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SPATIO-TEMPORAL VARIABILITY OF PRECIPITATION IN THE VENEZUELAN AMAZON

VARIABILIDADE ESPAÇO-TEMPORAL DA PRECIPITAÇÃO NA AMAZÔNIA VENEZUELANA

VARIABILIDAD ESPACIO-TEMPORAL DE LA PRECIPITACIÓN EN LA AMAZONÍA VENEZOLANA

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Abstract: The Amazon region has a fundamental role in the global hydrological balance. Thus, the spatial and temporal precipitation analyses are essential to evaluate the impacts of climate change. However, there is still an information gap in the Venezuelan Amazon. This research aimed to analyze the spatial and temporal patterns of twelve years (2000-2011) of precipitation data from ten sites in the Venezuelan Amazon. The spatial and temporal structures of interannual precipitation variability were analyzed. The Mann-Kendall non-parametric test was used to determine if annual precipitation trends at each site can be identified using a time series that includes a seasonal component. The global Moran index was used to evaluate spatial autocorrelation of precipitation between observations based on Era-Interim. When the 10 sites were separated into groups of average annual precipitation, two homogeneous groups of precipitation were distinguished. The monthly precipitation at each site also defined the homogeneous precipitation groups. These results showed that in this region of the Amazon a unimodal pattern of precipitation predominates at the different sites, with a long period of precipitation and a period with less precipitation between December and March. This pattern is explained by the Intertropical Convergence Zone, which is shifted to more southern latitudes during these months, thus modifying the precipitation dynamics in the Amazon. Furthermore, the main consequences in the precipitation pattern in the Amazon are the influence of the South Atlantic Convergence Zone with the occurrence of high precipitation. Assessing the local spatial association by ERA-Interim, it is noted that the clusters of precipitation (Moran index) express the variability as a function of the significance level of the local indexes' values.

Keywords: Seasonality. Precipitation variability. SACZ. Intertropical Convergence Zone.

Resumo: A região amazônica desempenha um papel fundamental no balanço hídrico global. Assim, a análise espaço-temporal da precipitação é essencial para a avaliação dos impactos das mudanças climáticas. No entanto, ainda existe uma lacuna de informação na Amazônia venezuelana. O objetivo deste trabalho é analisar o padrão espaço-temporal de 12 anos da precipitação na Amazônia venezuelana a partir de dados de superfície da região. Foram utilizados dados diários de precipitação pluvial para um período de 12 anos (2000-2011) de 10 localidades da Amazônia venezuelana. As estruturas temporais e espaciais da variabilidade interanual da precipitação foram avaliadas. Foi utilizado o teste não paramétrico de Mann-Kendall para determinar se as tendências anuais de precipitação em cada local podem ser identificadas em uma série temporal que inclua um componente sazonal. Para avaliar a autocorrelação espacial da precipitação entre as observações com base no Era-Interim, o índice global de Moran foi usado. Foram distinguidos dois grupos homogêneos de precipitação, quando as localidades são separadas por médias anuais. Com relação à precipitação mensal por localidade, as variáveis (meses) que definem os grupos homogêneos de precipitação. Os resultados mostram que nesta região da Amazônia prevalece um padrão unimodal de precipitação nas diferentes localidades, com um longo período de chuva e um período menos chuvoso entre dezembro e março. Esse padrão é explicado pela Zona de Convergência Intertropical que nesses meses se encontra deslocado para latitudes mais ao sul, modulando a dinâmica das chuvas na Amazônia. Outra das principais consequências no padrão de precipitação na Amazônia é a influência da Zona de Convergência do Atlântico Sul com a ocorrência dos altos índices pluviais. Ao

avaliar a associação espacial local pelo ERA-Interim, observa-se que os grupos de precipitação (índice de Moran) expressam a variabilidade existente em função do nível de significância dos valores de seus índices locais.
Palavras-Chave: Sazonalidade. Variabilidade de precipitação. ZCAS. Zona de Convergência Intertropicintertropical.

Resumen: La región del Amazonas desempeña un papel fundamental en el balance hídrico mundial. Por lo tanto, el análisis espacio-temporal de las precipitaciones es esencial para la evaluación de los impactos del cambio climático. Sin embargo, todavía existe un vacío de información en la Amazonia venezolana. El objetivo de este trabajo es analizar el patrón espacio-temporal de 12 años de precipitación en la Amazonia venezolana a partir de datos superficiales de la región. Se utilizaron datos de precipitaciones diarias para un período de 12 años (2000-2011) de 10 localidades de la Amazonia venezolana. Se evaluaron las estructuras temporales y espaciales de la variabilidad interanual de las precipitaciones. Se utilizó la prueba no paramétrica de Mann-Kendall para determinar si las tendencias anuales de la precipitación en cada sitio pueden identificarse en una serie temporal que incluye un componente estacional. Para evaluar la autocorrelación espacial de la precipitación entre las observaciones basadas en Era-Interim, se utilizó el índice global de Moran. Se han distinguido dos grupos homogéneos de precipitaciones cuando las localidades están separadas por las medias anuales. En cuanto a la precipitación mensual por localidad, las variables (meses) que definen los grupos homogéneos de precipitación. Los resultados muestran que en esta región amazónica predomina un patrón unimodal de precipitaciones en las diferentes localidades, con un periodo de lluvias largo y otro menos lluvioso entre diciembre y marzo. Este patrón se explica por la Zona de Convergencia Intertropical, que en estos meses se desplaza hacia latitudes más meridionales, modulando la dinámica de las lluvias en la Amazonia. Otra de las principales consecuencias del régimen de lluvias en la Amazonia es la influencia de la Zona de Convergencia del Atlántico Sur, con la ocurrencia de altos índices de precipitación. Al evaluar la asociación espacial local mediante ERA-Interim, se observa que los clusters de precipitación (índice de Moran) expresan la variabilidad existente en función del nivel de significación de sus valores de índice local.
Palabras clave: Estacionalidad. Variabilidad de las precipitaciones. SACZ. Zona de convergencia intertropical.

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INTRODUCTION

The Amazon is one of the most important biogeographic regions in the world due to its dominant role in the generation of ecosystem goods and services that have local and global impacts (GLOOR, 2013; CASTELLO & MACEDO, 2016; VILLA et al., 2017; 2020). This region has 40% of the world´s tropical forests and is a key component in the Earth´s climate system (ARAGÃO et al., 2014; ZHANG et al., 2015). The Amazon also plays a fundamental role in the global hydrological balance (ZHANG et al., 2015; COE et al., 2016), because it is one of the regions that has high precipitation and evapotranspiration rates due to the vast extension of tropical forest (VAN DER ENT et al., 2010; MAEDA et al., 2017). Furthermore, Amazon has a dense hydrological network that accounts for approximately 18% of the total discharge of freshwater into the Atlantic Ocean (JAHFER et al., 2017). However, the different hydrological patterns and processes are strongly altered due to land-use change and climate change (ARAGÃO et al., 2014; MARENGO & ESPINOZA, 2016; FONSECA et al., 2017). Thus, spatial and temporal analysis of precipitation is essential to evaluate the impacts of climate change, mainly through the future scenarios analysis of hydrological resources management and conservation in the Amazon.

The temporal series precipitation analysis has been increased for their relevance on climatic and hydrological processes (MARENGO & ESPINOZA, 2016; ALVES et al., 2017), on the anthropogenic activities associated with agriculture (LIMA et al., 2014; LAWRENCE & VANDECAR, 2015) and also due to the direct feedback effect on the dynamics and functioning of forest ecosystems (DAVIDSON et al., 2012; ZEMP et al., 2017). However, research with this integrative approach is limited, mainly due to the lack of land-based meteorological and precipitation stations in the different countries of the Amazon region. For instance, the Venezuelan Amazon is an isolated part of the country that is still largely unknown (ESPINOZA et al., 2009; OLIVERO et al., 2016).

Interannual precipitation variability in the Amazon basin has been attributed to variations in sea surface temperatures (SST) in both the tropical Pacific and Atlantic oceans (ESPINOZA et al., 2009; MARENGO et al., 2012). Furthermore, the Amazonian precipitation variability is influenced by the large-scale tropical climatic modes associated with the El Niño/Southern Oscillation (ENSO) cycle in the Pacific Ocean (MARENGO et al., 2012; SOUSA et al., 2015; FONSECA et al., 2017). The regions with the highest average precipitation values (> 3,000 mm year^{-1}) are located in the northeast of the Amazon basin, near the Atlantic Ocean, due to the large influence of the Intertropical Convergence Zone (ITCZ), as also occurs in the northwestern region of the basin (ESPINOZA et al., 2009; MARENGO et al., 2012; SOUSA et al., 2015; FONSECA et al., 2017). The ITCZ is a large-scale tropical system that determines the precipitation in the Amazon region, mainly during the first half of the year (GILLE & Da MOTA, 2014; SILVA-FERREIRA et al., 2015; SEGURA et al., 2020). Precipitation rates are also considered to be high in the southeastern region of the basin, near the average position of the South Atlantic Convergence Zone (SACZ). This position is established during the southern hemisphere summer from the northeastern of the Amazon basin and spreads in the direction of the subtropical Atlantic Ocean (ESPINOZA et al., 2009; MARENGO et al., 2012). In this precipitation distribution gradient, there is a distinct reduction in the direction of the tropics, with values above 2,000 mm year^{-1} in the southeastern region of Brazil, and below 1,500 mm year^{-1} at the Peruvian-Bolivian plateau region, as well as in the Brazilian State of Roraima. These precipitation values demonstrate the effects of the moisture content of the Atlantic Ocean due to the interference of the Guyana Shield (FISCH et al., 1998; MARENGO, 2004; MARENGO & ESPINOZA, 2016). However, there is still an information gap on spatio-temporal patterns of precipitation variability in the Venezuelan Amazon.

Interannual precipitation variability in the Amazon basin is largely influenced by the *El Niño* Southern Oscillation (ENSO), due to cyclic heating of the central-eastern Pacific Ocean when the sea surface temperature (SST) is above the climatological normal (SOUZA et al., 2000; LIEBMANN & MARENGO, 2001; RONCHAIL et al., 2002). Furthermore, during *El Niño* events an intense decrease in precipitation in the northern and northeastern regions of the Amazon basin is evident, while in these same regions, there is a higher precipitation rate during *La Niña* years (SOUZA et al., 2000). This precipitation trend diminishes to the western and southern regions of the basin (RONCHAIL & GALLAIRE, 2006), and could be related to the ENSO signal present in the southeast of South America (ESPINOZA et al., 2009). In the tropical Andes of Bolivia and the south of Peru, precipitation is below normal during *El Niño* events (GARREAUD & ACEITUNO, 2001; RONCHAIL & GALLAIRE, 2006). Recently, the impacts of the ENSO have become more pronounced in the Brazilian Amazon, mainly caused by a significant precipitation reduction in the eastern region of the basin (SOUZA et al., 2015; MARTORANO et al., 2017). In this context, Martorano et al. (2017)

observed that a combination of atmospheric drivers, timescales, and climate has an important effect on the precipitation extremes of eastern Amazon. Moreover, these researchers concluded that there are higher precipitation rates during *La Niña* years and a deficit during *El Niño*, with a strong intensification of water deficit during the last two decades in this region.

However, Venezuela is the country with the fewest studies and the largest information gap on precipitation patterns among all the basin countries (ESPINOZA et al., 2009). The Amazonas state is part of one of Venezuela's most conserved biogeographic regions, which present a high biological diversity that provides important ecosystem goods and services (HUBER, 1995; OLIVERO et al., 2016). These benefits have been obtained mainly through small-scale agricultural production (shifting cultivation), and the collection of food and medicine (VILLA et al., 2018), which are also distributed across the country. Despite limited studies, it is also presumed that the Amazonian forests of Venezuela have played a key role in regulating hydrological and climatic processes on a local and regional scale. They have been essential to maintain dynamics in the Orinoco basin. Thus, the time series analysis of precipitation in the different localities of the Amazonas state can also represent a useful tool to study the consequences of land-use changes at the regional level. One advance is the investigation of the climatological data available in the region to understand the spatial and temporal precipitation variability, thus providing basic knowledge for the local and regional water resources management.

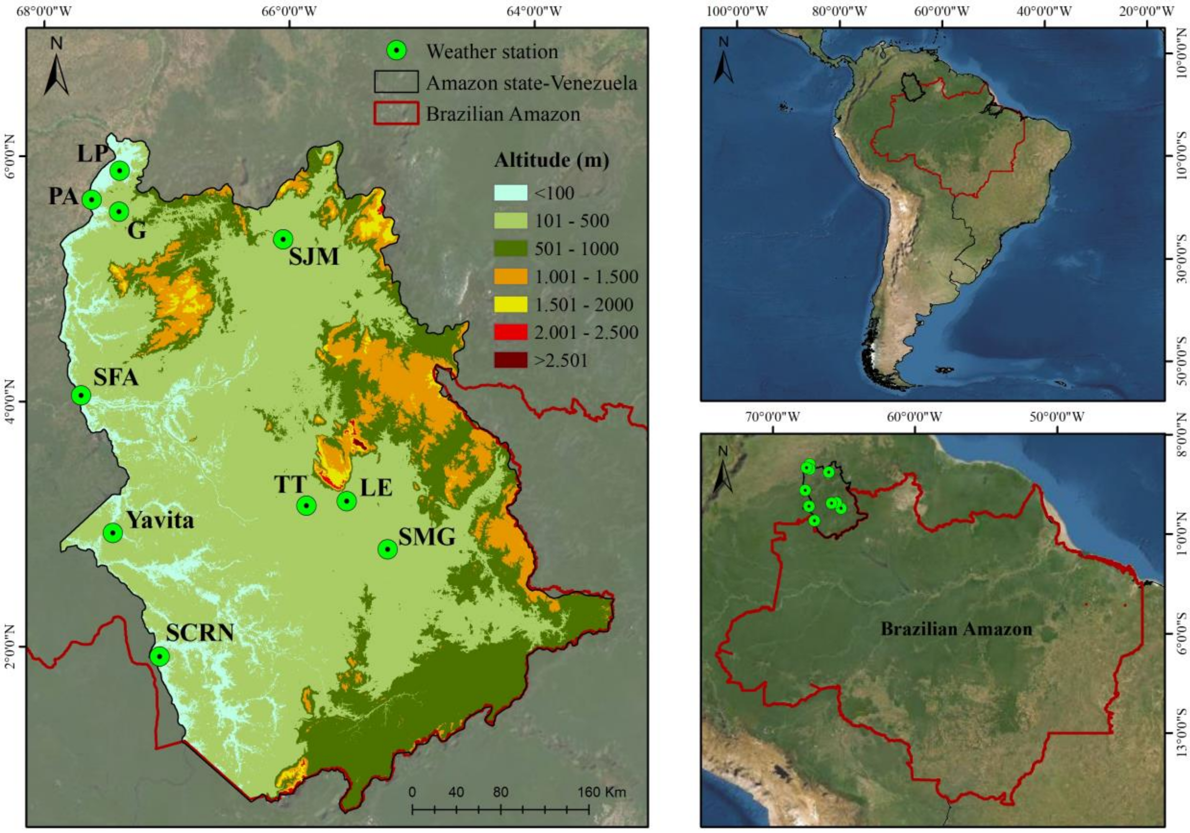
This research aimed to analyze the spatial and temporal precipitation variability in the Venezuelan Amazon using data from land-based meteorological and precipitation stations in the region. Specifically, it was evaluated: 1) the spatial precipitation variability obtained from GRID data from the European Centre for Medium-Range Weather Forecasts (ECMWF model); 2) the monthly precipitation pattern (2000-2011); 3) the annual average and interannual precipitation variability in the Amazonas State. Furthermore, 4) the precipitation homogeneity was evaluated along spatial and temporal scales (monthly and annual). Finally, it was expected 5) to identify the trend of deviations in precipitation time series based on daily observations in the Amazon State, Venezuela.

MATERIAL AND METHODS

Study Area and Data Collection

Twelve years (2000-2011) of daily precipitation data from ten sites in the Venezuelan Amazon were used in this analysis (Supplementary material S1). The data were provided by the hydrology department of the Ministry of the Environment and Natural Resources of the State of Amazonas, Venezuela. The weather stations were established at the following sites (Figure 1): Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G, Átures municipality), San Juan de Manapiare (SJM, Manapiare municipality), San Fernando de Atabapo (SFA, Atabapo municipality), San Carlos de Rio Negro (SCRN, Rio Negro municipality), Yavita (Y, Maroa municipality), Tama-Tama (TT), La Esmeralda (LE) and Santa Maria de Los Guaica (SMG, Alto Orinoco municipality). The data were organized into monthly and annual scales for all sites.

Figure 1. Localization of the study area in relation to South America, the Amazon region, and Amazonas State, Venezuela showing locations of 10 precipitation stations.



Source: Elaborated by the authors (2020)

Due to the lack of land-based meteorological stations spread across the Venezuelan Amazon region, grid data were used to analyze the spatial variability of precipitation using interpolation techniques. The period of 1990 to 2014 of the Era-Interim reanalysis set, produced by ECMWF, was used as a reference. The data were obtained in a 10-day scale at a spatial resolution of 25 × 25 km (longitude × latitude). Subsequently, the performance of the GRID data in estimating precipitation in the Venezuelan Amazon was evaluated.

Data Analysis

The precipitation data distribution and homogeneity were evaluated using Shapiro-Wilk and Q-Q graphs (CRAWLEY, 2013). Since the data did not show a normal distribution, the Kruskal-Wallis test was used to compare precipitation patterns between periods and sites, followed by Dunn´s test for multiple comparisons of means (DINNO, 2017). These statistical analyses were conducted using the 'car' and 'dunn.test' packages in the R software (R STUDIO CORE TEAM, 2019).

The Mann-Kendall (M-K) non-parametric test was used to identify trends and deviations in temporal precipitation series at each site based on seasonal scales (ZILLI et al., 2017). Thus, The M-K test (at 95% significance level) allows assuming that the null hypothesis (H_0) is based on lack of trend identically distributed in climate extremes over time and that the alternative hypothesis (H_1) is based on the evidence of monotonic trend between the data (increasing or decreasing). These analyses were performed in the "trend" package (POHLERT, 2020), using seasonal scales, which presume that significant changes based on the period of higher precipitation may indicate climate changes. This test is used to determine trends in time series analysis, in which a deviation greater than zero means that the trend is greater (YENILMEZ et al., 2011). An ascending or descending monotone trend means that precipitation increases or constantly decreases through time (ESPINOZA et al., 2009). The test is based on the null hypothesis that there are no trends in the analyzed series. Before implementing the Mann-Kendall test, procedures were conducted to eliminate spatial and temporal autocorrelation of the data (YUE et al., 2002; YUE & WANG, 2004).

The spatial autocorrelation of precipitation between observations based on the data assimilation system in Era-Interim (BERRISFORD et al., 2011) was evaluated using the Moran index (Eq. 1 and Eq. 3). Thus, the global Moran Index was used to identify whether the precipitation data had random or clustered effects. Conversely, the local Moran index indicates the significant spatial groupings of similar values, for example Moran's Index value near +1.0 indicates clustering while an index value near -1.0 indicates dispersion (ANSELIN, 1995).

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} Z_i Z_j w_{ij}}{S_0 \sum_{i=1}^{n} Z_i^2} \qquad \text{(Eq.1)}$$

Where n is the number of populations (n polygons); wij is the element of the proximity matrix W, n x n, which expresses the spatial relationship between n populations.

$$Z_i = (x_i - \bar{x}), and \ Z_j = \left(x_j - \bar{x}\right) to \ i \neq j = 1, \ldots, n$$

where observed values of populations i and j are centered on the average of the variables x; and S_0 is defined by the following equation:

$$So = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \qquad \text{(Eq.2)}$$

If there is spatial autocorrelation between observations, the precipitation stations do not have a random value. It is possible to apply the local Moran index, which allows identifying spatial association patterns. According to Celebioglu and Dall'erba (2009), the local Moran index I can be specified by equation (3):

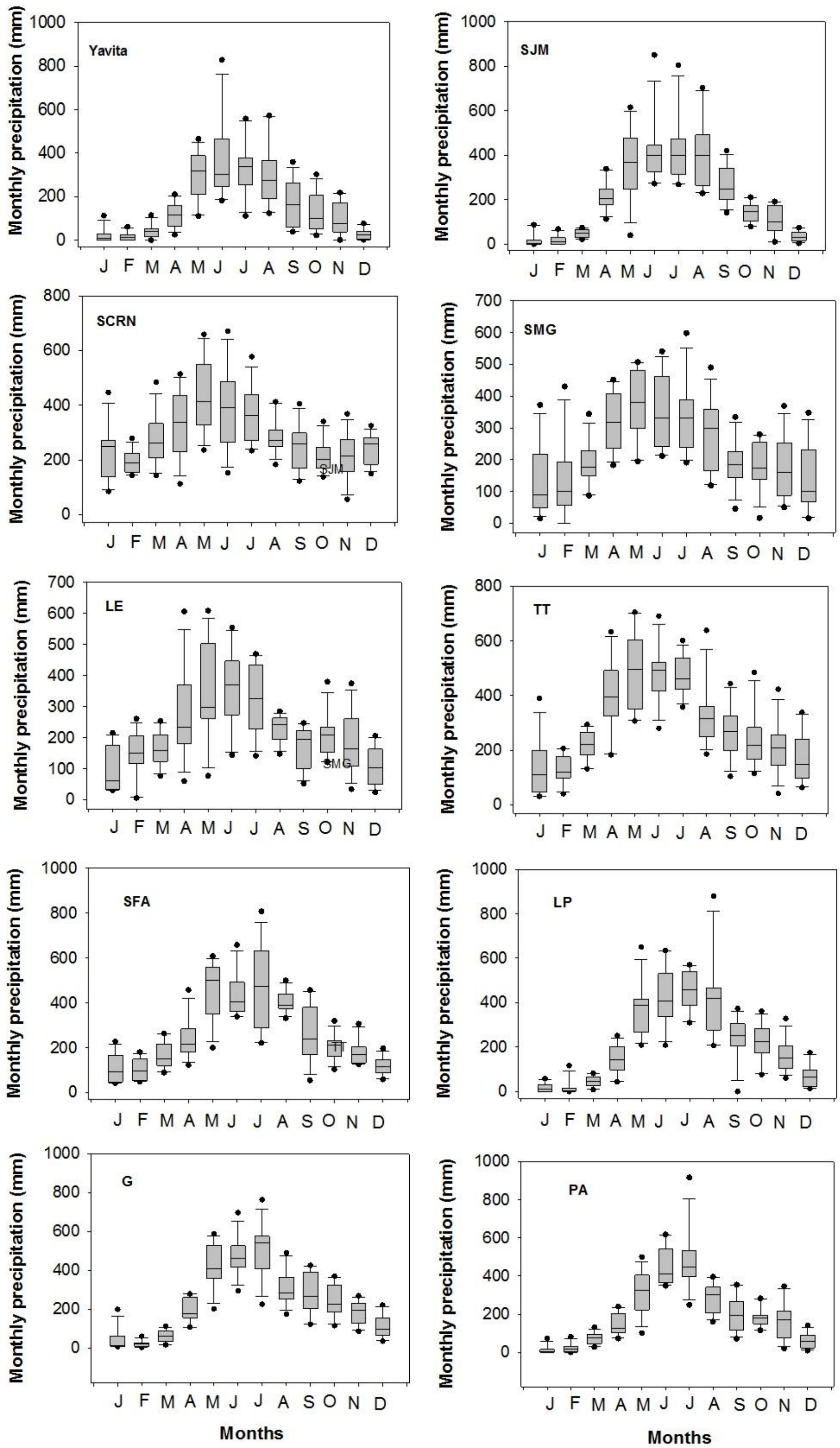
$$I = \frac{x_i - \mu}{\sigma_0^2} \sum_{j=1}^{n} w_{ij} (xj - \mu), \ \ i = 1, \ldots n \qquad \text{(Eq. 3)}$$

where σ_0^2 is the population variance of the variable understudy in the n municipalities; x_i is the observation of a variable of interest in municipality i for i = 1, ..., n, and μ is the average of n municipalities (populations). Thus, to develop the spatial analysis of the study area and estimate the spatial autocorrelation, algorithms were used in ArcMap 10.7 software (ESRI, 2019). It is important to emphasize that each point identified on the map refers to the information estimated by ERA-Interim, in a GRID of 25 km, characterized as a remote point of precipitation observation.

RESULTS AND DISCUSSION

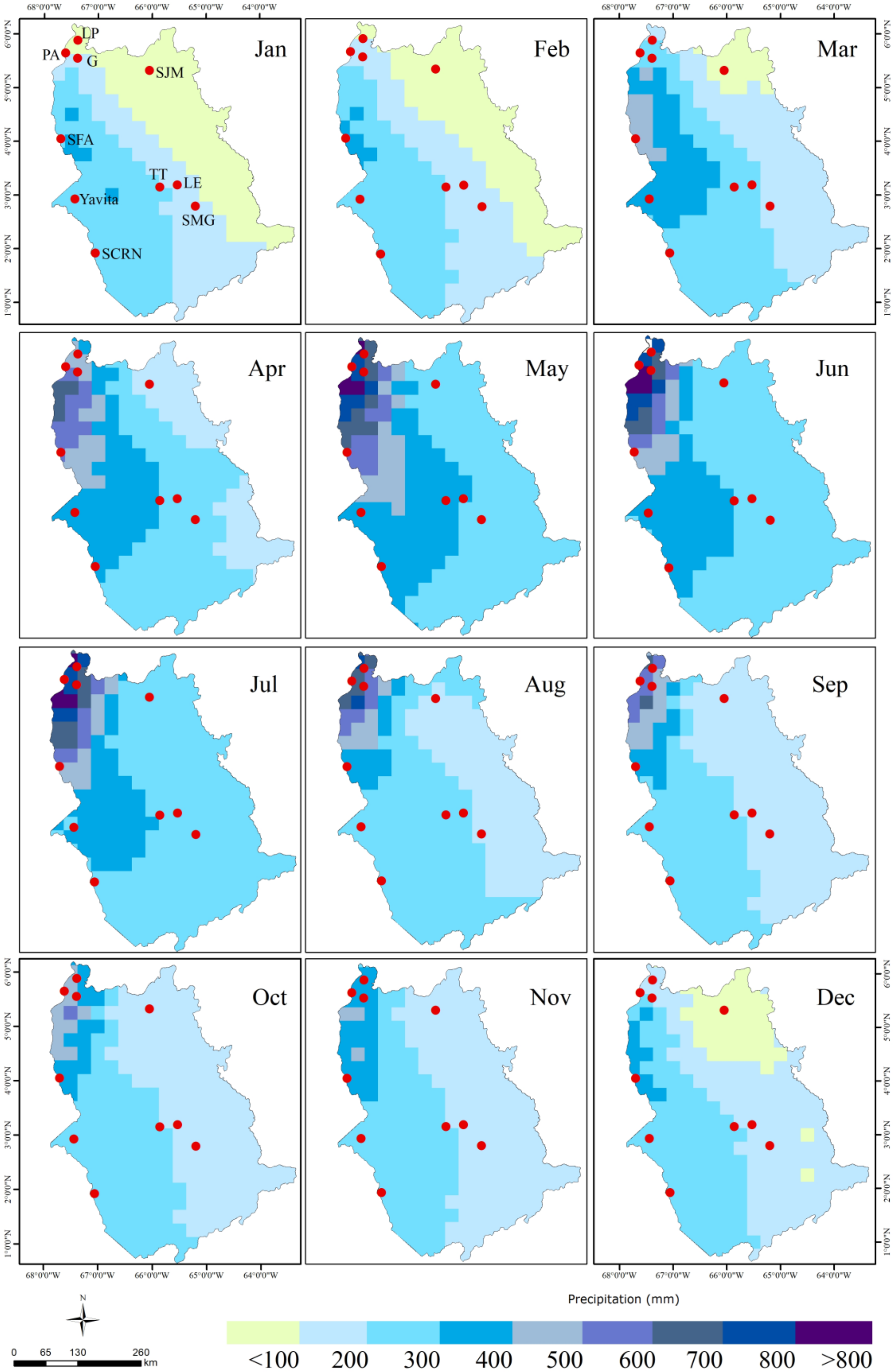
The homogeneous series of average precipitation (2000-2011) of the stations have a unimodal pattern (being one wet and dry season per year) with two distinct periods across the different sites, a long period of precipitation between April and October, and a period with less precipitation between December and March (Figure 2 and 3). During the period of greatest precipitation, the highest values occurred from May to June (approximately 400 mm). The period of least precipitation, in general, occurred in January at all sites (approximately 200 mm). Thus, November presents a transitional period. The variability of precipitation analysis in the Venezuelan Amazon showed that precipitation is mainly concentrated in the northwestern region and extends to the southeast (Figure 2), with greater precipitation between May and July, with totals above 800 mm per month (Figure 2). The northeastern region has the lowest precipitation between December and March (Figures 2 and 3), with values below 100 mm per month. The area with values below 100 mm per month is extended from the northeast to the region's southeast between January and February (Figure 2).

Figure 2. Monthly precipitation pattern (2000-2011) at different sites in Amazonas State, Venezuela. Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G), San Juan de Manapiare (SJM), San Fernando de Atabapo (SFA), San Carlos de Río Negro (SCRN), Yavita (Y), Tama-Tama (TT), La Esmeralda (LE) and Santa María de Los Guaica (SMG).



Source: Elaborated by the authors (2020)

Figure 3. Annual average precipitation at each site in Amazonas State, Venezuela. Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G), San Juan de Manapiare (SJM), San Fernando de Atabapo (SFA), San Carlos de Río Negro (SCRN), Yavita (Y), Tama-Tama (TT), La Esmeralda (LE) and Santa María de Los Guaica (SMG).

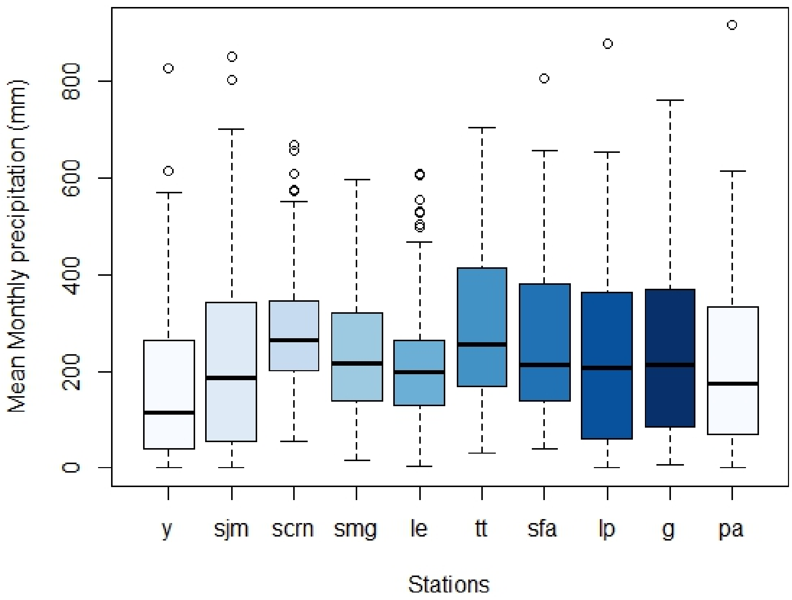


Source: Elaborated by the authors (2020)

This precipitation pattern coincides with the one observed in the northern region of the Brazilian Amazon, indicating that unimodal patterns represent a rainy period and another less rainy period, where monthly precipitation is generally below 100 mm (ESPINOZA et al., 2009). However, this pattern is contrary to those observed in other regions of the Amazon (ESPINOZA et al., 2009; QUADRO et al., 2012; COE et al., 2016).

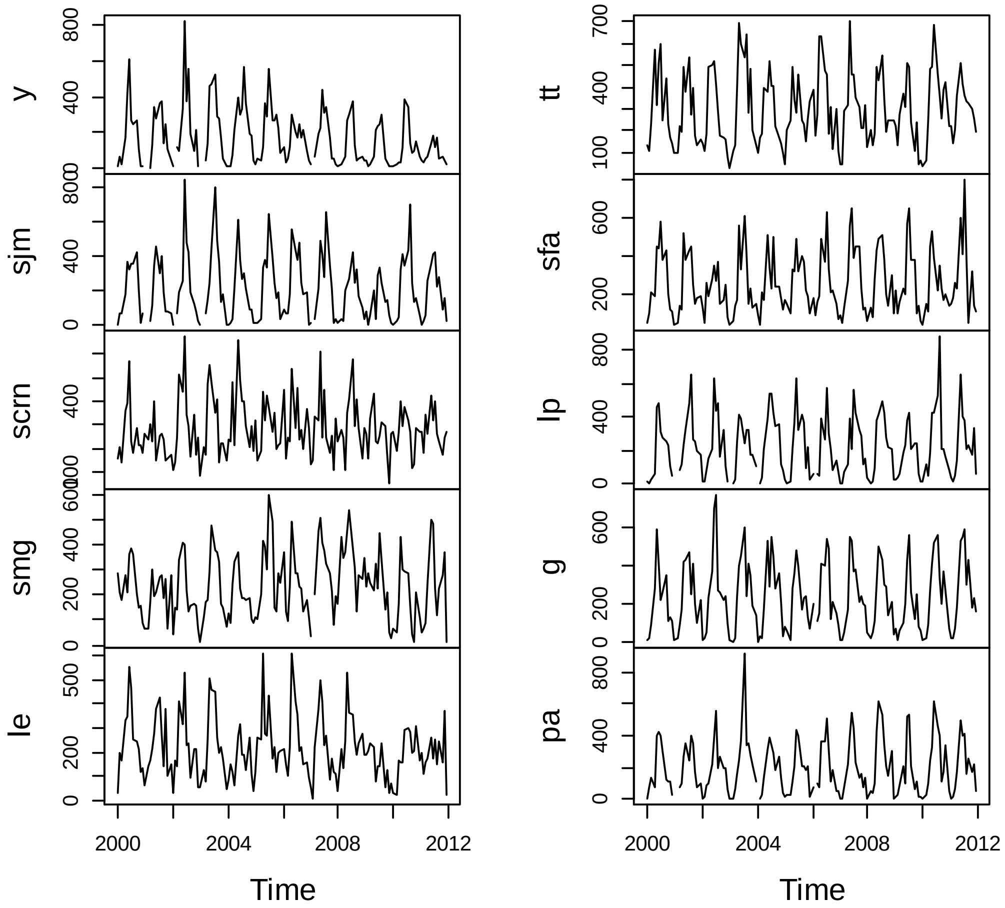
There were significant differences ($F_{1,138} = 12.34$; $p < 0.001$) between the sites concerning monthly precipitation during the period 2000-2011. Thus, there were no significant differences in monthly precipitation between the sites on an annual scale (Figure 4). The interannual variability of precipitation showed a similar trend between years with the highest and the lowest precipitation (Figure 5). Therefore, these results show that the effects of seasonality are diminished at the annual scale. Consequently, there is a reduction in monthly precipitation oscillations, probably affecting the frequency, intensity, and durability at the local scale. Thus, the precipitation regimes, in terms of annual totals, are very similar between sites. This trend in precipitation is similar to the one that occurs in the northeastern region of the Amazon, where there is a precipitation rate of 2,800 mm year^{-1}, with precipitation relatively constant during the entire year (COE et al., 2016).

Figure 4. Interannual variability of precipitation in the Amazonas State, Venezuela. Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G), San Juan de Manapiare (SJM), San Fernando de Atabapo (SFA), San Carlos de Río Negro (SCRN), Yavita (Y), Tama-Tama (TT), La Esmeralda (LE) and Santa María de Los Guaica (SMG).



Source: Elaborated by the authors (2020)

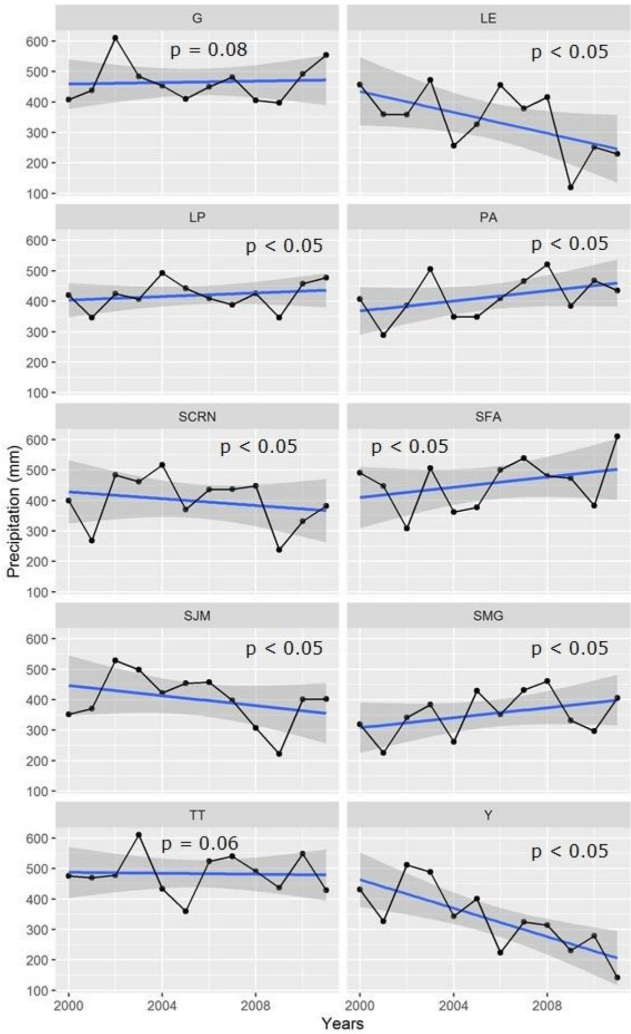
Figure 5. Trend of the Mann-Kendall annual test in the Amazonas State, Venezuela. Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G), San Juan de Manapiare (SJM), San Fernando de Atabapo (SFA), San Carlos de Río Negro (SCRN), Yavita (Y), Tama-Tama (TT), La Esmeralda (LE) and Santa María de Los Guaica (SMG). The significant linear trend at least at the 95% a confidence level is indicated (MK $p < 0.05$).



Source: Elaborated by the authors (2020)

The Mann-Kendall trends were not significant at an annual scale at most sites, which remained relatively stable and constant over time (Figure 6). Thus, the results show a significant negative trend for the Yavita and La Esmeralda (LE), which indicated a significant reduction in the rainy season between 2000 and 2011 at these sites. The annual and seasonal precipitation for the whole Amazon shows insignificant negative trends (SATYAMURTY et al., 2010). Conversely, the negative trend for the Yavita site can be related to local land-use changes that affect convective precipitation. Finally, significant positive trends ($p<0.05$) were recorded to Puerto Ayacucho (PA), and San Fernando de Atabapo (SFA)(Figure 6).

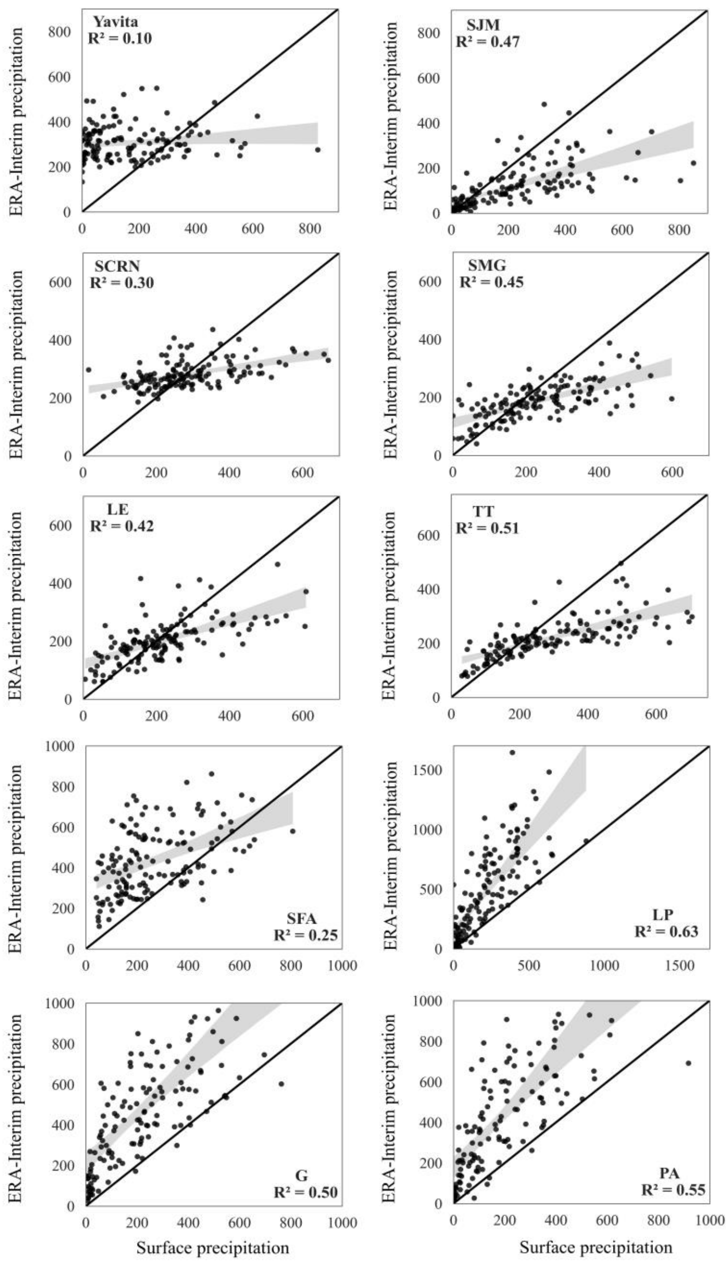
Figure 6. Performance of ERA-Interim GRID data compared to surface stations in the Venezuelan Amazon.



Source: Elaborated by the authors (2020)

The precipitation variability in the Venezuelan Amazon expresses monthly ERA-Interim (ECMWF) reanalysis data between 2000 and 2011. These results allow evaluating the performance of the data in GRID, thus validating the observed data. For example, Yavita, SCRN and SFA stations, located in the Venezuelan Amazon western region, have average values that showed overestimations by ERA-Interim (Figure 7). Consequently, the performance was worse between the observed and estimated values, with R^2 of 0.10, 0.30 and 0.25, respectively. On the other hand, the stations located to the northwest of the region (LP, PA and G), showed a better performance with R^2 of 0.63, 0.55 and 0.50, respectively, indicating that although the values indicate overestimations in the GRID data of ERA-Interim, there were higher approximation between the observed data at surface weather stations. In this context, Moraes et al. (2020), evaluating the performance of surface stations with GRID data from ERA-Interim in the Brazilian Amazon, also observed locations with reduced precision in predicting the information obtained with R^2 values less than 0.29. The authors pointed out that the low accuracy was mainly concentrated in places northwest of the Brazilian Amazon, a region bordering the Venezuelan Amazon, due to the reduced network of meteorological observations in that region.

Figure 7. Spatial variability of precipitation in the Venezuelan Amazon obtained from GRID data from the ECMWF model. Puerto Ayacucho (PA), Limon de Parhueña (LP), Gavilán (G), San Juan de Manapiare (SJM), San Fernando de Atabapo (SFA), San Carlos de Río Negro (SCRN), Yavita (Y), Tama-Tama (TT), La Esmeralda (LE) and Santa María de Los Guaica (SMG).

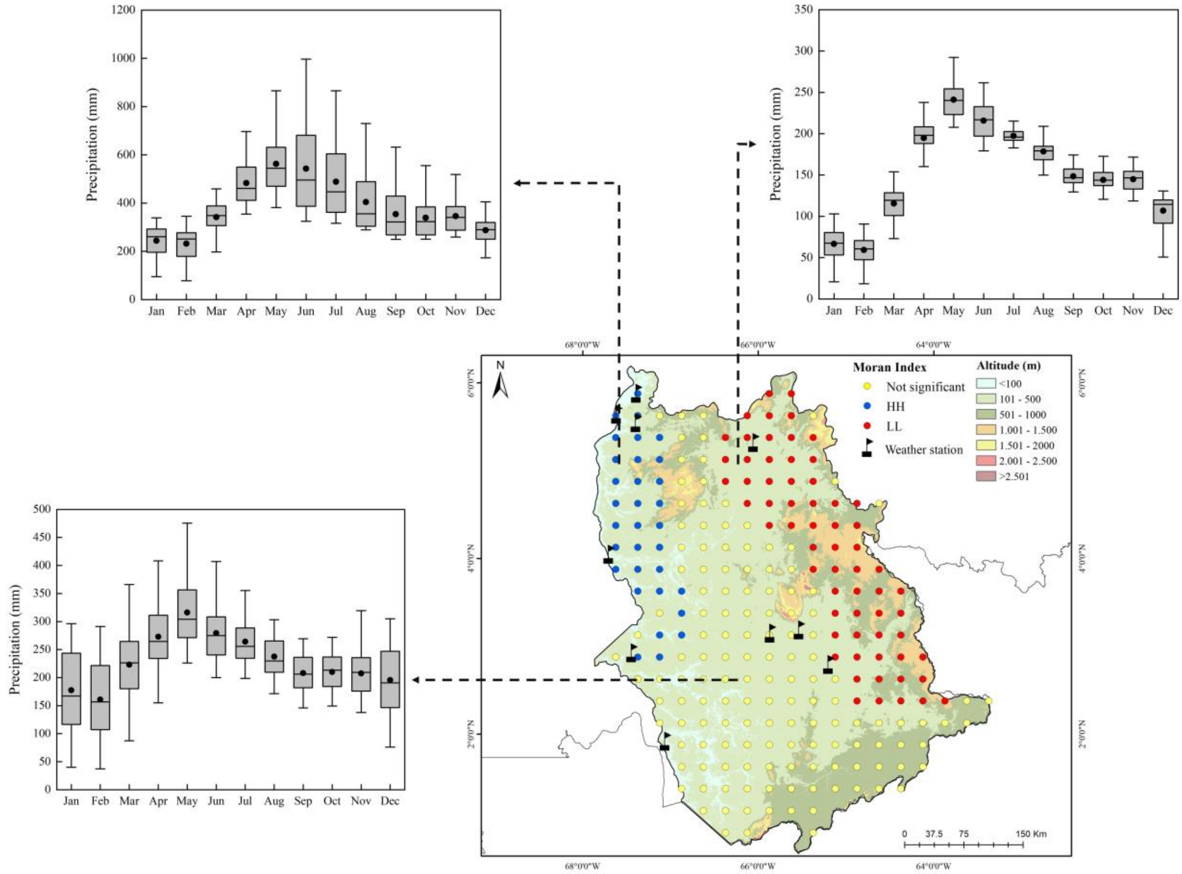


Source: Elaborated by the authors (2020)

Moraes et al. (2020) evaluated the performance of surface stations with ERA-Interim GRID data in the Brazilian Amazon. The authors observed sites with low accuracy in predicting temperature and precipitation on the monthly and 10-day period scale, with R^2 values <0.29. The low performances were mainly concentrated at sites in the northwestern Brazilian Amazon, a border region with the Venezuelan Amazon, due to the reduced network of meteorological observations. On the monthly scale, Li et al. (2008) and Debortoli et al. (2015) identified a stronger seasonal component due to a long-lasting season with less rain in the south of the Amazon. In addition to the reduced monitoring network, the low precision in GRID estimates can be explained by the low coupling of ERA-Interim data to the surface, inherent to the factors that promote the transport of mass and energy in the atmospheric system at different scales further to the local, at the macro and mesoscale level (BETTS & DIAS, 2010). Convective systems in the Amazon are quite complex and heterogeneous and are categorized as a special convective regime different from other regions of the world (BETTS & DIAS, 2010; LIN et al., 2016).

Assessing the local spatial association by ERA-Interim, it is noted that the clusters of precipitation (Moran index) express the variability as a function of the significance level of the local indexes values. However, some locations did not show spatial autocorrelation at a significance level of 5% (Figure 8). This group is located mainly in the central region, north and south of the Venezuelan Amazon. Two significant distinct groups were identified, one of higher precipitation average (HH) and another of low precipitation average (LL). In the HH cluster, LP, PA, G and SFA surface stations predominate, meanwhile in the LL region, the SJM station is predominant. The HH groups have higher precipitation averages between May and June, indicating that in these months, the rain events can reach values of the order of 600 mm, identified in the northwest region (Figure. 8). The lowest accumulated precipitation occurs between January and February, with averages less than 200 mm. The LL grouping presents values of approximately 250 mm in the rainiest month, being concentrated in May and June, and the lowest averages in January and February, being that the average values did not reach 100 mm. The lower average annual precipitation and more extended dry season (4–5 months with <100 mm precipitation), typical of the south and southeastern portions of the Basin, are associated with seasonal shifts in the position of the ITCZ (SILVA FERREIRA et al., 2015; HAGHTALAB et al., 2020; SEGURA et al., 2020).

Figure 8. Cluster map by the Moran index for precipitation in the Venezuelan Amazon. High (HH) and low (LL) precipitation averages.



Source: Elaborated by the authors (2020)

The differences between the north sites were probably associated with the altitude, where convective precipitation at a local scale has a significant influence. Thus, the Upper Orinoco precipitation group is possibly influenced by orographic precipitation from the Parima Mountains. In other regions of the Amazon, the Serra do Mar and Serra da Mantiqueira Mountain chains have an essential role in the intensification of orographic precipitation by contributing to precipitation maximums (GRIMM et al., 2011). On the other hand, probably two atmospheric processes are controlling the identified groups in this study. The first process can be associated with the convection over the continental SACZ, which the moisture transport is controlled by the low-level flow from the tropical Atlantic Ocean, including the Intertropical Convergence Zone (ITCZ). The second process is based on upward motion over the western Amazon, which is conducted by meridional circulation between the tropical North Atlantic and western tropical South America (SEGURA et al., 2020). Previous studies have shown that the precipitation variability in the Amazon can be explained by the manifestation of a wide range of meteorological systems, like the Intertropical Convergence Zone (ITCZ), and South Atlantic Convergence Zone (SACZ), and meso- and local-scale systems (SILVA FERREIRA et al., 2015; SEGURA et al., 2020).

Overall, in the Amazon region, the nucleus of maximum precipitation is associated with atmospheric thermodynamic processes (MARENGO et al., 2012); but it has also been observed that the regions of the Amazon that have the highest precipitation are located near the Atlantic Ocean and are subjected to the preponderant influence of the ITCZ (COE et al., 2016; MARTORANO et al., 2017). Furthermore, the period of higher activity of Southern Atlantic Convergence Zone can probably coincide with the lowest precipitation. For instance, previous studies have documented those warm conditions in the equatorial Pacific (i.e. El Niño events) produce a precipitation deficit in Amazon, which can be extreme, as observed in 2010 and 2016 (PANISSET et al., 2018; MARENGO & ESPINOZA, 2016). Conversely, extreme precipitation and the resulting flooding often have been associated with cold conditions in the equatorial Pacific (i.e. *La Niña* events), such as in 2011 and 2012 (ESPINOZA et al., 2012). In this study, it is presumed that probably the temporal and spatial variability of precipitation in the Venezuelan Amazon can also depend on atmospheric responses to oscillations in ENSO and on the temperature of the surface of the tropical North Atlantic Ocean, a concept that has been corroborated in other studies (MARENGO et al., 2010; 2012; COE et al., 2016; MARTORANO et al., 2017). However, Marengo et al. (2012) state that intense and reduced precipitation are not exclusively associated with ENSO events, but it is also associated to the irregular moisture transport from the tropical North Atlantic Ocean to the Amazon, and from the north to the south of the Amazon, thus altering the interannual water cycle.

CONCLUSIONS

The results show for the first time the temporal and spatial precipitation pattern in the Venezuelan Amazon. Thus, it was observed the typical unimodal pattern of precipitation across the Venezuelan Amazon. A novelty of this study is that two homogeneous groups of precipitation were identified, the first of higher precipitation average located between the west and northwest range of the region and, the second group of lower precipitation average, between the southeast and northeast range. Although more evidence and studies are needed, it is presumed that these precipitation groups can also be affected by two main processes, such as the Intertropical Convergence Zone (ITCZ), and South Atlantic Convergence Zone (SACZ), and meso- and local-scale systems. Furthermore, the variability of precipitation analysis between the GRID data and the ECMWF model in the Venezuelan Amazon showed that precipitation is mainly concentrated in the northwestern region and extends to the southeast, with greater precipitation between May and July, with totals above 800 mm per month. However, it is presumed that there may be a low precision in the GRID estimates due to the reduced network of meteorological stations. This fact can be explained by the low coupling of the ERA-Interim data to the surface, which may be related to the mass and energy transport in the atmospheric system at different spatial scales.

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