Spatial Trends of Extreme Precipitation Events in the Paraná River Basin

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ABSTRACT

This work presents an analysis of the observed trends in extreme precipitation events in the Paraná River basin (PRB) from 1977 to 2016 (40 yr) based on daily records from 853 stations. The Mann–Kendall test and inverse-distance-weighted interpolation were applied to annual and seasonal precipitation and also for four extreme precipitation indices. The results show that the negative trends (significance at 95% confidence level) in annual and seasonal series are mainly located in the northern and northeastern parts of the basin. In contrast, except in the autumn season, positive trends were concentrated in the southern and southeastern regions of the basin, most notably for annual and summer precipitation. The spatial distributions of the indices of annual maximum 5-day precipitation and number of rainstorms indicate that significant positive trends are mostly located in the south-southeast part of the basin and that significant negative trends are mostly located in the north-northeast part. The index of the annual number of dry days shows that 88% of significant trends are positive and that most of these are located in the northern region of the PRB, which is a region with a high number of consecutive dry days (≥90). The simple daily intensity index showed the highest number of stations (263) with mostly positive significant trends.

1. Introduction

Precipitation is considered to be one of the most important variables in the fields of hydrology, meteorology, and climate. Its variation patterns may affect agriculture and livestock development, the public and industrial water supply, hydropower generation, or even the risk of floods in urban areas. Therefore, understanding and identifying the spatial behavior of precipitation during both extremely dry and wet spells is relevant for offering subsidies for policy makers to improve the planning and sustainable management of water resources as well as to warn regions about further increases or decreases rainfall rates. In addition, attributing the increases or decreases in the frequency of precipitation events to global warming has been the focus of many investigations (Huntington 2006; Min et al. 2011; Trenberth 2011; Armal et al. 2018). Both understanding the behavior of precipitation extremes and improving the performance of global models in predicting future scenarios are issues of great importance in modern environmental sciences.

The Paraná River basin (PRB) plays an important role in the economic activity and development of Brazil. The watershed plays a major role in food production and has the largest installed capacity and energy generation in Brazil, with 156 hydropower plants that provide more than 45 000 MW of electricity (National Agency of Electric Energy 2019). Previous studies have reported that this region has presented changes in precipitation. By studying 59 stations during the period between 1950 and 1999, Dufek and Ambrizzi (2008) investigated trends using the Mann–Kendall (MK) test for six annual precipitation indicators in São Paulo state, which is
located in the central-eastern region of the PRB. Their results showed that the region presents positive significant trends in annual total precipitation, maximum 5-day precipitation, and consecutive wet days, representing 59.3%, 20.3%, and 32.2% of stations, respectively. In accordance with these results, they observed a significant negative trend in consecutive dry days in 23.7% of stations. In the southern part of the basin, Luiz Silva et al. (2015) observed significant positive trends for the annual maximum number of consecutive dry days and for the annual number of days with more than 30 mm of precipitation.

Some studies such as Silva Dias et al. (2013) and Pedron et al. (2017) identified a significant increase in extreme events of rainfall that may be related to the urbanization of the metropolitan regions of São Paulo and Curitiba cities, respectively. These authors used local daily rainfall from individual stations. Teixeira and Satyamurty (2011) also observed significant trends in annual heavy and extreme rainfall occurrence in southern Brazil within a 45-yr period (1960–2004), using cluster analysis and area-mean time series. However, the trends in southeastern Brazil were not significant in their study, which may be a result of the restrictive methodology of extreme events identification (Teixeira and Satyamurty 2011). Nevertheless, Zilli et al. (2017) observed an increase of rainy days and extreme events over the state of São Paulo, contributing to positive trends in total seasonal precipitation. These authors used more than 70 years of data with individual stations and gridded data, and their results suggest that the spatial patterns of trends are influenced by the proximity of large urban centers.

Although some studies have investigated the precipitation trends in the PRB over the past decades, most of these studies have been local (Silva Dias et al. 1995; Pedron et al. 2017) or regional (Dufek and Ambrízzi 2008; Luiz Silva et al. 2015) or used limited numbers of precipitation stations or cluster analysis (Zandonad et al. 2016; Teixeira and Satyamurty 2011; Liebmann et al. 2004). The main goal of this work is to analyze the spatial trends in the Paraná River basin that have not been covered by previous research and extend the trend analysis period. Besides that, the current study describes the method of the quality control assessment for the precipitation data. The analysis of the spatial trends was performed on annual and seasonal precipitation totals as well as for the extreme precipitation indicators at 853 stations from 1977 to 2016.

2. Materials and methods
   a. Study area

   The study area comprises the Brazilian Paraná River basin, which extends from 26°50.02’ to 15°25.01’S latitude and from 55°55.05’ to 43°34.06’W longitude, with a drainage area of 879,873 km². The PRB is one of the most important and largest watersheds in Brazil; it is located in the central-southern region of Brazil, which covers six Brazilian states (São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais, Goiás, and Santa Catarina) and the Federal District (Fig. 1). Currently, the PRB has an estimated population of more than 65 million inhabitants, with 93% of its population living in urban areas (Brazilian Institute of Geography and Statistics 2019). According to the Brazilian National Water Agency (ANA), this region has the highest demand for water resources in Brazil, equivalent to 736 m³ s⁻¹, most of which are used for agricultural (42%) and industrial (27%) activities.

   The PRB extends over an area large enough to cross different climatic zones as described by Reboita et al. (2017). Precipitation over the basin is generated by several meteorological and climatic phenomena crossing diverse temporal and spatial scales. Due to its location in a subtropical region of the South American continent, the PRB is susceptible to a series of convective systems that range from small-scale, isolated convective cells to frontal systems with hundreds of kilometers in their longest axis. The northern part of the basin is located north of the Tropic of Capricorn line and characterized by wet summers and dry winters, a regime of precipitation strongly associated with the South American monsoon system (SAMS) (Grimm et al. 2007; Carvalho et al. 2011; Marengo et al. 2012).

   During the summer, the South Atlantic convergence zone, a system associated with strong and continuous precipitation that expands from the central parts of the Amazon region to the subtropical eastern coastal of Brazil, strongly influences precipitation in the central and northernmost parts of the PRB (Carvalho et al. 2004). Furthermore, the Bolivian high, the upper-level anticyclonic system associated with surface heating (Rao et al. 1996), frequently induces strong convection in the central and western parts of the PRB.

   In the southern parts of the PRB, the precipitation is strongly influenced by baroclinic systems (Morales Rodríguez et al. 2010), with rainfall equally spread throughout the year. Moreover, it is also influenced by mesoscale convective systems (MCS), mainly during spring and summer. The formation of such MCSs, in turn, is strongly connected to the South American low-level jet (SALLJ), which brings heat and moisture from the tropical areas of South America to this region (Marengo et al. 2002; Salio et al. 2007). Recent studies showed that the spatiotemporal intensity distribution and frequency of SALLJ is modulated and influenced by the low-frequency events such as the Atlantic multidecadal
oscillation and El Niño–Southern Oscillation (ENSO) (Jones and Carvalho 2018; Montini et al. 2019). Locally, MCS includes squall lines and mesoscale convective complexes, as described by Velasco and Fritsch (1987).

Baroclinic instabilities influence precipitation in most of the PRB. They are associated with transient systems such as cold fronts and frontogenetic effects (Satyamurty and De Mattos 1989) connected to the presence of the upper-level subtropical jet. Squall lines can be seen year-round and are associated with sea breeze in the east of the PRB.

To facilitate understanding of the results and discussion, the study area was divided into six subbasins: Paranáiba (I), Grande (II), Tietê (III), Paraná (IV), Paranapanema (V), and Iguaçu (VI) (see Fig. 1).

b. Dataset description, quality control, and preprocessing

The dataset of 40 years of daily precipitation totals, from 1 January 1977 to 31 December 2016, from gauges distributed over the PRB was provided by ANA. The set comprises 5107 rain gauge stations from 149 different institutions. Before use, these data were thoroughly controlled via the following steps:

(i) Double records and typographical errors were verified. Several consecutive repeated values above 1 mm day$^{-1}$ and precipitation above 250 mm day$^{-1}$ were considered as missing data. Stations with values above 250 mm day$^{-1}$ were verified if possible before considering them as missing data. The values were analyzed by comparing the amounts of rainfall among nearby stations.

(ii) Stations missing more than 10% of their data during the period from 1 January 1977 to 31 December 2016 were disregarded.

(iii) Missing data were not filled, and, to avoid misleading detection of a trend as a result of missing data, years with more than 14 missing data were not considered in the trend analysis. For the analysis of seasonal totals (3 months), seasons with more than three missing data were disregarded.

(iv) A test of homogeneity was performed on the annual precipitation time series by using the standard normal homogeneity test (SNHT) (Alexandersson 1986). SNHT has been previously used in several studies for the homogeneity analysis of precipitation time series (e.g., Jónsdóttir et al. 2006; Javari 2016). Data series that presented nonhomogeneity were disregarded.

Fig. 1. Geographic location and topographic map of the PRB with its subbasins, showing the spatial distribution of the 853 weather stations used in this paper.
(v) Autocorrelation was tested on both annual and seasonal precipitation as a quality check, because no autocorrelation is expected in precipitation data, and to assure that no serially correlated time series will be tested for trends (e.g., Yue et al. 2002).

After data quality control, 853 gauge stations were selected. Most gauge stations are located in the Paraná (IV) subbasin, mainly in the southeastern part of the PRB, followed by the Grande (II) and Paranapanema (V) ones, which have 209 (24.5%), 171 (20%), and 146 (17%) stations, respectively. The highest number of rain gauges in the east side of the basin is due to the majority of the stations being located on large rivers, where most of the hydropower plants are located, and surrounding densely populated areas. The spatial distribution of the rain gauges is illustrated in Fig. 1.

These daily precipitation series were the basis for creating series of accumulated annual and seasonal precipitation. Seasons follow the austral ones: summer (December, January, and February), autumn (March, April, and May), winter (June, July, and August), and spring (September, October, and November). In addition, four indices used in the Statistical and Regional Dynamical Downscaling of Extremes for European Regions (STARDEX; Goodess et al. 2005) were selected to analyze extreme precipitation. To evaluate the intensity of extreme precipitation events, series of annual 5-day maximum precipitation (px5d) and simple daily intensity (pint) were generated. To assess the persistence of precipitation, the indices of longest dry period (pxcdd) and rainstorm days (pn50) were generated. An overview of these indices is given in Table 1.

c. Methods

Annual and seasonal precipitation were interpolated over the PRB using inverse-distance-weighted (IDW) interpolation. Trends were tested by the MK test, and their statistical significance was tested by bootstrap. This section presents the description of these methods.

1) MK TEST

The nonparametric statistical MK test (Mann 1945; Kendall 1975) was used to analyze the trends in the annual, seasonal, and daily precipitation amounts at all 853 stations (1977–2016). The MK test is widely used to investigate trends in series of meteorological variables (e.g., Marengo et al. 1998; Dufek and Ambrizzi 2008; Li et al. 2011, 2010; Shifteh Some’e et al. 2012; Sayemuzzaman and Jha 2014; Shi et al. 2016). We applied the MK test on the indices of the accumulated annual and seasonal rainfall as well as on the indices calculated and described in Table 1.

The MK test is calculated using Eqs. (1)–(4):

\[
S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \text{sgn}(x_i - x_j),
\]

\[
\text{sgn}(x) = \begin{cases} 
+1, & \text{if } (x_i - x_j) > 0 \\
0, & \text{if } (x_i - x_j) = 0 \\
-1, & \text{if } (x_i - x_j) < 0 
\end{cases}
\]

\[
\text{VAR}(S) = \frac{n(n-1)(2n+5) - \sum_{j=1}^{m} t_j(t_j - 1)(2t_j + 5)}{18},
\]

and

\[
Z_{MK} = \begin{cases} 
\frac{S - 1}{\text{VAR}(S)^{1/2}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S + 1}{\text{VAR}(S)^{1/2}} & \text{if } S < 0
\end{cases}
\]

where \(n\) represents the length of the dataset; \(x_i\) and \(x_j\) are the data values in \(i\) and \(j\), respectively; \(t_j\) represents the number of observations for the \(j\)th group; \(m\) is the number of groups; and \(Z_{MK}\) indicates that there is an increasing trend (positive value) or decreasing trend (negative value) with time in the analyzed variable. When \(|Z_{MK}| > Z_{1} - (\alpha/2)\), the null hypothesis is rejected and a significant trend is detected in the dataset. The value of \(Z_{1} - (\alpha/2)\) is available from the standard normal distribution table. In this study, statistical significance at the 95% confidence level (\(\alpha = 0.05\)) was adopted. Therefore, the null hypothesis of no trend is rejected when \(|Z_{MK}| > 1.96\).

Bootstrap method

According to Clarke (2010), the effect of spatial correlation between stations should be considered when a trend detection is applied. The spatial correlation was evaluated by testing the significance level of the MK test using the bootstrap method (Efron 1979), which is suggested by Douglas et al. (2000). For all the indices (Table 1), 500 random samples from the original time series and their trends were calculated. The original data were considered to be statistically significant if the resampled series trend fell into the upper or lower 5% of the bootstrapped distribution.

2) IDW INTERPOLATION

To analyze the spatial distribution of trends in precipitation, the IDW interpolation method was used. This interpolation technique was applied to the annual and
seasonal average precipitation totals as well as to the extreme precipitation indices. IDW has been carried out in several studies for the spatial interpolation of precipitation and has provided satisfactory results (e.g., Cannarozzo et al. 2006; Lu and Wong 2008; Gemmer et al. 2011; Chen et al. 2017). The IDW interpolator essentially depends on the number of observations around the point of interest, with individual contributions diminishing with distance. The local influence of observations is defined using Eqs. (5) and (6):

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i) \quad \text{and} \quad \lambda_i = \frac{d_i^{-p}}{\sum_{i=1}^{N} d_i^{-p}}, \quad \sum_{i=1}^{N} \lambda_i = 1,$$

where $Z(S_0)$ represents the prediction value at point $S_0$, $Z(S_i)$ is the observed value at point $S_i$, $N$ is the number of observations surrounding the prediction point, $\lambda_i$ is the weight assigned to each observed point, $p$ is a power parameter, and $d_0$ is the distance from the target to the observation.

### 3. Results and discussion

**Trends and interpolated values of precipitation**

The results of the trends obtained by the MK test and the interpolated values obtained using the IDW method for the annual and seasonal average accumulated precipitation as well as for the precipitation indices from 1977 to 2016 are shown in Figs. 2–4. The results and their discussions are presented in the following sections.

1) **ANNUAL AND SEASONAL PRECIPITATION**

The interpolated annual average precipitation (Fig. 2e) clarifies that the higher values of accumulated annual precipitation over the PRB, exceeding 1850 mm, are located in the southern PRB (west of the Iguacu and southeast of the Paraná subbasins). On the other hand, the lower values, lower than 1400 mm, predominate in the center (mostly in the lower Tietê and northeast of the Paraná subbasins). Seventy of the 853 stations (8%) showed trends at the 95% confidence level of significance. Of them, 36 presented significant negative trends, being mostly located in the Grande (20) and Paranaiba (8) subbasins. Thirty-four series (4%) presented significant positive trends, and they are concentrated in parts of the Parana panema (12), Iguacu (11), and Parana (9) subbasins (see Fig. 2e).

In contrast to the accumulated annual precipitation patterns, the north and northeast of the PRB (i.e., the Paranaiba and Grande subbasins) are the regions with the highest summer precipitation values (>800 mm), while the southern region (i.e., the Iguacu subbasin) presents the lowest values (<500 mm) (Fig. 2a). The high rates of precipitation in the northern part of the PRB are characterized by the activity of the SAMS during the austral summer (Grimm et al. 2007; Carvalho et al. 2011). Among the series of accumulated summer precipitation, 39 showed significant trends. Negative trends are observed mostly in the Paranaiba and Grande subbasins, with 9 and 4 stations, respectively. Positive trends are concentrated in the southeast of the Parana, Iguacu, and Parana panema subbasins with 12, 5, and 4 stations, respectively (Fig. 2a).

Precipitation totals in autumn show great spatial variability with higher precipitation values of more than 450 mm in the southeastern region (Iguacu), as seen in Fig. 2b. All the significant trends in autumn were negative, and they were mainly located in the central portion and northeastern region of the PRB (Fig. 2b).

Figure 2c shows that the winter precipitation in the PRB increases from north to south, from less than 30 mm (north of the Paranaiba subbasin) to more than 240 mm (southeast of the Parana and south of the Parana panema and Iguacu subbasins). As mentioned before, this scenario of low rainfall in the northern part of the basin occurs due to the presence of the SAMS, which is responsible for the low precipitation rates in winter and high rates in austral summer (Fig. 2a) (Grimm et al. 2007; Carvalho et al. 2011). For this season, few stations presented significant trends, with a clear north–south separation. Negative trends predominated in the north (9) and positive in the south (4).

The series of spring precipitation showed totals ranging from 350 to 500 mm. Statistically significant

### Table 1. List of precipitation indices selected.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulated precipitation</td>
<td>Annual or seasonal precipitation totals</td>
<td>mm</td>
</tr>
<tr>
<td>5-day max precipitation (px5d)</td>
<td>Annual greatest 5-day total precipitation</td>
<td>mm</td>
</tr>
<tr>
<td>Simple daily intensity (pint)</td>
<td>Annual mean precipitation per rain day (&gt;1 mm day⁻¹)</td>
<td>mm day⁻¹</td>
</tr>
<tr>
<td>Longest dry period (pxcdd)</td>
<td>Annual max no. of consecutive dry days (&lt;1 mm day⁻¹)</td>
<td>days</td>
</tr>
<tr>
<td>Rainstorm days (pn50)</td>
<td>Annual no. of days with precipitation &gt;50 mm day⁻¹</td>
<td>days</td>
</tr>
</tbody>
</table>
negative trends predominated in the northeastern region of the PRB, with 16 stations in the Grande subbasin (Fig. 2d).

The spatial distribution of trends of annual and seasonal total precipitation shows that significant negative trends are mostly located in the Paranaiba and Grande subbasins. A decreasing amount of precipitation in those regions may have a significant impact on energy generation as these basins house 70 hydropower plants that, together, provide more than 17,000 MW of electricity.
In contrast, the significant positive trends are concentrated in the Paranapanema and Iguaçu subbasins, notably in the summer season, which explains most of the annual trends. Figures 4a–e show the spatial distribution of only significant trends (positive or negative) in both indices as a result of the comparison of the indicators from Figs. 2 and 3. Negative significant trends in annual totals in the northern portion of the basin could be associated with the decreasing of precipitation during the summer, spring, or autumn seasons, as shown in Figs. 4a–c. Similarly, the positive significant trends in annual totals in the southern areas of the basin follow the trend in summer rainfall (Fig. 4a). Almeida et al. (2017) found equivalent results for annual and seasonal trends in the Brazilian Legal Amazon region for the 40-yr period 1973–2013. Stations with significant positive annual trends were associated with positive trends during the wet season. On the other hand, significant negative annual trends were associated with the negative trends in the dry season. Liebmann et al. (2004), studying the La Plata basin, observed a positive trend of up to 10.89 mm in the January–March season, during the period of 1976–99, over the southern parts of the PRB. This trend was
correlated with positive trends in the southwestern Atlantic sea surface temperature and streamflow in the area that essentially coincides with the Iguaçu subbasin, but with no obvious causes, according to the authors. Haylock et al. (2006) analyzed trends using gridded data (2° × 2°) from 1960 to 2000 over South America. Their results indicated a positive trend in annual total precipitation for most of the region related to PRB, except for a small part over the northern region. The present work found negative trends in an area that covers the northeastern part of the PRB (Fig. 2e). The discrepancies between the results presented in this work and Haylock et al. (2006) may be due to the different time span and spatial resolution. The gridded analysis performed by the authors may have influenced the local effects that are associated, for example, with urbanization. A study made by Yu and Liu (2015) using the Weather Research and Forecasting (WRF) Model...

Fig. 4. Spatial distribution of trends at the 95% confidence level for both (a) annual precipitation and summer precipitation, (b) annual precipitation and autumn precipitation, (c) annual precipitation and spring precipitation, (d) summer precipitation and pn50, and (e) winter precipitation (for negative significant trend) and pxcdd (for positive significant trend). The triangles show the significant trend (red is negative, and black is positive) at both indices, and the black asterisks represent the opposite trends of the displayed indices. The indices are defined in Table 1.
coupled with a multilayer urban canopy model shows that urbanization plays a significant role in frontal-type rainfall. They demonstrated through simulations that the urbanization and land-use change of Beijing caused the spatial distribution of precipitation to become more concentrated. The different period of study (1977–2016 vs 1960–2000) may also cause changes in trends. This further suggests that there may not be a steady positive or negative trend for the accumulated precipitation in the region.

A recent drought event in the PRB has been experienced by the eastern part of the basin during the years 2014–15. According to Coelho et al. (2016), during the summer of 2014, the South Atlantic convergence zone, the mechanism responsible for most of the rainfall during summer months, was practically absent in the period. The anomalous dry season was attributed to a global circulation pattern connecting the Pacific and Atlantic Oceans that in turn caused a lasting subsidence over the basin. However, the authors point out the negative anomaly in summer precipitation as the main cause of the long-lasting drought. In our study, as shown in Figs. 4a and 4b, the trend of decrease in annual precipitation is a result of trends evident in the summer, autumn, and spring seasons.

2) EXTREME PRECIPITATION EVENTS

The annual 5-day maximum precipitation index (px5d) presented both significant positive and negative trends during 1977–2016 (Fig. 3a). Positive trends were observed in 20 locations mostly in the central portion of the basin. Some of these stations are located in regions with px5d values greater than 225 mm, which indicates an increase of extreme events during this period. On the other hand, the 14 stations with negative trends were mostly located in the northern and northeastern regions of the PRB (Fig. 3a). An increasing of the rainfall amount increases the probability of flooding and, therefore, special attention should be given to the lower Paranapanema sub-basin, where nine of the stations that presented significant positive trends are located. Previous studies have analyzed extreme precipitation events in this area and other parts of the PRB that caused considerable damage to local economies (e.g., Camilloni and Barros 2000). Moreover, a significant positive trend in px5d was detected in other basins in South America such as the Cauca River in southwestern Colombia (Avila et al. 2019).

Simple daily intensity (pint) is the index with the highest number of stations showing significant trends, with 263 of 853 stations (31%). A total of 87% of these stations exhibit positive trends and are mostly located in the Paraná sub-basin, with 70 stations, followed by the Paranapanema (54) and Iguaçu (48) subbasins (Fig. 3b). This result is in accordance with those found by Zandonadi et al. (2016) that presented an increase of the trends in almost all domains of the PRB. According to Peterson et al. (2001), the pint index summarizes the wet part of the year. Therefore, the results indicate that most of the areas in the PRB basin are experiencing a lengthening of the wet season. The opposite was observed by Bezerra et al. (2019) over the São Francisco River basin, north of the PRB, in the Brazilian semi-arid region. They found mainly negative trends in pint, indicating the shortening of the rainfall season in that region.

Liebmann et al. (2004) connects the increase of the pint index, in an area covering PRB, to the positive trend observed in precipitation during the January—March season. Although summer in this work comprises December to February, the trends presented here are consistent with their results. On the other hand, the neutral trends found by Liebmann et al. (2004) in an area that corresponds to the northern part of the PRB are not consistent with the findings presented here. The one-decade-longer time span of the data in this work could explain these discrepancies. For instance, with a longer analysis period, the present work may have captured more phase change of climate variability than previous studies. As reported by several studies (e.g., Jacques-Coper and Garreaud 2015; Miller et al. 1994), the large-scale modes of variability have a significant influence on the regional precipitation regime within the basin. Also, the spatial resolution (2.5° × 2.5°) analysis used by the authors may have contributed to the trend differences. In the study by Haylock et al. (2006), the trends identified for pint show a clear pattern of increasing over areas of the PRB, which is consistent with the present study.

Figure 3c shows that the longest dry period (pxcdd) increases from south to north in the PRB. Pxcdd ranged from 30 days in the Iguaçu subbasin to more than 90 days in the northern region of the Paraná subbasin. This gradient is connected to the different sources of precipitation from south to north and is clearly connected to the dry winters characteristic of the South American monsoon (Fig. 2c). Positive trends represent the majority (88%) of significant trends of pxcdd. Most of these (15) are located in the northern region of the PRB, particularly in northern Paraná, which is the region that presents a high number of dry days (>90). The significant positive trends in pxcdd found at four stations in the upper Paraná subbasin can be explained by the negative trends in precipitation during winter (Fig. 4e). Evidence of increasing of consecutive dry days in the Paraná subbasin was also found by Zandonadi et al. (2016), but with no stations with a significant trend at the 95% confidence level during the period between 1986
and 2011. An increase in the annual maximum number of consecutive days without rainfall in these areas may have a significant impact in water supply to the largest city of Goiás state, Goiânia, and the federal capital of Brazil, Brasília, with an estimated population of 1.5 and 3.0 million inhabitants, respectively (Brazilian Institute of Geography and Statistics 2019). According to ANA, the Corumbá IV reservoir, located in the northern part of the PRB (within the area of significant positive trends of the pxced index) with an area of 173 km², is responsible for the water supply of 1.3 million inhabitants.

The remaining stations with significant positive pxced trends are located in the upper Tietê subbasin and the western parts of the Iguaçu subbasin. The results obtained in the Tietê and Iguaçu subbasins are consistent with those found by Dufek and Ambrizzi (2008) and Luiz Silva et al. (2015), respectively.

The interpolated values of the pn50 indicator show regions with climatological mean exceeding 9 days per year with rainfall values greater than 50 mm. The MK test showed significant trends at 85 stations (10%), of which 60 are positive and 25 are negative. Positive trends are mostly located in the south and negative ones in the northeast of the PRB (Fig. 3c). One of the main contributors to extreme precipitation events over the PRB, the SALLJ, has been analyzed recently in terms of its spatiotemporal variability. Montini et al. (2019) reported trends of SALLJ from 1979 to 2016 within the same period of the present study. Their results showed significant increasing trends in strength and frequency of SALLJ over southern Brazil. These may likely contribute to the increase of rainstorm days (>50 mm day⁻¹) in the south of the PRB. The significant positive trends in rainstorm days may be a contributor to the positive trend in summer rainfall in the southern areas of the PRB observed here. As shown in Fig. 4d, six stations revealed positive trends at 95% confidence level in both summer and pn50 indices. Such behavior has been previously observed in other parts of the world (Jiang et al. 2007).

4. Conclusions

This paper analyzed the annual and seasonal precipitation, as well as extreme precipitation indices, in the PRB. The spatial distributions of the positive and negative significant trends at the 95% confidence level were analyzed using 40 years of data, ranging from 1977 to 2016. The spatial distribution of these data was obtained using the IDW method, and their trends were obtained using the MK test.

Previous studies have shown that the occurrence of extremes in the PRB undergoes intense spatial and temporal variation (Liebmann et al. 2001; Grimm 2011) and that there are many climate regimes affecting the different subbasins of the PRB (see Salio et al. 2007; Zamboni et al. 2010; Tedeschi et al. 2013). Thus, depending on the time scale involved and the resolution used, these studies may not be conclusive or may not agree with the results found in this work. Hence, the importance of the results presented here lies in the fact that they explore trend analysis of extremes over all PRB as well as an update in terms of the number of stations analyzed. Furthermore, these conclusions are based on longer precipitation series, which increases the probability that a given time scale is properly represented, in contrast with previous works, which focused on the trends in rainfall extremes in the PRB for previous or shorter periods. For instance, Silva Dias et al. (2013) found through long-term analysis of data from one rain gauge located in São Paulo city that the climatic indices such as the Pacific decadal oscillation, ENSO, and the North Atlantic Oscillation explained 85% of the increasing frequency of extremes during the dry season. Also, the study performed by Teixeira and Satyamurty (2011) suggests that longer time series are necessary to ensure the existence of monotonic trends.

The results revealed that the Paraná River basin has many stations located in different subbasins recording precipitation series with monotonic trends. Hence, this information, as well as knowledge about the regions that present trends in precipitation, is of interest for policy makers and managers in the implementation of future conservation and sustainable use of water resources. These results also represent an update relative to previous studies, as this study used a large number of rain gauges and a longer rainfall time series.

Special attention should be paid to the northern and southern regions of the basin, which presented decreasing and increasing trends in precipitation amounts, respectively. In the southern part of the basin, an increase of extreme precipitation events with rainfall greater than 50 mm day⁻¹ is shown by these analyses. In the northern region of the PRB, an increasing number of dry days may have an impact on economic activity since it is an important region for agriculture production and energy generation and is the location of one of the largest urban centers of Brazil.

In a forthcoming study, the authors will further evaluate the potential impact of changes in land use and land cover and climate shift in the PRB over the last decades on hydrological processes, and they will link this research with changes in precipitation in the basin.
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