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Comparison of Climate Data from NASA POWER Reanalysis and Data Measured at Surface Weather Stations for Application in Brazilian Paving Projects

Comparação dos Dados Climáticos da Reanálise NASA POWER e Dados Medidos em Estações Meteorológicas de Superfície para Aplicação em Projetos de Pavimentação no Brasil

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Abstract

For the consideration of climate in paving projects, climate data with adequate quality and availability are required. In the Brazilian context, the current practice is to use data measured at the surface meteorological stations of the National Institute of Meteorology (INMET). Another possibility is to use data from reanalyses such as NASA POWER, which has an extensive database and excellent spatial coverage. Thus, this study aims to perform statistical comparisons between NASA POWER climate data and those measured by INMET in different locations in Brazil, to understand and quantify their respective differences and support future analyses regarding the use of NASA POWER reanalysis in projects related to the paving area. For this analysis, hourly climate data of air temperature, solar radiation, wind speed, precipitation, and humidity were considered and evaluated using statistical indices. Based on the analysis of 476 locations in Brazil, in general, the findings indicated that the air temperature, humidity, and solar radiation data from the NASA POWER reanalysis revealed good agreement with the data measured by INMET. However, hourly wind speed and precipitation data from NASA POWER did not show good agreement with the data measured by INMET. The climate data from the NASA POWER reanalysis have great potential for use in future paving projects in the country, mainly in regions with few ground meteorological stations (e.g., the North region). However, it is important to validate its use through pavement performance simulations, especially due to discrepancies in hourly wind speed data.

Keywords: Climate; Statistical; Pavements

Resumo

Para a consideração do clima em projetos de pavimentação, são necessários dados climáticos com boa qualidade e disponibilidade. No contexto brasileiro, a prática atual é utilizar dados medidos nas estações meteorológicas de superfície do Instituto Nacional de Meteorologia (INMET). Outra possibilidade é a utilização de dados de reanálises como a NASA POWER, que possui um extenso banco de dados e excelente cobertura espacial. Assim, este estudo tem como objetivo realizar comparações estatísticas entre os dados climáticos NASA POWER e os dados medidos pelo INMET em diferentes locais do Brasil, a fim de compreender e quantificar as diferenças e apoiar futuras análises do uso da reanálise NASA POWER em projetos relacionados à área de pavimentação. Para isso, foram considerados dados climáticos horários de temperatura do ar, radiação solar, velocidade do vento, precipitação e umidade, avaliados por meio de índices estatísticos. Com base na análise de 476 locais no Brasil, em geral, os achados indicaram que os dados de temperatura do ar, umidade e radiação solar da reanálise NASA POWER revelaram boa concordância com os dados medidos pelo INMET. Todavia, os dados de velocidade do vento e precipitação provenientes da reanálise não apresentaram boa concordância com os dados medidos pelo INMET. Os dados climáticos da reanálise NASA POWER têm grande potencial para utilização em futuros projetos de pavimentação no país, principalmente em regiões com poucas estações meteorológicas terrestres (por exemplo, a região Norte). No entanto, é importante validar seu uso através de simulações de desempenho dos pavimentos, especialmente devido às discrepâncias nos dados horários de velocidade do vento.

Palavras-chave: Clima; Estatísticas; Pavimentos

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1 Introduction

Pavement performance depends on many factors, including traffic, weather conditions, structure and material properties. Climatic conditions are relevant factors in the behavior of asphalt pavements and, consequently, in the performance and useful durability of these structures (Hasan, Hiller & You 2015; Haslett et al. 2021; Specht et al. 2017). According to the Federal Highway Administration (FHWA), climatic factors alone can contribute up to 36% of the total damage to flexible pavements (Revelli et al. 2023). Therefore, in paving projects, climate data with good quality and availability is of critical importance.

Relying on several studies on the impact of climate on pavements deterioration, Titus-Glover (2021) summarized the main climate parameters, namely: solar radiation and cloud cover; air temperature; precipitation and humidity; and wind speed. These variables influence directly pavement temperature, water damage to the structure, and asphalt aging. The difference in climatic conditions has a significant impact on the load capacity and performance of the asphalt pavements, as it relates to the formation of rutting, cracking, aging, and other defects (Gopisetti et al. 2022; Motta 1991; Wang et al. 2019).

There are already mechanistic-empirical pavement design methods studied in Brazil that consider the climate in the design process: CAP 3D, FlexPave™, and AASHTOWare Pavement ME. The first one, that is, CAP 3D, uses air temperature data from surface weather stations of the National Institute of Meteorology (INMET) (Santos et al. 2020). In the second and third ones, that is, FlexPave™ and in AASHTOWare, the pavement temperature is obtained through the Enhanced Integrated Climatic Model (EICM), in which climate data from the MERRA-2 reanalysis (Modern Era Retrospective Analysis for Research and Applications) is generally used, made available by the National Aeronautics and Space Administration (NASA). EICM is a one-dimensional coupled heat and moisture flow model used to predict or simulate the changes in behavior and characteristics of pavement and materials as a function of climate, using air temperature, wind speed, sunshine percentage, precipitation, and relative humidity as input data. There are also studies that consider air temperature data for the calculation and definition of the Performance Grade (PG) of asphalt binders, which draw on the Superpave methodology (Cunha, Zegarra & Fernandes Júnior 2007; Faccin et al. 2021; Leite & Tonial 1994).

In Brazil, it is worth noting the predominance of climate data from INMET stations for studies related to paving. The national meteorological network operated by the Institute presents significant variation in terms of station density by Federative states (Siefert et al. 2021). In a survey carried out on the INMET website, on 07/16/2023, the findings indicated: 723 active stations, with 666 of them in "operating" status, and a database of 1,223 stations. Although the data measured at the stations faithfully represent the location of data collection, as reported by Faccin et al. (2021), there are several stations that were recently implemented, others with missing data or historical series with measurement failures, and some that have been deactivated, which reduces the number of stations that can be used. Moreover, in some regions of the country (e.g., the North), there are few ground meteorological stations to collect this data, which can affect the data quality to be used in pavement projects to be carried out in these regions.

Taking this into account, another possibility is the use of indirect methods for obtaining climate data (Bustos, Ferrelli & Piccolo 2017), such as reanalyses. According to Rosa et al. (2023), among the various reanalyses datasets, the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) has been recently highlighted. The platform provides solar and meteorological data at multiple temporal levels, according to the spatial resolution of the source data (NASA, 2023), with hourly data available from the year 2001. POWER meteorological parameters (such as air temperature, dew point temperature, wind speed, relative humidity, and precipitation) are derived from the MERRA-2 assimilation model (Gelaro et al. 2017), developed by NASA's Global Modeling and Assimilation Office (GMAO). MERRA-2 is the state-of-the-art atmospheric reanalysis of the modern satellite era, increasingly used in climate monitoring (Claudino et al. 2021). The MERRA-2 data are based on analysis of a combination of ground, satellite, ocean, and atmospheric observations. The result is uniformly gridded data that covers the entire globe, with a spatial resolution of 0.5° latitude by 0.625° longitude. In Brazil, there are 2,278 cells covering the entire territorial extension. Figure 1 presents the location of the 723 active INMET surface meteorological stations (567 automatic and 156 conventional) and the centroids of the 2,278 MERRA-2 cells located in the country.

MERRA-2 data is recommended and adopted in the American Mechanistic-Empirical Design of Pavements Guide (MEPDG) and in the calculation of the PG for selection of asphalt binders (LTPP Bind 3.1) in the United States of America (U.S.A.) (Schwartz et al. 2015). The use of reanalysis data in U.S.A. paving projects is supported by studies that have demonstrated their suitability (Li et al. 2018; Schwartz, Forman & Leininger 2019; Ziedan et al. 2019).

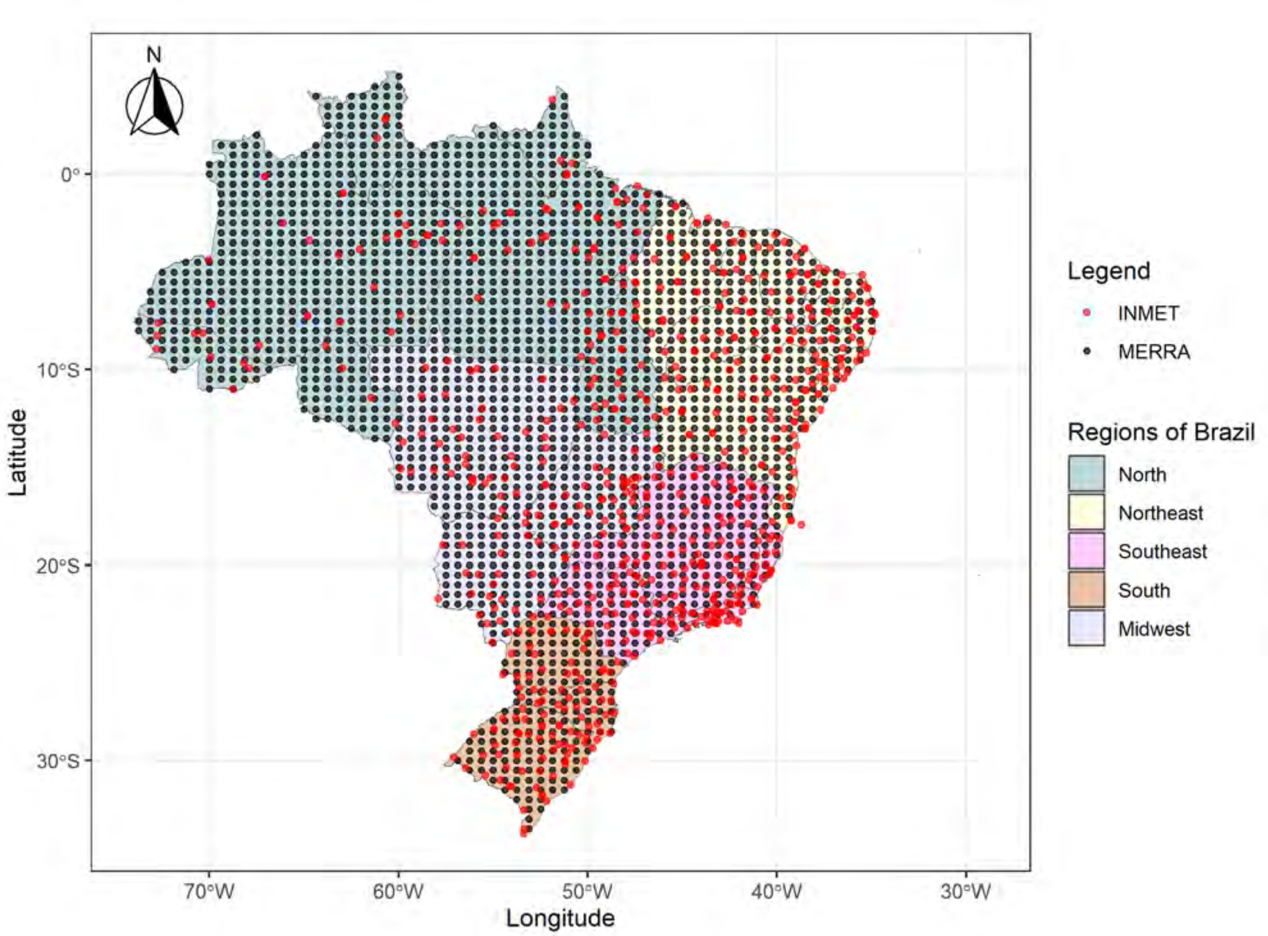

Figure 1 Location of the 723 active INMET surface meteorological stations and centroids of the 2,278 MERRA-2 centroids located in Brazil.

In NASA POWER, the hourly radiation dataset (e.g., incident solar radiation and extraterrestrial radiation) is derived from NASA CERES SYN 1-deg product, with a global grid of 1° latitude by 1° longitude spatial resolution (NASA, 2023). The Clouds and the Earth's Radiant Energy System (CERES) project provides satellite-based observations of Earth's radiation budget (ERB) and clouds. It uses measurements from CERES instruments flying on several satellites along with data from many other instruments to produce a comprehensive set of ERB data products for climate, weather and applied science research. Cao et al. (2022), when evaluating different radiation databases in China, found that CERES SYN 1-deg performed better than ERA5 and MERRA-2 reanalyses.

It is worth noticing that reanalyses, such as NASA POWER, can be considered valuable input sources of climate data for use in projects related to paving area in Brazil, since they have an extensive database and excellent spatial coverage. Nonetheless, the main limitation of its use in the country is still the lack of evaluations of the databases and the proof of its suitability for this purpose. Faccin et al. (2022), when comparing historical air temperature data from MERRA-2 with those observed at two INMET meteorological stations in Rio Grande do Sul State, Southern Brazil, concluded that the hourly air temperature data from the reanalysis and INMET stations presents strong linear correlations, with very similar distributions and frequencies. However, the MERRA-2, in general, underestimated the air temperature values, with average errors less than 0.9 °C. Regarding the wind, Siefert et al. (2021), when evaluating surface wind speed data on a daily scale, from observational data from 521 ground meteorological stations for the period 2000–2018 in Brazil, concluded that MERRA-2 presents limitations and uncertainties for data simulation. The authors took into consideration the trend and daily dispersion of the observed series, and concluded a trend towards overestimation of average wind speeds in some regions of the country, and a tendency towards underestimation in other regions.

These differences in climate parameters impact the responses of the models used to calculate the pavement temperatures and may even lead to unrealistic performance results. Gopisetti et al. (2022), when evaluating the performance of flexible pavements and four sources of climate data, observed disagreements in performance predictions when considering the MERRA-2 climate parameters. In this context, there are no studies available that have evaluated the suitability of NASA POWER reanalysis for pavement projects in tropical countries such as Brazil. Furthermore, it is necessary to know the real differences in the climate data obtained by NASA POWER, to assess the impact of using reanalysis in paving projects in the country.

It is worth considering that there are currently several other climate databases, which are not the subject of this study. For instance, satellite and radar observations, and other reanalyses in addition to NASA POWER. The precision of these databases presents values different from those found for NASA POWER in this paper and can be consulted in several studies published in the climate area, such as Costa et al. (2019), Cavalcante et al. (2020), Tang et al. (2020), Braga et al. (2021), and Silva et al. (2022). Bearing in mind the importance of obtaining reliable meteorological data to support scientific research and projects related to the area of road infrastructure, the objective of this article is to carry out statistical comparisons between NASA POWER climate data and those measured by surface weather stations, in different locations in Brazil, with the aim of understanding and quantifying the differences and supporting future analyses of the feasibility of using NASA POWER reanalysis in projects related to paving. In order to achieve this goal, hourly climate data of air temperature, solar radiation, wind speed, precipitation, and humidity were considered.

2 Data and Methodology

Figure 2 presents the methodology adopted in this study, identifying the main steps necessary to achieve the proposed objective. It addresses the acquisition and processing of data and, finally, the statistical analysis.

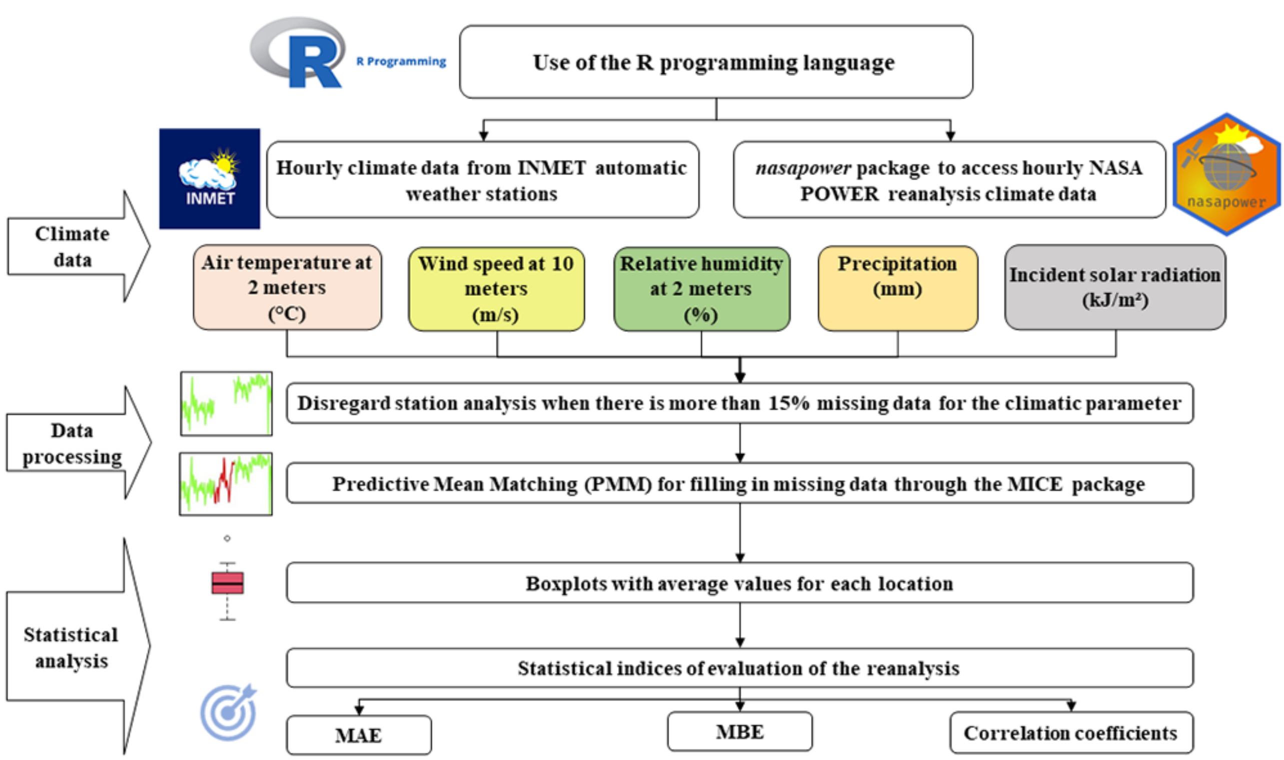

Figure 2 Methodology flowchart.

2.1 Climate Data: Acquisition and Processing

2021 hourly meteorological data were obtained from two sources: from the National Institute of Meteorology of Brazil (INMET, 2023); and from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER), Project funded through the NASA Earth Science/ Applied Science Program (named NASA POWER). Statistical evaluations of these two sources provided an initial assessment of their similarities and differences, and helped to identify any potential data issues that will serve as the basis for future studies in the area of road infrastructure. The hourly weather data of air temperature, wind speed, incident solar radiation, relative humidity, and precipitation were considered, as they are the most relevant in the behavior and performance of asphalt pavements.

There were 476 locations evaluated, coinciding with the INMET automatic surface weather stations with 2021 data available, according to the location shown in Figure 3. Data from INMET conventional stations were not used because they do not have hourly data and the main pavement design methods require hourly weather data. The data series estimated by the NASA POWER reanalysis was obtained by extracting the values of the cells in which the INMET station is located, using the nasapower package (Sparks, 2018, 2024) and R programming language (R Core Team, 2023). Nasapower is an R package that provides the functionality to interface with NASA's POWER API to download global meteorology, surface solar energy and climatology data from NASA POWER into your R session as an organized data structure.

As highlighted in the Introduction section, the INMET data present many stations with missing data. Therefore, it was adopted as a criterion to disregard the climate variable when there is more than 15% of missing

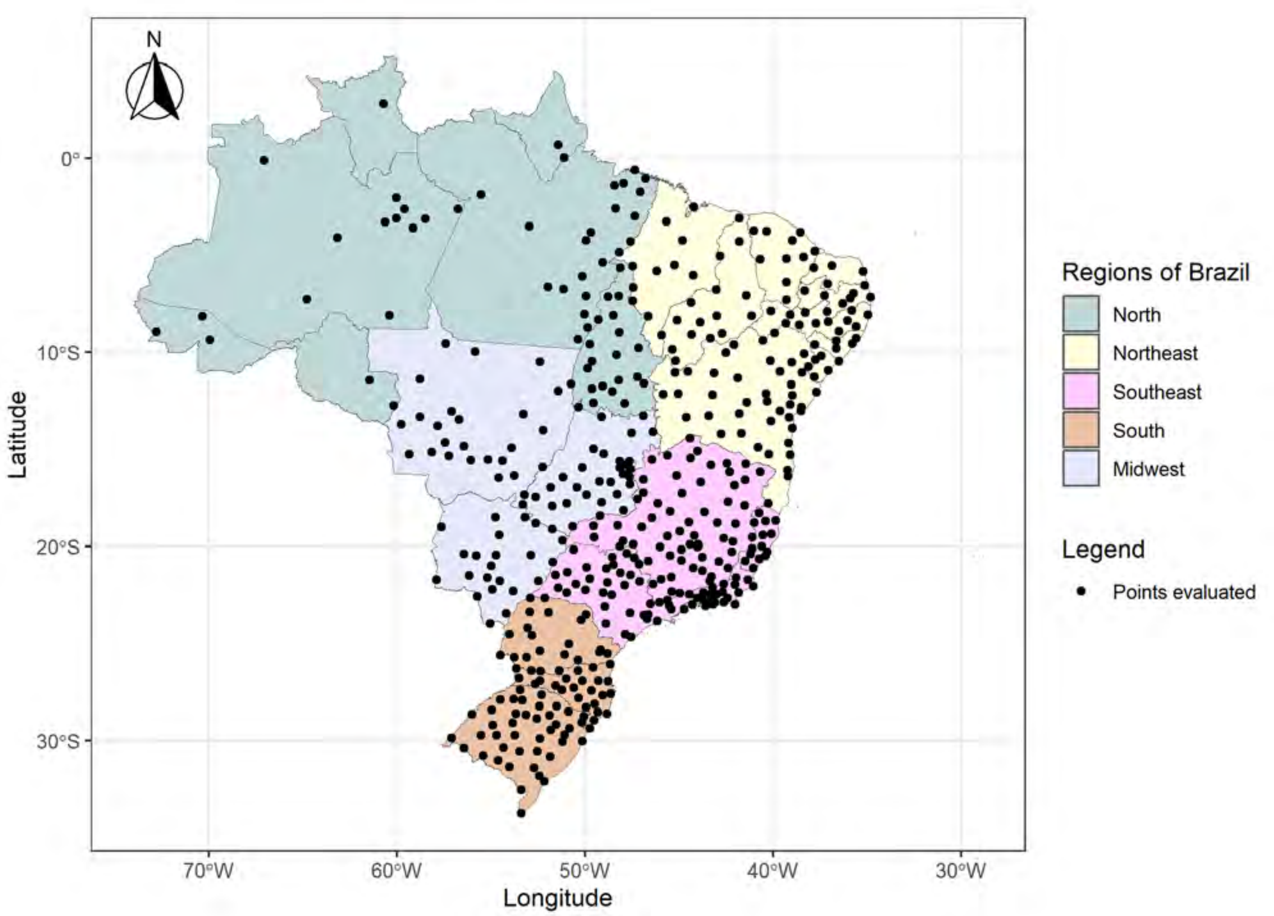

Figure 3 Map with the location of the 476 locations evaluated.

data for the evaluated period, as adopted in other research related to the climate area (Abatzoglou 2013; Miquelluti & Ozaki 2021). In the case of missing data, there is a need to fill in these gaps, ensuring a better evaluation of the variable. Thus, to fill in these gaps, the R software package called Multivariate Imputation by Chained Equations (MICE) (Horton & Lipstitz 2001) was used, considering the multiple imputation method Predictive Mean Matching (PMM). The PMM method is considered to have low uncertainty, since it combines elements of regression, nearest neighbor, and hot deck imputation (parametric and non-parametric techniques). According to Dos Santos et al. (2021), the technique has a number of advantages over other methods for treating missing data in time series, being widely used in research in the area of climatology. Alves and Gomes (2020) observed in their study that the method performs well in filling in longer data series, such as air temperature and precipitation data, considered in this study.

2.2 Statistical Analysis

Statistical analyses were performed using the R programming language (R Core Team, 2023). First, descriptive statistical analyses were carried out, presenting the results through a comparative visual analysis of the climate data using boxplots with minimum, average, and maximum values.

The performance of the climate data from NASA POWER reanalysis was evaluated in order to indicate whether the data is consistent with the data observed by INMET, based on the following statistical indices: Mean Bias Error (MBE), Mean Absolute Error (MAE), Pearson's correlation coefficient (r), and Spearman's correlation coefficient (p) for precipitation data, according to the Equations 1, 2, 3, and 4. According to Nogueira and Moreira (2015), the MBE indicates whether the modeled data are underestimated (i.e., negative value) or overestimated (i.e., positive value) in relation to the observed data. The absolute error (MAE) is an average of the absolute errors, used to quantify the proximity between the estimated data and the observed data. The correlation coefficient assesses the degree of correlation between the two sets of data, ranging from -1 (i.e., perfect negative correlation) to +1 (i.e., perfect positive correlation).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_r - x_0| \quad (1)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(x_r - x_0) \quad (2)$$

$$r = \frac{\sum\left(x_0 - \bar{x}_0\right)\left(x_r - \bar{x}_r\right)}{\sqrt{\sum\left(x_0 - \bar{x}_0\right)^2 \sum\left(x_r - \bar{x}_r\right)^2}} \quad (3)$$

$$p = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \quad (4)$$

In which:

x_0 = the value of the climate variable measured at the INMET station;

x_r = the value of the climatic variable estimated by the reanalysis product;

$\bar{x}_0$ = Mean of variable;

$\bar{x}_r$ = Mean of variable;

d_i = difference between the two ranks of each observation;

n = the number of observations.

The statistical indices are presented through maps (MAE, MBE, and correlation), to demonstrate the spatial variation of individual values in the country, identifying possible locations with significant values that deserve highlighting, and through boxplots (MBE), which demonstrate the trends and variability of all the evaluated points.

3 Results and Discussions

Figure 4 presents the accumulated percentages of missing data for the 476 INMET stations evaluated in the period, for each of the 5 climate variables. It is possible to notice that there is a lot of missing data in the INMET stations, regardless of the climate data, with more than approximately 50% of the stations presenting 15% or more missing data in the period.

Figure 5 presents the boxplots of the average (5A), minimum (5B), and maximum (5C) air temperature values, demonstrating the relationship between the databases through lines that connect the values measured by INMET and those obtained from the NASA POWER reanalysis. As shown in Figure 5, a high similarity of hourly temperatures can be observed for both data sources. To better understand these differences, Figure 6 shows the values of the statistical indices considered, namely: MAE (6A), MBE (6B and 6C) and Pearson's Correlation (6D).

According to Figures 6B and 6C, it can be identified that, for most locations, NASA POWER has a slight tendency

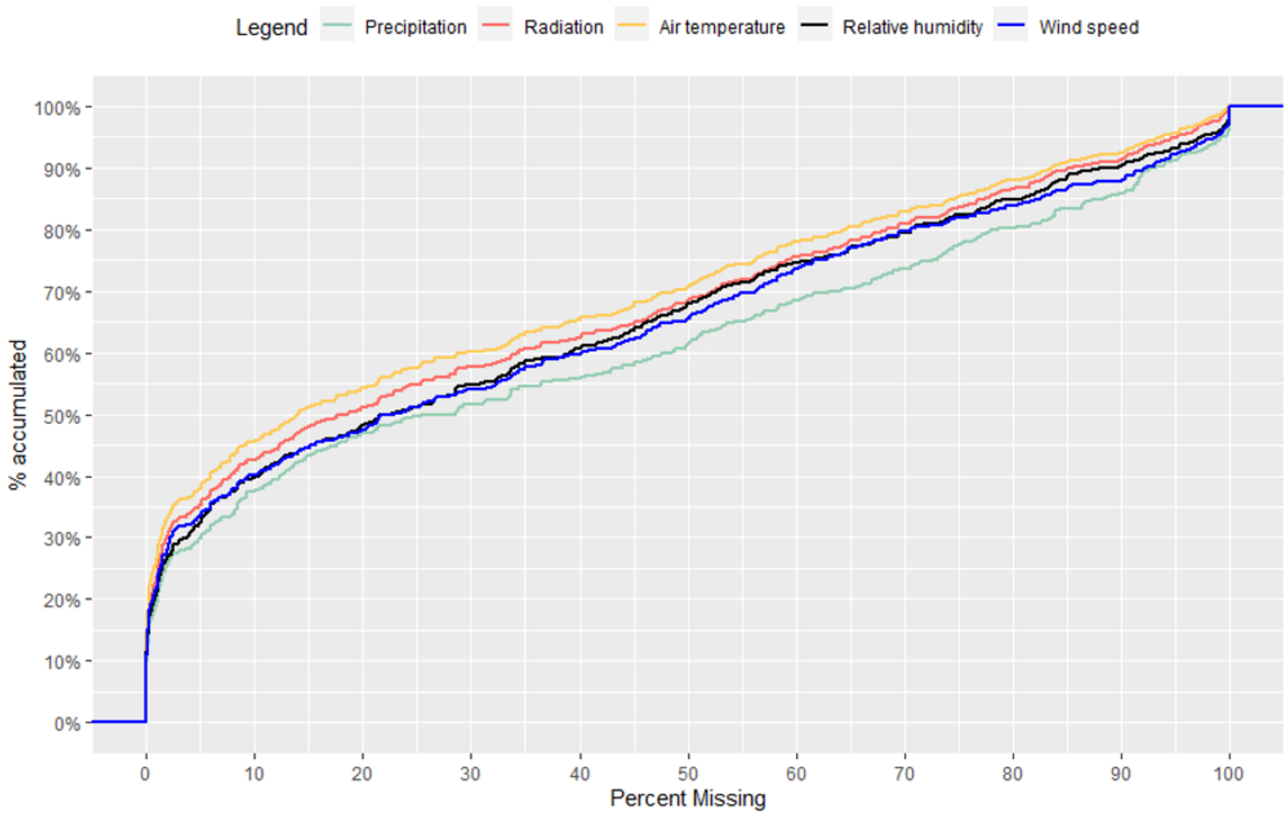

Figure 4 Accumulated percentage (%) of missing data at INMET stations.

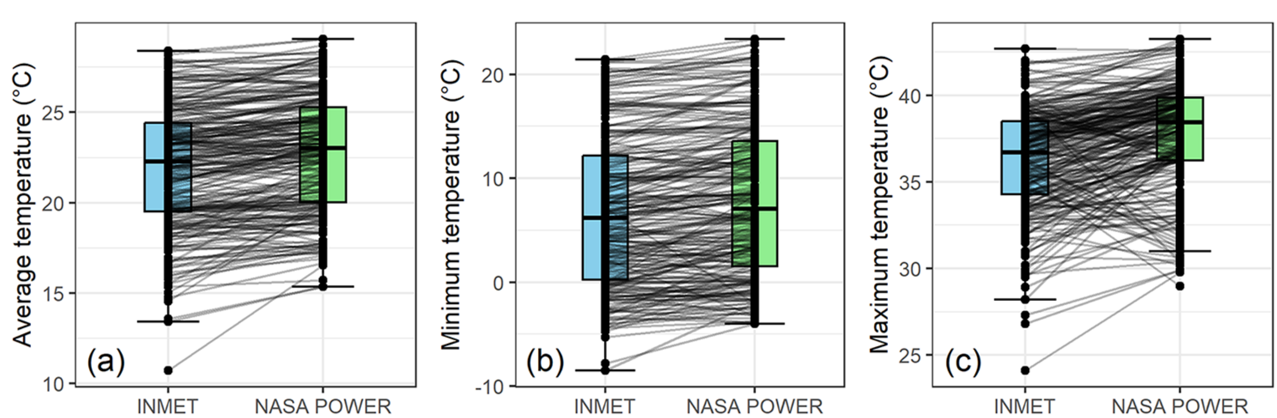

Figure 5 Boxplots of hourly air temperature data (°C) with different scales in the y-axis: A. Average; B. Minimum; C. Maximum.

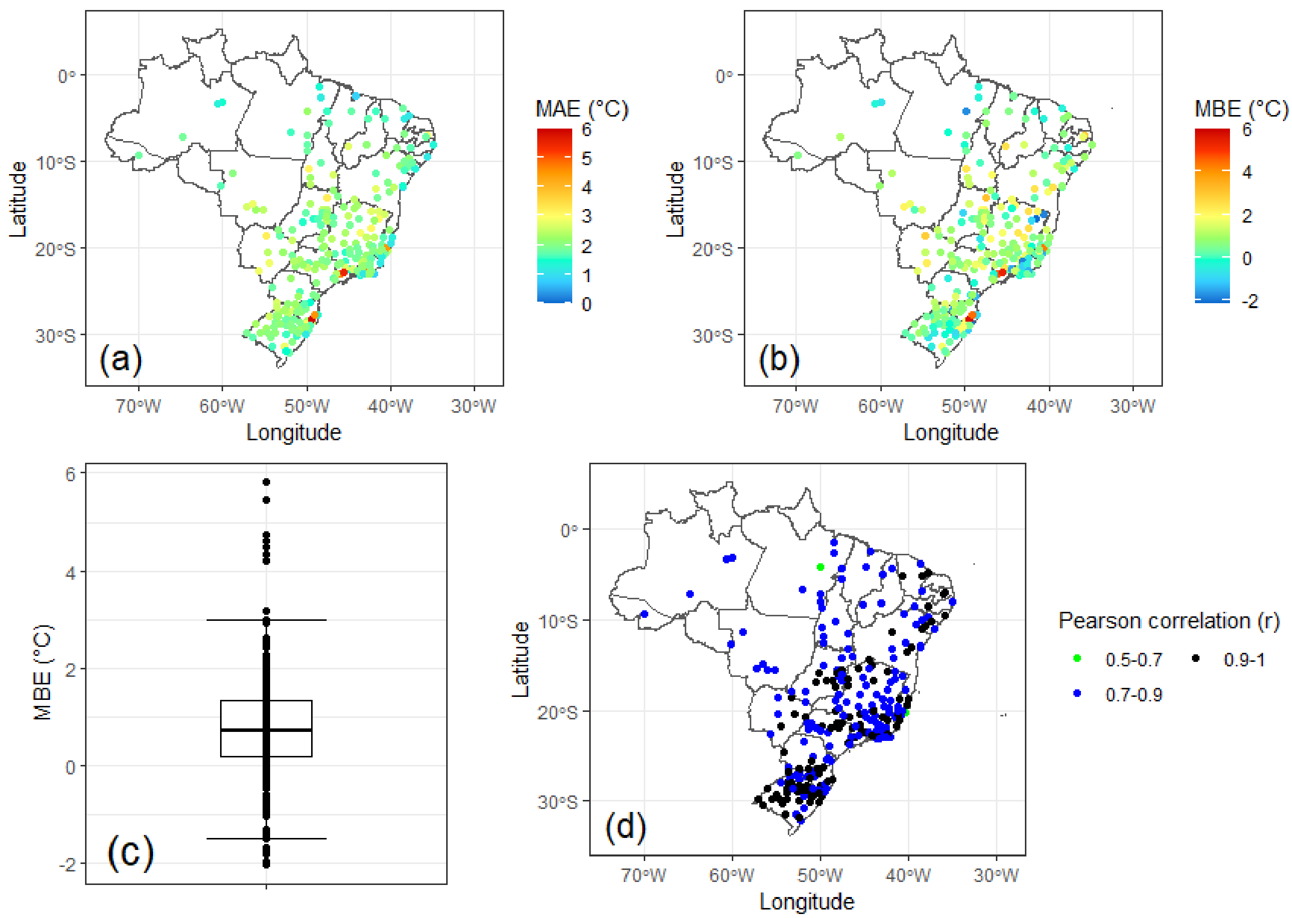

Figure 6 Values for hourly air temperature (°C): A. MAE; B-C. MBE; D. Pearson Correlation.

to overestimate the hourly average temperature data (mean error values greater than 0 °C for 75% of locations evaluated – Figure 6C), with some locations presenting MBE values of almost 6 °C (Figure 6B), located in mountainous areas: regions of the States of Santa Catarina (INMET stations A845 and A870), São Paulo (INMET station A706), Minas Gerais (INMET station A509), and Rio de Janeiro (INMET stations A624 and A618). However, there are places where NASA POWER underestimates temperature values (mean errors up to -2 °C). The Mean Absolute Error (MAE) values, for the most part, present values between 1 °C and 3 °C, which demonstrates proximity between the data, as shown in Figure 6A. With the exception of three locations (green dots on the Pearson Correlation map – Figure 6D - INMET stations A612, A235 and A912), strong or very strong positive linear relationships were found, indicating good correspondence between the two data sources.

Most of these temperature discrepancies for the two databases can be explained by differences in Earth surface elevation at the reanalysis grid point and at the ground-based weather station, as discussed by Faccin et al. (2022) and in the study conducted in the U.S.A. by the FHWA (Schwartz et al. 2015). White et al. (2008), when evaluating the NASA POWER reanalysis in the U.S.A., concluded that very inclined terrains, mountainous and coastal regions might have a large influence on the air temperature reanalysis data, suggesting the need for adjustments for elevation (lapse rate) effects.

Based on this, it can be concluded that there is a consistent agreement between the meteorological air temperature statistics from NASA POWER and INMET, similar to what was observed in the FWHA research conducted in the USA when evaluating the MERRA-2 reanalysis (Schwartz et al., 2015). Monteiro et al. (2017), when comparing data from the NASA POWER reanalysis and INMET for 203 locations in Brazil, concluded that the reanalysis reproduces air temperature data satisfactorily for most of the Brazilian territory at daily time scales. It is understood that the use of air temperature data from the NASA POWER reanalysis for paving projects is feasible, highlighting that this climate variable is very important for flexible pavement distress predictions (Li et al. 2013; Yang et al. 2017).

For the wind speed at 10m above ground level, illustrated in Figure 7, different from the air temperature results, greater disagreements are observed between the databases. To better understand these differences, Figure 8 illustrates the values of the statistical indices evaluated: MAE (8A), MBE (8B and 8C), and Pearson's Correlation (8D).

According to Figures 8B and 8C, the NASA POWER, in general, overestimates the hourly wind speed values for most locations, especially in the northeast region of the country as can be seen on the map in Figure 8B. The mean error values greater than 0 m/s can be identified in 75% of the evaluated locations, with some locations showing MBE values of approximately 4 m/s (Figures 8B and 8C). However, there are places where reanalysis underestimates wind speed values (mean errors up to -2 m/s). The mean absolute error (MAE) values demonstrate that there is no proximity between the data (Figure 8A). Siefert et al. (2021) also observed a trend towards overestimation of daily wind speeds from the MERRA-2 reanalysis for the different Brazilian climate zones. Monteiro et al. (2017) observed that comparisons of extreme and mean wind speed data from INMET and NASA POWER were only reasonable when evaluated at 203 locations in Brazil. The Pearson correlation values (see Figure 8D) indicate that most locations have moderate (green points), weak (yellow) and insignificant correlations (red), demonstrating that there is no good correspondence between the two bases, when considering hourly data. According to Davidson and Millsteinv (2022), wind speed data from reanalyses can be noisy and exhibit a wide range of biases and errors, variously attributed to terrain effects, poor coverage of assimilated inputs, and model resolution.

The overestimation of wind speed increases the heat loss to ambient temperature, reducing the temperature of pavement, as reported in the study by Farzan et al. (2021), which may impact the final performance and the selection of the type of asphalt binder. Yang et al. (2017), in a comprehensive study for the state of Michigan, selecting six representative geographic locations and two typical traffic levels to assess the sensitivity of AASHTOWare Pavement ME, observed that predicting pavement distress is moderately sensitive to wind speed. Given this, it is understood that discrepancies in hourly wind speed deserve further evaluation for use in paving projects in Brazil.

Regarding hourly relative humidity, it is possible to observe good agreement between the databases for the average (see Figure 9A) and minimum (see Figure 9B) values, and considerable disagreements for the maximum values (see Figure 9C). The results indicate that NASA POWER underestimates the humidity values in some places and overestimates them in others, as can be seen in the boxplots, in which the relationship between the data from the two databases is demonstrated. In order to complement the analyses, Figure 6 presents the results of the statistical indices considered: MAE (10A), MBE (10B and 10C), and Pearson's Correlation (10D).

According to Figures 10B and 10C, it can be identified that NASA POWER either overestimates the average relative humidity data by up to 10% or underestimates it by up to almost 20%. According to the map in Figure 10B, the largest mean bias errors are identified in different locations across the country. Furthermore, the median of the values is very near to zero, with more than 50% of the data presenting MBE values between -5% and

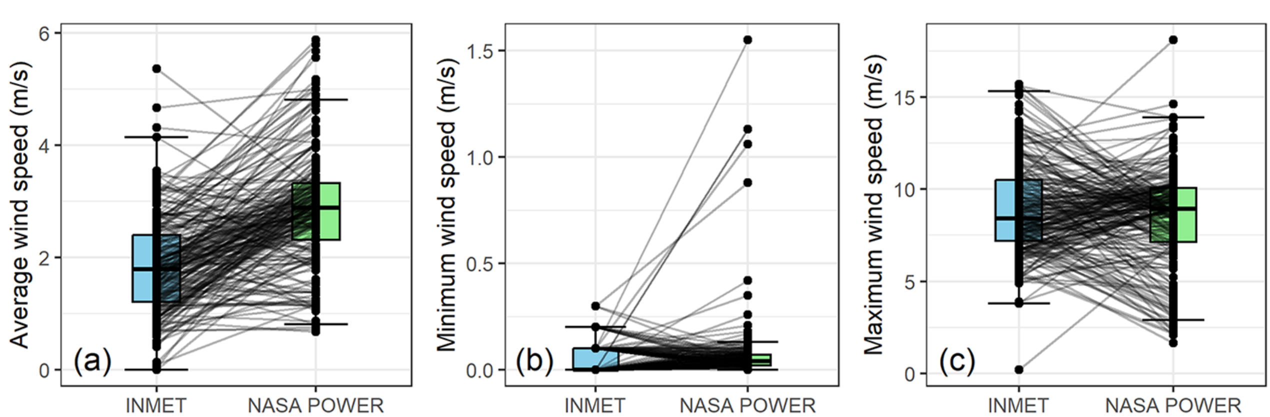

Figure 7 Boxplots of hourly wind speed data (m/s with different scales in the y-axis): A. Average; B. Minimum; C. Maximum.

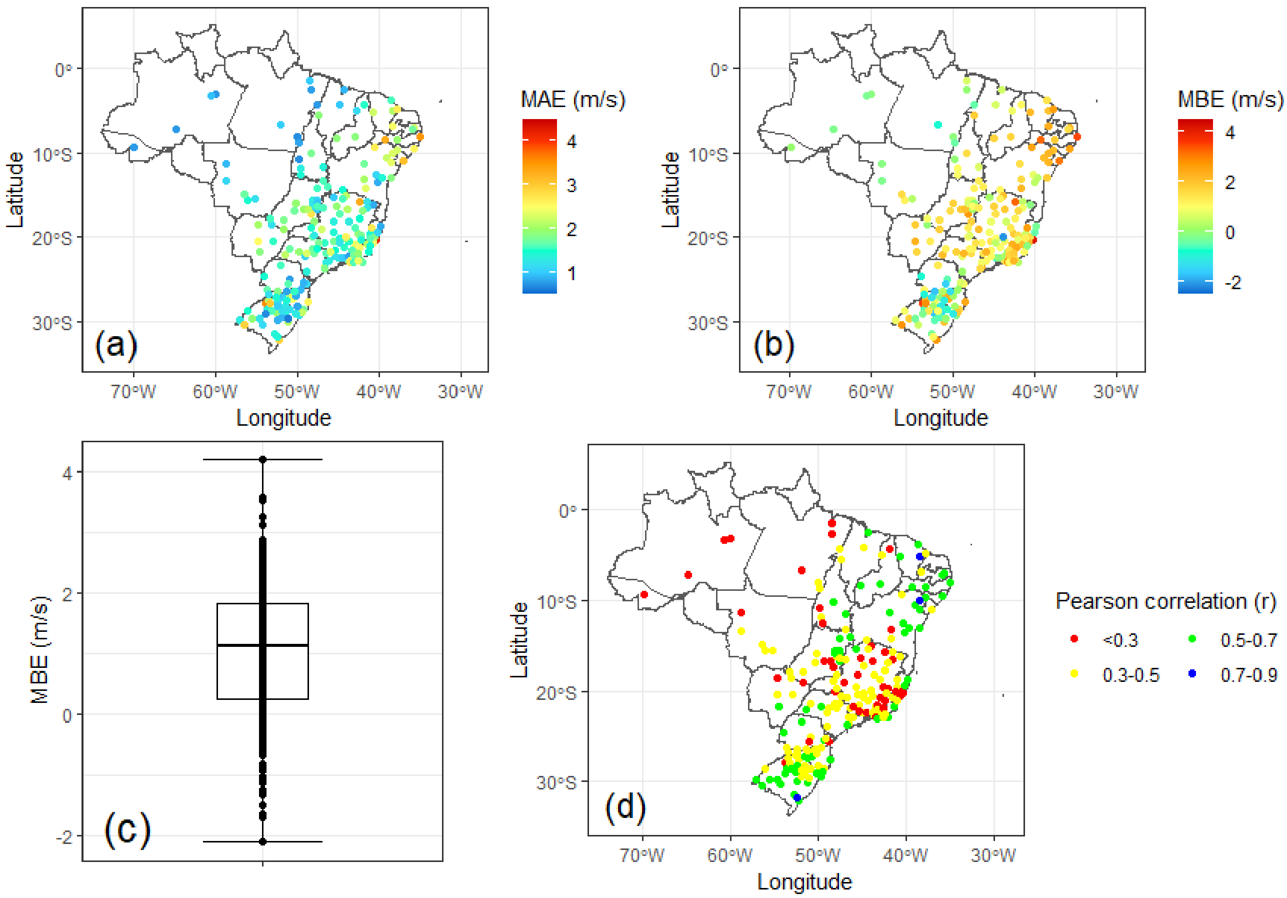

Figure 8 Values for hourly wind speed (m/s): A. MAE; B-C. MBE; D. Pearson Correlation.

+5% (see Figure 10C). The mean absolute error (MAE) values vary between 4% and 20%, as shown in Figure 10A. With the exception of a few locations (yellow and green dots on the correlation map), most locations show strong or very strong positive linear relationships, which indicates proper correspondence between the two data sources.

Yang et al. (2017) concluded that relative humidity was the least important parameter out of the five climate variables used in the EICM model, namely: air temperature, wind speed, sunshine percentage, and precipitation. These results probably represent the Brazilian reality because the models used in paving projects are little impacted by relative humidity. Therefore, it can be concluded that the agreement between NASA POWER and INMET meteorological statistics is consistently similar for relative humidity, leading to the inference that the use of reanalysis for this climate variable is feasible in paving projects in Brazil.

Analyzing the hourly precipitation data (see Figure 11A), it is possible to state that the average is similar between the databases. However, these findings are biased due to the high number of hourly data with values equal to zero (without precipitation). Another highlight is that NASA POWER is not able to capture the extreme precipitation events that occur throughout the year adequately (see Figure 11C). Furthermore, Figure 6 presents the results of the statistical indices considered: MAE (12A), MBE (12B and 12C), and Spearman Correlation (12D).

According to Figures 12B and 12C, the precipitation estimated by NASA POWER is slightly underestimated at most locations (75% of locations with MBE less than 0, as shown in Figure 12C). The mean absolute error (MAE) values vary between 0.0 and 0.8mm, as shown in Figure 12A. The results are near to zero due to the large number of hours without precipitation recorded in both databases, which can make hourly analysis difficult.

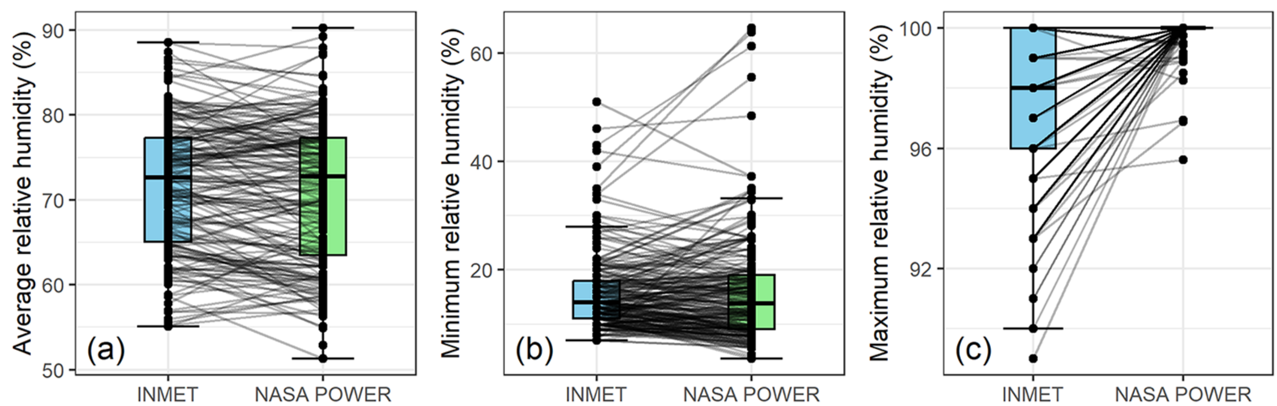

Figure 9 Boxplots of hourly relative humidity data (%) with different scales in the y-axis: A. Average; B. Minimum; C. Maximum.

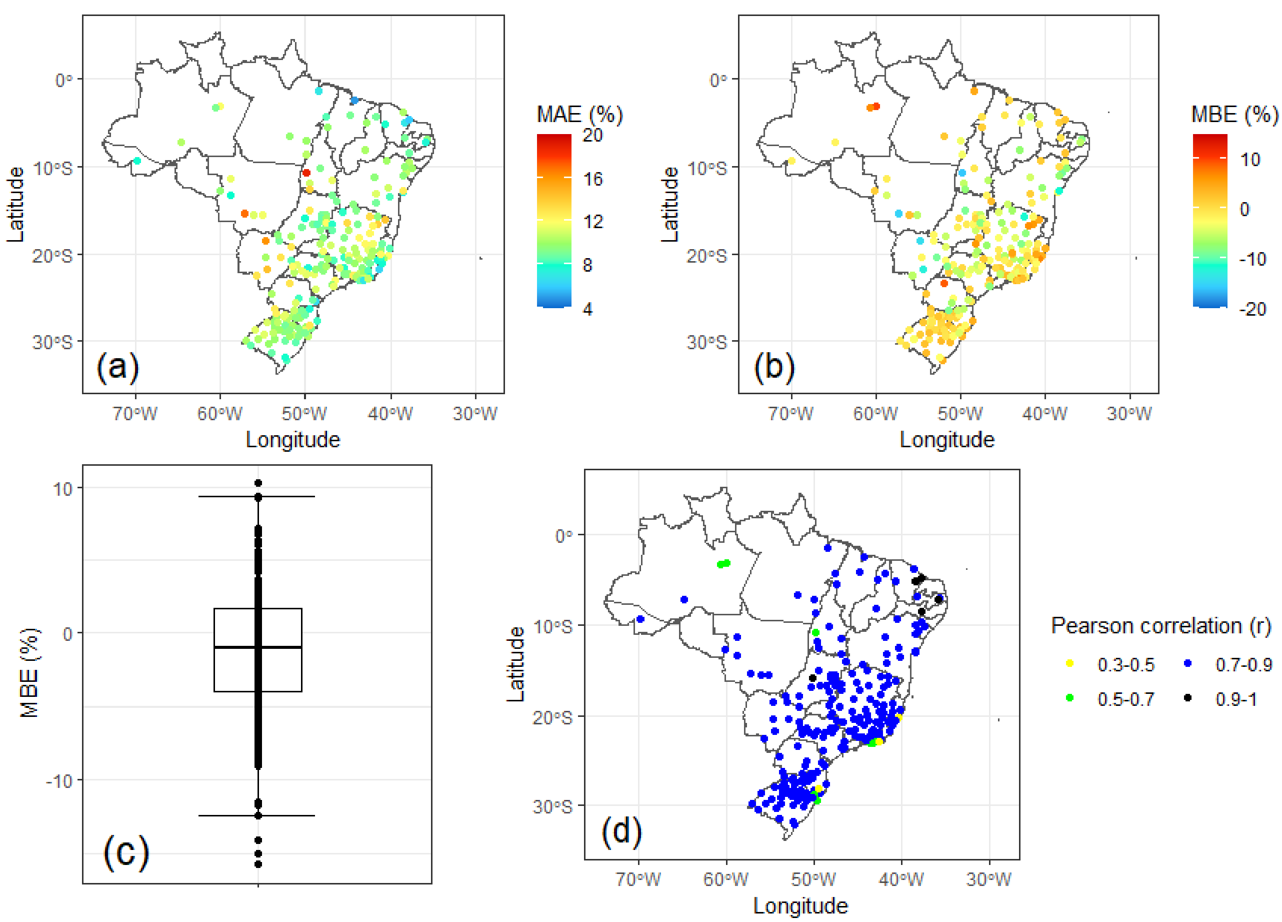

Figure 10 Values for hourly relative humidity (%): A. MAE; B-C. MBE; D. Pearson Correlation.

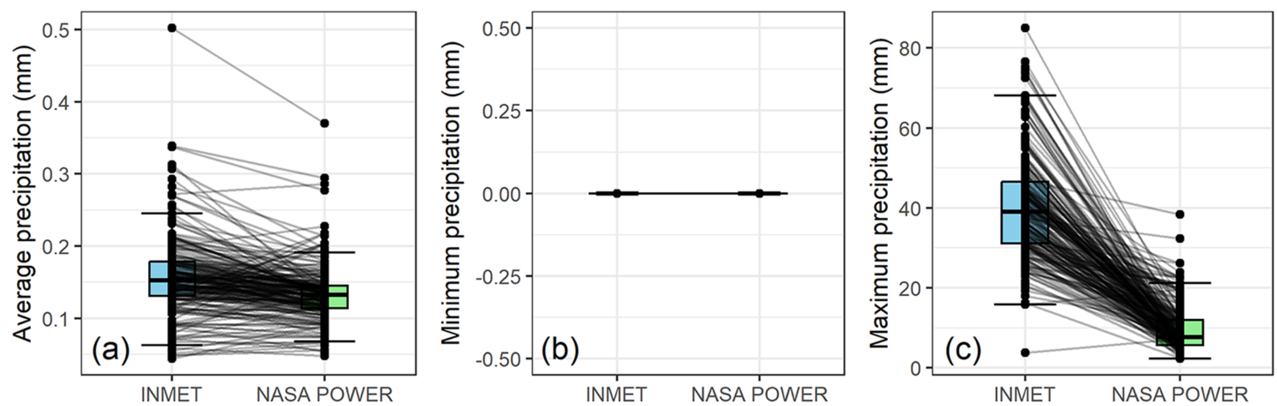

Figure 11 Boxplots of hourly precipitation data (mm) with different scales in the y-axis: A. Average; B. Minimum; C. Maximum.

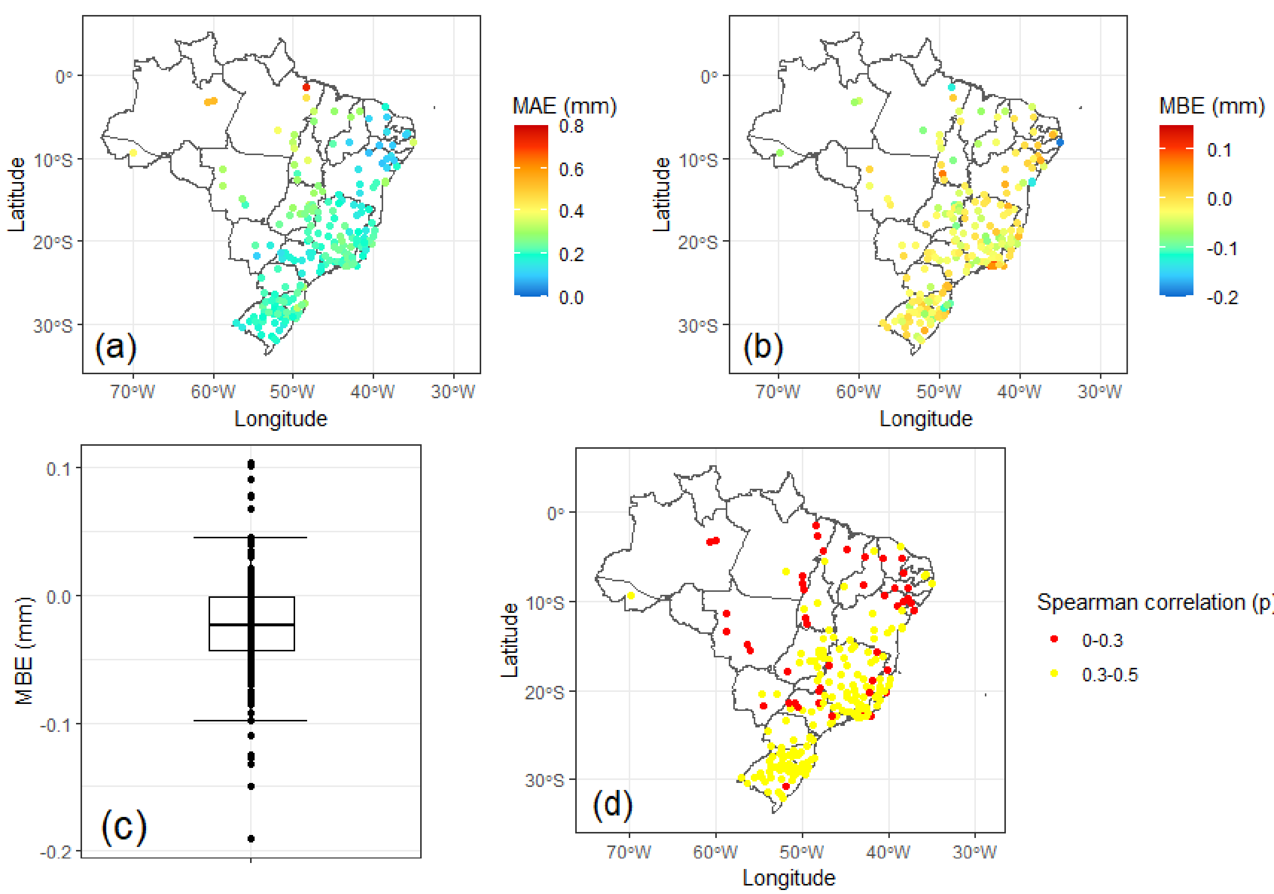

Figure 12 Values for hourly precipitation (mm): A. MAE; B-C. MBE; D. Spearman Correlation.

The Spearman correlation values indicate that most locations have weak (yellow) and negligible (red) correlations, which demonstrates that there is no good correspondence between the two bases when considering hourly data. Hamal et al. (2020) highlight those uncertainties in MERRA-2 precipitation products still deserve attention by developers and users of data and terrain has a significant impact on precipitation distribution.

The EICM does not include the effects of precipitation in its temperature modeling (Schwartz et al. 2015). However, precipitation can impact the asphalt layer or the other layers of the pavement, changing its water content (Gubler et al. 2005), consequently influencing the behavior and performance of flexible pavements (Brondani et al. 2022). Taking it into account, it is understood that it is necessary to expand the analyses to precipitation daily, monthly and annual data, allowing a better evaluation of the NASA POWER base for use in paving projects in the Brazil.

Regarding incident solar radiation (see Figure 13), good correspondence can be seen between the databases. Results indicate that NASA POWER generally overestimates radiation values for most locations. Another important point is that NASA POWER is not able to capture very well the maximum values of radiation that occur in the year (see Figure 13C). This statement can be confirmed by analyzing the boxplots, in which the relationship between the two databases is demonstrated. To better understand the differences between the databases, Figure 14 displays the values of the statistical indices evaluated: MAE (14A), MBE (14B and 14C), and Pearson's Correlation (14D).

According to Figures 14B and 14C, it can be comprehended that the incident solar radiation estimated by NASA POWER is slightly overestimated for most locations (75% of locations with MBE greater than 0 kJ/m²). With the exception of a few locations (red and dark blue points on the map in Figure 14B), most of the data presents a mean bias error between -100 kJ/m² and +100 kJ/m². The mean absolute error (MAE) values vary between 100 and 600 kJ/m², as shown in Figure 14A. With the exception of two locations (green dots on the correlation map), either strong or very strong positive linear relationships were found, indicating good correspondence between the two data sources. Monteiro et al. (2017), when considering daily time scales, concluded that the NASA POWER reanalysis satisfactorily reproduces solar radiation data for most of the Brazilian territory, with satisfactory performance for the statistical indices evaluated. As a result, it can be concluded that the agreement between reanalysis and INMET meteorological statistics is consistently similar for the incident solar radiation. Hence, the use of solar radiation data from the NASA POWER reanalysis for paving projects is feasible, highlighting that exposure of asphalt surfacing to intense solar radiation leads to weathering, oxidation, and hardening, causing raveling and block cracking distresses (Titus-Glover 2021).

Most of these discrepancies between the two databases can be explained by the fact that the NASA POWER reanalysis considers the average values of a grid, whereas the INMET stations present punctual data. This situation leads to the comparison of different locations; for example, the INMET A806 stations, located at sea level and in a coastal area; and the A870, located in a mountainous region and at an altitude of 881 meters, which are compared with the same NASA POWER / MERRA-2 database in the grid area (cell 66451) (see Table 1). This evidences a limitation of the direct comparison of the data, not taking into account the differences in elevation and local microclimates, requiring future studies to deepen these analyses. For temperature, for instance, according to Fritzsons et al. (2016), the relationship between altitude

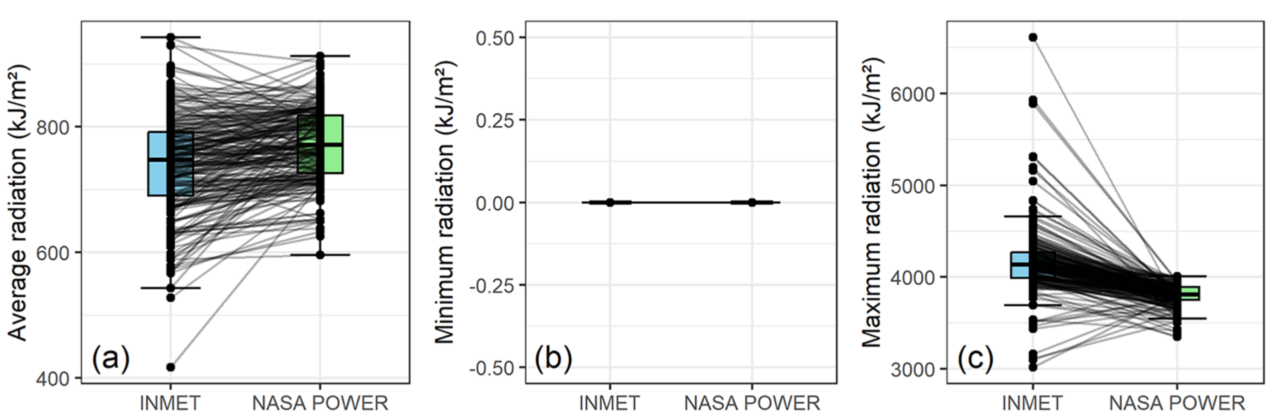

Figure 13 Boxplots of hourly incident solar radiation data (kJ/m²) with different scales in the y-axis: A. Average; B. Minimum; C. Maximum.

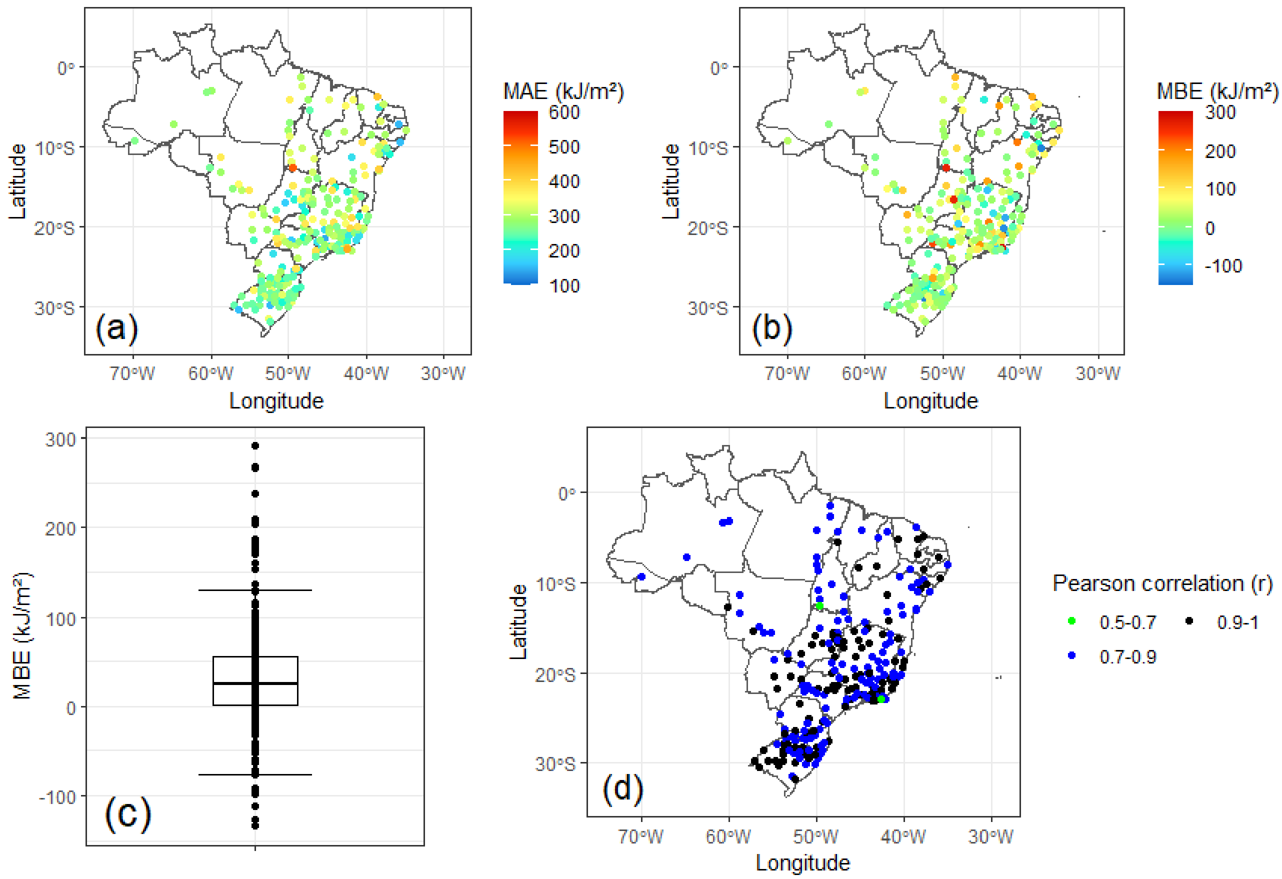

Figure 14 Values for hourly incident solar radiation (kJ/m²): A. MAE; B-C. MBE; D. Pearson Correlation.

Table 1 Example of two INMET stations located within a NASA POWER / MERRA-2 cell.

Data source	Identification	Centroid location		City	Altitude (m)
		Latitude(º)	Longitude (º)		
NASA POWER / MERRA-2	ID 66451	-27.5000	-48.7500	Antônio Carlos/SC	200
INMET	A806	-27.6025	-48.6199	Florianópolis/SC	4.87
INMET	A870	-27.6786	-49.0419	Rancho Queimado/SC	881

and temperature is especially important for tropical and subtropical regions, and, in general, in nearby regions, it is expected that a reduction in air temperature as altitude increases, making it necessary to study temperature adjustment mechanisms as a function of these variations.

The data demonstrate that the grid mean may not be sufficient to represent all locations in mountainous regions and/or with isolated microclimates. However, in general, in these regions, there will also be no INMET station that can realistically represent these microclimatic meteorological histories. In the current version of NASA POWER, it will have a grid point centroid no more than approximately 44 km from any project site for meteorological data and 78 km for solar parameters, which is generally sufficient for the large part of the Brazilian territory that presents flat relief. As for the INMET stations, in most of the country, the ground weather stations will be at great distances from the project, in some cases representing hundreds of kilometers. This situation demonstrates the potential of reanalysis data for use in paving projects in Brazil.

4 Conclusions

This study presented an evaluation of the climate data of air temperature, wind speed, humidity, precipitation, and incident solar radiation from NASA POWER reanalysis, considering hourly temporal resolution for Brazil and the data measured by INMET surface weather stations. A key aspect of the reanalysis data is its full availability in terms of temporal and spatial coverage, so that its evaluation with observed data is fundamental for the identification of uncertainties in its use in studies that comprise simulations in the paving area. Based on the evaluation of 476 locations in Brazil, it can be concluded that:

The hourly air temperature data from the NASA POWER reanalysis indicate good agreement with the data measured by INMET, inferring that its use in paving projects in Brazil is feasible. Temperature adjustment is recommended for the design locations on reanalysis grids with complex terrain;

The hourly wind speed data from the NASA POWER reanalysis do not show good agreement with the data measured by INMET, making it necessary to assess the impact of these differences on pavement temperature and, consequently, on the prediction of pavement performance in Brazil;

The hourly relative humidity data from the NASA POWER reanalysis show good agreement with the data measured by INMET, understanding that its use in paving projects in Brazil is feasible;

The hourly precipitation data from the NASA POWER reanalysis do not demonstrate good agreement with the data measured by INMET. It should be noted that, as the EICM does not consider precipitation, these discrepancies would not be a problem in the calculation of pavement temperature. However, in order to analyze the impact of precipitation on drainage and moisture damage, it is necessary to assess the impact of these differences on the performance of pavements in the country;

The hourly incident solar radiation data from the NASA POWER reanalysis show good agreement with the data measured by INMET, understanding that its use in paving projects in Brazil is feasible.

The objective was reached in the present paper, better knowing the differences and potentialities/deficiencies of climate data from NASA POWER reanalysis and the data measured at surface weather stations, which will subsidize future analyses on the viability of using the reanalysis in projects related to paving in Brazil. Obviously, in locations that have sufficient data and near to surface weather stations, these data have less bias because they are measured. However, due to the smaller spatial coverage and missing data from INMET, it is concluded that the climate data from the NASA POWER reanalysis have great potential for use in future paving projects in the country, especially in regions of Brazil with few INMET stations (e.g., the North region). Both the uniform spatial distribution and the availability of historical series reinforce its benefits in relation to data from INMET stations. Nonetheless, it is important to validate its use through performance simulations, especially due to discrepancies for hourly wind speed data.

Given this, the best alternative is to use data measured at surface meteorological stations (e.g., INMET) when all data is available and near to the project site. In cases when measured data is not available or is very far from the project, the use of NASA POWER data is a viable alternative for the variable’s relative humidity, solar radiation and air temperature, recommending adjustments in the air temperature values according to differences in altitude. However, for wind speed and precipitation variables, it is better to use the values measured at INMET stations or look to evaluate other data sources, such as other reanalyses or data measured at ground stations from other institutes/companies.

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Cléber Faccin: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Luciano Pivoto Specht:** validation; writing – review and editing; supervision. **Pedro Orlando Borges de Almeida Junior:** writing – original draft. **Silvio Lisboa Schuster:** writing – original draft. **Lorenzo Chaves Pacheco:** writing – review and editing.

Conflict of interest

The authors declare no conflict of interest.

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