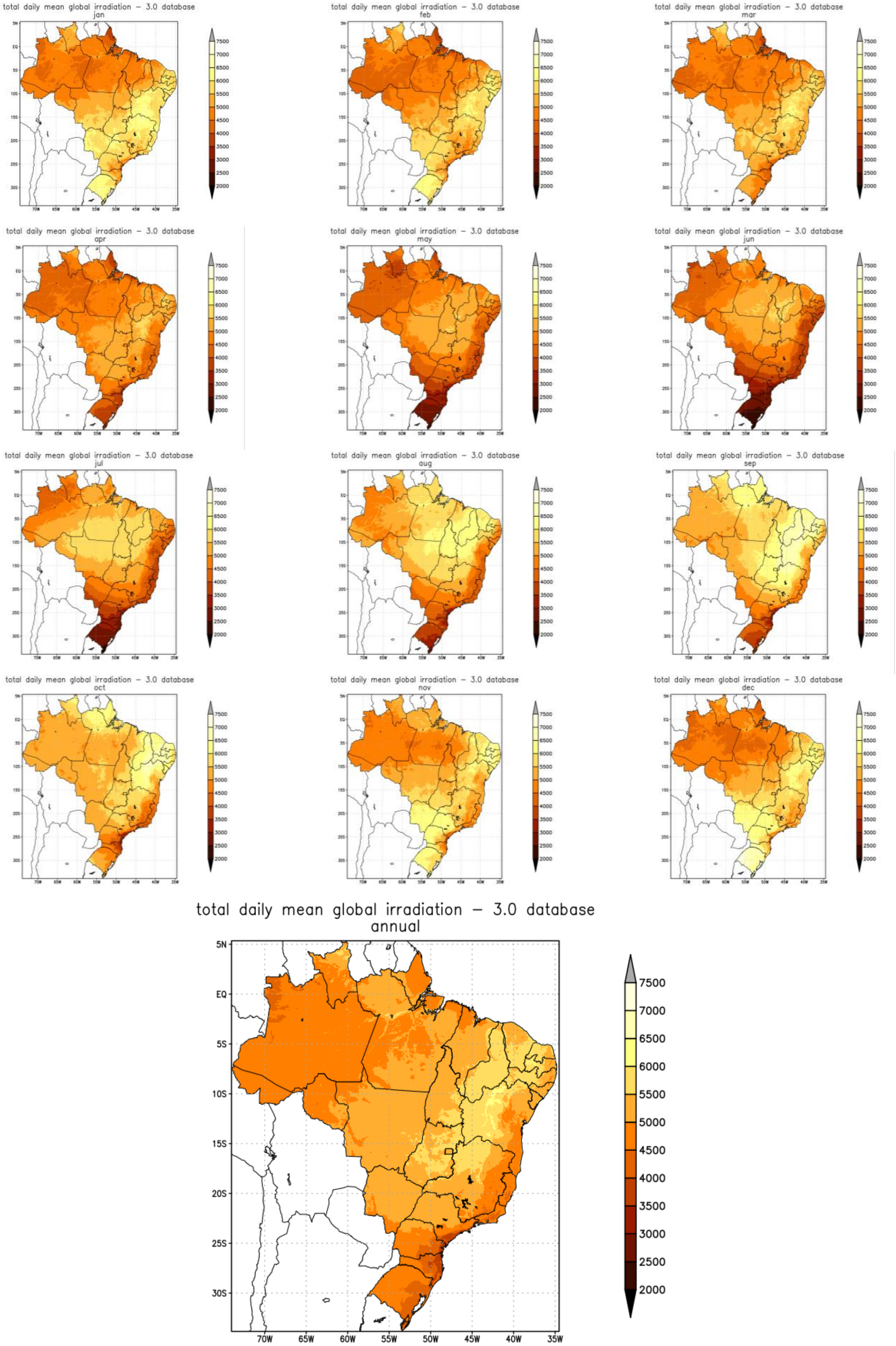

Fig. 2: Annual total daily mean of Global Horizontal Irradiation – simulations from 2018 to 2024.

Figure 3 presents GHI evaluations conducted at eight SONDA network sites (CGR, CPA, NAT, ORN, PMA, PTR, SMS, and SPK), as well as an overall assessment combining all sites to 2023 and 2024 period, in order to demonstrate the improvements achieved with the implemented clear-sky model. A strong agreement can be observed between the simulated and observed values, with Coefficients of Determination (R^2) exceeding 0.99 in all cases.

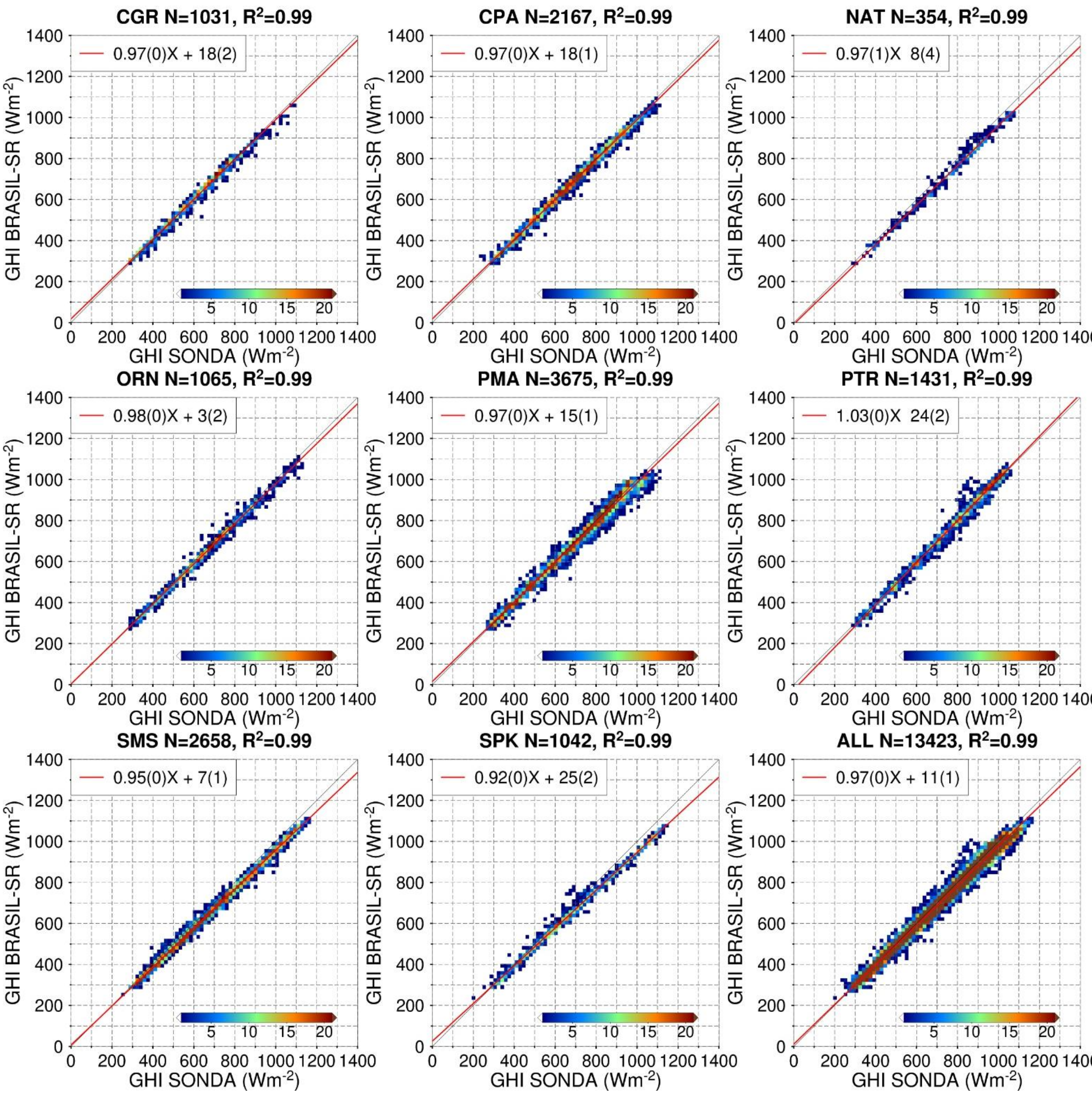

Fig. 3: 2023 and 2024 GHI Scatterplots from SONDA observed data versus BRASIL-SR in Clear-Sky conditions.

These analyses revealed relevant improvements regarding clear-sky simulations. Figure 4 presents scatterplots of GHI measured and simulated by the BRASIL-SR model at the SONDA Network sites, as well as for aggregated data representing the entire country (BR). Coefficient of determination (R^2) values above 0.8 were observed for all stations, except for Brasília and Campo Grande Fazenda, demonstrating the model's good capability to represent GHI behavior. The corresponding bias and RMSE values are presented in Table 1.

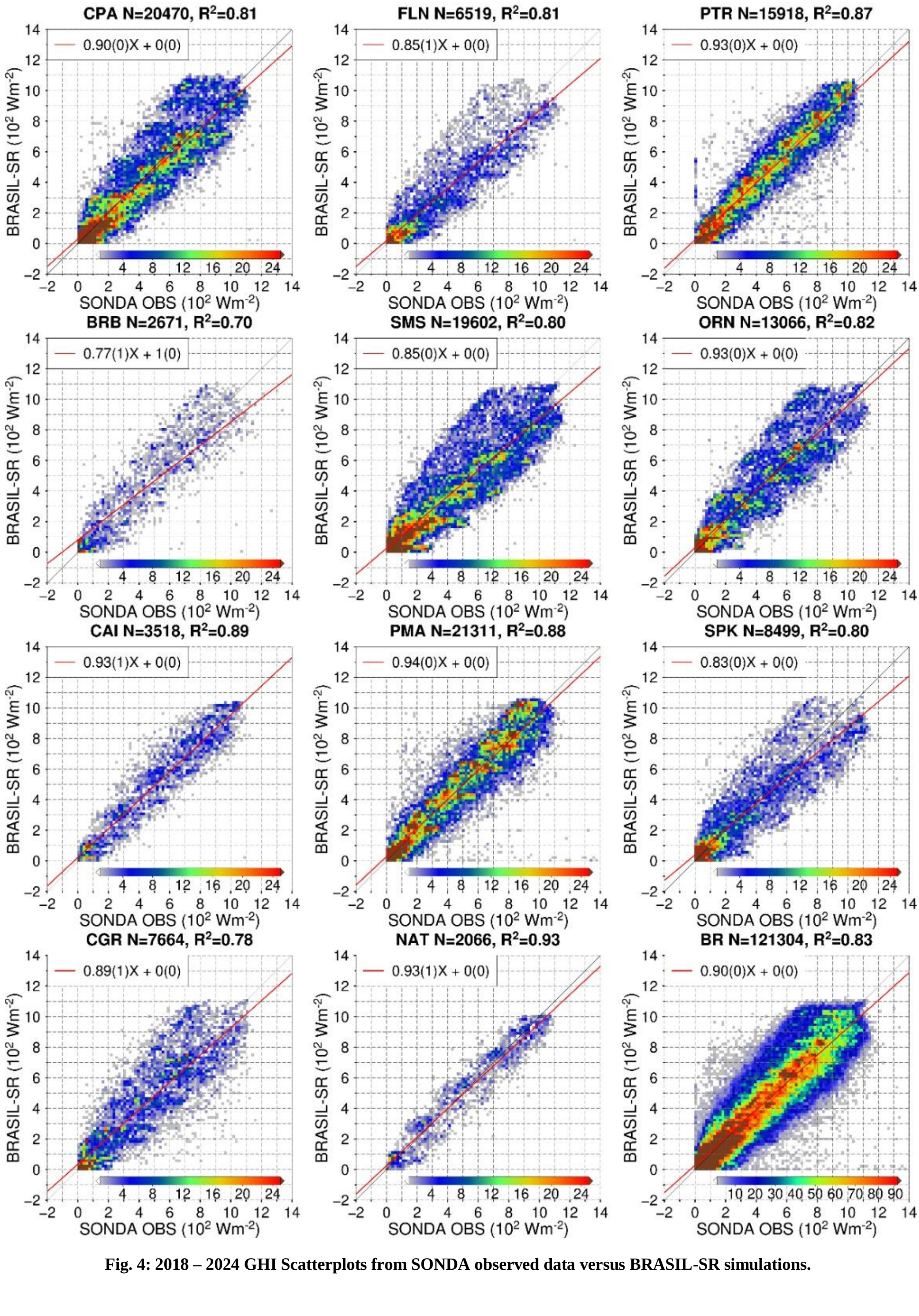

Fig. 4: 2018 – 2024 GHI Scatterplots from SONDA observed data versus BRASIL-SR simulations.

Table 1: bias, root mean square error (RMSE) and coefficient of determination (R^2) of the simulations.

Site	Bias(%)	RMSE(%)	R^2
CPA	-1	38	0.81
FLN	-9	40	0.81
PTR	-1	26	0.87
BRB	-3	47	0.70
SMS	-8	40	0.80
ORN	0	35	0.82
CAI	-1	22	0.89
PMA	0	28	0.88
SPK	-4	41	0.80
CGR	-1	39	0.78
NAT	-1	17	0.93
All sites (BR)	-2	34	0.83

Despite the low bias values and high R^2 values, Table 1 shows relatively high RMSE values. This type of behavior in an intercomparison indicates that the model does not exhibit a systematic tendency, that it is able to correctly identify and capture the variability and overall trend of the data, but that large-magnitude errors are still present in the comparisons. This may suggest the existence of relevant outliers within the datasets used for validation, indicating that the quality control procedures applied were not sufficiently robust to detect them.

Another key aspect to highlight is the reduction in bias compared with the data generated by previous versions of the BRASIL-SR model, indicating an overall improvement in the simulations resulting from the implemented updates. These differences are primarily attributed to the integration of the new clear-sky model and the revised C_{eff} parameterization, both of which play a critical role in this preliminary evaluation.

To assess the results in terms of annual total daily mean from the new simulations versus those from the BRASIL-SR model used in the Brazilian Atlas of Solar Energy - 2nd Edition, Figure 5 presents both datasets and a map illustrating the differences between them. The findings confirm observations from previous evaluations, such as a clearer depiction of the spatial features of GHI, stemming from the higher spatial and temporal resolution of the satellite imagery employed in the simulations.

The difference map (Figure 5c) shows that nearly the entire eastern portion of Brazil presents negative values, indicating a decrease in the average estimates of the new database for this region. In contrast, most of the North and Central-West regions exhibit positive values, representing an adjustment that increases the global solar radiation estimates compared with those in the Brazilian Atlas of Solar Energy - 2nd Edition. Additionally, increases in global solar radiation are observed in flooded areas, associated with lake breeze phenomena - a pattern noted in previous studies (Gonçalves et al., 2020; Carvalho et al., 2025) - and now more accurately quantified in this version of the model.

4. Conclusions

The main objective of the analyses presented here was to report the results of the most recent simulations and adjustments made to the BRASIL-SR model code, while also considering an extended dataset from the GOES-16 satellite, covering the period from 2018 to 2024. The purpose was to assess the effectiveness of the implemented improvements - particularly the new τ_{cloud} values and the new clear-sky model - in comparison with both the updated model versions under development and those used in the Brazilian Atlas of Solar Energy

- 2nd Edition (Pereira et al., 2017). The improvements in clear-sky parameterizations aimed at reducing bias under low-visibility conditions, especially in regions affected by aerosols, as well as enhancements in surface albedo representation and the inclusion of bidirectional reflectance distribution functions (BRDF) for areas with large water bodies, were also evaluated.

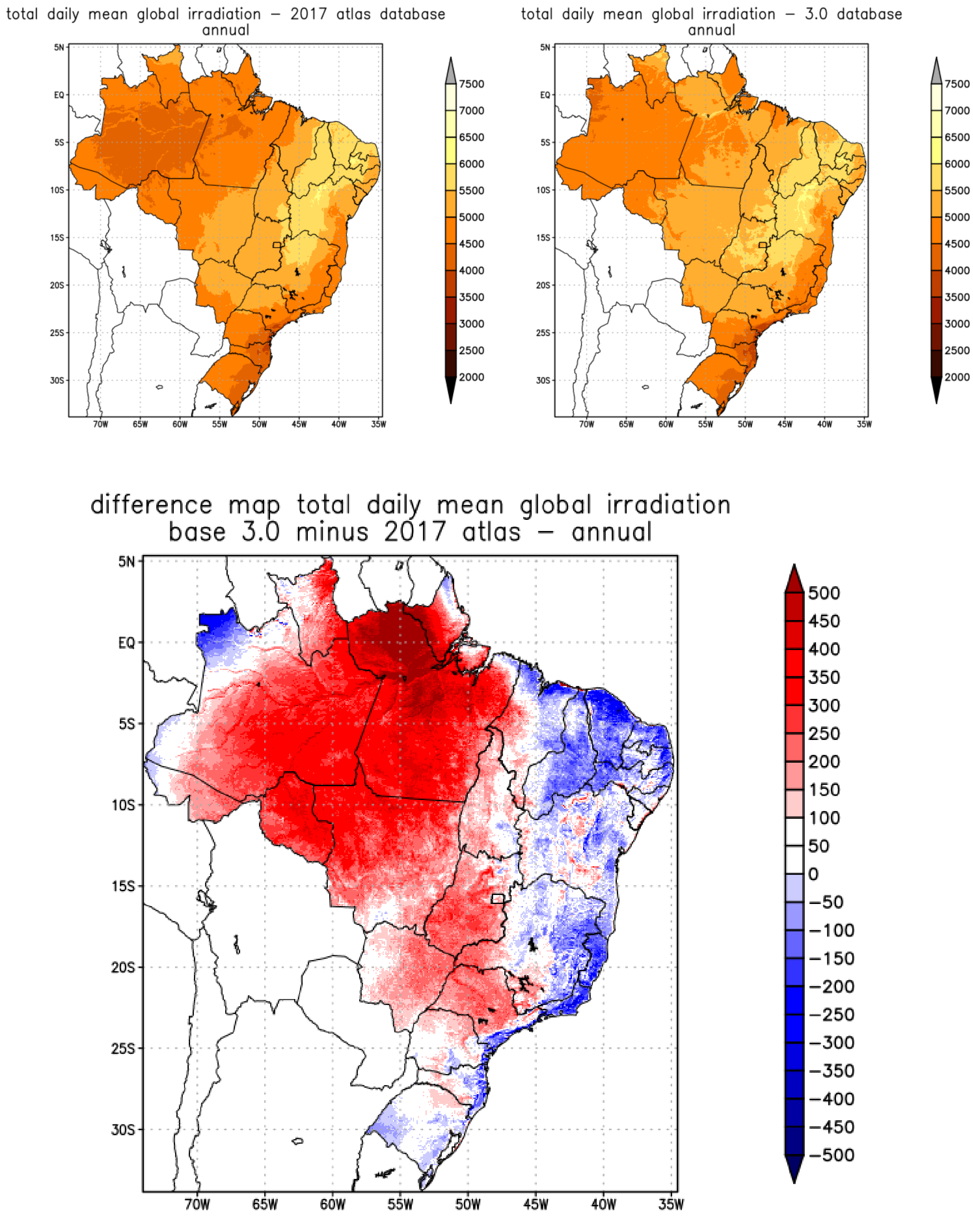

Fig. 5: total daily mean global horizontal irradiation maps: new database data (a); Brazilian Atlas of Solar Energy - 2nd Edition (b); and the difference map between them (c).

In general, the simulation evaluations yielded consistent and meaningful results. Validations under clear-sky conditions showed Coefficients of Determination above 0.99, along with bias values ranging from 2% to –5% (not shown). The analyses under overcast-sky conditions were also satisfactory; however, RMSE values indicated the presence of spurious observed data within the series used for validation.

It is important to mention that the data generated in the second edition of the Atlas underwent statistical post-processing to reduce simulation bias, which was not applied in these analyses. The results revealed a more detailed representation of solar radiation features and characteristics, reflecting the enhanced spatial and temporal resolution of GOES-16. An increase in the average daily global radiation was also observed during the dry months, linked to the new parameterizations and the use of more refined input data. Further evaluations are still being conducted on the direct and diffuse radiation partitioning models, as well as on longer data periods that will enable a more comprehensive assessment of cloud-related aspects and their interannual variability.

It should be noted that the evaluations presented here are preliminary; nevertheless, the overall results were satisfactory, indicating significant improvements in the BRASIL-SR model.

5. Acknowledgments

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