Precipitation patterns and their variability in the southern region of Brazil

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ABSTRACT

Climate change is a long-term transformation of climate patterns, which can be natural or anthropogenic. Signs of climate change can manifest themselves in different ways: through the occurrence of extreme events, rising ocean levels, melting glaciers, among others. Negative impacts are produced by climate change and are one of humanity's biggest concerns, since its effects reach the entire planet with different consequences. Considering the need for actions aimed at contributing to the process of mitigating climate change, the importance of knowing changes in regional climate patterns is emphasized. This study aims to analyze changes in precipitation patterns over time in the southern region of Brazil, including variability, trends, anomalies, droughts and excess rainfall. Daily precipitation data from 1961 to 2020 were used, collected at 15 meteorological stations in the region. Various statistical analyzes were carried out, such as averages, maximum and minimum values, seasonal and annual anomalies, frequency distribution, Mann-Kendall trend tests and the Normalized Precipitation Index (SPI). The results indicate that climate change trends are positive in terms of increasing rainfall volumes, altering rainfall dispersion patterns (volume). In other words, rainfall is more irregular in terms of distribution throughout the seasons. The big highlight was Florianópolis -SC, which during the summer had the highest volume of rain among the meteorological stations studied.

Keywords: cold fronts; Climate Anomalies, Extreme Events, Climate Patterns, Precipitation.

PADRÕES DE PRECIPITAÇÃO E SUAS VARIABILIDADES NA REGIÃO SUL DO BRASIL

RESUMO

As mudanças climáticas são transformações ao longo prazo dos padrões climáticos, que podem ser naturais ou antropogênicas. Os sinais de mudanças do clima podem se manifestar de diversas formas: pela ocorrência de eventos extremos, pela elevação do nível dos oceanos, pelo derretimento de geleiras, entre outras. Impactos negativos são produzidos pelas mudanças climáticas e se apresentam como uma das maiores preocupações da humanidade, uma vez que seus efeitos alcançam todo o planeta com diversos desdobramentos. Considerando a necessidade de ações que visem contribuir com o processo de mitigação das mudanças climáticas, enfatiza-se a importância em conhecer as alterações dos padrões climáticos regionais. Este estudo tem como objetivo analisar as mudanças nos padrões de precipitação ao longo do tempo na região Sul do Brasil, incluindo variabilidade, tendências, anomalias, secas e excesso de chuva. Foram utilizados dados diários de precipitação de 1961 a 2020, coletados em 15 estações meteorológicas na região. Realizadas diversas análises estatísticas, como médias, valores máximos e mínimos, anomalias sazonais e anuais, distribuição de frequência, testes de tendência de Mann-Kendall e o Índice de Precipitação Normalizada (SPI). Os resultados indicam que as tendências de mudanças climáticas são positivas no que refere ao aumento dos volumes de chuva, alterando os padrões de dispersão pluviométrico (volume). Ou seja, as chuvas estão mais irregulares quanto a distribuição ao longo das estações do ano. O grande destaque foi para Florianópolis-SC que durante o verão apresentou o maior volume de chuva entre as estações meteorológicas estudadas.

Palavras-Chave: Anomalias Climáticas, Eventos extremos, Padrões Climáticos, Precipitação.
Introduction

Climate change is among the most talked about and investigated global risks (Guerra, 2021). According to data from the IPCC (IPCC, 2021), the climate crisis is worsening rapidly, causing much more serious impacts than predicted. There is a need for cities to become resilient when it comes to environmental disasters, and this has been a priority in several countries around the world. This resilience aims to enable managers and communities to adapt in cases of extreme events, in order to minimize such threats (Khazai et al., 2018).

Due to the importance of the issue of climate change, the United Nations (UN), through the 2030 Agenda, establishes the Sustainable Development Goals (SDGs), urgent measures with the aim of combating climate change and its impacts. Objective number 13, entitled “Action against global climate change”, describes, among the various impacts, extreme precipitation events, such as droughts and floods.

The analysis of spatial and temporal patterns of extreme weather events has received increasing attention since the late 1990s, due to the intensification of social and environmental risk in several regions of the planet (Ohba and Sugimoto, 2019; Santos and Galvani, 2019; Olmo et al., 2020; Silveira, 2021; Thomassen, 2021; Rojpratak and Suphratid, 2022).

It is noteworthy that extreme precipitation events are among the most serious, frequent and widespread natural disasters, capable of causing significant damage to ecosystems and agricultural production (Landrum and Holland, 2020). Thus, extreme precipitation events have become more routine across the planet due to the combination of climate change and atmospheric circulation. It is essential to increase understanding about these events, aiming to reduce the social, economic and environmental impacts caused by them. For this reason, extreme precipitation events have been the focus of several studies (Wanderley et al., 2021; Ohba and Sugimoto, 2019; Santos and Galvani, 2019; Priya and Agilan, 2022; Rojpratak and Supharatid, 2022).

According to published studies, several regions of the world have been affected by these events. Azevedo (2018), Cunha (2018) and Marengo (2018) conducted research on the Northeast region of Brazil. Pramudya (2019) investigated Indonesia, and Tigkas (2020) focused on Greece. Zhão et al. (2020), Ng et al. (2021) and Tang et al. (2021) observed a significant increase in the intensity and frequency of precipitation extremes in most of China in recent years, showing that such events are becoming more frequent at a global level.

According to a recent WMO report (Smith, 2021), over the past 50 years, more than 34% of all recorded disasters, 22% of related deaths (1.01 million), and 57% of related economic losses (2.84 billion dollars) were consequences of extreme precipitation events.

The occurrence of extreme precipitation plays a significant role in meteorological disasters, and it is of utmost importance to mitigate its socioeconomic effects. This requires timely, accurate and detailed weather forecasts that have high resolution and long-term coverage, capable of providing specific information at the local level (Wang, 2017).

Extreme precipitation is the main cause of floods, urban flooding, debris flow and soil erosion, which threaten the life safety of millions of people and the development of the economy (Nie & Sun, 2021; Tang et al., 2021).

The drought phenomenon needs to be carefully monitored and investigated as it harms the local economy and the population (Rossato et al., 2017). To study the drought situation, it is necessary to use indices that can demonstrate the presence of drought or excess rainfall, which are widely studied, whether they are rainfall distribution, precipitation anomalies and positive or negative trends.

In their study, Santos et al., (2019) used the Standardized Precipitation Index (SPI) in stations in the São Francisco River Basin, verifying that the months from November to January were the wettest for the region studied. Terassi et al., (2019) used the SPI to identify rainfall patterns in the Itararé River basin, in Paraná, concluding that in autumn and winter, there was a greater frequency than the relative drought categories, while in spring there was the greater predominance of normality and summer was characterized by a greater frequency of wetter months. Almeida et al., (2023) applied the SPI in a study focused on the state of São Paulo and found that the spatial pattern of dry and rainy climate extremes presents significant regional differences throughout the state.

The SPI is an index widely used on a global scale. Kamruzaman (2022) used it in a study conducted in Bangladesh, finding that the drought...
trend in the northwest and southwest regions has gradually increased over the past few decades, while the drought trend in the southeast and northeast regions has steadily decreased over the past decade. Wang (2022) applied the SPI in China, showing that there is no clear evidence that the drought situation is worsening in the mentioned region, with some exceptions in specific regions.

Other studies evaluated trends of increase or decrease in precipitation in a given region using the non-parametric Mann-Kendall test. Studies such as that of Junior and Lucena (2020), which applied the test in Rio Grande do Norte, found that the rainiest months for the region occurred between February and April. However, no significant trends were identified.

Sam et al., (2022) conducted a study in Nigeria, while Khavse and Chaudhary (2022) did so in India, and Lipon das (2022) in Bangladesh. Both studies showed that precipitation patterns have changed over the years.

Sá (2018) carried out a study in the municipality of Lages, in the mountainous region of Santa Catarina, and the results indicated positive precipitation trends.

The occurrence of extreme events has increased over the years, as indicated in the report published in 2021 by the IPCC, which highlights that the increase in the frequency and intensity of extreme weather events, such as heat waves, floods and intense storms, is linked to climate change caused by human activity (IPCC, 2021). According to Mann et al., (2018), changes in the climate patterns of extreme events, such as droughts, intense rains and hurricanes, are identified in different parts of the world. The researchers concluded that the probability of extreme events has increased considerably due to human influences on the climate, mainly due to greenhouse gas emissions. The intensity of these events has also been a concern at a global level.

The increase in droughts and floods causes major impacts, being capable of generating several aggravating factors of economic, environmental and social relevance. When reaching a certain region, extreme events generate consequences, such as landslides, falling trees, power outages, floods and floods, causing destruction. Given its importance, there are several studies on extreme events in different regions of Brazil. Junior and Chaves (2021) studied several municipalities in Brazil and concluded that the most common disasters that occur in Brazilian urban space are the result of the interaction between natural and human factors. Oliveira and Ferreira (2021) found that the extreme events in Juiz de Fora - MG occurred during the rainy season, between October and March, and that all events were associated with the passage of Frontal Systems that lead to the convergence of humidity in the region Amazon, mainly in the summer. Gomes (2022) verified the risk areas related to extreme events in the urban area of the municipality of Independência in Ceará and concluded that the extreme events derive from the actions of the Intertropical Convergence Zone (ITCZ) associated with La Niña.

This problematization arises from the urgent need to understand how climate patterns are evolving in the southern region of Brazil and how these changes can impact local communities, the regional economy and natural ecosystems. The study seeks to identify not only typical rainfall patterns, but also examine trends over time between climatological normals, including possible changes in the frequencies and intensities of extreme events such as droughts and intense rainfall.

By investing in advanced weather forecasts, it is possible to reduce the negative impacts of disasters related to extreme precipitation, protecting lives, property and economic resources. This proactive approach is critical to promoting community resilience in the face of increasingly complex climate challenges (Pendergrass, 2018; Smith, 2021).

By analyzing precipitation variability, the study aims to provide valuable insights for the planning and management of water resources, agriculture, natural disaster prevention and other areas of strategic importance for the southern region of Brazil. Understanding these climate patterns is critical to inform public policies, large-scale and sustainable agricultural practices, and climate change adaptation measures.

Not limited to just the scientific understanding of climate phenomena, but also encompassing ethical, social, political and economic issues. They demand a holistic and collaborative approach, which involves governments, civil society, the private sector and local communities. In short, it represents a multifaceted challenge that requires an integrated and collaborative approach to guarantee the environmental, social and economic sustainability of present and future generations.

In this way, the study seeks to identify the different precipitation patterns in the southern region of Brazil, in terms of its variability (distribution, trends, anomalies, droughts and excess rainfall).
Material and methods

Study area

The southern region of Brazil is located between latitudes 22°30' S and 33°45' S and longitudes 57°59' W and 48°00' W (Figure 1), covering more than 7% of the Brazilian territory. It presents an elevation variation that goes from sea level along the coast of the Atlantic Ocean, to reaching altitudes of up to 1,818 meters in the mountains. This region is characterized by a diversity of landscapes, including lake areas, slopes and mountains, coastal and inland plains, river valleys, plateaus with ridges. (WREGGE, 2012)

The economy of the southern region is responsible for 16.2% of GDP - National Gross Domestic Product, distributed in the agricultural, extractivism, industry, commerce and services sectors. According to the Brazilian Institute of Geography and Statistics (IBGE, 2021), the economy evolved from a completely agricultural matrix to industrial diversification, both of which are the population's main sources of income. It is noteworthy that such activities can be strongly influenced by atypical precipitation patterns, as well as by the occurrence of extreme events.

According to the Köppen climate classification, the southern region of Brazil is predominantly characterized by a humid subtropical climate (Cfa and Cfb). This type of climate is influenced by a combination of factors such as latitude, altitude and the influence of air masses of polar origin (Fernandes et al., 2021). In general, the humid subtropical climate in the southern region of Brazil is marked by four distinct seasons throughout the year. The southern region also has well-distributed rainfall throughout the year, without a pronounced dry season. Rainfall rates are generally high, varying between 1,200 mm and 2,000 mm annually. The presence of cold fronts and frontal systems contributes to the occurrence of frequent rains (Nimer, 1989).

Conventional and automatic meteorological stations are important sources for the climate characterization of these regions. The present study included 15 meteorological stations, distributed in the southern region of Brazil, covering the states of Paraná, Santa Catarina and Rio Grande do Sul, whose distribution can be seen in Figure 01 and information in Table 1.

Figure 1- Location of the Southern Region of Brazil and spatial distribution of meteorological stations.
Meteorological Data

Data from the National Institute of Meteorology of Brazil (INMET) was used, which is a federal body under the direct administration of the Ministry of Agriculture, Livestock and Supply (MAPA), which was created in 1909 with the mission of providing meteorological information to Brazilian society, and constructively influence the decision-making process, contributing to the sustainable development of the country. This mission is achieved through monitoring, analysis and forecasting of weather and climate, which are based on applied research, partnership work and sharing of knowledge, with an emphasis on practical and reliable results (INMET, 2022).

Daily precipitation series were analyzed in the reference period 1961 - 2020, which was subdivided into two data series representative of climatological normals: 1961-1990 (NCI) and 1991-2020 (NCII) climatological normals are recommendations from the World Meteorological Organization (WMO) – being reference periods for climate comparison criteria to verify changes in climatological patterns. Each series comprises a 30-year data set for each climatological normal, as shown in Table 2.

<table>
<thead>
<tr>
<th>Weather Stations</th>
<th>Code</th>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraná</td>
<td>01</td>
<td>Maringá</td>
<td>-51.91</td>
<td>-23.4</td>
<td>542</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>Londrina</td>
<td>-51.14</td>
<td>-23.32</td>
<td>566</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>Castro</td>
<td>-49.99</td>
<td>-24.78</td>
<td>994.68</td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>Curitiba</td>
<td>-49.23</td>
<td>-25.44</td>
<td>923.5</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>Irati</td>
<td>-50.63</td>
<td>-25.50</td>
<td>881.69</td>
</tr>
<tr>
<td>Santa Catarina</td>
<td>06</td>
<td>Florianópolis-48.62</td>
<td>-27.60</td>
<td>4.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>07</td>
<td>Urussanga</td>
<td>-49.31</td>
<td>-28.53</td>
<td>40.5</td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>Saint joaquim</td>
<td>-49.93</td>
<td>-28.27</td>
<td>1400.07</td>
</tr>
<tr>
<td></td>
<td>09</td>
<td>Lages</td>
<td>-50.33</td>
<td>-27.80</td>
<td>952.73</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Caminhos Novos</td>
<td>-51.21</td>
<td>-27.38</td>
<td>962.86</td>
</tr>
<tr>
<td>Rio Grande do Sul</td>
<td>11</td>
<td>Torres</td>
<td>-49.71</td>
<td>-29.35</td>
<td>4.66</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Porto Alegre</td>
<td>-51.17</td>
<td>-30.05</td>
<td>41.18</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Bento Gonçalves</td>
<td>-51.53</td>
<td>-29.16</td>
<td>624.1</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Cruz Alta</td>
<td>-53.61</td>
<td>-28.62</td>
<td>475.52</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Bagé</td>
<td>-54.11</td>
<td>-31.30</td>
<td>245.66</td>
</tr>
</tbody>
</table>

Table 2 - NCI adopted in the study

<table>
<thead>
<tr>
<th>Climatological Normal</th>
<th>Interval</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCI</td>
<td>1961-1990</td>
<td>30 years</td>
</tr>
<tr>
<td>NCII</td>
<td>1991-2020</td>
<td>30 years</td>
</tr>
</tbody>
</table>


"Climatological Normals" are obtained by calculating the averages of meteorological parameters, following criteria recommended by the World Meteorological Organization (WMO).

Consistency analyses

The daily precipitation series were organized and composed using regional weighting, dispersion and absolute value analysis methods. For data consistency purposes, standards established by the climatological data quality control guide published by the World Meteorological Organization (WMO), in the climatological data program, were used, as per the following items:

* Identification of missing or repeated data (monthly series of less than 20 days were disregarded, as well as annual series with more than 2 months without data);
* Occurrence of unacceptable extreme values (values that exceed historical limits for each of the meteorological variables used).
Statistical analyses

After collecting the precipitation data, analyzes were applied at different temporal scales: annual, seasonal (summer – DJF, autumn – MAM, winter – JJA and spring – SON) and monthly. It reads: DJF – December / January / February, MAM – March / April / May, JJA – June / July / August and SON – September / October / November, as recommended by the WMO.

For the purposes of analyzing climate variability, the following statistical tests will be used: descriptive statistics (averages, absolute values – maximum and minimum), seasonal and annual anomalies (climatology x climatological normals), (Wilks, 1962).

Mann-Kendall test

The Mann-Kendall test is widely used in studies for analyzing climatological historical series of the most diverse meteorological elements, such as air temperature and precipitation. Data series over long periods may not follow a normal distribution when it has a time index component. This is related to the fact that the event series over long periods may not follow a normal distribution when it has a time index component. Furthermore, the normal distribution is a limiting distribution of the distribution considered, see the central limit theorem. The significance of S for the null hypothesis can be obtained through a two-sided test, which can be rejected for large values of the ZMK statistic.

\[ ZMK = \begin{cases} \frac{s-1}{\sqrt{\text{Var}(S)}} & \text{se } S > 0 \\ 0 & \text{se } S = 0 \\ \frac{s+1}{\sqrt{\text{Var}(S)}} & \text{se } S < 0 \end{cases} \] (4)

Finally, the evaluation is given by the acceptance or rejection of the null hypothesis (H0) based on the level of significance adopted, in this case 5%. Therefore, H_0 will not be rejected whenever -1.96 < ZMK < 1.96. Trends of increase or reduction present positive or negative values of ZMK, respectively.

The precipitation trends of the series, whether positive or negative, were evaluated. The non-parametric test using the Mann-Kendall was used, at 5% significance, when p-value <0.05, the null hypothesis is rejected in favor of the alternative hypothesis, that is, there is a trend in the series. To perform the Mann-Kendall test in the present study, the R Studio 4.2.2 software with the Trend package and Excel 2019 were used.

Normalized Precipitation Index (SPI).

Precipitation extremes were assessed using the Normalized Precipitation Index (SPI) calculation. SPI was developed by McKee et al. (1993) to quantify extreme precipitation variations on different time scales, making it suitable for characterizing the short-, long-term and seasonal patterns of an area or region.

The SPI calculation begins by determining a probability density function that describes time series. The function is given by Equation 5:

\[ g(x) = \frac{x^{\alpha - 1}e^{-x/\beta}}{\beta^\alpha \Gamma(\alpha)} \text{for } X > 0 \] (5)

Where, \( \alpha > 0 \) shape parameter; \( \beta > 0 \) scale parameter; \( x > 0 \), the amount of precipitation (mm) and \( \Gamma(\alpha) \) the full gamma function.

To estimate the parameters \( \alpha \) and \( \beta \) of the gamma distribution, the method defined by Equation 6 was used:

\[ \alpha = \frac{1}{4A} \left( 1 + \sqrt{1 + \frac{4A}{3}} \right) \] (6)

\[ \beta = \frac{x}{\alpha} \]

Being \( \bar{x} \) the arithmetic mean of precipitation, ln is the Neperian logarithm and \( n \) is the number of observations.

\[ A = \ln(\bar{x}) - \frac{\ln \Gamma(n)}{n} \] (7)

\[ \Gamma(n) = \frac{n!}{(n-1)!} \]

Lapa, C. H. A., Campos, C. C., Quadro, M. F. L., Rufato, D. P.
Where on is number of observations.

In this way, the cumulative distribution is then transformed into probability distribution normal with mean equal to zero and standard deviation equal to one. Then the accumulated probability occurrence of each monthly value is estimated. The normal function applies to this probability inverse to find the SPI value. The SPI is the difference in precipitation observed minus the average of the time interval specific, divided by the standard deviation, as per.

$$SPI = Z_i = \frac{(P_i - \bar{P})}{\sigma_i}$$ (8)

Where, $P_i$ is the observed precipitation; $\bar{P}$ and $\sigma_i$ are respectively the mean and deviation set series standard.

The SPI classification can be seen in Table 3, where McKee et al. (1993) used SPI values to define the existence or not of drought and its degree of intensity. According to the authors, drought occurs whenever the SPI value is continuously negative, reaching an intensity equal to or less than minus one (-1.0).

The classification is based on the limits indicated in Table 3, allowing us to characterize not only droughts, but also wetter periods. This method has the great advantage of standardizing the analysis, allowing completely different regions to be compared, such as regions with wetter and rainier climates with more arid and drier regions.

<table>
<thead>
<tr>
<th>SPI Values</th>
<th>Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 2.00$</td>
<td>Extreme rainfall</td>
</tr>
<tr>
<td>1.50 to 1.99</td>
<td>Severe rains</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>Moderate rains</td>
</tr>
<tr>
<td>- 0.90 to 0.99</td>
<td>Normal</td>
</tr>
<tr>
<td>- 1.00 to - 1.49</td>
<td>Moderately dry</td>
</tr>
<tr>
<td>- 1.50 to - 1.99</td>
<td>Very dry</td>
</tr>
<tr>
<td>$\leq -2.00$</td>
<td>Extremely dry</td>
</tr>
</tbody>
</table>

**Results and discussions**

**Climatological precipitation normals**

Monthly values (Table 3) and seasonal precipitation differences between the two climatological normals (Table 4) were analyzed.

In both states in the southern region of Brazil, most months had higher average monthly rainfall in the NCII, with emphasis on the state of Santa Catarina (91.6%) of the months. However, it is worth highlighting that although rainfall volumes are higher, it is important to observe their distribution. According to IPCC (2022), the increase in extreme events has contributed to a greater average volume of rain, but does not represent an adequate temporal distribution. The month of August stands out for presenting a reduction in rainfall volumes throughout the southern region of Brazil.

In Paraná, the highest volumes of rain are concentrated in the month of January, both in the NCI (196 mm) and NCII (213.1 mm). In Santa Catarina and Rio Grande do Sul the highest volumes occur in both the summer and spring months, 209 mm (January) and 176.8 mm (October), respectively.

Therefore, in relation to the average monthly precipitation volumes, the period 1991-2020, that is, the NCII, presented higher volumes in most months, a result that demonstrates an increase in the volume of precipitation in the last 30 years.

On a spatial and seasonal scale (Table 4), in most locations an increase in average rainfall volumes was observed in the second period (NCII), with emphasis on summer and spring. The northernmost locations in the southern region, especially Castro-PR, stood out due to the negative differences between the two periods, that is, the reduction in rainfall volumes. In Curitiba-PR, Florianópolis-SC and Torres-RS, located close to the coast of the southern region of Brazil, the average increase in rainfall volumes in the summer stood out in relation to other locations.

Based on the paired hypothesis test used to evaluate the significance of the differences, where the significance differences for the southern region of Brazil were validated. It was found that, for summer, autumn and spring, the differences were significant, while in winter no statistical significance was demonstrated.
Table 3 – Monthly precipitation (mm) for the states of PR, SC and RS of NCI and NCII climatological normals

<table>
<thead>
<tr>
<th>Month</th>
<th>Paraná NCI</th>
<th>Paraná NCII</th>
<th>Santa Catarina NCI</th>
<th>Santa Catarina NCII</th>
<th>Rio Grande do Sul NCI</th>
<th>Rio Grande do Sul NCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>196.0</td>
<td>213.1</td>
<td>168.2</td>
<td>209.0</td>
<td>117.5</td>
<td>146.3</td>
</tr>
<tr>
<td>Feb</td>
<td>152.8</td>
<td>180.6</td>
<td>173.6</td>
<td>180.1</td>
<td>126.4</td>
<td>137.5</td>
</tr>
<tr>
<td>Mar</td>
<td>136.5</td>
<td>133.3</td>
<td>146.6</td>
<td>148.9</td>
<td>124.3</td>
<td>127.0</td>
</tr>
<tr>
<td>Apr</td>
<td>107.6</td>
<td>97.1</td>
<td>100.0</td>
<td>116.4</td>
<td>96.3</td>
<td>133.6</td>
</tr>
<tr>
<td>May</td>
<td>113.2</td>
<td>107.3</td>
<td>106.8</td>
<td>137.1</td>
<td>92.5</td>
<td>125.7</td>
</tr>
<tr>
<td>Jun</td>
<td>109.7</td>
<td>111.2</td>
<td>106.5</td>
<td>118.5</td>
<td>122.4</td>
<td>129.0</td>
</tr>
<tr>
<td>Jul</td>
<td>84.2</td>
<td>88.3</td>
<td>121.2</td>
<td>138.5</td>
<td>127.6</td>
<td>147.8</td>
</tr>
<tr>
<td>Aug</td>
<td>73.6</td>
<td>71.7</td>
<td>124.8</td>
<td>117.0</td>
<td>140.0</td>
<td>123.0</td>
</tr>
<tr>
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<td>118.7</td>
<td>127.0</td>
<td>149.2</td>
<td>162.2</td>
<td>160.3</td>
<td>146.0</td>
</tr>
<tr>
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<td>144.6</td>
<td>183.6</td>
<td>135.6</td>
<td>176.8</td>
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<tr>
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<td>134.7</td>
<td>126.9</td>
<td>141.9</td>
<td>117.9</td>
<td>123.3</td>
</tr>
<tr>
<td>Dec</td>
<td>179.9</td>
<td>162.6</td>
<td>146.1</td>
<td>165.1</td>
<td>121.2</td>
<td>132.0</td>
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</table>


Table 4 – Differences in precipitation (mm) between NCI and NCII seasonal averages, for the states of PR, SC and RS

<table>
<thead>
<tr>
<th>Code</th>
<th>Seasons</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>01</td>
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<td>-4.0</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>Castro</td>
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</tr>
<tr>
<td>04</td>
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</tr>
<tr>
<td>05</td>
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<td>1.7</td>
<td>1.3</td>
<td>17.0</td>
</tr>
<tr>
<td>06</td>
<td>Florianópolis</td>
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<td>8.4</td>
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</tr>
<tr>
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<td>Urussanga</td>
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<td>15.4</td>
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<td>7.3</td>
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<td>São Joaquim</td>
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<tr>
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<td>14.7</td>
<td>17.0</td>
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<td></td>
</tr>
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<td>Torres</td>
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<td>16.1</td>
<td>16.1</td>
</tr>
<tr>
<td>12</td>
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<td>-3.7</td>
</tr>
<tr>
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<td>Bento Gonçalves</td>
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<td>16.5</td>
<td>-1.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>14</td>
<td>Cruz Alta</td>
<td>21.3</td>
<td>27.7</td>
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</tr>
<tr>
<td>15</td>
<td>Bagé</td>
<td>12.2</td>
<td>43.3</td>
<td>-1.6</td>
<td>10.8</td>
</tr>
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</table>


Figures 2 and 3 show the absolute precipitation values in 24 hours (mm). Extreme precipitation values effectively contribute to the increase in monthly rainfall volume. In summer, the highest 24-hour rainfall totals occur in NCII, indicating an increase in extreme precipitation events in this second period (1991 to 2020). In only 33% of the locations were the values higher in the NCI.

In Torres-RS, daily rainfall of 257.3 mm was recorded (Feb/2014). In most locations, episodes of rain exceeding 100 mm were recorded. The city of Porto Alegre-RS had the lowest volume of rain in 24 hours compared to other locations: 79mm in February 2012.

It is noteworthy that in winter the daily rainfall totals increased in intensity (66.7%), such as the locations of Londrina (231.4 mm), Irati (175.5 mm), Castro (153.6 mm) and Maringá (151.5 mm), all in the State of Paraná.

Florianópolis also stood out for the occurrence of 146.2 mm in 24 hours, which occurred in July 2015. This episode of rain caused several problems in the city, in Campos Novos the value approached the capital of Santa Catarina, totaling 143.5 mm in July 2015. 1999, while in the mountains of Santa Catarina in the municipality of
Lages, it reached a volume of 113.3 mm in 24 hours, which occurred in August 2011. It is important to highlight the high extreme values in summer as well as in winter, with great emphasis on the state of Paraná, where all meteorological seasons have a very significant increase.

Figure 2 – Absolute precipitation value (mm) in 24 hours, during the summer (a) and winter (b) seasons.
It can be seen in Figure 3, referring to the transition seasons, autumn and spring, where, in most locations, the occurrence of absolute values increased in intensity in NCII, but to a lesser extent than in summer and winter.

In autumn, the highest daily precipitation values occurred in Florianópolis, both in the NCII (253 mm) and in the NCI (187 mm), in the years 2010 and 1978, respectively.

In October 2001, the town of Lages-SC recorded a volume of 177 mm in 24 hours. The maximum volume occurring at the NCI had been 122 mm (1979).

Another piece of evidence found in the respective study is that when analyzing the year in which the most extreme event occurred, in the NCI the years 1982/83 were the most frequent, especially in winter, in more than 50% of the locations studied.

This flood was accentuated by the climate phenomenon called El Niño, which is characterized by the abnormal warming of surface waters in the Equatorial Pacific Ocean. During 1983, a strong El Niño episode occurred, which resulted in significant changes in weather patterns around the world, including Brazil. El Niño is generally associated with an increase in the frequency and intensity of rainfall in certain areas, especially in the southern region of Brazil. Some studies, such as that carried out by Wollmann and Satori (2010), examined the relationship between El Niño and flood episodes in Rio Grande do Sul, while Fontana et al. (1996) investigated the relationship between El Niño and precipitation in the same region.

In general, based on the results presented, it is evident that in the southern region of Brazil there was a significant increase in the volume of rainfall in more recent years (NCII / 1991-2020) when compared to the previous climatological normal (NCI / 1961-1990). This conclusion is in line with several studies that analyzed precipitation trends in the southern region of Brazil. Junges and Tonietto (2022) highlighted an increase in the volume of precipitation in the Serra Gaúcha, in the period from 1991 to 2020 compared to 1961 to 1990. The results of Da Silva et al. (2017) identified an increase in the intensity and frequency of precipitation events in southern Brazil between 1991 and 2010.

Freire et al. (2017), when investigating the temporal evolution of extreme precipitation events in the state of Santa Catarina, found an increase in the intensity and frequency of these events in the period from 1991 to 2012.

Global climate change has been a subject of concern in recent years, and the increase in rainfall observed may be a reflection of this trend. Changes in climate patterns, such as an increase in the planet's average temperature, extreme weather events and changes in atmospheric circulation patterns, can affect the distribution and intensity of rainfall.

**Precipitation > 50(mm)**

Based on the data presented in Figures 4 and 5, it is possible to conclude that the southern region of Brazil has experienced an increase in the frequency of rainfall with a volume greater than 50 mm. This increase is significant, being 25% in the...
state of Paraná, 45% in Santa Catarina and 44% in Rio Grande do Sul.

This tendency to increase the frequency of intense rains may indicate changes in the region’s climate pattern, which could impact several socioeconomic and environmental aspects. Cities and regions with a higher frequency of rainfall above 50 mm may face challenges related to floods, floods and other extreme events, which can cause damage to infrastructure, agriculture, ecosystems and local communities.

Figure 4 - Number of days with precipitation greater than 50 (mm) between climatological normals I and II, in Paraná (a) and Santa Catarina (b)
The differences between climatological normals were quite significant in relation to the volume of rainfall greater than 50 mm in the states of the southern region of Brazil (Table 5). In Paraná, there were 538 events in NCI, increasing to 672 events in NCII, with emphasis on the months of January, which received the highest volume of rain and February, which recorded the highest growth of 55% in relation to climatological normals. In Santa Catarina, 521 events occurred in NCI, increasing to 748 events in NCII, with emphasis on the month of May, which saw a growth of 120%. In Rio Grande do Sul, 583 events were registered in NCI, increasing to 839 events in NCII, with emphasis on the months of April and May, which saw growth greater than 100%.

Among the meteorological stations in the southern region of Brazil (Table 5), the biggest highlights were: Campos Novos-SC, which went from 109 events (NCI) to 233 events (NCII). Maringá-PR, which obtained 117 events (NCI) to 170 events (NCII). Cruz Alta-RS, whose number of events was 153 (NCI), increasing to 242 events (NCII).

Table 5 – Number of days with rainfall greater than 50mm, between NCI and NCII.

<table>
<thead>
<tr>
<th></th>
<th>PR</th>
<th>NCI</th>
<th>NCII</th>
<th>SC</th>
<th>NCI</th>
<th>NCII</th>
<th>RS</th>
<th>NCI</th>
<th>NCII</th>
</tr>
</thead>
<tbody>
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<td>Maringá</td>
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<td>Florianópolis</td>
<td>105</td>
<td>140</td>
<td>Torres</td>
<td>83</td>
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<td>London</td>
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<td>Urussanga</td>
<td>101</td>
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<td>Saint joaquin</td>
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<td>Curitiba</td>
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<td>118</td>
<td>Lages</td>
<td>100</td>
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<td>Cruz Alta</td>
<td>153</td>
<td>242</td>
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<tr>
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<td>233</td>
<td>Bagé</td>
<td>139</td>
<td>188</td>
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<tr>
<td>Total</td>
<td>538</td>
<td>672</td>
<td>Total</td>
<td>521</td>
<td>748</td>
<td>Total</td>
<td>583</td>
<td>839</td>
<td></td>
</tr>
</tbody>
</table>

Source: Author, 2023

Rainfall frequencies in Paraná, Santa Catarina and Rio Grande do Sul

Figure 6 shows the number of days with rainy values (minimum, average and maximum) among climatological normals on a monthly basis, for the states of Paraná, Santa Catarina and Rio Grande do Sul, respectively.

It is important to note that the minimum and maximum values occurred during NCII in the state of Paraná in July, August (minimum) and January (maximum), that is, presenting the lowest occurrences of rainy days during winter and the maximum during summer.

In Santa Catarina at NCI the season with the lowest number of rainy days was in autumn and during NCII it became winter, the same pattern was repeated in Rio Grande do Sul.
It is possible to observe that there has been an increase in the amount of rainfall over the years, which can affect the distribution of rainfall throughout the seasons in the southern region of Brazil.

This can have consequences for agriculture, water resource management and even social impacts, depending on local communities' dependence on rainfall. The increase in the number of days with rain may indicate changes in the rainfall pattern, such as an increase in the frequency of light rains or heavy rains. This can affect soil erosion, water quality, urban drainage and even the risk of flooding and landslides.

Studies such as Teixeira and Satyamurty (2011); Nunes and Da Silva (2013) revealed that there was an increase in the number of intense rain events in the southern region of Brazil. Furthermore, projections indicate a continued increase in these events in the future.

![Figure 6 - Rainy days in Paraná - NCI (a), NCII (b), Santa Catarina - NCI (c) NCII (d) and Rio Grande do Sul - NCI (e) NCII (f)](image-url)
Precipitation anomalies

The results were calculated based on the climatological normal itself, that is, (1961 to 1990) and (1991 to 2020), they were grouped by each state in the southern region of Brazil, they are discussed seasonally (Figures 7 and 8), organized from 1961 to 2020, based on the climate normal from 1961 to 1990 (NCI).

Figure 7 - Seasonal precipitation anomalies (mm) for summer (a) and winter (b)
Based on Figures 7 and 8, it is observed that positive precipitation anomalies were more frequent in more recent years, especially from the 90s onwards. In winter, an increase of 73.3% was observed in the last 30 years (NCII). The negative anomalies in 2020 were influenced by the occurrence of La Nina, a phenomenon that causes a cooling in the surface waters of the equatorial Pacific Ocean, favoring a reduction in precipitation in the southern region of Brazil.

In general, positive anomalies stand out more than negative anomalies, with maximum positive differences of 218.7 mm (SC - winter 1983), 144.2 mm (RS - spring 2009) and 119.7 mm (PR - spring 1972). Regarding negative precipitation anomalies, that is, values below expectations, the following stand out: -84.1 (RS - spring 1971), -80.0 mm (PR - summer 1979) and -74.6 mm (SC - fall 2020).


From the data analyzed, we can conclude that there has been an increase in the occurrence of positive precipitation anomalies in the southern region of Brazil over the last few decades. Precipitation values above expected were more frequent, especially in some specific years in the states of Paraná, Santa Catarina and Rio Grande do Sul. On the other hand, negative anomalies were also observed, with precipitation values below expectations, although to a lesser extent. proportion. This information indicates significant variations in the climatic conditions of the southern region over time.
The results obtained can be seen in Figure 9, through precipitation trend analysis using the Mann-Kendall test at 5% significance. Where the positive sign (+) indicates an increasing trend and the sign (-) a reduction in precipitation over the years, and (●) when the test is without significance, that is, p-value > 0.05, then there is no trend (point) over the years.

![Figure 9](image)

Figure 9 - Trend of precipitation change using the Mann-Kendall test with data from NCI (a) and NCII (b)
Positive trend (+) or negative trend (-) (p<0.05); (●) = not significant (p>0.05).

In general and in agreement with previous results, the state of Santa Catarina stands out for the most significant increase in rainfall volumes over the years.

Standardized Precipitation Index (SPI)
The main characteristic of SPI is the possibility of using it to monitor both wet and dry conditions on different time scales. This temporal flexibility makes it possible to use SPI in various applications.

The analysis of drought/rainfall events was carried out using the SPI for each of the states in the southern region of Brazil (Figure 10). The classification criteria, presented by Mckee et al. (1993), classify SPI values into three categories: moderate, severe or extreme. The results of this analysis are presented below for the time scales of...
3 and 12 months (the shorter the time scale, the greater the accuracy).
Further north of the southern region, in the state of Paraná, there is a greater variation between periods with excessive rainfall and extremely dry periods, with a much greater severity when compared to other states. In general, some years stand out for presenting extreme drought conditions (SPI ≤ -2.00), such as: 1963, 1978 to 1979, 1985/86 and 2020. The years 1982/83, 1998/99, 2010 and 2015/16 stood out for periods with extreme rainfall (SPI ≥ 2.00).

The states of Santa Catarina and Rio Grande do Sul have lower variability, with fewer conditions of extremely dry or rainy periods (-2.0 ≥ SPI ≥ 2.00). In both states, conditions were concentrated between 0 ≤ SPI ≤ 1, that is, within normal limits. However, some years stood out, such as 1983, where in SC the conditions were extreme rainfall (3 months) and in RS it was moderate rainfall, both on a 3-month time scale. As previously mentioned, due to El Niño, the year 1983 saw one of the biggest floods in the state of Santa Catarina, both in terms of rainfall volumes and spatial scale.

In these two states, SC and RS, there were few indicators of drier extreme rainfall, with the majority of cases close to normality (0 ≤ SPI ≤ 0.99). The years 1978 and 2020 stand out, which are closer to the moderately dry condition. In general, it is observed that the occurrence of larger volumes of rain is more frequent than the drought phenomenon.

**Conclusions**

The results found in the study indicate that the volume of precipitation in the southern region of Brazil was greater in Climatological Normal II (NCII) compared to Climatological Normal I (NCI), demonstrating an increase over the last 30 years. This increase in precipitation was especially evident during the summer in the cities of Curitiba-PR, Florianópolis-SC and Torres-RS, where the greatest differences in seasonal precipitation averages were observed.

Furthermore, during NCII, the highest absolute precipitation values in a 24-hour period were recorded. It was also observed that the number of days with rainfall greater than 50 mm was greater during NCII in all meteorological stations analyzed.

An important observation is that positive anomalies, that is, positive deviations from the mean, stood out more than negative anomalies, suggesting a trend of increasing precipitation over time.

These results highlight changes in the characteristics of precipitation in the southern region of Brazil, indicating an increase in rainfall volumes, especially during the summer, and the occurrence of high-intensity events. This information is relevant for understanding climate trends in the region, contributing to risk management, decision-making and the development of climate change adaptation strategies.

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