Climate Profiles in Brazilian Microregions

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Abstract: Brazil’s territory is considerably large and characterized by a variety of climate patterns, which allows the identification of regional climate specificities. The objective of this study was to identify a typology of climatic characteristics for the microregions of Brazil using the grade of membership (GoM) method, which is a multivariate technique based on the fuzzy sets theory. The meteorological variables used were: precipitation (mm), relative humidity (%), maximum and minimum temperature (°C) and wind speed (m/s), obtained from the interpolated database elaborated by Xavier comprising the period from January 1981 to December 2013. Three predominant homoclimatic profiles were found. The GoM method also allowed the identification of five mixed profiles, which is unprecedent in studies in Brazil and corroborates the regional climate diversity in the country. Furthermore, the heterogeneities of Brazilian climates could be better outlined. The extreme profiles—“predominant 1—P1”, “predominant 2—P2” and “predominant 3—P3”—accounted for 42.9% (236) of the total microregions. Additionally, approximately half (53.9%) of the microregions were classified as featuring characteristics of at least two profiles—that is, they presented mixed profiles with hybrid characteristics. These hybrid microregions were located mostly at transition zones between climates.

Keywords: Grade of Membership; homogeneous regions; precipitation; relative air humidity; maximum and minimum temperatures; wind speed

1. Introduction

The Brazilian territory occupies an area of 8,514,876 km², and therefore, a wide variety of meteorological systems and climatic forces act throughout its extension. [1] updated the Köppen’s climate classification [2] of Brazil based on precipitation and temperature data comprising the years 1950 and 1990. This study pointed out that, in Brazil, there is a predominance of three climate zones and 12 types of climates. However, other techniques of climate regionalization using multivariate methods can also be analyzed, such as hierarchical methods such as cluster analysis. The motivation of the present study is to present another possibility of analysis of the climatic variability in Brazil using the Grade of Membership (GoM) technique, which is widely used in social and health sciences [3–6] but has not yet been used for climatological studies in Brazil.

The climate in the North of Brazil is modulated by the influence of the Amazon rainforest and has the highest accumulated annual rainfall in the country. Some areas can exceed 5000 mm/year in anomalously wet years [7]. On the other hand, in the Northeast of Brazil (NEB), the annual precipitation...
varies from 300 mm in the semiarid region to 1200 mm in the coast [8]. The Midwest region has different precipitation and temperature regimes, with a strong performance of mesoscale convective systems (MCS) and their associations with the South Atlantic convergence zone (SACZ), which modulate the maximum precipitation during the summer months [9]. In the Southeast, different atmospheric systems contribute to rainfall distribution throughout the year, such as the propagation of cold fronts, coastal cyclones, tropical and prefrontal squall lines and breeze circulation [10]. In the South region, the climate presents remarkable contrasts in the precipitation and temperature regimes due to its geographical location between the tropics and the middle latitudes [11].

Considering this wide climatic diversity in Brazil, objective analyses are important to characterize specific regions at different spatial scales—for example, the microregions. This information could be used, for example, to develop public policies associated with the management of water resources, energy efficiency and distribution, the proliferation of climate-dependent diseases, tourism and agriculture, among others. Issues related to climate variability have become one of the great scientific challenges of our century [12] and have been the subject of study in several areas of knowledge [13,14].

Studies that aimed to investigate climate variability in Brazil have been carried out based on objective analyses of large amounts of data, usually through multivariate techniques such as cluster analysis. In the Northeast region of the country, the studies by Oliveira et al. (2017), Rodrigues et al. (2019) and Teixeira de Aguiar e junior (2020) [8,15,16] delimited several homogeneous climate subregions. In the Amazon, Santos et al. (2015) [7] identified six homogeneous rainfall subregions, while Teixeira and Satyamurti [11] analyzed the annual frequency of heavy and extreme rainfall events in the Southeast and South regions of Brazil.

Despite the wide use of a cluster analysis, grouping methods based on the fuzzy sets theories (such as the Grade of Membership—GoM) present some advantages, such as the separation of individuals based on the degree of belonging to a certain cluster, allowing a microregion to partially pertain to different groups, which is not possible in cluster analysis [3]. Regarding climate studies in Brazil, the existence of transition areas (e.g., Amazon rainforest—savannas and savannas—semiarid drylands of the Northeast region) indicate that a hierarchical cluster analysis might not be sufficient to characterize such diverse climate patterns in a large continental area such as Brazil. Thus, the use of methods based on the fuzzy sets theories such as the GoM are potentially more adequate to such an endeavor, despite the lack of studies using this method for climate and meteorological purposes in Brazil.

Thus, the main objective of the study is to elaborate a homoclimatic typology for the microregions of Brazil, taking into account the following meteorological variables: Precipitation (mm), relative humidity (%), maximum temperature (°C), minimum temperature (°C) and wind speed (m/s) during the period from January 1980 to December 2013, based on the GoM method.

2. Materials and Methods

2.1. Data

The meteorological variables used in this research were: Precipitation (mm), relative humidity (%), maximum temperature (°C) minimum temperature (°C) and wind speed (m/s). These variables were extracted from the database developed by Xavier et al. (2016) [17]. It is a dataset available in the form of a horizontal grid with 0.25° × 0.25° spacing and daily sampling, covering the period from 1 January 1980 to 31 December 2013. For the application of these variables in the GoM method, monthly climatological averages for each variable were calculated, except for the monthly accumulated rainfall. The time series were extracted from the midpoint of each microregion in Brazil, shown in Figure 1. The microregion is delimited by a set of grid points; it was decided to identify it by the average of these grid points, thus defining the midpoint of each microregion and using that point as a reference. As the datasets consist of interpolated data in a regular grid, there might be no information on the border regions of the Brazilian territory. Thus, information regarding the microregions that comprised
the capital cities located on this border (Aracajú-SE, Belém-PA, Curitiba-PR, Fortaleza-CE, Natal-RN, Maceió-AL, Vitória-ES and Recife-PE) were complemented with data collected on the monitoring network of the National Meteorological Institute (INMET).

Figure 1. Study area: Brazil subdivided by microregions.

The series of meteorological data in Brazil presented several gaps, as reported in the scientific literature [18]. In the INMET data series used to complement the data by Xavier et al. (2016) [17], 14% of the missing data were identified, which were imputed through the bootstrap method, following the methodology adopted by Rodrigues et al. (2019) [15] and Davison and Hinkley [19]. In this study, the GoM technique was used to define profiles of climate similarities considering the 558 microregions of Brazil and a wide set of previously selected meteorological variables. To use the GoM methodology, it is necessary to prepare the database by organizing its variables in sequential categories, because the method requires the categories to be ordinal and always start at a value of 0. Thus, to compose the model, the selected variables were categorized using the percentiles as thresholds, originating three groups: the 25% smallest (below P25), the 50% central (between P25 and P75) and the 25% largest (above P75). Thus, three intervals were obtained for each variable capable of climatologically discriminating the microregions of Brazil. This type of division is widely used in the literature [20].

Thus, the analysis was carried out throughout the Brazilian territory, considering the 558 microregions [21] as shown in Figure 1.

2.2. Grade of Membership Method

The GoM method was developed based on fuzzy sets theories proposed by Zadeh (1965) [22]. Initially, it is considered that the units of analysis of the study (the Brazilian microregions) are not organized in well-defined sets and may partly belong to multiple sets with different attributes; therefore, the method considers that a microregion can have different degrees of belonging to multiple sets [3,4,23].
The method defines extreme profiles and computes the degree of belonging of each microregion to each profile using the maximum likelihood method and based on the individual $g_{ik}$ characteristics of each microregion [20].

Therefore, the GoM method retrieves degrees or scores of belonging ($g_{ik}$) to the $k$-th extreme profiles for each microregion [3,4,24,25]. The $g_{ik}$ scores range from 0 (null belonging, i.e., the region does not share any characteristic with the profile $k$) to 1 (total belonging, i.e., the region share all characteristics with the profile $k$). Scores between 0 and 1 indicate that the microregion is a partial individual of that extreme profile. It is worth highlighting that an extreme profile represents a group composed of all meteorological characteristics attributed to it. Thus, the degree of belonging $g_{ik}$ is estimated for each microregion and to the $k$-th profile, while the sum of all $g_{ik}$ is equal to 1 for each microregion [26,27].

Another parameter estimated by the GoM is $\lambda_{kjl}$, which is the probability that the $l$-th response category of the $j$-th meteorological variables is associated with the $k$-th extreme profile. Thus, $\lambda_{kjl}$ estimates the probability of existence of a microregion that fully belongs to a given $k$ extreme profile, while $g_{ik}$ would represent the degree of proximity of each observation to this extreme profile [28,29].

The probability of a response $l$ for the $j$-th variable in the microregion $i$, conditioned to the $g_{ik}$ scores, is given by:

$$Pr(Y_{ijl} = 1.0) = \sum_{k=1}^{K} g_{ik} \cdot \lambda_{kjl}$$

where each $g_{ik}$ is supposedly known and ranges from 0 to 1.

Based on these assumptions, the probability model for the construction of the maximum likelihood estimation procedure is formulated. The likelihood model can be written as:

$$L(y) = \prod_{i=1}^{I} \prod_{j=1}^{J} \prod_{l=1}^{L} \left( \sum_{k=1}^{K} g_{ik} \cdot \lambda_{kjl} \right)^{y_{ijl}}$$

where $I$ is the number of microregions, $J$ is the number of variables included in the dimension of the observation space, $L_j$ is the number of categories for each of the $J$ and $K$ is the number of extreme profiles.

The parameters $g_{ik}$ and $\lambda_{kjl}$ were estimated using the R software, version 3.5.2 (http://www.r-project.org) through a computational routine developed as an R-Script, called GoMRcpp.R [30]. For more details on the applicability of the GoMRcpp.R routine, see Guedes et al., 2016 [20].

Three extreme profiles were constructed from the meteorological variables mentioned above. GoM allows the profile to be characterized by the distribution of the parameters $\lambda_{kjl}$ according to each of the categories of each variable, as well as the degrees of belonging of each attribute to one of the profiles. The Ratio (E/O) establishes a criterion for the description of the profiles generated according to their predominant characteristics. In this work [29], Ratio ($\frac{E}{O}$) > 1.2 was taken as significant for the construction of the profile [20]. To define the belonging of the microregions to the extreme profiles and to identify those that partially belong to more than one profile, pertinence scores were divided into quartiles and considered “predominant of pure profile $k$” microregions with 75% or more of characteristics of a given profile—that is, $g_{ik} \geq 0.75$. The mixed profiles were considered when $0.50 \leq g_{ik} \leq 0.74$; the amorphous profile was considered when the microregion did not show belonging to any profile—that is, $g_{ik} < 0.50$.

To check if there were statistically significant differences between the profiles formed, the analysis of variance (ANOVA) was applied, which is a technique capable of comparing several averages simultaneously [31]. The existence of different groups was verified, followed by the Tukey multiple comparison test, which is used to test differences between means by evaluating them pairwise [32]. The level of significance considered for the statistical tests was 5%.
3. Results

3.1. General Characteristics of Pure Profiles

To apply the GoM method, the variables considered in the study were initially categorized according to the quartiles. The threshold values were calculated and used with the following classifications: (a) accumulated precipitation: 484.1 mm to 1092.9 mm (low), 1092.9 mm to 1675.3 mm (moderate) and 1675.3 mm to 3303.9 mm (high); (b) average minimum temperature: 12.1 °C to 16.0 °C (low), 16.0 °C to 21.4 °C (moderate) and 21.4 °C to 23.9 °C (high); (c) average maximum temperature was: 21.9 °C to 27.3 °C (low), 27.3 °C to 31.9 °C (moderate) and 31.9 °C to 33.7 °C (high); (d) average wind speed: 0.6 m/s to 1.2 m/s (low), 1.2 m/s to 1.9 m/s (moderate) and 1.9 m/s to 4.3 m/s (high) and (e) variation in relative air humidity was: 59.8% to 70.2% (low), 70.2% to 77.3% (moderate) and 77.3% to 98.5% (high).

The results related to the application of the GoM method for the construction of the typology based on the variables selected for the microregions of Brazil are presented in Table 1, which shows the absolute and relative frequencies and estimates of $\lambda_{kjl}$, according to the selected variables.

Table 1. Absolute frequencies, relatives and estimates of $\lambda_{kjl}$, according to predominant profiles and categories of variables.

| Categories                  | Observed Frequencies | Estimated Probabilities $\lambda_{kjl}(E)$ | Ratio $(E/O)$ |
|-----------------------------|----------------------|--------------------------------------------|---------------|
|                             | Absolute (O) | Relative (O) | Profile P1 | Profile P2 | Profile P3 | K1 | K2 | K3 |
|-------------------------------|-------------|--------------|------------|------------|------------|----|----|----|
| **Accumulated Precipitation** |             |              |            |            |            |    |    |    |
| low                           | 138.0       | 0.251        | 0.0        | 1.0        | 0.0        | 0.0 | 4.0 | 0.0 |
| moderate                      | 275.0       | 0.500        | 1.0        | 0.0        | 0.0        | 2.0 | 0.0 | 0.0 |
| high                          | 137.0       | 0.249        | 0.0        | 0.0        | 1.0        | 0.0 | 0.0 | 4.0 |
| **Average of Minimum Temperature** |             |              |            |            |            |    |    |    |
| low                           | 137.0       | 0.249        | 0.3        | 0.0        | 0.5        | 1.1 | 0.0 | 1.9 |
| moderate                      | 275.0       | 0.500        | 0.7        | 0.5        | 0.0        | 1.5 | 1.1 | 0.0 |
| high                          | 138.0       | 0.251        | 0.0        | 0.5        | 0.5        | 0.0 | 1.9 | 2.1 |
| **Average of Maximum Temperature** |             |              |            |            |            |    |    |    |
| low                           | 137.0       | 0.249        | 0.3        | 0.0        | 0.5        | 1.0 | 0.0 | 1.9 |
| moderate                      | 276.0       | 0.502        | 0.8        | 0.6        | 0.0        | 1.5 | 1.1 | 0.0 |
| high                          | 137.0       | 0.249        | 0.0        | 0.4        | 0.5        | 0.0 | 1.7 | 2.1 |
| **Average of Wind Speed**     |             |              |            |            |            |    |    |    |
| low                           | 139.0       | 0.253        | 0.3        | 0.0        | 0.5        | 1.0 | 0.0 | 2.0 |
| moderate                      | 273.0       | 0.496        | 0.8        | 0.0        | 0.5        | 1.5 | 0.0 | 1.0 |
| high                          | 138.0       | 0.251        | 0.0        | 1.0        | 0.0        | 0.0 | 4.0 | 0.0 |
| **Average of Relative Humidity of the Air** |             |              |            |            |            |    |    |    |
| low                           | 138.0       | 0.251        | 0.0        | 1.0        | 0.0        | 0.0 | 4.0 | 0.0 |
| moderate                      | 275.0       | 0.500        | 1.0        | 0.0        | 0.0        | 2.0 | 0.0 | 0.0 |
| high                          | 137.0       | 0.249        | 0.0        | 0.0        | 1.0        | 0.0 | 0.0 | 4.0 |

The P1 profile was characterized by the microregions with meteorological variables in the ranges considered moderate, at the thresholds of the central 50%—that is, the variables showed values limited between Q25 and Q75. It was the profile with the highest prevalence: 117 microregions (21.3%) (Table 2). The accumulated precipitation of this group varied between 1092.9 mm and 1675.3 mm, with an average of 1439.9 mm and a standard deviation (sd) of 132.1 mm, being the third-highest average of precipitation between the groups, presenting significant differences when compared the others (Table 3). The minimum temperature ranged from 16.0 °C to 21.4 °C, with an average of
16.4 °C, and the maximum temperature was between 27.3 °C to 31.9 °C, with an average of 27.4 °C and sd = 1.8 °C. The results of the Tukey test indicated that precipitation, maximum temperature and minimum temperature were determinant for the formation of P1, being statistically different from the other profiles. Wind speed varied from 1.2 m/s to 1.9 m/s, the average being equal to 1.3 m/s, with a sd of 0.2 m/s, and relative humidity between 70.2% to 77.3%, with an average of 74.1% and sd = 2.1%, being among the lowest relative humidity rates in the country.

The microregions characterized in profile P2 showed low precipitation and relative humidity associated with higher values of the maximum temperature, minimum temperature and wind speed. It was predominant in 10.1% (Table 2) of the Brazilian microregions. It encompasses microregions with low accumulated precipitation, ranging from 484.1 mm to 1092.9 mm (average of 713.2 mm and sd = 110.1 mm), as described in Table 3. P2 precipitation is statistically different from the other profiles, the group with the lowest accumulated precipitation. The minimum temperature ranged from 21.4 °C to 23.9 °C, with an average of 21.5 °C and sd = 1.1 °C. The maximum temperature observed ranged from 31.9 °C to 33.7 °C, with an average of 32.3 °C and sd = 1.1 °C. The wind speed showed an average of 2.4 m/s, with a standard deviation of 0.2 m/s. The average relative air humidity was 65.7%, with a standard deviation of 3%. This profile showed the highest minimum and maximum temperatures, as well as the highest average wind speed, differing statistically from the averages of the other profiles formed.

Finally, the P3 profile was described by high precipitation and relative humidity associated with low wind speed, while the minimum and maximum temperatures were presented as low and high. For this reason, the P3 profile was divided into two, as they were very distinct regions from a climatic perspective. Thus, the P3-S profile was characterized by high precipitation and low temperature, typical of the Southern region of Brazil, while the P3-N profile, located in the North, showed high precipitation and average temperature. They represented a total of 11.4% (Table 2) of the microregions. The accumulated rainfall ranged from 1675.3 mm to 3303.9 mm, with the subdivision P3-N with an average of 2111.5 mm and sd = 296.8 mm and P3-S with an average of 1776.0 mm and sd = 121.8 mm. The wind speed for the P3-N group averaged 0.9 m/s, with sd = 0.2 m/s, and for the P3-S group, the average was 1.4 m/s and sd = 0.2 m/s, while the relative humidity of the air for the P3-N profile presented an average of 81.1%, with sd = 2.7%, and for P3-S, the average was 80.1% and sd = 1.6%, being the profile with the highest relative air humidity among all analyzed profiles. The microregions of the P3-N profile showed high temperatures, with a minimum ranging from 21.4 °C to 23.9 °C (average = 22.1 °C and sd = 1 °C) and maximum between 31.9 °C to 33.7 °C (average = 32.3 °C and sd = 0.4 °C), and these temperatures were statistically equal to those of the P2 profile. The microregions of P3-S showed relatively lower temperatures compared to all other profiles. In this case, the minimums ranged from 12.1 °C to 16.0 °C (average = 14.1 °C and sd = 1.2 °C), while the maximums varied between 21.9 °C to 27.3 °C, with an average of 24.3 °C and sd = 1.2 °C, these temperature averages being statistically different from the others.

| Profile Predominance | Frequency | %    |
|----------------------|-----------|------|
| Predominant 1 (P1)   | 117       | 21.3%|
| Mixed, predominance of P1 with characteristic of P2 (PM12) | 85 | 15.5%|
| Mixed, predominance of P1 with characteristic of P3 (PM13) | 39 | 7.1%|
| Microregions with characteristics of P1 | 241 | 43.8%|
| Predominant 2 (P2)   | 56        | 10.2%|
| Mixed, predominance of P2 with characteristic of P1 (PM21) | 72 | 13.1%|
| Microregions with characteristics of P2 | 128 | 23.3%|
| Predominant 3 (P3)   | 63        | 11.5%|
| Mixed, predominance of P3 with characteristic of P1 (PM31) | 100 | 18.2%|
| Microregions with characteristics of P3 | 163 | 29.6%|
| Amorphous            | 18        | 3.3%|
Table 3. Descriptive statistics of the predominant and mixed profiles built for the Brazilian microregions, according to the meteorological variables.

| Profiles | Variables | Minimum Temperature | Maximum Temperature | Precipitation | Wind Speed | Relative Humidity |
|----------|-----------|---------------------|---------------------|---------------|------------|------------------|
|          |           | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| predominant 1 (P1) | 16.4 $^e$ | 1.7 | 27.4 $^d$ | 1.8 | 1439.9 $^c$ | 132.1 | 1.3 $^{de}$ | 0.2 | 74.1 $^d$ | 2.1 |
| mixed 1.2 (PM12) | 19.1 $^d$ | 1.7 | 29.7 $^c$ | 0.9 | 1340.9 $^d$ | 207 | 1.6 $^c$ | 0.6 | 71.9 $^e$ | 8.6 |
| mixed 1.3 (PM13) | 19.8 $^{cd}$ | 2.1 | 30.9 $^b$ | 2.6 | 1521.2 $^c$ | 183.3 | 1.2 $^{ef}$ | 0.3 | 75.3 $^{cd}$ | 2.9 |
| predominant 2 (P2) | 21.5 $^a$ | 1.1 | 32.3 $^a$ | 1.1 | 713.2 $^f$ | 110.1 | 2.4 $^a$ | 0.2 | 65.7 $^f$ | 3 |
| mixed 2.1 (PM21) | 20.5 $^{bc}$ | 1.3 | 30.6 $^b$ | 1.4 | 878.7 $^e$ | 208.9 | 2.1 $^b$ | 0.5 | 71.4 $^{ef}$ | 7.1 |
| predominant 3—NORTH (P3-N) | 22.1 $^a$ | 1 | 32.3 $^a$ | 0.4 | 2111.5 $^a$ | 296.8 | 0.9 $^f$ | 0.2 | 81.1 $^a$ | 2.7 |
| mixed 31 NORTH (PM31—N) | 22.2 $^a$ | 1.2 | 31.9 $^a$ | 0.5 | 2131.9 $^a$ | 482.6 | 1.2 $^{ef}$ | 0.4 | 81.3 $^a$ | 11.4 |
| predominant 3—SOUTH (P3-S) | 14.1 $^f$ | 1.2 | 24.3 $^e$ | 1.2 | 1776.0 $^b$ | 121.8 | 1.4 $^{cde}$ | 0.2 | 80.1 $^{ab}$ | 1.6 |
| mixed 31—SOUTH (PM31-S) | 14.5 $^f$ | 1 | 25.1 $^e$ | 1.2 | 1743.2 $^b$ | 208.9 | 1.5 $^{cd}$ | 0.3 | 77.4 $^{bc}$ | 2.6 |
| Amorphous | 21.3 $^{ab}$ | 1.8 | 31.3 $^{ab}$ | 2.5 | 1342.5 $^{cd}$ | 248.3 | 1.8 $^c$ | 0.7 | 74.2 $^d$ | 7.4 |

Means followed by the same letter do not differ, by Tukey’s test, at 5% probability.
3.2. Mixed and Amorphous Profiles

The GoM method allows the microregions to partially belong to several predominant profiles. Thus, five mixed profiles were identified, which presented hybrid meteorological characteristics. The distribution of these profiles, as well as their proportions, are shown in Table 3.

The P1 profile presented two mixed profiles: the PM12 and the PM13. The first profile has a predominance of 1 with a characteristic of 2 and comprises 15.4% of the microregions. It is characterized by moderate temperatures, an average annual rainfall of 1341 mm, an average wind speed of 1.6 m/s and relative humidity of approximately 71.9%. This profile was similar to the profile P2 regarding the variable relative humidity of the air (Table 3), comprising values characterized as low, while PM13 (predominance of P1 with the characteristics of P3) groups represented 7.0% of the Brazilian microregions, being similar to the P3 profile for the maximum temperature and wind speed variables. In this group, precipitation has an average of 1532 mm, maximum temperature with an average of 30.9 °C and minimum temperature with an average of 19.8 °C, low wind speed and relative humidity of the air with an average of 75.3%.

The P2, characterized by high temperatures and low precipitation, formed only one mixed profile, PM21, with predominant characteristics of P2 with attributes of P1. This group represented 13.09% of the microregions, with characteristics similar to the P1 profile, especially regarding the relative humidity of the air. It presents low accumulated precipitation, with average values of 878.7 mm, average of high minimum and maximum temperatures, average wind speed of 2.1 m/s and has the second-lowest average of relative humidity (71.4%).

The mixed profile formed from P3 was called PM31, as it presented characteristics of P1. PM31-N are the microregions that have a predominance of P3-N with the characteristics of P1 (8.18%) with the highest average of precipitation, 2131.9 mm and sd = 296.8 mm (Table 3), with an average of maximum and minimum temperatures among the highest in the country (31.9 °C and 22.2 °C, respectively), the highest average of relative humidity (81.3%) and the second-lowest average of wind speed (1.2 m/s). While PM31-S, a predominance of P3-S with a characteristic of P1 that comprised 10% of the microregions, featured a low average of temperatures (minimum of 14.5 °C and maximum of 25.1 °C), average accumulated precipitation of 1.743 mm, an average relative air humidity of 77.4% and wind speed with an average of 1.5 m/s. Both were similar to the profile P1 regarding wind speed, presenting the lowest averages among the microregions of Brazil.

It is noteworthy that a very small number of microregions was not configured as belonging to any of the established profiles. These comprised the amorphous profile, representing 18 microregions that did not fit any of the established profiles and accounting for 3.27% of the total. These microregions were allocated as such because their climate characteristics were not associated with any specific profile. They are characterized by maximum temperatures, with an average of 31.3 °C and sd = 2.5 °C. The average of the minimum temperature was equal to 21.3 °C, and the average annual precipitation was estimated at 1342.5 mm, with a deviation of 248.3 mm. The average wind speed was of 1.8 m/s and relative humidity of approximately 74.2%. Although the amorphous profile has no similarity with the other profiles, the variability of the characteristics of the microregions that belong to it are less prominent.

3.3. Spatial Analysis of Profiles

Figure 2a shows the spatial distribution of the homoclimatic profiles defined by the GoM considering the microregions of Brazil. Figure 2b reveals the spatial distribution of the predominant profiles, while Figure 2c features the spatial distribution of the mixed profiles obtained by applying the GoM.
The thematic maps constructed demonstrate a regional spatial differentiation. Figure 2b reveals the homoclimatic regions according to the predominant profiles, and it is observed that the microregions with characteristics of P1 are spatially concentrated in the South-Central regions of the country, comprising the microregions located in the states of the Southeast region of Brazil, while it is also possible to identify the climatic characteristics of the predominant profile 1 in some states belonging to the Midwest region, such as Mato Grosso do Sul. The Southern region of the country also reveals areas with characteristics of this profile, especially the North of Paraná and the Eastern portion of the Rio Grande do Sul. This profile is composed of microregions with intermediate characteristics of the variables accumulated: precipitation, minimum and maximum temperatures, wind speed and relative humidity.

When analyzing the semiarid region of Brazil, it can be seen that the microregions located in the inlands of the Northeast region present characteristics of the predominant profile 2 that encompasses microregions with low accumulated precipitation, high minimum and maximum temperatures, wind speeds classified as high and low relative air humidity, as shown in Figure 2b.

The visual inspection of the same thematic map also shows that the microregions located in the North of the country have characteristics of the predominant 3-N profile, identified by high rainfall rates and high temperatures, influenced by squall lines. This region has the highest annual accumulated
rainfall. The microregions located in the Southern part of the state of Paraná east of Santa Catarina and south of Rio de Janeiro have the characteristics of the predominant 3-S profile.

Among the microregions of the amorphous profile (Figure 2a), 14 are located in the Northeast region, mainly on the border between Maranhão and Piauí or on the border between the semiarid region and the Amazon Basin. Some microregions located in the coastal region of the state of Pernambuco also did not fit any of the profiles defined by the GoM.

Figure 2c shows the spatial distribution of the microregions according to the mixed profiles—that is, those that presented simultaneous characteristics of two profiles. Analyzing the spatial location of these microregions, it is observed that they are located in the transition regions between the predominant profiles. Mixed profiles appear in areas that are influenced by different atmospheric systems. An example is the region located between the North and Northeast regions, where the high rainfall amounts in the first half of the year are affected mainly by the positioning of the Intertropical Convergence Zone (ITCZ) [33].

One can observe the presence of three mixed profiles (Figure 2c): PM31-N, PM13 and PM21 in the transition area from the high precipitation profile in the North region to the low precipitation profile in the semiarid region of the Northeast. This area corresponds to the transition between the Amazon rainforest region and the semiarid region, with a predominance of typical savanna vegetation. The PM31-N profile is identified mostly over the North region. The microregions located in the Southern part of the state of Mato Grosso, in Maranhão and on the coast of Rio de Janeiro were classified as PM13. Located mainly on the borders of P2, the PM21 is formed by microregions from all states in the Northeast and the semiarid region of Minas Gerais.

The coastal region of Northeast Brazil was characterized by the prevalence of two mixed profiles: the PM21 and the PM12. This area is influenced by several atmospheric systems that differentiate their climatic characteristics from the region represented by P2, such as the easterly wave disturbances (EWD), upper tropospheric cyclonic vortices (UTCV) and the effect of sea and land breezes on precipitation [8].

The PM12 is located in the transition region between the P1 and P2 profiles, encompassing the microregions that presented moderate climatic characteristics, with low precipitation and high-temperature profiles typical of the semiarid region. It consists of microregions located in the state of Minas Gerais, São Paulo, Goiás and in the coastal region of the Northeast.

The PM31-S is located surrounding the P3-S profile. It is predominantly identified by the microregions located in the Southern region of the country and on the border of the states of Espírito Santo and Minas Gerais. They have simultaneous characteristics from P3-S and P1.

4. Discussion and Conclusions

Several studies have been carried out with the aim of detecting climate variability in Brazil using multivariate statistical techniques [8,9,11,15,34,35]. Thus, the present study is unprecedented in applying the GoM algorithm methodology in homoclimatic zoning, enabling the identification of regions with hybrid climatic characteristics.

The novelty of the present research is the use of five meteorological variables for the elaboration of the climatic typology for the entire Brazilian territory, leading to a more robust characterization of the subregions defined by the method.

The analysis of the results shows that the microregions that exhibit characteristics of the “predominant 1—P1” extreme profile are those that have moderate conditions of the meteorological variables and contribute predominantly, with 21.3% of the total cases. Mixed profiles with a predominance of P1 contribute to 22.6% of the total, which results in 43.9% of all cases being represented predominantly by P1. The group of microregions called “predominant 2—P2” have characteristics of low accumulated precipitation, high minimum and maximum temperatures and wind speed and low relative humidity. The extreme profile of type 2 accounts for 10.2%, and the mixed profiles with a predominance of P2 represent 13.1% of total microregions. Lastly is the so-called “predominant 3” profile, with characteristics of high accumulated precipitation and relative humidity,
minimum temperature and maximum temperature with mixed characteristics (low and high) and wind speed classified as low that accounted for 11.4% of the microregions, and the mixed profiles with a predominance of profile 3 encompass 18.2% of the analyzed units. It is noteworthy that approximately half (296–53.9%) of the microregions have degrees of belonging to at least two types of profiles, the so-called mixed profiles. Furthermore, 236 microregions featured GoM scores equivalent to just one extreme type.

Studies carried out in Brazil took into account only the precipitation variable and aimed at defining the climatology of maximum and minimum extreme events, such as the works by Rao et al. (2016) [9] that used global daily precipitation databases from the Climate Research Center (CPC) and INMET for the period from 1979 to 2011. The authors found that the maximum rainfall occurs in the North and South regions of Brazil. The minimum rainfall values were identified in the semiarid region of the Northeast and presented a transition zone extending from the Midwest region towards the state of Maranhão. Some regions defined by the present article corroborate the work developed by Rao et al. (2016) [9], as we identified the P3-N and P3-S profiles as those of maximum precipitation and the P2 profile with minimum values comprising microregions in the boundaries of the Brazilian semiarid region. The PM12 profile mixes characteristics of the moderate-to-low precipitation profile, comprising the transition region between the Midwest and the state of Maranhão.

Other works developed for some regions of the country also aimed to define homogeneous regions [7,8,36]. The study developed by [7] studied the distribution of precipitation in the Amazon Basin. The authors identified that this region can be represented by three clusters with Silhouette Index (SI) = 0.43. Region 1 defined in that study corresponded to the mixed profiles PM31-N and PM13 influenced by the SACZ and the Bolivian high [37], while regions 2 and 3 in that study corresponded to profile P3-N, which is influenced by the ITCZ and coastal squall lines [38–40]. The profiles defined based on the interactions of the five meteorological variables described regions of mixed profiles surrounding the Amazon region, delimiting a transition zone between the climate typical of the Central portion of the Amazon forest towards the other Brazilian biomes.

In the Northeast region, studies by Oliveira et al., Rodrigues et al. and Palharini and Vila [8,15,36] previously used monthly precipitation data for the application of a cluster analysis.

In the Southern region of the country, the work carried out by Wrege et al. [41] led to the formation of six clusters based on evapotranspiration estimated in the period from 1976 to 2005: Group 1 formed by meteorological stations located in the North of Paraná; Group 2 formed by stations in the coast of Santa Catarina, the Southeast and the West of Paraná; Group 3 formed by stations in the South of Rio Grande do Sul; Group 4 in the Southwest of Paraná and West of Santa Catarina; Group 5 in the mountainous regions of Paraná (south of the state), Santa Catarina (Central region) and Rio Grande do Sul and Group 6 in the Northwest region of Rio Grande do Sul.

These results are comparable to the ones found in the present study, with three groups also verified in the South region: the profile P1 located in the North of Paraná characterized by the transition between hot climates of the low latitudes and cold climates of the middle latitudes, with an important wet period occurring more during summer than winter. The occurrence of drought periods coincides with the coldest period of the year [42]. The P3-S, located in the coastal zone of Paraná and Santa Catarina, is the tropical region with the highest rainfall in the South region, comprising the Serra do Mar mountainous formation, with total annual rainfall ranging from 3500 to 4000 mm [43]. Finally, the PM31-S identified in the South of Paraná, Santa Catarina and part of Rio Grande do Sul featured a temperate climate and are the coldest areas in the states of the Southern region of the country, with frequent occurrences of frosts in the autumn and winter, due to the combination of the middle latitudes with predominantly high altitudes [42].

It is noticeable that the interaction of the variables’ precipitation, maximum temperature, minimum temperature, relative humidity and wind speed produced a better characterization of homogeneous zones, and the GoM made it possible to identify areas that are influenced by the various atmospheric systems operating in Brazil.
Due to the scientific interest in studies that aim to identify and group regions with similar climate variability, and the various multivariate analysis techniques used for this purpose, this work presented a proposal for the climatic classification of microregions of Brazil using the GoM method. The application of this method allowed the identification of nine homoclimatic regions in Brazil. The climatic map developed in this study highlighted the influence of different climates found in the Brazilian territory, defining homoclimatic regions based on the combination of several meteorological characteristics, being a pioneer study in this sense, as well as in the use of the GoM method for this purpose. The definition of mixed profiles provided an important regional detail to understand the influence of atmospheric systems in transition regions between regional climates and can be used as an important reference for future work.

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