Quality of grid-based meteorological data in Brazil: a study in climatically contrasting regions

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Abstract

Meteorological information is fundamental in agriculture, tourism, and civil defense, used for monitoring, weather forecasting, and climate analysis. In Brazil, the National Institute of Meteorology (INMET) is responsible for collecting and disseminating this data, which often has gaps. To mitigate these deficiencies, databases have been developed to fill these gaps. In this context, the present was developed in order to compare observed meteorological data from four Brazilian municipalities with distinct climates to the estimates provided by the XAVIER gridded database. A 30-year historical series (1979 to 2018) was used for covering the following variables: maximum and minimum air temperature, relative humidity, wind speed, precipitation, and global solar radiation. Several statistical indicators were employed for the comparative analysis. It was observed that temperature estimates had high accuracy, with performance indices considered excellent. Global solar radiation also had promising results. However, wind speed revealed variability, presenting challenges for estimation. For relative humidity and precipitation, mixed performance was found across the municipalities but were generally considered satisfactory. This study highlights the potential of the XAVIER database as a resource to complement existing gaps in meteorological data.

Keywords: Database. Meteorological gaps. XAVIER.

Introduction

Meteorological information is essential in various sectors, such as agriculture, maritime, aviation, fishing, and tourism, serving multiple purposes. Additionally, these data are crucial for collecting meteorological and climatological statistical information. Climatological data is also important for the study of past climates, as evidenced in the Climatological Normals, which are obtained by calculating the averages of meteorological parameters according to criteria established by the World Meteorological Organization (WMO) (INMET, 2024).

In Brazil, most meteorological stations are managed by the National Institute of Meteorology (INMET), which provides data on maximum, minimum, and average air temperatures, solar radiation or sunshine hours, precipitation, relative humidity, and wind speed (DUARTE, SENTELHAS, 2019). In addition to monitoring, collecting, storing, and disseminating meteorological information, INMET is responsible for weather forecasting and issuing weather bulletins, particularly for agriculture and civil defense (ARAUJO et al., 2024).

One of the main challenges in analyzing data from meteorological stations is the incompleteness of the information. This gap can occur due to equipment failures, especially in automatic stations, or the absence of observers at conventional stations. Since these data are used for various research purposes, developing methods to fill these gaps becomes a relevant issue (BIER, FERRAZ, 2017). This drives scientists to explore alternatives for creating long-term, reliable meteorological databases to complement existing climate data and establish virtual meteorological stations, thus increasing climatic information in various country regions (MONTEIRO et al., 2017).

One approach used for this purpose is interpolation, a technique several authors employ. Notably, Xavier et al. (2016) developed a daily gridded dataset for meteorological variables across Brazil, covering the historical series from 1980 to 2013, which was later extended to 1961-2020 (XAVIER et al., 2022). This database has been applied in various studies to fill temporal gaps to create long historical series for various applications, such as: local climate trend analysis and projections (SANTOS et al., 2024); evaluating the potential and limitations of crops according to available water using the crop water requirement satisfaction index (JOSÉ et al., 2025); frequency and distribution of reference evapotranspiration in watersheds (JOSE et al., 2021); calibrating and evaluating models for estimating solar radiation (SANTOS et al., 2022); and calibration and evaluation of models for estimating reference evapotranspiration (FIGUEIRÓ et al., 2025).

Given the vast climatic diversity of Brazil, resulting from its large territorial extension, the present study was developed in order to compare observed meteorological data from stations located in four municipalities from different Brazilian regions with data obtained from a gridded database developed by Xavier. The goal was to assess the suitability of this database to fill the gaps in the INMET data for the studied cities.

Material and methods

This study was conducted using data from four Brazilian municipalities located in regions with distinct climatic characteristics: Manaus, in the Amazon region; Pirenópolis, in the savanna region; Salvador, in the coastal region; and Uruguaiana, in the far south of Brazil, as specified in Table 1. The meteorological data analyzed cover the period from 1979 to 2018 and were extracted from the Meteorological Database for Teaching and Research, made available by the National Institute of Meteorology (INMET).

The variables included in this study were: maximum air temperature (Tx, °C), minimum air temperature (Tn, °C), relative humidity (RH, %), wind speed (WS, m s^{-1}), precipitation (PP, mm), and sunshine duration (n, hours). The sunshine data were specifically used to estimate global solar radiation (Rs, MJ m^{-2} day^{-1}) using the Angstrom-Prescott model (ANGSTROM, 1924; PRESCOTT, 1940).

The estimation of meteorological data was carried out according to the methodology proposed by Xavier et al. (2022), which covers the entire Brazilian territory and is based on various interpolation strategies. This approach results in a grid with a resolution of 0.1° latitude by 0.1° longitude. This is particularly relevant due to Brazil's climatic heterogeneity, with significant variations in atmospheric conditions across different regions. Furthermore, the generated grid allows not only temporal analysis of meteorological variables but also spatial evaluation, contributing to a deeper understanding of climate patterns at both regional and national scales.

For the comparative statistical analysis between the observed data (INMET) and the estimated data (XAVIER), several indicators were employed. The methodology included graphical visualization, regression analysis, and calculation

Table 1. Location of the municipalities and the respective geographic coordinates of the corresponding meteorological station.

Municipalities	Stade	Latitude	Longitude	Altitude
Manaus	AM	03.10°S	60.02°W	61.25 m
Pirenópolis	GO	15.86°S	48.97°W	766.92 m
Salvador	BA	13.01°S	38.51°W	47.35 m
Uruguaiana	RS	29.84°S	57.08°W	74.41 m

Source: authors (2025)

of the linear (a) and angular (b) coefficients, as well as the coefficient of determination (R^2) and the correlation coefficient (r). Additionally, the mean absolute error (MAE), root mean square error (RMSE), index of agreement (d) (WILLMOTT et al., 1985), and performance index (c) (CAMARGO, SENTELHAS, 1997) were evaluated.

Results and discussion

When analyzing the climatological normal for the municipalities of Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS from 1979 to 2018, significant diversity in the local climates was observed, as shown in Figure 1. The precipitation pattern varies across the cities: in Manaus and Pirenópolis, the highest rainfall occurs from November to April, with a large discrepancy compared to the other months. Although Uruguaiana has a similar trend of concentrated precipitation, it is more evenly distributed throughout the year. On the other hand, Salvador stands out from the other municipalities, with the highest rainfall recorded in April, May, June, and July. The total annual precipitation is 3075.8 mm in Manaus, 2281.1 mm in Pirenópolis, 2503.8 mm in Salvador, and 1902.5 mm in Uruguaiana.

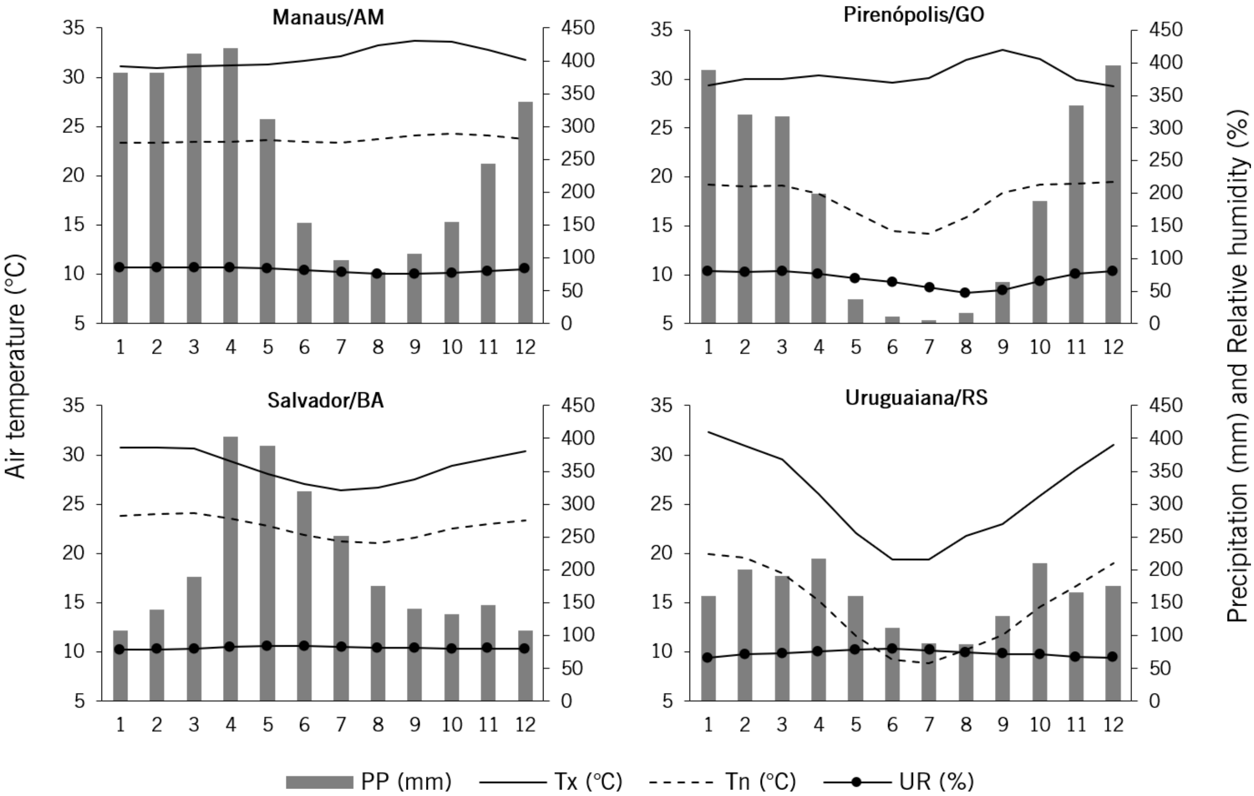
Regarding air temperature, both maximum temperature (Tx) and minimum temperature (Tn) exhibited greater variability throughout the year in Uruguaiana. The highest temperature is recorded in January (32.3°C), while the lowest occurs in July (8.9°C), with an annual average temperature of 20.2°C. In Manaus, the lowest temperature is also observed in July, at 23.3°C. The Tx remains equal to or above 31.0°C throughout the year, and the annual average temperature is 27.9°C. In Pirenópolis, the thermal amplitude increases from May to October, peaking in August (16.1°C), with an annual average of 24.1°C. In contrast, Salvador has a nearly constant thermal amplitude throughout the year, varying between 5.1°C and 7.0°C, with an annual average temperature of 25.8°C.

Regarding relative humidity, Uruguaiana has the greatest amplitude, with a maximum value in June (80.0 %) and a minimum in January (66.0 %). The highest humidity and lowest amplitudes are observed in Salvador and Manaus, consistent with the high-water availability in these regions, with minimum values of 78.8 % and 75.8 %, respectively, and annual amplitudes of 5.4 % and 10.5 %. Pirenópolis records the lowest annual average relative humidity, at 68.8 %.

Statistical results of the observed values from the INMET meteorological stations and the estimated data from the XAVIER database on a daily scale are presented in Table 2, covering the municipalities of Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS, for the period from 1979 to 2018. When considering the coefficient of determination (R^2), the best fits were observed in the following descending order: maximum and minimum air temperature, global solar radiation, relative humidity, precipitation, and wind speed.

When analyzing the maximum (Tx) and minimum (Tn) air temperatures, it was found that the XAVIER database had high accuracy and precision in estimating these variables. The correlation coefficients (r) were equal to or greater than 0.97, while the agreement index (d) reached values equal to or greater than 0.98, reaching 1.00 in some municipalities (Table 2). Additionally, the coefficient of determination (R^2) showed high values ($\geq$ 0.94), highlighting a good fit between the observed and estimated data. The performance index (c) remained above 0.94, classified as “great” in all municipalities analyzed. Excellent regression fit was illustrated in Figure 2, with values aligning with the 1:1 line, indicating ideal results for the coefficients of determination and angular coefficients (1.00) in some municipalities.

Figure 1. Climatic patterns of Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS from 1979 to 2018.



Source: authors (2025)

Similar results were identified by Araujo et al. (2024) in a study conducted in the mesoregions of the Vale do Jequitinhonha and Northern Minas Gerais, where performance was classified as "great" for all municipalities, with values of 0.98 for Tx and Tn. Rasera et al. (2023) also reported that the XAVIER database demonstrated good performance in daily estimates for municipalities in São Paulo, Minas Gerais, Bahia, and Sergipe, with performance indices (c) of 0.98 and 0.70 for Tx and Tn, respectively, in addition to high values of r ($\geq$ 0.80) and d ($\geq$ 0.87).

Regarding relative humidity (RH), variable performance across the municipalities was observed, with performance index (c) values of 0.93, 0.87, 0.80, and 0.67 for Pirenópolis, Uruguaiana, Manaus, and Salvador, respectively (Figure 2). The two lowest values were recorded in municipalities with higher levels of water vapor in the atmosphere, suggesting that this factor may limit the estimation of UR. The correlation coefficients were 0.79 (Manaus) and 0.60 (Salvador), but both had the lowest mean absolute error (MAE) and root mean square error (RMSE) values, less than 3.63 % (MAE) and 4.46 % (RMSE). The performance found for UR was similar to that of municipalities in Minas Gerais, where performance index (c) values ranged from 0.74 to 0.93, and the index of agreement (d) ranged from 0.85 to 0.92, with coefficients of determination varying from 69 % to 92 % (ARAUJO et al., 2024). Duarte and Sentelhas (2019) reporteded values of 0.96, 0.98, and 0.94 for the correlation coefficient, index of agreement, and performance index, respectively.

Regarding global solar radiation (Rs), the database reached good performance in the estimation (Figure 3). Mean absolute error (MAE) and root mean square error (RMSE) were low, equal to or less than 2.21 and 2.66 MJ m^{-2} day^{-1},

Table 2. Statistical parameters for observed (INMET) and estimated (XAVIER) values daily for Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS from 1979 to 2018.

Mun	Var	a	b	R^2	r	MAE	RMSE	d	c	ICS	MEs	MOb	OM
Manaus	Tx	0.84	0.97	0.98	0.99	0.16	0.28	1.00	0.99	GT	32.07	32.06	2.05
	Tn	2.20	0.91	0.94	0.97	0.21	0.35	0.98	0.95	GT	23.76	23.69	1.52
	RH	33.84	0.60	0.79	0.89	3.62	4.65	0.90	0.80	VG	82.70	81.46	14.68
	Rs	0.67	0.85	0.94	0.97	2.09	2.42	0.94	0.91	GT	16.13	18.15	2.16
	WS	0.21	0.55	0.72	0.85	0.37	0.51	0.84	0.71	GO	0.80	1.06	3.98
	PP	2.83	0.56	0.68	0.82	4.14	7.96	0.87	0.72	GO	6.36	6.32	1.42
Pirenópolis	Tx	-0.20	1.00	1.00	1.00	0.31	0.34	1.00	0.99	GT	30.26	30.56	7.22
	Tn	-0.21	1.00	1.00	1.00	0.29	0.30	1.00	1.00	GT	17.48	17.77	1.58
	RH	1.90	0.93	0.92	0.96	4.04	5.11	0.97	0.93	GT	65.99	68.66	1.27
	Rs	1.49	0.85	0.90	0.95	1.65	1.98	0.95	0.90	GT	17.95	19.31	1.35
	WS	0.41	0.43	0.70	0.84	0.77	0.97	0.70	0.58	NG	1.26	1.99	2.96
	PP	1.56	0.62	0.73	0.85	2.58	5.91	0.90	0.76	VG	4.46	4.66	1.31
Salvador	Tx	0.29	0.99	0.98	0.99	0.18	0.34	0.99	0.98	GT	28.96	28.85	2.42
	Tn	1.81	0.92	0.96	0.98	0.23	0.32	0.99	0.97	GT	22.73	22.75	2.45
	RH	18.15	0.76	0.60	0.77	3.48	4.31	0.86	0.67	GO	79.87	81.30	2.53
	Rs	1.39	0.83	0.92	0.96	2.21	2.66	0.94	0.90	GT	18.07	20.08	2.06
	WS	0.75	0.44	0.60	0.77	0.43	0.58	0.79	0.61	ME	1.46	1.62	16.75
	PP	1.68	0.61	0.70	0.84	2.86	7.09	0.89	0.75	GO	4.84	5.16	0.44
Uruguaiana	Tx	0.27	0.99	1.00	1.00	0.15	0.45	1.00	1.00	GT	25.82	25.73	19.19
	Tn	0.23	0.99	0.99	1.00	0.19	0.43	1.00	1.00	GT	14.42	14.30	18.73
	RH	15.92	0.78	0.84	0.91	4.17	5.33	0.95	0.87	GT	72.89	72.71	17.42
	Rs	0.89	0.93	0.94	0.97	1.44	1.99	0.98	0.95	GT	16.70	17.06	20.62
	WS	0.62	0.54	0.68	0.83	0.65	0.90	0.84	0.69	GO	1.79	2.17	27.39
	PP	1.06	0.68	0.76	0.87	2.18	6.27	0.92	0.80	VG	3.78	4.02	19.43

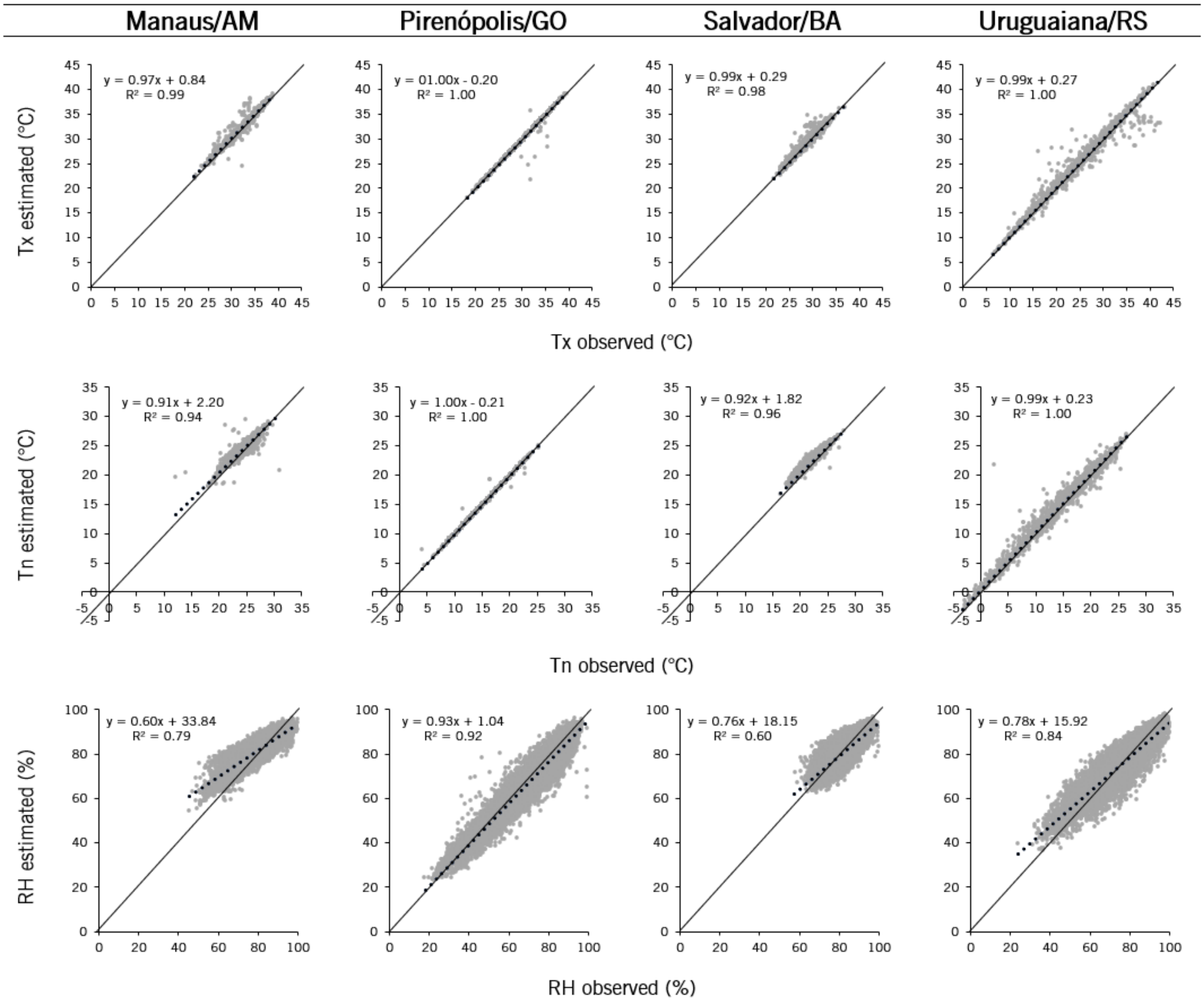
Mun – Municipalities, Var – Meteorological variable, a – Linear coefficient, b – Angular coefficient, R^2 – Coefficient of determination, r – Correlation coefficient, MAE – Mean absolute error, RMSE – Root mean square error, d – Index of agreement, c – Performance index, ICS – Interpretation of the performance index as proposed by Camargo and Sentelhas (1997), MEs – Estimated daily mean, MOb – Observed daily mean, OM – Omissions (%), Tx – Maximum air temperature (°C), Tn – Minimum air temperature (°C), RH – Relative humidity (%), WS – Wind speed (m s^{-1}), PP – Precipitation (mm), Rs – Global solar radiation (MJ m^{-2} day^{-1}), GT – Great, VG – Very good, GO – Good, ME – Medium, NG – Not Good.

Source: authors (2025)

respectively. Performance was classified as "great" (c ≥ 0.90) in all four municipalities, with high indices of agreement (≥ 0.94) and correlation coefficients (≥ 0.95). The best fit was found in Uruguaiana, where the highest R^2, r, d, and c values were observed. When evaluating the estimated and observed daily means, an underestimation of 0.36 MJ m^{-2} day^{-1} was found for this municipality (Figure 3). Moreira Júnior et al. (2020) also confirmed the good performance of the database in estimating Rs for Mato Grosso do Sul, with statistical parameters of 0.96, 0.96, and 0.92 for correlation coefficient, index of agreement, and performance index, respectively.

Wind speed (WS) was the variable with the poorest fits in this study. Despite showing good values for correlation coefficients (≥ 0.77) and

Figure 2. Maximum temperature (Tx, °C), minimum temperature (Tn, °C), and relative humidity (RH, %) observed (INMET) and estimated (XAVIER) on a daily scale for Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS during the period from 1979 to 2018.

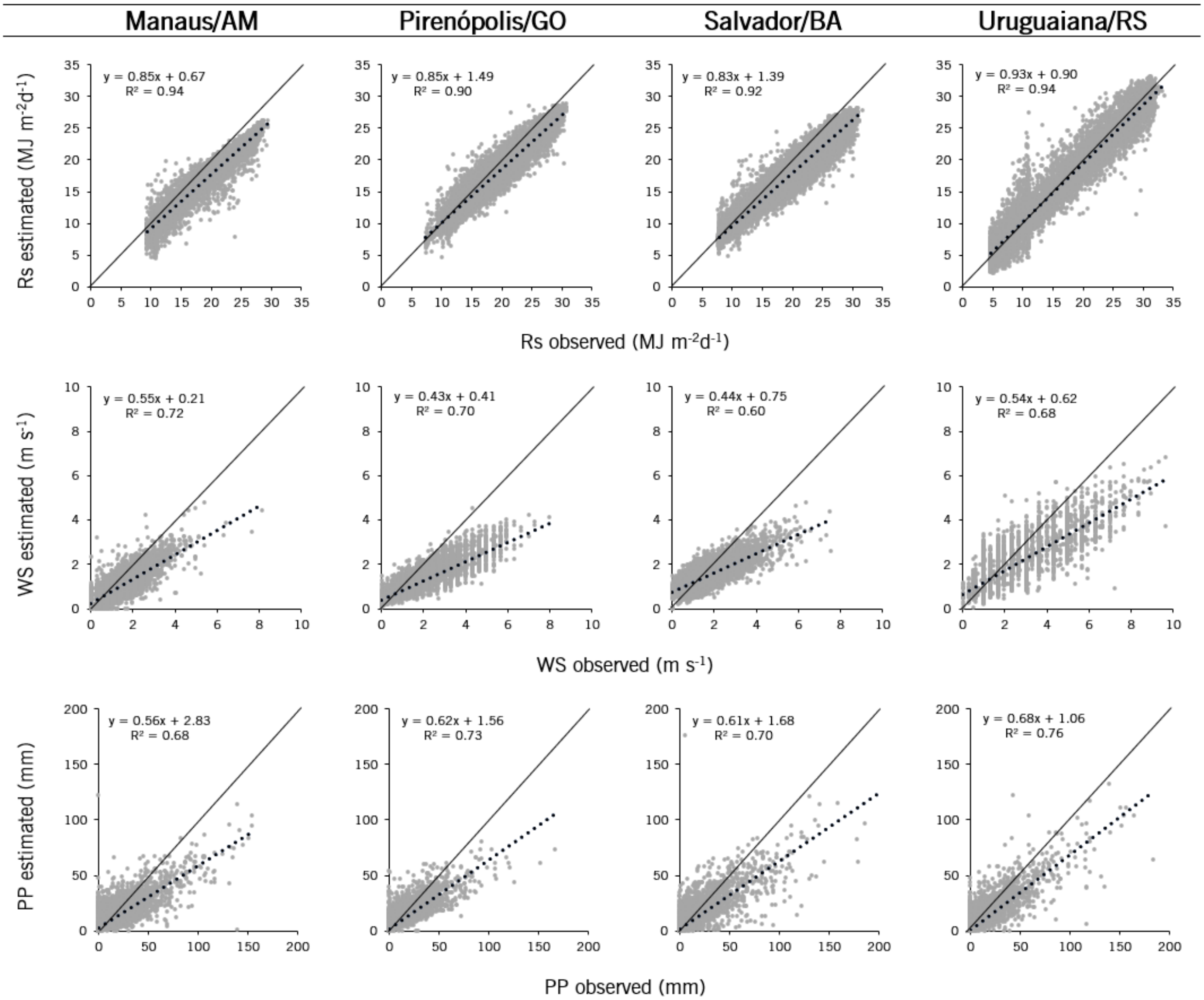


Source: authors (2025)

indices of agreement (≥ 0.70), the performance indices were classified as "good" for Manaus (c = 0.71) and Uruguaiana (c = 0.69), "medium" for Salvador (c = 0.61), and "not good" for Pirenópolis (c = 0.58). According to Araujo et al. (2024), accuracy, measured by the index of agreement, ranged from 0.70 to 0.79, indicating acceptable performance. On the other hand, the performance index ranged from 0.50 to 0.65, being classified as "bad," "not good," and "medium." The authors argue that, although these results are not ideal, they are understandable due to the high variability of wind, which is influenced by several external factors, making its prediction a significant challenge in meteorology. Duarte and Sentelhas (2019) reported values of 0.75 for the correlation coefficient, 0.82 for the index of agreement, and 0.61 for the performance index.

Precipitation (PP), which also presents high spatial variability, has considerable performance in this study (Figure 3). In the analyzed municipalities, the performance was classified as "very good" in Pirenópolis and Uruguaiana (c = 0.76 and 0.80, respectively) and "good" in Manaus and Salvador (c = 0.72 and 0.75, respectively). Additionally,

Figure 3. Global solar radiation (Rs, MJ m^{-2} day^{-1}), wind speed (WS, m s^{-1}), and precipitation (PP, mm) observed (INMET) and estimated (XAVIER) on a daily scale for Manaus/AM, Pirenópolis/GO, Salvador/BA, and Uruguaiana/RS from 1979 to 2018.



Source: authors (2025)

the indices of agreement and correlation coefficients were high, equal to or greater than 0.87 and 0.82, respectively. Veber et al. (2019) concluded that the interpolated data correlated well with the observed information, allowing its complementary use in hydrological studies in Pelotas/RS. Rasera et al. (2023) also classified the XAVIER database estimation as “very good,” with a performance index 0.76. Other statistical indicators were also satisfactory, with d = 0.90, r = 0.84, and R^2 = 0.70.

Finally, when observing PP and WS, despite their high spatial variability, the XAVIER grid database underestimates the observed values, showing the lowest values for the angular coefficient (b), below 0.69, with a minimum of 0.43. Additionally, in some municipalities, high data omission rates were identified.

Conclusions

The analysis of the meteorological data estimated by the XAVIER database showed satisfactory overall performance across several variables, especially regarding the maximum and minimum air temperatures, which demonstrated high accuracy and agreement with the observed data. Global solar radiation also showed promising results. Relative humidity displayed good performance but with limited adjustment in regions with high humidity, specifically in Salvador, where the performance was lower. Wind speed exhibited significant variability across municipalities, indicating challenges in estimating this variable. Finally, precipitation showed variable but satisfactory performance, considering its inherent variability.

Although there are limitations in some variables, the database's ability to provide complementary estimates is undeniable. This study underscores the importance of continuing research on the spatial variability of meteorological conditions, aiming to improve estimation tools and enhance understanding of regional climatic phenomena.

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