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RAINFALL TREND AND VARIABILITY IN RIO GRANDE DO SUL, BRAZIL

Tendência e Variabilidade da chuva no Rio Grande do Sul, Brasil

Tendencia y variabilidad de la lluvia en Rio Grande do Sul, Brasil

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Abstract: Understanding the behavior of precipitation in face of climate change is crucial for mitigating its effects and improving the management of natural resources. Thus, this study investigated the temporal trends and variability of rainfall in the state of Rio Grande do Sul, Brazil. 271 series of Annual Total Rainfall (ATR), Monthly Total Rainfall (MTR), and Annual Maximum Daily Rainfall (AMDR) were analyzed (1912 to 2018). Mann-Kendall, Sen's Slope, and Pettitt's tests were employed for temporal trend analysis, and the Standardized Index of Rainfall Anomalies (SRAI) and the Precipitation Concentration Index (PCI) for variability analysis. A significant increasing trend of ATR was found in 42 series, and a decrease in 3 series. Pettit's test showed the changing year in 30 of 45 ATR's series. Regarding AMDR, an increasing trend was observed in 27 series and a decrease in 8, and the year of change was found in 18 of the 35 séries. The SRAI varied between -3.55 and 2.88, but in most years ART was “near normal”. The annual PCI showed that ART was uniformly distributed over the months in most years. In the North of RS spring has the best distribution of rainfall, while in the South, winter. MTR distribution is more irregular during the Autumn, and in Summer MTR is most irregular in the southwest mesoregion. Given the consequences of changes in rainfall, the importance of studies like this is highlighted for supporting the natural resources management, as the mitigation of socioeconomic and environmental impacts resulting from climate changes.

Keywords: Stationarity. Heavy rainfall. Anomalies. Mann Kendall’s test. Pettitt’s test.

Resumo: Compreender o comportamento da chuva frente às mudanças climáticas é fundamental para mitigar seus efeitos e melhorar a gestão dos recursos naturais. Assim, este estudo investigou as tendências temporais e a variabilidade da chuva no Rio Grande do Sul, Brasil. Foram analisadas 271 séries de Precipitação Total Anual (PTA), Precipitação Total Mensal (PTM) e Precipitação Diária Máxima Anual (PMDA) (1912 a 2018). Os testes Mann-Kendall, Sen's Slope e Pettitt foram empregados para análise de tendência, e o Índice Padronizado de Anomalias de Chuva (IAC) e o Índice de Concentração de Precipitação (ICP) para análise de variabilidade. Foram encontradas tendencias de aumento significativo 42 séries de PTA e de diminuição em 3. O teste Pettit mostrou o ano de mudança em 30 das 45 séries de PTA. Em relação à PMDA, observou-se tendência de aumento em 27 séries e diminuição em 8, e o ano de mudança foi encontrado em 18 das 35 séries. O IAC variou entre -3,55 e 2,88, mas na maioria dos anos a PTA foi “aproximadamente normal”. O ICP anual mostrou que a PTA foi uniforme nos meses da maioria dos anos. No Norte a primavera tem a melhor distribuição das chuvas, enquanto no Sul, o inverno. A distribuição da PTM é mais irregular no outono, e no verão a PTM é mais irregular na mesorregião sudoeste. Diante das consequências das mudanças na chuva, destaca-se a importância desses estudos para subsidiar a gestão dos recursos naturais, mitigando os impactos socioeconômicos e ambientais decorrentes das mudanças climáticas.

Palavras-chave: Estacionariedade. Chuvas intensas. Anomalias. Teste Mann-Kendall. Teste Pettitt.

Resumen: Entender el comportamiento de la lluvia ante el cambio climático es fundamental para mitigar sus efectos y mejorar la gestión de los recursos naturales. Así, este estudio investigó las tendencias temporales y la variabilidad de la lluvia en Rio Grande do Sul, Brasil. Se analizaron 271 series de Precipitación Total Anual (PTA), Precipitación Total Mensual (PTM) y Precipitación Máxima Diaria Anual (PMDA) (1912 a 2018). Se utilizaron las pruebas de Mann-Kendall, Sen’s Slope y Pettitt para el análisis de tendencia, y el Índice de Anomalías de Lluvia (IAC) y el Índice de Concentración de Precipitación (ICP) para el análisis de variabilidad. Se encontraron tendencias significativas positivas en 42 series de PTA y negativas en 3. La prueba de Pettit mostró el año de cambio en 30 de las 45 series de PTA. Relativo a PMDA, se observó una tendencia de aumento en 27 series y una disminución en 8, y el año de cambio se encontró en 18 de las 35 series. El IAC osciló entre -3,55 y 2,88, pero en la mayoría de los años el PTA fue “aproximadamente normal”. El ICP anual mostró que la PTA fue uniforme en los meses de la mayoría de los años. En el Norte, la primavera presenta la mejor distribución de las lluvias, mientras que en el Sur, el invierno. La distribución de PTM es más irregular en otoño, y en verano la PTM es más irregular en la mesorregión suroeste. Dadas las consecuencias de los cambios en las precipitaciones, se destaca la importancia de estos estudios para apoyar la gestión de los recursos naturales, mitigando los impactos socioeconómicos y ambientales derivados del cambio climático.

Palabras clave: Estacionariedad. Lluvias intensas. Anomalías. Prueba de Mann-Kendall. Prueba de Pettitt.

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1. INTRODUCTION

Global warming and climate change are considered the most serious environmental problems of the 21st century, especially in developing countries (BIRARA et al. 2018). According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), impacts can already be noticed in several places, such as changes in extreme meteorological and climatic events.

An increasing trend on the global average temperature of 0.85°C, was observed, between 1880 and 2012, and in extreme rainfall events, which are more intense and frequent at tropical humid places and medium latitudes (IPCC, 2014). In Brazil, the climate scenario is similar to the global trend, with significant changes in temperature, rainfall patterns, and climatic extremes such as droughts and floods (ASSIS et al. 2012).

In this context, rainfall is one of the most important variables as its behavior influences environmental, economic, and social dynamics. Information about this variable is used to support natural resources management, but its consequences in extreme situations such as droughts, floods in rural and urban areas, soil erosion, and landslides can cause serious losses and damages to socioeconomic activities and the environment (SOARES et al. 2014; OLIVEIRA, 2019).

In developing countries, agricultural production remains the main source of income in most rural areas (BIRARA et al. 2018). Currently, the southern region of Brazil has a good part of the economy associated with agribusiness and the climatic variability can determine favorable years or losses in production. In Rio Grande do Sul state (RS), approximately 10% of the Gross Domestic Product (GDP) is of agricultural origin (IBGE, 2014). However, most of the agricultural areas are not irrigated, making crops highly dependent on rainfall that occurs during crop development (CERA; FERRAZ, 2015; RADIN et al. 2018).

Thus, in the face of the effects of climate change, adaptations in many sectors of the economy will be crucial to protect the means of production and ensure, for example, food security. Since rainfall variability and trends are often mentioned as facilitators of socioeconomic and environmental problems and, given the uncertainty in the dynamics of hydrological processes, studies have been conducted to investigate the spatial and temporal behavior of rainfall (BIRARA et al. 2018; SOBRAL et al. 2018).

Rainfall variability can be analyzed using simple statistics or climatic indexes to check anomalies and their distribution throughout time, while changes and temporal trends in hydrological series can be are examined using parametric and non-parametric tests (ASFAW et al. 2018). For this purpose, non-parametric tests such as Mann-Whitney (Mann; Whitney, 1947), Friedman (Friedman, 1937), Mann-Kendall (Mann, 1945; Kendall, 1975), Sen's Slope (Sen, 1968), and Pettitt (Pettitt, 1979) are the most frequently used for not requiring that the data conform to a normal distribution and are more resistant to abrupt changes and gaps in the series (ONYUTHA, 2016).

Around the world, several studies point to changes in rainfall patterns. Bari et al. (2016) found an increase in pre-and post-monsoon rainfall in almost all seasons of Bangladesh's northern region. Amiri and Mesgari (2017) modeled the temporal variability of rainfall in Northeast Iran, using the Precipitation Concentration Index (PCI), and found high interannual variability in the mean annual total rainfall. Asfaw et al. (2018), analyzing the variability and trends in rainfall and temperature in Ethiopia, found an inter-annual and intra-annual variability of rainfall thru the PCI and the Standardized Index of Rain Anomalies (SRAI) demonstrated an increase in the number of dry years. Besides, with Mann-Kendall's (MK) test, a significant increasing trend in mean temperature was observed. However, there may be temporal and spatial variations between climatically different regions, considering that global changes are not uniform (AKINSANOLA et al. 2015).

According to Sobral et al. (2018), Brazil constantly suffers from extreme events, especially of heavy rainfall events, floods, landslides and droughts. Pinheiro et al. (2013), analyzing rainfall series of 18 rain gauges in Southern Brazil, found significant increasing trends in 16. Silva et al. (2017) studied the variability of the SRAI in the Brazilian Northeast, between 1975 and 2016, and found a decrease in the rainfall regime in the last seven years. Gonçalves and Back (2018) investigated the rainfall variability and trends in southern Brazil and found that in its extreme south rainfall is well distributed throughout the year, but in the north, there is a rainy season that goes from spring to autumn. Also, summer was the season with the greatest number of series showing an increasing trend of rainfall. Sobral et al. (2018), evaluating the spatial and interannual variability of rainfall in the state of Rio de Janeiro, found that the total annual rainfall in the northern region has high variability.

Given the above and the effects of global climate change, it is evident the need to understand the spatial and temporal behavior of rainfall to anticipate future scenarios and support water and other natural resources management. Thus, this study aimed to investigate temporal trends and variability of rainfall in the state of Rio Grande do Sul, southern Brazil.

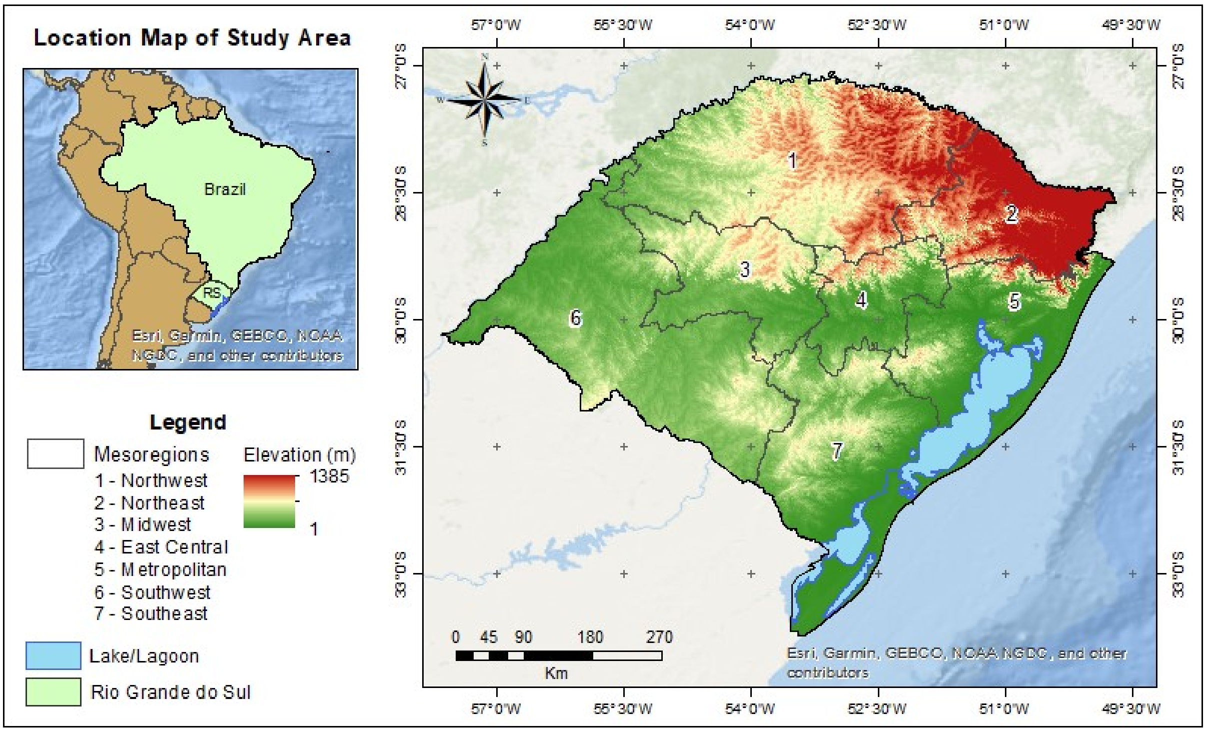
2. METHODOLOGY

2.1. Study Area

The state of Rio Grande do Sul (RS) is located in the southern region of Brazil (Figure 1), between the longitudes -49º and -58º and latitudes -27º and -34º. With an area of approximately 282.000 km², RS is subdivided into 497 municipalities with an estimated population of 11 million inhabitants (IBGE, 2019).

The RS relief (Fig.1) consists of plateaus, depressions, mountains, and the coastal plain. Regarding vegetation, it is characteristic of two important Brazilian biomes: the Atlantic Forest and the Pampa. The Atlantic Forest is present in the North-Northeast of RS, occupying 37% of the territory. Currently, only 7.5% of the remaining areas of the Atlantic Forest remain, with a high degree of fragmentation concerning the original vegetation cover. The Pampa covers 63% of the territory and extends throughout the southern half and the western frontier (ROESCH et al. 2009; IBGE 2019), with the presence of grasses, creeping plants, some trees, shrubs, and non-dominant forest formations (KUPLICH et al. 2018).

Figure 1 - Location of the study area and its relief, illustrated by the digital elevation model.



Source: the authors.

According to Fritzsons et al. (2015), the climate of RS is mainly influenced by the relief, altitude, latitude and distance from the sea. Kuinchtner and Buriol (2001), using Köppen's climatic classification, inserted RS's climate into types Cfa and Cfb: subtropical humid and super humid in all seasons, with warm and moderately warm summer, respectively. The Cfa climate is predominant in the state, while the Cfb type occurs only at the highest parts of the Plateau and the Northeast and Southeast Mountain ranges.

Rainfall is well distributed throughout the year, as the state is located in a mid-latitude that receives precipitating systems of tropical and extratropical origin (SATYAMURTY et al. 1998; GRIMM, 2009; NUNES; PEREIRA, 2017). However, the average monthly rainfall is not spatially homogeneous and varies seasonally. According to Reboita et al. (2010), generally, the northern half of RS has higher rainfall values, except in the coldest semester, whose greater presence of polar air masses from the South makes the distribution of precipitation more homogeneous, causing the Southern RS to present its greatest volumes in this period.

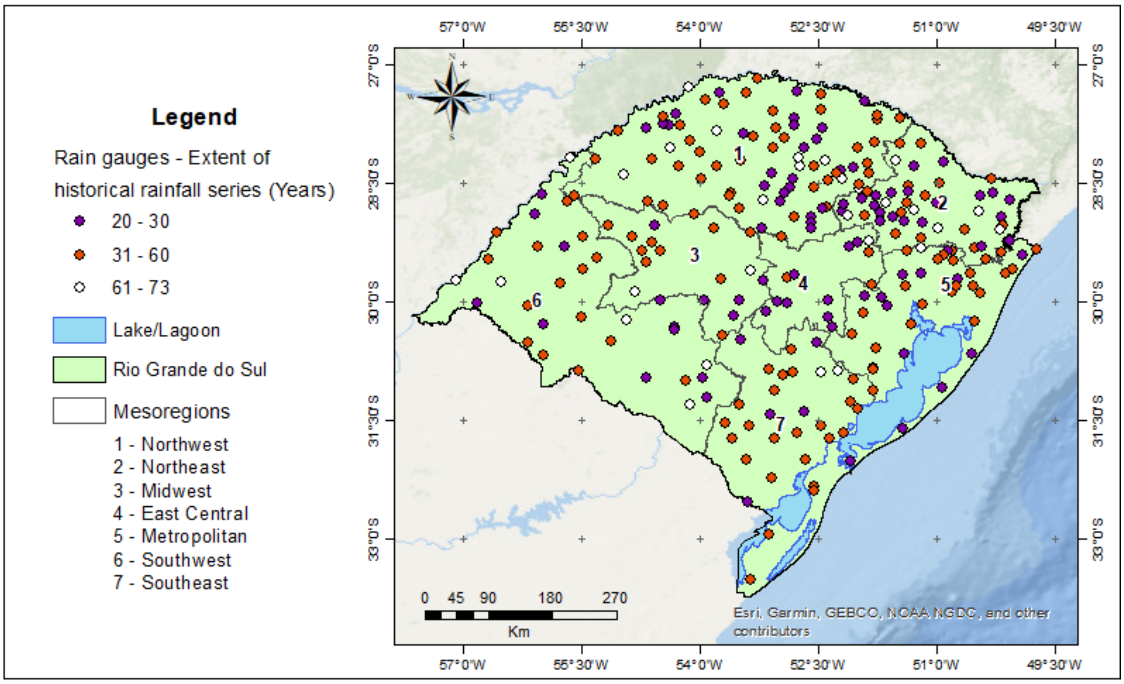
In the hot semester (from October to April), convective rainfall gains importance due to convective systems of continental origin, coming from surface heating and wet transport from the North (REBOITA et al. 2010). The flow from the North, which comes from the

Amazon, transports heat and humidity to the Chaco plain, feeding back into the continental low-pressure center (SALIO et al. 2007). Such a system acts as a source of convective systems (SELUCHI; SAULO, 2012) that, transported by the west flow at high levels, reach the RS frequently and, especially, the North half (VELASCO; FRITSCH, 1987; GRIMM, 2009). Commonly, the continental low-pressure center evolves into an extratropical cyclone off the coast of Uruguay (GAN; RAO, 1991), passing through RS and causing instability (CABALLERO et al. 2018). In addition, changes in the precipitation regime happen when phenomena such as La Niña and El Niño - South Oscillation (ENOS) occur (MATZENAUER et al. 2017).

2.2. Hydrological data

Historical series of total daily rainfall of 554 rain gauges were acquired from the HydroWeb - Hydrological Information System of the National Water Agency (ANA). After the processing following the failure criteria, the historical series of the variables Annual Total Rainfall (ATR) and Annual Maximum Daily Rainfall (AMDR) were constituted considering the years with up to 30 days of failure, and Monthly Total Rainfall (MTR), considering months with up to 3 days, as shown in Figure 2.

Figure 2 - Spatial distribution of rain gauges whose data met the criteria established for the constitution of the rainfall series, as well as the extension of the series.



Source: the authors.

Thus, the hydrological data was processed using the System of Hydrological Data Acquisition and Analysis (SYHDA) (VARGAS et al. 2019), and from the processing of 554 rain gauges series, 271 series of ATR, MTR, and AMDR were obtained, with extension between 20 and 73 years (Figure 2).

2.3. Trend analysis

The trend analysis was conducted in the ATR and AMDR series according to the recommendations of the World Meteorological Organization (WMO), that is, using the Mann-Kendall (MK) non-parametric trend test (IRANNEZHAD et al. 2016), associated with the Sen's Slope (SS) test. The MK test (MANN, 1945; KENDALL, 1975) is widely used to detect significant monotonic trends in hydrometeorological series (ZAMANI et al. 2016). In this test, each value in the series is compared with the remaining values, in sequential order, counting the number of times that the remaining terms are less than or greater than the value analyzed.

The S statistic of MK test is calculated by the following (Mann, 1945; Kendall, 1975):

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} Signal(x_j - x_i) \quad (1)$$

Em que:

$$Signal = \begin{cases} 1\ se\ (x_j - x_i) > 0 \\ 0\ se\ (x_j - x_i) = 0 \\ -1\ se\ (x_j - x_i) < 0 \end{cases} \quad (2)$$

where S is the test’s statistic, x_j e x_i are the Variable values at the timesteps j e i, and n is the number of obserations of the serie in question. The probability associated to S is calculated to quantify the significancy of the trend, using the Z_{MK} statistic:

$$Z_{MK_{Calc}} = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}\ se\ S > 0 \\ 0\ se\ S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}\ se\ S < 0 \end{cases} \quad (3)$$

with Z been the Standardized statistic of the test.

The null hypothesis (H_0) tested is that the data constitute a random sample of N independent and identically distributed values, that is, there is no trend in the series. To assess the presence of a statistically significant trend, the Z_{MK} is compared with the level of significance (α) adopted for the test.

The SS test (SEN, 1968) aims to provide the magnitude of the statistically significant trend. The SS selects, among all the slope lines formed by each pair of points in the sample, the one corresponding to the median slope, indicating whether or not there was a trend and its magnitude (YUE et al. 2002; HUANG et al. 2014):

$$Q_j = \frac{(x_j - x_i)}{j - k} \tag{4}$$

where i = 1, 2, ... n; n is the number of pairs at the serie of the variable, x_j e x_k are the Variable values at the timesteps j e k. The median (β) of the values of Q_i represents the magnitude of the trend and its calculated by equations 5 and 6:

$$\beta = \frac{1}{2}\left(\frac{Q_n}{2} + \frac{Q_{n+2}}{2}\right) \; if \; n \; is \; even \tag{5}$$

$$\beta = \left(\frac{Q_{n+1}}{2}\right) \; if \; n \; is \; odd \tag{6}$$

Although the MK and Sen's Slope tests provide information about the trend and its magnitude in the hydrological series, it is not possible to infer about the moment over the time when the change occurred in the data. For this purpose, the Pettitt test was used.

Pettitt's test (PETTITT, 1979) is a non-parametric homogeneity test that aims to identify a point of change in the historical series of a continuous variable. The test checks whether two observations belong to the same population and finds the point of sudden change in the series mean.

The U statistic of Pettitt's test is given by the equation (Pettitt, 1979):

$$U_{t,T} = \sum_{j=1}^{t} \sum_{j=i+1}^{T} D_{ji} = \begin{cases} -1 \; if \; (x_j - x_i) > 0 \\ 0 \; if \; (x_j - x_i) = 0 \\ 1 \; if \; (x_j - x_i) < 0 \end{cases} \tag{7}$$

In this test, the null hypothesis (H0) tested is that there is no significant point of abrupt change in the series. The MK, SS, and Pettitt tests were performed with *RStudio*, considering a significance level of 5% (α = 0.05).

2.4. Variability analysis

Rainfall variability was investigated on the AMDR, ATR and MTR series with no significant trend, using the Standardized Rainfall Anomaly Index (SRAI) and the Precipitation Concentration Index (PCI). SRAI (ROOY, 1965) allows the identification of dry and rainy years in a historical series of ATR and has been widely used to assess the occurrence and severity of droughts (WMO, 2012). SRAI is calculated by the equation (ALEMU; BAWOKE, 2019):

$$SRAI_i = \frac{x_i - \bar{x}}{s} \qquad (8)$$

Where $SRAI_i$ is the Standardized Rainfall Anomaly Index for the year i; X_i is the Annual Total Rainfall (ATR) recorded in the year i (mm); $\bar{X}$ is the mean ATR of the series over the observed period (mm) and S is the standard deviation of the ATR during the observed period (mm). SRAI's classification was performed as proposed by McKee (1993), described in Table 1.

Table 1 - SRAI classification according to McKee (1993).

Standardized Rainfall Anomaly Index (SRAI)	Category
> 2	Extremely wet
1,5 to 1,9	Very wet
1,0 to 1,49	Moderately wet
0,99 to -0,99	Near normal to Normal
-1,0 to -1,49	Moderately dry
-1,5 to -1,99	Severely dry
> -2	Extremely dry

Source: the authors.

The PCI (OLIVER, 1980) provides an understanding of rainfall temporal distribution over months or seasons and can be used as an indicator of hydrological risks such as droughts and floods (GOCIC et al. 2016). The PCI is calculated using the Monthly Total Rainfall (MTR) series, and on the annual and seasonal scales, given by equations 2 and 3 (DE LUIS et al. 2011):

$$PCI_{Annual} = \frac{\sum_{i=1}^{12} {P_i}^2}{(\sum_{i=1}^{12} P_i)^2} * 100 \qquad (9)$$

Where PCI_{Annual} is the Precipitation Concentration Index on an annual scale and P_i is the MTR of the month i (mm).

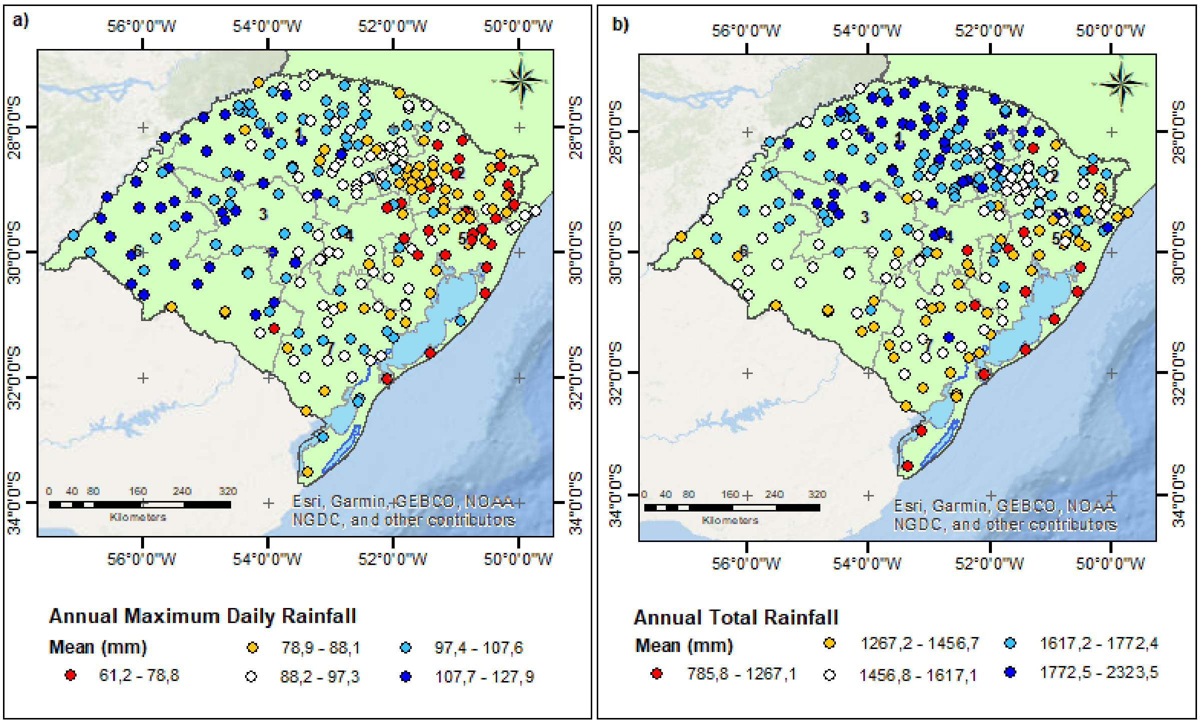
$$PCI_{Seasonal} = \frac{\sum_{i=1}^{3} {P_i}^2}{(\sum_{i=1}^{3} P_i)^2} * 25 \quad (10)$$

Where $PCI_{Seasonal}$ is the Precipitation Concentration Index on a seasonal scale and P_i is the MTR of the i month of the season considered (mm). For the $PCI_{Seasonal}$, the months of January, February and March were included in the summer; April, May and June in the autumn; July, August and September in winter; and October, November and December in the spring. Oliver (1980) suggests (for both scales) that PCI ≤ 10 indicate a uniform distribution of precipitation; 11 ≤ PCI ≤ 15 indicates a moderate concentration of precipitation; 16 ≤ PCI ≤ 20 indicate an irregular distribution of precipitation; and PCI ≥ 21 indicate a strong irregularity in the distribution of rain (high concentration).

3. RESULTS AND DISCUSSION

Figures 3a and 3b show the spatial distribution of the mean values of ATR and AMDR, respectively. The average ATR varied between 785.8 mm and 2323.5 mm, with the highest values in the Northwest of RS and the lowest in the coastal region (Fig.3b). In 211 series the CV is considered moderate to high, as it varies between 20.01% and 40%, and in only 2 the CV values are classified as very high (> 40%) (HADJU et al. 2013). In general, a difference was observed in the spatial variation of the ATR when analyzing only the plateau region of the Sierra of Northeast and the rest of the RS. According to Cera and Ferraz (2015), the cold fronts that regularly pass through the state do favor this good distribution of rainfall. However, AMDR varied considerably, as it is heavily influenced by specific local characteristics and the orographic effect, which conditions its high spatial and temporal variability.

Figure 3 - Spatial distribution of the mean values of Annual Maximum Daily Rainfall (AMDR) (a) and Annual Total Rainfall (ATR) (b) based on the analyzed series



Source: the authors.

The mean AMDR varied between 61.20 mm and 127.90 mm (Fig.3a). The lowest AMDR values were observed in the Northeast and Metropolitan mesoregions, and on the Southeast coast, while the highest average AMDRs (between 97.37 mm and 127.85 mm) were observed in the Northwest, Midwest and Southwest mesoregions, in 107 rain gauges (38%). AMDR's CV ranged between 12.55% and 52.53%, and it's considered low in only 11 series, whose rain gauges are located in the Northwest and Northeast mesoregions. CV value is between 20.01 and 30% in 180 series, classified as moderate, and in 73, is considered high. In other series, the CV is very high, according to Hadju et al. (2013).

Also, it is important to highlight that in these places occur the highest levels of the annual rainfall erosivity of RS (between 8000 and 12000 $MJ.mm.ha^{-1}.h^{-1}$ per year) (ROESCH et al. 2009; TRINDADE et al. 2016). Besides, Latosols, Argisols, and Litolic Neossols (SEPLAG, 2019) are also found in that area, in addition to the Pampa biome, which mainly due to their textural and cultivation characteristics become more susceptible to water erosion. Therefore, this combination of heavy and erosive rainfall, soils with a low tolerance for Erosion, and a degrading biome demonstrates the fragility of the environment and points to the importance of analyzing the behavior of rainfall in these regions, for example, to adapt practices of management and conservation of soil and water.

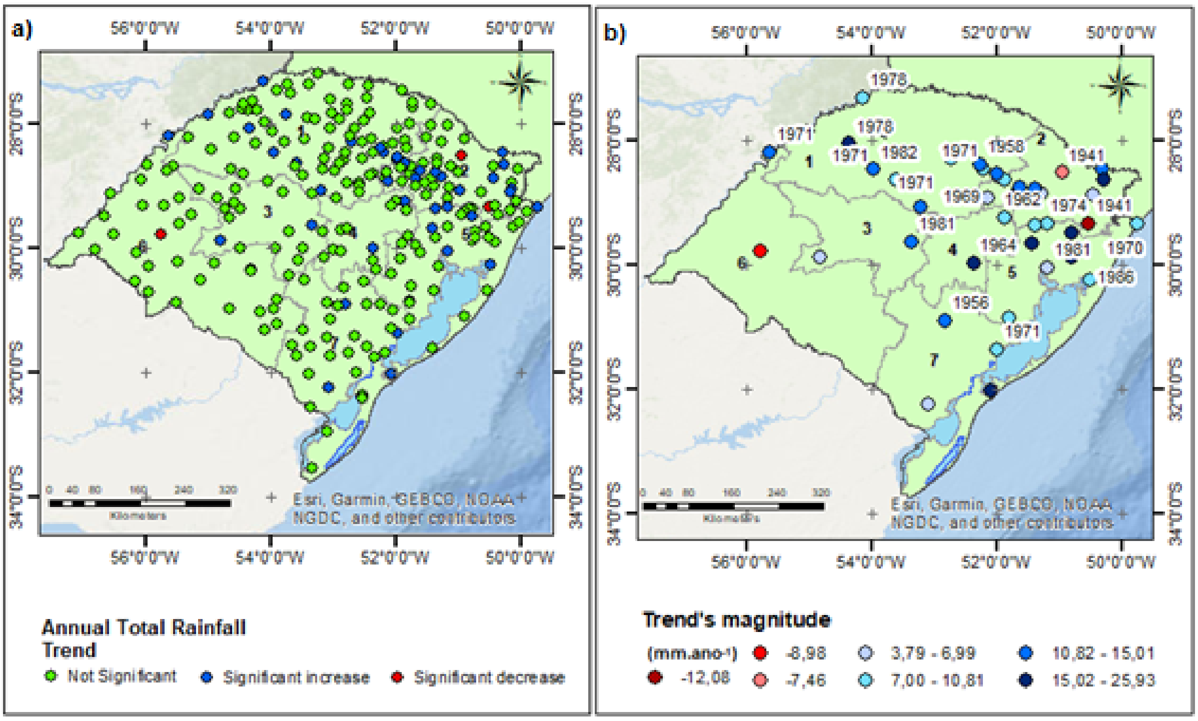
3.1. Temporal trends

3.1.1. Annual Total Rainfall (ATR)

With MK's test, significant trends were found in 45 of 271 historical ATR series. In Figure 4a it is shown the location of the 42 rain gauges whose series showed an increasing trend, and the 3 whose series showed a decreasing trend for the ATR. Most are located in the northern half of RS, at Northwest, Northeast, and Metropolitan mesoregions. The series whose trend was significant has 50 years, on average. In Figure 4b it is possible to verify the magnitude of the increasing or decreasing trend in ATR.

In the series with a decreasing trend in ATR, the magnitude varied between -7.46 mm.year^{-1} and -12.08 mm.year^{-1}. In the series with an increasing trend of ATR, the magnitude varied between 3.79 mm.year^{-1} and 25.93 mm.year^{-1} (Fig.4b). The highest positive magnitudes (> 10 mm.year^{-1}) are located, mainly, in the Northwest, Northeast, and Metropolitan mesoregions, where the highest volumes of ATR occur. These results corroborate those obtained by Guedes et al. (2019), who found a positive trend in 4 of 8 ATR series in the North of RS, and Cera and Ferraz (2015) and Sansigolo and Kayano (2010), who also obtained similar results by studying rainfall in RS.

Figure 4 - Result of the Mann-Kendall test (a) and Sen's Slope and Pettitt's tests (b) of the ATR series. Obs.: It is identified in (b), in the form of a label, the year in which there was a significant change in the series, according to Pettitt's test.

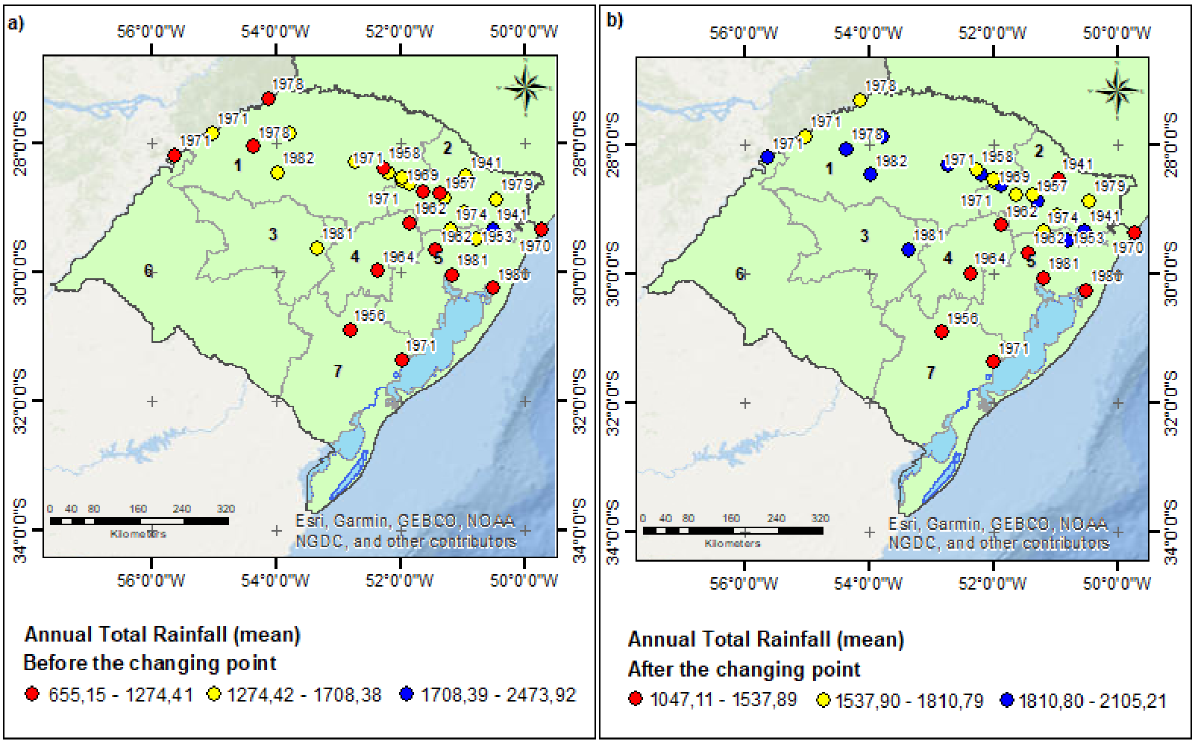


Source: the authors.

Pettitt's test identified the year in which there was a significant abrupt change in 30 of the 45 series of ATR, in which 9 showed a change in 1971 (Fig.4b) with an increase in the average ATR of the series (Figure 5). Figure 5 is showing the average of the ATR series before (5a) and after (5b) the year of change in the series.

The smallest increases in the average ATR, after the year of change, occur in series of the Southeast, Center-East, and Metropolitan mesoregions. On the other hand, the biggest differences are located in the Northeast and Northwest regions, in which there was, predominantly, an increase in ATR. At rain gauge 2855001, in the Northwest mesoregion, the average ATR of the series before 1971 was 1232.10 mm, and afterward, 1948.43 mm.

Figure 5 - Average ATR of the series before (a) and after (b) the year of change identified by the Pettitt test.



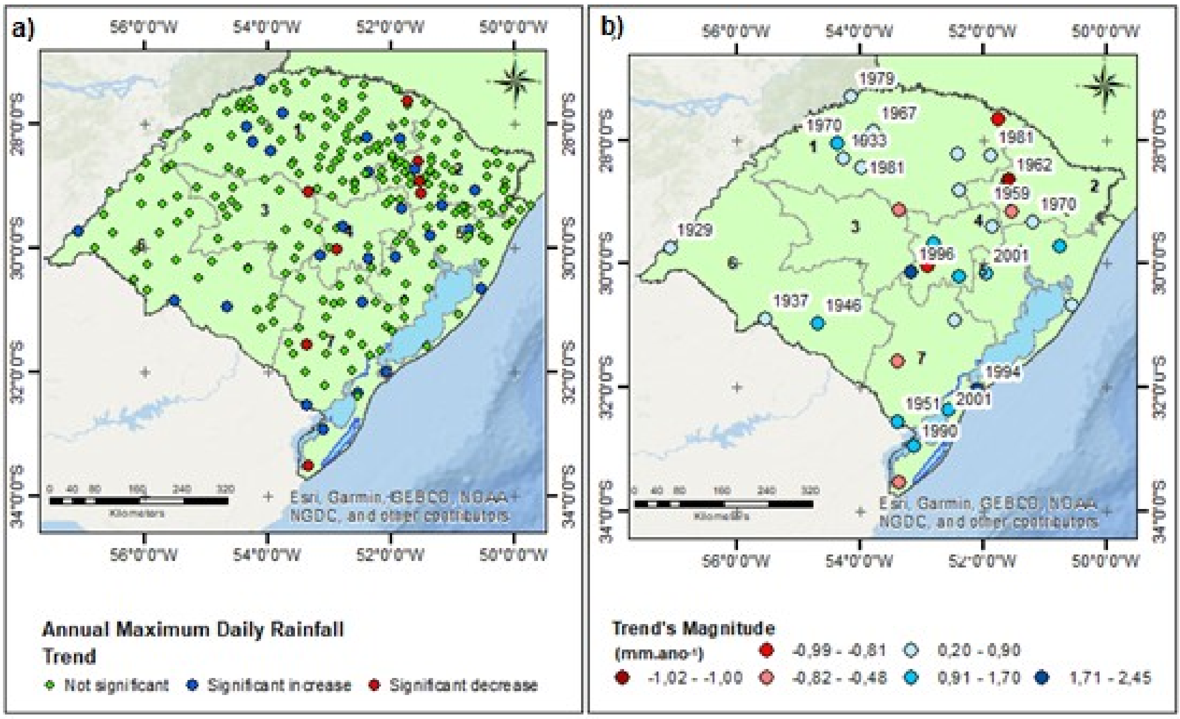
Source: the authors.

3.1.2. Annual Máximum Daily Rainfall (AMDR)

MK's test results showed a significant trend in 35 of the 271 series of AMDR (Fig.6a), in which 27 were increasing and 8 were decreasing. Most of the series with trend are in the northern half of RS and the average length of the series is approximately 45 years, with 14 of the 35 series between 22 and 33 years old. Among the 33 series that showed a trend, only 2 can be considered of low variability (CV <20%), which is another important point related to the use of the MK test. According to Yue et al. (2002), series characteristics such as size and variability are strictly related to the power of the test to detect trends, which may influence the results.

The magnitude of the decrease (Fig.6b) of the AMDR varied between -1.02 mm.year^{-1} and -0.48 mm year^{-1}, while the increase was between 0.20 mm.year^{-1} and 2.45 mm .year^{-1}. Of the series with a negative trend, the highest magnitudes were found in the North region, decreasing in the South direction, while the highest positive magnitudes (between 1 mm.year^{-1} and 2.5 mm.year^{-1}) are located in the Southeast portion of RS. These results are similar to those found by Gonçalves and Back (2018), who found significant trends of increased rainfall in the Southeast region of RS.

Figure 6 - Result of the Mann-Kendall test (a) and Sen's Slope and Pettitt's tests (b) of the AMDR series. Obs.: It is identified in (b), in the form of a label, the year in which there was a significant change in the series, according to Pettitt's test.



Source: the authors.

Of the 35 series with a significant trend, the year detected by the Pettitt's test was significant in 18 (Fig.6b). The results of the SS and Pettitt's test for the AMDR series, where the changing point was significant, can be seen in Table 2. The changing years in the AMDR series varied considerably, but in the North, there is a predominance of the period between 1960 and 1980, and in the coast and central region of the state, within the last 20 years.

Of the 18 rain gauges where the year of change in the series was significant, in 16 the trend was for an increase in AMDR. In these series, the change in AMDR of the series was 28.46 mm, on average, and these values varied by about 37%. At station 2854003, in the Northwest region, was observed the greatest difference in the average before and after the changing year (1970), equal to 50.20 mm.

In the series with a negative trend (2851002 and 2951003), the difference in the average of the AMDR series was 19.10 mm, when compared before and after the changing point. As AMDR is often used in modeling the design storm for hydraulic structures' projects, an increase in AMDR can influence the intensity-duration-frequency (IDF) relationship of heavy rainfall, which may result in a decrease in the capacity of hydraulic structures to control floods and inundations.

Table 2 - Results of Sen's Slope and Pettitt's tests of the AMDR series in which the identified changing point was significant.

Rain gauge number	Observed period	Trends magnitude ($mm.year^{-1}$)	Changing point (year)	*p* value	μ_1 – mean of the series before the changing point (mm)	μ_2 - mean of the series after the changing point (mm)
2753007	1948-2012	0.282	1967	0.015	91.69	109.83
2754001	1950-2016	0.805	1979	0.00009	70.45	99.88
2851002	1953-1979	-1.020	1966	0.013	92.44	73.69
2851020	1963-2012	0.513	1981	0.036	82.78	100.62
2853003	1960-2018	0.584	1981	0.010	87.59	114.27
2854003	1945-2016	0.985	1970	0.0003	52.44	102.65
2854007	1915-1983	0.662	1933	0.00008	71.51	103.65
2951003	1936-1997	-0.595	1959	0.005	88.28	68.80
2951022	1944-2016	0.380	1970	0.008	76.44	93.35
2957001	1913-1998	0.691	1929	0.001	76.77	115.91
3051031	1983-2016	1.116	2001	0.025	78.99	97.19
3053021	1987-2016	2.340	1996	0.016	72.07	104.14
3054014	1934-1961	1.198	1946	0.001	67.36	99.28
3055001	1913-1982	0.375	1937	0.011	75.88	93.67
3252006	1965-2018	0.986	2001	0.038	88.49	118.18
3252024	1986-2017	2.450	1994	0.010	43.07	90.28
3253003	1966-2017	1.033	1990	0.024	83.41	112.11
3253005	1934-1962	1.035	1951	0.034	71.93	91.26

Source: the authors.

Furthermore, the hydromorphic soils in the region are characterized as naturally poorly drained (DA SILVA; PARFITT, 2004). Zanchin et al. (2017) mentioned that, between 2003 and 2015, cities in the southern RS (such as Pelotas, Rio Grande, Piratini, and São Lourenço do Sul) already observe the effects of changes in rainfall, as almost 58% of natural disasters that occur in municipalities of southern RS are floods and flash floods.

In addition, in places that showed an increasing trend of ATR and AMDR, and soils susceptible to erosion occur, an increase in erosion processes and, consequently, soil loss may be observed. In the Southwest mesoregion, for example, in which the erosive potential of rainfall is high, in association with the type, use and land cover, it can suffer from high rates of soil loss (ROESCH et al. 2009; TRINDADE et al. 2016).

Another point raised by Fernandes and Amaral (1996) is that both extreme rainfall events and rainy periods can contribute to mass movements occurrence, as both promote soil waterlogging. The Northeast and Northwest regions, in which there was an increase in ATR and AMDR, are inserted in the geomorphological unit of Escarpa da Serra Geral, characterized as an area with rugged, sloping terrain and susceptible to mass movements (LEMOS, 2014). The most common movements are the shallows of the type “slides”, which happen in the contact between the rock and the soil, mainly in places of superficial and low developed soils (PAIXÃO, 2015). According to Reckziegel (2012), between 1991 and 2005, 48 mass movements were identified in RS, but only 5 were notified to the Civil Defense. Thus, these results indicate locations that may need attention and reinforce the importance of knowledge about changes in rainfall, mainly to anticipate and minimize its undesired effects on the environment and socioeconomic conditions.

3.2. Variability

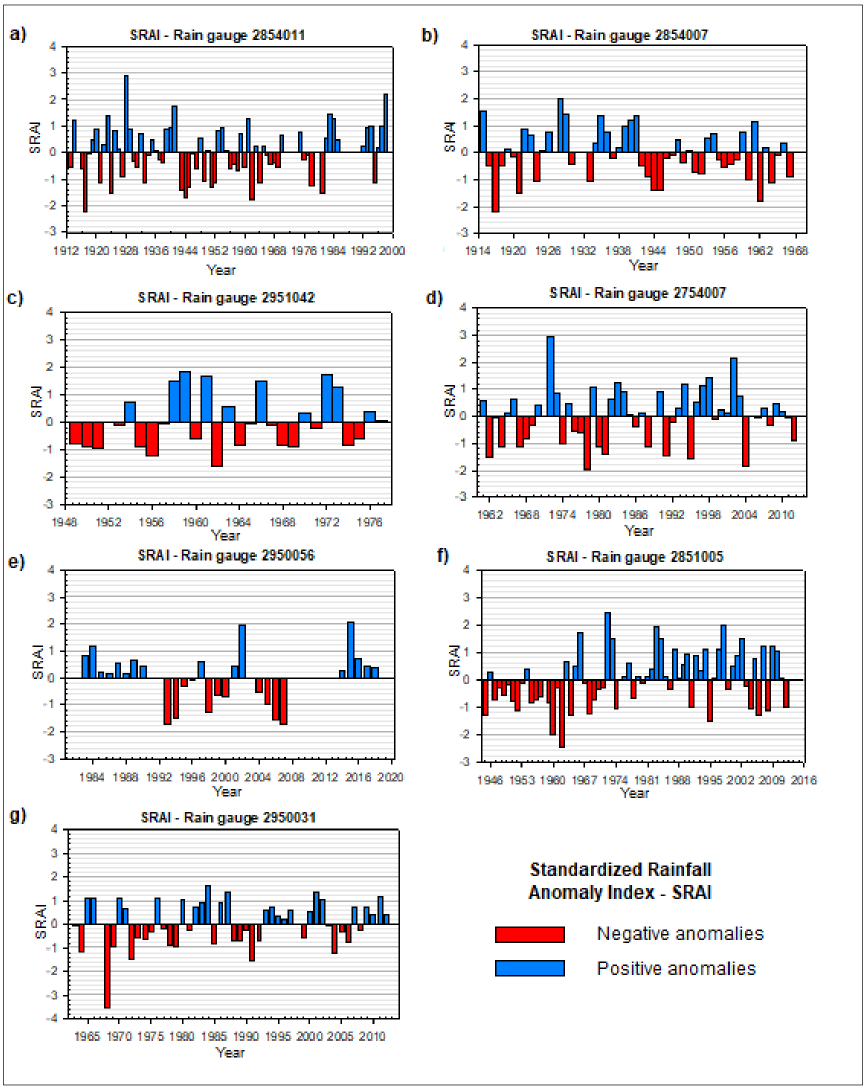
3.2.1. Standardized Rainfall Anomaly Index (SRAI)

The SRAI analysis showed that the index varied between -3.55 and 2.88. According to McKee's classification (1993), most years (between 58% and 80% of the years between 1912 and 2018) were approximately normal concerning ATR. The presence of more wet than dry years was also noted, but the difference is small.

Given the large number of stations used, in Figure 7 it's shown only the graphs of the ATR series in which the highest SRAI values were observed in each class. In the rain gauge 2854011 (Fig.7a), located in the Northwest mesoregion of the state, the greatest positive anomaly of the “extremely wet” class (2.88) occurred in 1928, in which the ATR reached almost 2900 mm. In the serie of rain gauge 2854007 (Fig.7b), the largest SRAI was found to be classified as “very wet”, also in 1928, in which the ATR was approximately 2700 mm. In the serie of rain gauge 2951042 (Fig.7c), located in the Northeast mesoregion of the state, there was the greatest positive anomaly of the "moderately wet" class (1.49) in 1958.

Figure 7d shows the SRAI of the serie of rain gauge 2754007, in which the highest value of the class "approximately normal to normal" was found. About the negative anomalies, the series graph of rain gauge 2950056 (Fig.7e), located on the border with the state of Santa Catarina, shows the biggest negative anomaly of the "moderately dry" class (-1.497), but despite that, it is highlighted that the SRAI of the first eight years of the serie were positive. For the "severely dry" class, the maximum SRAI occurred at the serie of rain gauge 2851005 (Fig.7f), located in the North-Northeast mesoregion of the state.

Figure 7 - SRAI of the series which had the highest values of the classes "extremely wet" (a), "very wet" (b), "moderately wet" (c), "near normal to normal" (d), "moderately dry "(E)," severely dry "(f) and" extremely dry "(g).



Source: the authors.

The Index value was -1.999, in 1960, in which the ATR was equal to just over 1000 mm. The most extreme value of SRAI, equal to -3.55, was found at the series of rain gauge 2950031 (Fig.7g), in 1962. The rain gauge is located in the Northeast mesoregion, where the annual total this year was only 591 mm. Although the rain gauges mentioned above are found only in the northern region of the state, a difference has been identified regarding the spatial distribution of anomalies: in the series of rain gauges located in the north of the state, except for normal years, there are more moderately wet years and extremely wet than moderately dry and extremely dry; in the southern half, however, the reverse was observed.

A hypothesis for this would be the intensification of the forces that cause, climatologically, the northern half of the state to present rain in greater quantity than the southern half. As already mentioned, the low, hot and wet flow from the Amazon is associated with precipitating systems, that tend to reach the northern half of the state, preferably. When this flow is intensified and respects some criteria (originally, those of BONNER (1968)), it is possible to observe the Low-Level Jet (LLJ) (SALIO et al. 2002; MARENGO et al. 2004).

Silva et al. (2009) and Guedes et al. (2019) showed that LLJ tends to be more frequent in El Niño years, which results in wetter years in the northern half during this phase of ENOS. However, several studies (ROPPELEWSKI; HALPERT, 1987; RAO; HADA, 1990; GRIMM et al. 1998;2000) show the direct relationship between El Niño and the increase in average rainfall in southern Brazil in general, but especially in the spring, autumn and winter of the following year, while in La Niña events there is a decrease in precipitation. This influence of El Niño can also be observed in relation to extreme rainfall events (NUNES; SILVA, 2013; PEREIRA; NUNES, 2018). As a result, the occurrence of flooding in the municipalities located in the Uruguay River’s watershed, especially in the extreme north of the state (where the highest annual total rainfall is observed) is frequent and has been intensifying.

In June of 2014, the region accumulated approximately 504 mm of rainfall in one month (large part of the volume - 414 mm - occurring in one week), providing several social, economic and environmental consequences not only in the upper Uruguay River region, but along its entire channel on the border between Rio Grande do Sul, Santa Catarina and Argentina. Floods and inundations that affected a large population, the gates’ opening of several hydropower dams, and the rupture of a Small Hydropower Plant (SHP) located in Ponte Serrada, in the state of Santa Catarina (SANCHES et al. 2015). Besides, federal and state highways were closed due to mass movements and cracks in the runway. According to Herrmann et al. (2004), mass movements have as one of their main constraints to high rainfall and in Brazil, most landslides occur during and after rainy periods (PAIXÃO, 2015).

3.2.2. Precipitation Concentration Index (PCI)

PCI on an annual scale ranged from 8.54 to 24.8 (Fig. 8e). However, on average, about 58% of years have PCI less than or equal to 10, which means that there is a uniform distribution of ATR over the months of these years. In approximately 40% of the years, the PCI varied between 11 and 16, which indicates a moderate concentration of ATR in some months of the year.

A difference in the annual PCI was also observed when comparing the North and South regions. In the series in the north of the state, there are more years with PCI ≤ 10 (63% of years) than in the South (53% of years), indicating a better distribution of rain in that region. This also occurs when the values 11 ≤ PCI ≤ 16 are analyzed in the North of the state, with about 36% of the years of the series into this class, while in the Southern half this value is approximately 46%, reinforcing the observation that there is a difference in the temporal distribution of ATR between regions.

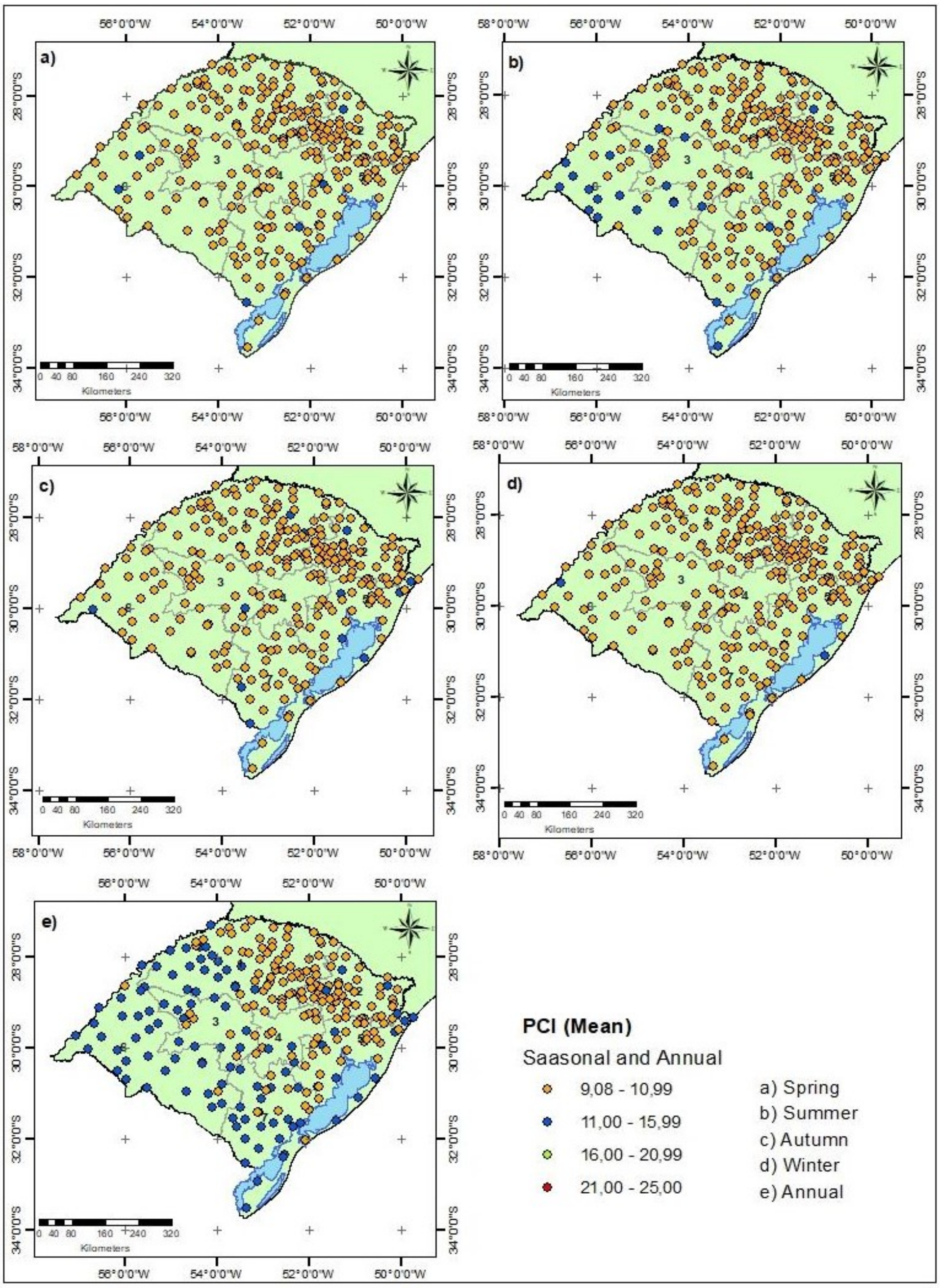
On a seasonal scale, it was observed that in the Northern region of RS, spring (Fig. 8a) is the season with the best uniformity of rainfall distribution, followed by summer, winter and autumn. On average, 83% of years have the PCI of spring ≤ 10. In summer, winter and autumn this percentage is 80.4%, 77.4% and 75.7%, respectively. In the southern region of the state, the season with the lowest concentration of rainfall is winter. In winter, 79% of years, on average, have a PCI ≤ 10, followed by spring with 76.4%, summer with 73% and autumn with 71.4%.

Also, it should be noted that autumn, being the season with the highest average percentage (26%) in the moderate concentration class, is the season that has the least uniformity of rainfall distribution among the seasons, both in the North and South regions of the RS. Besides, there was a spatial variability in the mean PCI of rain gauges, both on a seasonal and annual scale (Fig.8). The mean PCI in the spring varied between 9.08 and 11.48 (Fig.8a), in the autumn between 9.32 and 11.61 (Fig.8c) and in the winter between 9.34 and

12.30 (Fig.8d), however, the distribution of rainfall in these seasons is uniform throughout most of the state.

In the summer, the average PCI varied between and 9.11 and 11.94 and also indicate a uniform distribution of rainfall in the season. Nevertheless, PCI in the summer is more pronounced in several rain gauges in the western region (Fig.8b), which indicates that the rainfall is not as well distributed over the 3 months of this season as in the rest of the state.

Figure 8 - Spatial distribution of the mean PCI in the state of Rio Grande do Sul on a seasonal ((a) spring, (b) summer, (c) autumn and (d) winter), and annual (e) scale.



Source: the authors.

The mean annual PCI (Fig.8e) suggested that in the Northwest, on the western border and in the South of the state, there is a greater irregularity of ATR over the months. According to Gonçalves and Back (2018), in the summer the surface warms up, promoting moisture conduction to the interior of the continent, which tends to unstable the atmosphere and increase convective processes, resulting in intense and punctual rainfall events, especially in the west portion of the state.

RS has faced serious problems related to the distribution of rainfall. According to Gross (2015), the emergency decrees due to water scarcity occur mainly in the summer and in the municipalities that border Uruguay. In the municipality of Bagé, water rationing is recurrent in this period, directly affecting supply. A study by Brondani et al. (2013) in 2012 demonstrated that the population perceives the occurrence of drought for at least 20 years. In 2020, according to the Bagé Water and Sewage Department, the volume of rainfall between February and March was only 43 mm and the reservoirs were at critical levels, so water rationing was started in the municipality (DAEB, 2020).

Also, according to Berlato and Fontana (1999), the interannual variability of rainfall has also influenced the yield of RS crops, which has its Gross Domestic Product directly related to the performance of crops. The agricultural sector is affected from the preparation of the soil for planting to the harvest, and the effects of drought in the state are already observed in the summer crop of 2019/2020. In March 2020, the average productivity ($kg.ha^{-1}$) of soybeans is 32% below what was estimated, and that of corn about 26% lower, but there are municipalities in which losses reach 75%.

There was also a decrease in the productivity of other crops, such as beans, mainly in the southern region of the state (EMATER/RS, 2020). Thus, the use of irrigation in a supplementary way may be of interest in these places, considering that it brings benefits such as obtaining significant increases in productivity of several crops, as well as an increase in the duration of the annual planting period (GUIMARÃES; LANDAU, 2014).

4. FINAL CONSIDERATIONS

It was possible to conclude that the ATR in Rio Grande do Sul has low variability over time, contrasting what happens with AMDR. However, there is a notable spatial variability both in the volume of ATR - which decreases towards the South, and in its distribution over the months and seasons. It was evident that in some seasons, such as autumn, the distribution of rainfall over the months is more irregular, especially in the southern half of the state, which also has a greater number of years of water scarcity (represented by negative anomalies) compared to the North region.

Still, it was found that the most extreme AMDR events, the biggest temporal variations, as well as the biggest summer PCI and annual PCI occur in the southwestern mesoregion of the state, next to the Pampa biome, which is an area of remarkable environmental fragility, mainly, due to the combination of rainfall pattern, vegetation and type and land use.

87% of the AMDR series analyzed do not have a significant temporal trend. However, in most of the series that showed a significant increase in the AMDR, the same occurred in the last 40 years, mostly. In the series in which the changing point was identified, the difference in the AMDR average between before and after the year was up to 50 mm.

The variability of rainfall in some regions of RS causes some difficulties related to water availability, mainly for agricultural production, supply and floods. The trend towards an increase in AMDR, on the other hand, points to the intensification of already existing environmental problems such as soil loss, floods and inundations, as well as landslides. At these places, it is recommended that managers not only invest in structural measures, but also pay attention to the fact that mainly the hydrological projects of hydraulic structures must be reviewed and updated in the face of changes in the state's rainfall.

Besides, the structure of most municipalities to cope with natural disaster situations is precarious, therefore, studies like this are important to understand how cities can be affected, in addition to serving as input for the adaptation and creation of strategies and policies that assist in the management of natural resources, such as the management and conservation of soil and water, as well as the mitigation of social and environmental impacts resulting from current and future climate changes.

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