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ORIGINAL PAPER

Summer daily precipitation and wet day climatological features in southeast São Paulo, Brazil

Iara M. Scricco[1] · Caio A. S. Coelho[1]

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Abstract
The development of novel diagnostic tools for enhancing climate monitoring capabilities is being increasingly demanded by several important societal sectors, such as agriculture, energy production, and industry, among others. This study aims to contribute to such developments by characterizing the observed daily precipitation conditions within the climatic context for the austral summer months over the southeast region of the state of São Paulo, Brazil. The characterization was designed to quantify the climatological features of daily precipitation and of the number of rainy (or wet) days. The objective is to provide complementary information to the traditionally available monthly and annual precipitation monitoring. Such a diagnostic characterization can assist answering the following questions: How did daily precipitation behave in southeast São Paulo during the last two decades? What is the typical distribution of summer precipitation in southeast São Paulo? How many wet summer days are typically observed in southeast São Paulo? How many wet summer days were observed during the last two decades? What is the typical distribution of wet summer days in southeast São Paulo? How have the latest years been in terms of wet summer days? The daily precipitation and wet day characterization was performed using historical data for the 1998/1999 to 2017/2018 period. The representativeness of these characteristics was assessed using a four times longer time series from a meteorological station located within the investigated region. The analysis indicated that for the southeast region of the state of São Paulo, the 2013/2014 summer period presented values well below those previously recorded in association with exceptionally dry conditions established over this region, corroborating previous findings but now from the perspective of daily precipitation information.

1 Introduction

The demand for daily information for monitoring meteorological conditions and characteristics within a climatic context has grown in various socioeconomic sectors, such as agriculture, energy production, industry, and construction, among others. This continuous search for new information is accompanied by recent scientific and technological advances, which promote the development of novel climate monitoring tools and products for complementing those currently available.

Most climate studies that investigated precipitation have focused on the analysis of monthly, seasonal and annual data. For example, Coelho et al. (1999) described the climatological seasonal precipitation over Brazil based on 206 meteorological stations over the 1960–1998 period. Grimm (2003) described the climatological annual precipitation cycle over Brazil using monthly precipitation totals from 1175 stations for the 1956–1992 period. Fewer studies have investigated in detail daily data information, particularly analyzing the characteristics of climatological distributions of daily precipitation and of days classified as wet, highlighting the need for additional studies focused on these analyses. Daily precipitation analysis can, for example, aid information for monitoring weather condition characteristics within the climate context. In this context, Coelho et al. (2015, 2017) used daily precipitation data to define the climatological distribution of the beginning and end dates of the rainy season in São Paulo. Grimm and Tedeschi (2009) investigated precipitation extreme events defined as 3-day running mean above the 90th percentile of historical meteorological station time series. Some studies, such as Brunetti et al. (2001), have indicated the importance of analyzing the number of wet days, which may present more defined climate variability than the overall accumulated precipitation.

✉ Iara M. Scricco
iaramscricco@gmail.com

[1] Centro de Previsão de Tempo e Estudos Climáticos (CPTEC), Instituto Nacional de Pesquisas Espaciais (INPE), Rodovia Presidente Dutra, Km 40, SP-RJ, Cachoeira Paulista, SP 12630-000, Brazil

In Brazil, several studies have investigated various aspects of daily precipitation not restricted to climatological distribution analysis. These aspects have been investigated through the relationships between daily precipitation and other variables and phenomenon such as the El Niño Southern Oscillation (ENSO), and also by means of indices representing extreme climate events, linear trend analyses, and climate forecasts, among other approaches (Xavier et al. 1994; Santos and Brito 2007; Fischer et al. 2008; Silva and Azevedo 2008; Sugahara et al. 2009; Silva et al. 2011; Marcuzzo et al. 2012; Silva Dias et al. 2012; Raimundo et al. 2014; Romero et al. 2014). Focusing specifically on the state of São Paulo, Dufek and Ambrizzi (2008) evaluated trends in total precipitation and in extreme precipitation events. Coelho et al. (2015) characterized the climatological precipitation distribution over the southeastern region of the state of São Paulo, with particular attention devoted to the prolonged drought event observed during the 2013/2014 and

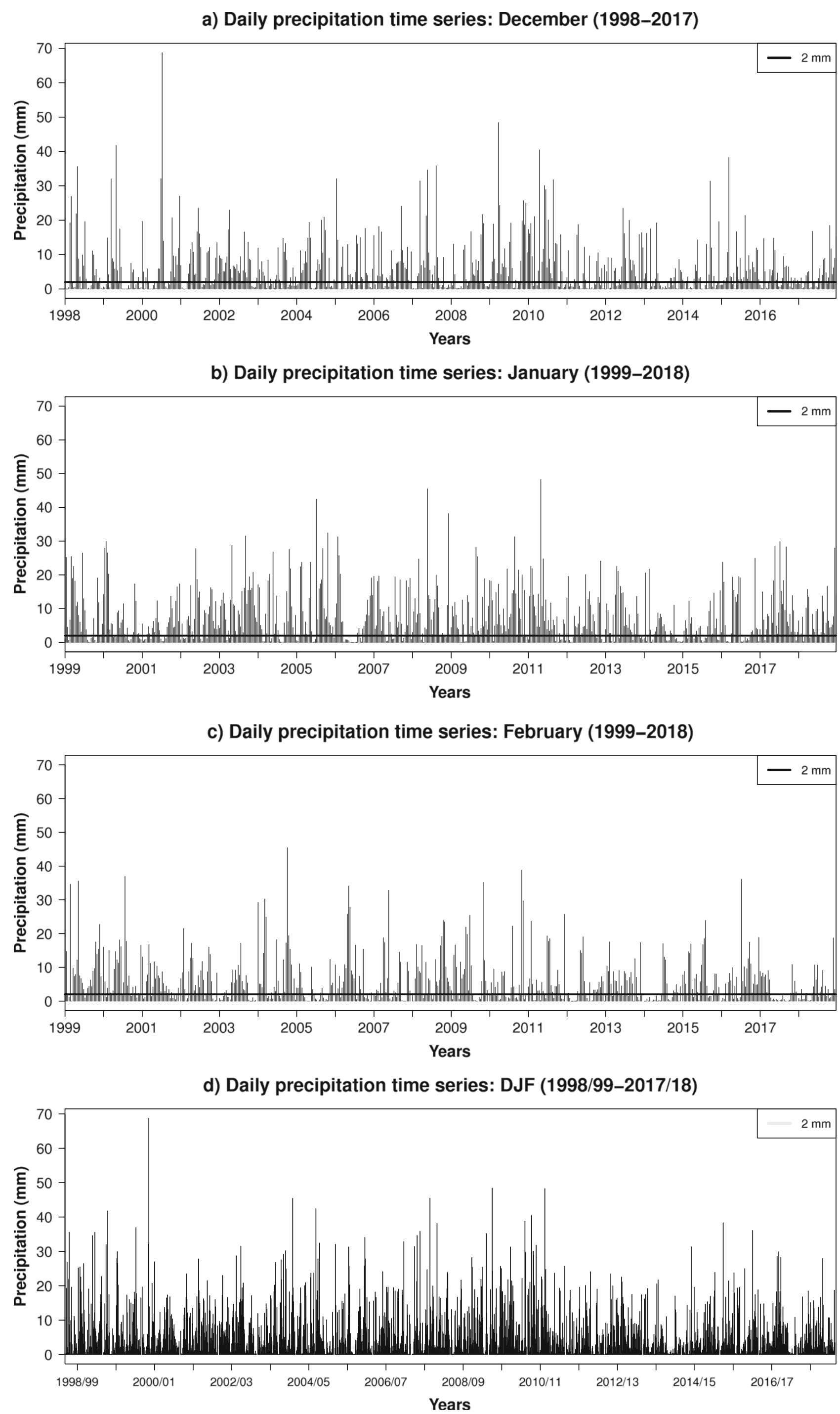

Fig. 1 Daily precipitation time series over São Paulo, Brazil, for the period 1998/1999–2017/2018: **a** December 1998 to 2017, **b** January 1999 to 2018, **c** February 1999 to 2018, and **d** DJF 1998/1999 to 2017/2018. The area between 22.5°S, 25°S, 47.5°W, and 45°W (black square in figure 1 in Coelho et al. 2015) represents the continental region of São Paulo State used in the daily precipitation diagnostics. These graphics were produced using observed meteorological station data from the Center for Weather Forecast and Climate Studies (CPTEC) of the Brazilian National Institute for Space Research (INPE), the Brazilian National Meteorological Service (INMET), and regional meteorological offices, interpolated to a regular 0.25° grid in latitude and longitude

Table 1 Mean, minimum (min), maximum (max), median, and standard deviation (SD) of daily precipitation (mm) over Sao Paulo, Brazil, for the December 1998–2017, January 1999–2018, February 1999–2018, and DJF 1998/1999–2017/2018 period

	Mean	Min	Max	Median	SD
Dec	6.28	0	68.73	3.48	7.83
Jan	7.81	0	48.27	5.06	7.80
Feb	6.12	0	45.43	3.84	7.11
DJF	6.76	0	68.73	4.21	7.63

2014/2015 austral summer months. Zilli et al. (2017) analyzed extreme precipitation trends over the state of São Paulo, also presented information on the number of wet days, and identified that daily precipitation extremes are becoming more intense and frequent in recent years. Harisson (1983) indicated for a region in South Africa that the variability in the number of wet days is correlated with inter-seasonal changes in the mean daily precipitation, corroborating with Zilli et al. (2017) who found that intense precipitation may result from the interaction of meteorological phenomena acting in various time scales.

Motivated by the demand for new and more detailed climate monitoring diagnostics information in terms of temporal sampling frequency, and the relevance of this information for several societal sectors, the objective of this study is to characterize the daily precipitation conditions within the climatic context focusing on the austral summer months for the southeastern region of the state of São Paulo. This region was previously investigated by Coelho et al. (2015) under other perspectives (see figure 1 of Coelho et al. 2015 to identify the geographical location of the investigated region). Both Coelho et al. (2015) and Grimm (2003) documented that climatologically the austral summer months mark the wet season for the southeast region of the state of São Paulo here investigated. Particularly, the present study aims to quantify the climatological characteristics of daily precipitation and the number of rainy (or wet) days in order to provide more detailed information to improve climate monitoring over the investigated region. The study aims to answer questions such as: How did daily austral summer precipitation behave in southeastern São Paulo during the last two decades? What is the typical distribution of austral summer daily precipitation in southeastern São Paulo? How many wet austral summer days are typically observed in southeastern São Paulo? How many wet austral summer days were observed during the last two decades? What is the typical distribution of wet austral summer days in southeastern São Paulo? How atypical have the past few years been in terms of wet austral summer days?

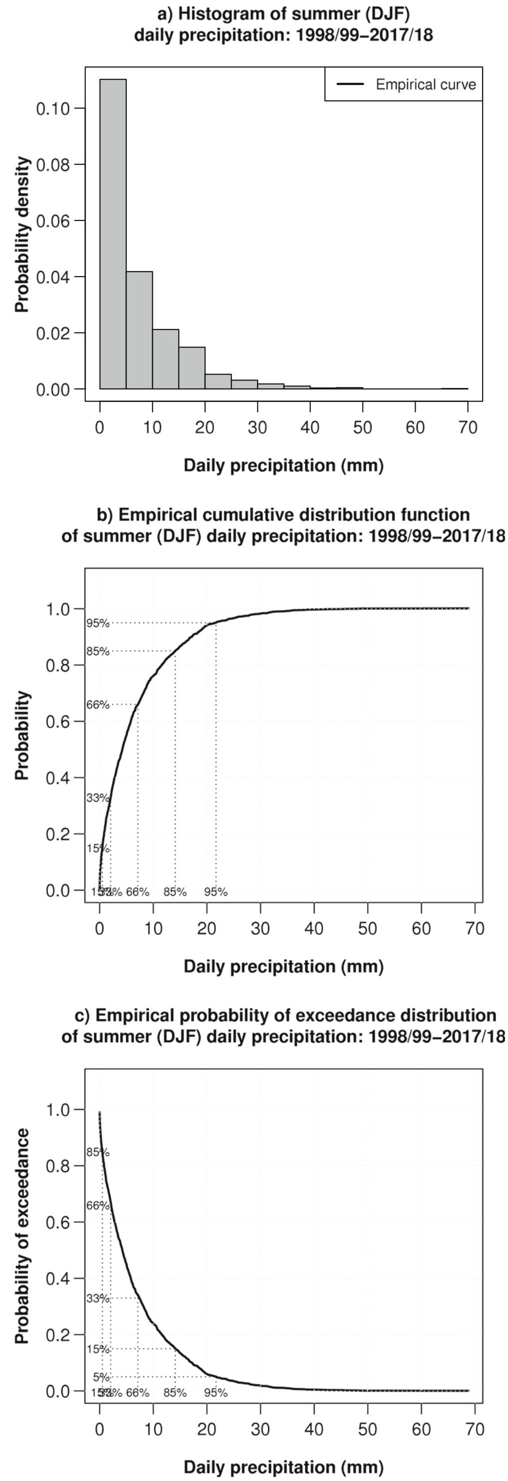

Fig. 2 Daily precipitation distribution for the 1998/1999–2017/2018 austral summer (DJF) months. **a** Histogram of austral summer (DJF) daily precipitation displayed as probability density so that it has a total area that adds up to the value of 1. **b** Empirical cumulative daily precipitation distribution functions for DJF 1998/1999–2017/2018 for the region of São Paulo investigated in this study. **c** Corresponding empirical probability of exceedance distribution functions of daily precipitation for DJF 1998/1999–2017/2018. The 33rd, 66th, 85th, and 95th percentile values of the empirical distribution are marked with dashed lines in (**b**) and (**c**)

Table 2 Mean, minimum (min), maximum (max), median, standard deviation (SD), kurtosis, asymmetry, and percentile values of the empirical distribution of daily precipitation over Sao Paulo, Brazil, for the1998/1999–2017/2018 period

	Mean	Min	Max	Median	SD	Kurtosis	Asymmetry
DJF	6.76	0	68.73	4.21	7.63	1.38	0.27
Percentile		5%	15%	33%	66%	85%	95%
		0.05	0.51	2.05	7.12	14.09	21.7

The study is organized as follows. Section 2 describes the time series and the climatological distribution of daily precipitation over the southeastern region of the state of São Paulo investigated in this study for the 1998/1999–2017/2018 period. Section 3 characterizes the time series and the climatological distribution of the number of rainy (or wet) days. Section 4 assesses the representativeness of the climatological distribution analysis performed in Sections 2 and 3 using an independent daily precipitation time series of a meteorological

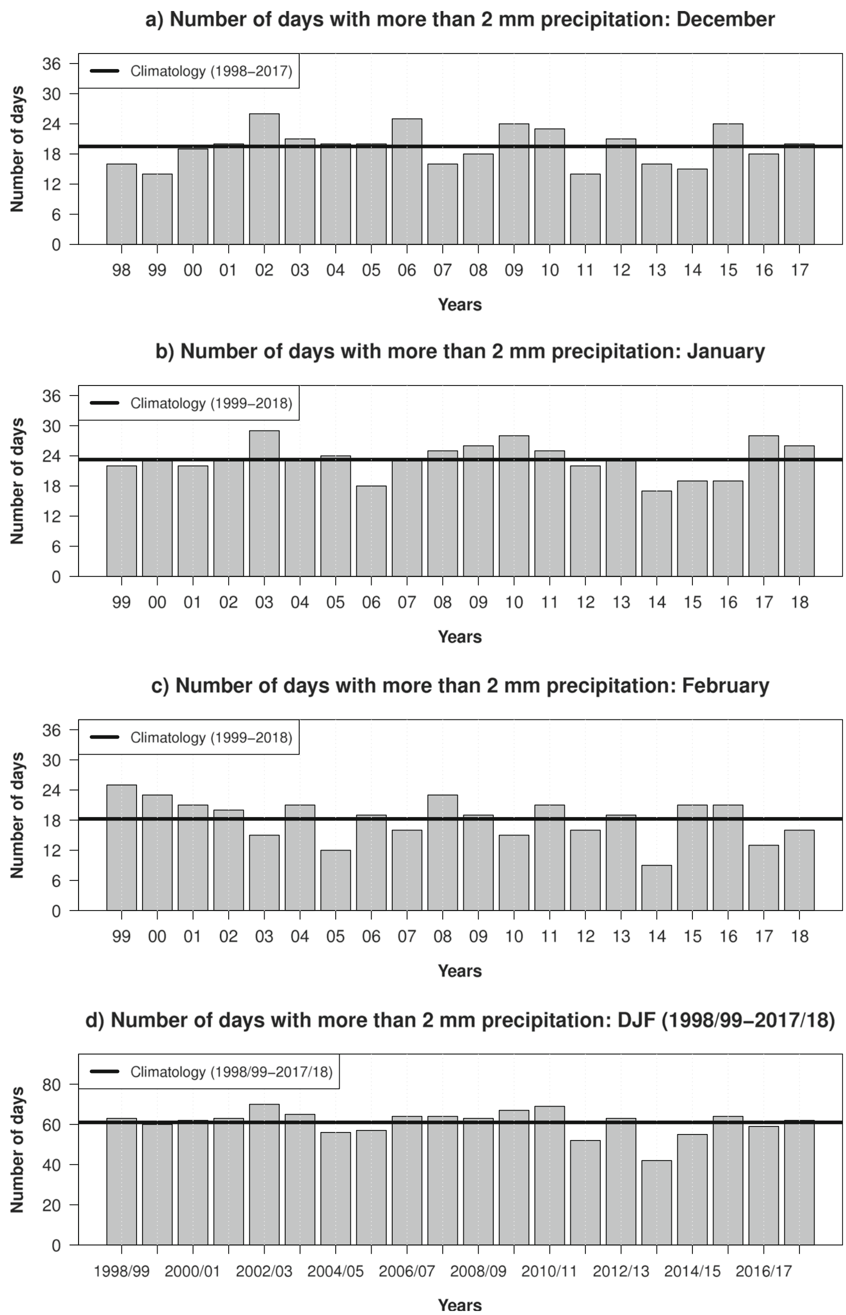

Fig. 3 Number of days with more than 2 mm precipitation in a December 1998 to 2017, **b** January 1999 to 2018, **c** February 1999 to 2018, **d** DJF 1998/1999 to 2017/2018. The black horizontal line represents the climatological mean over the investigated 20-year period

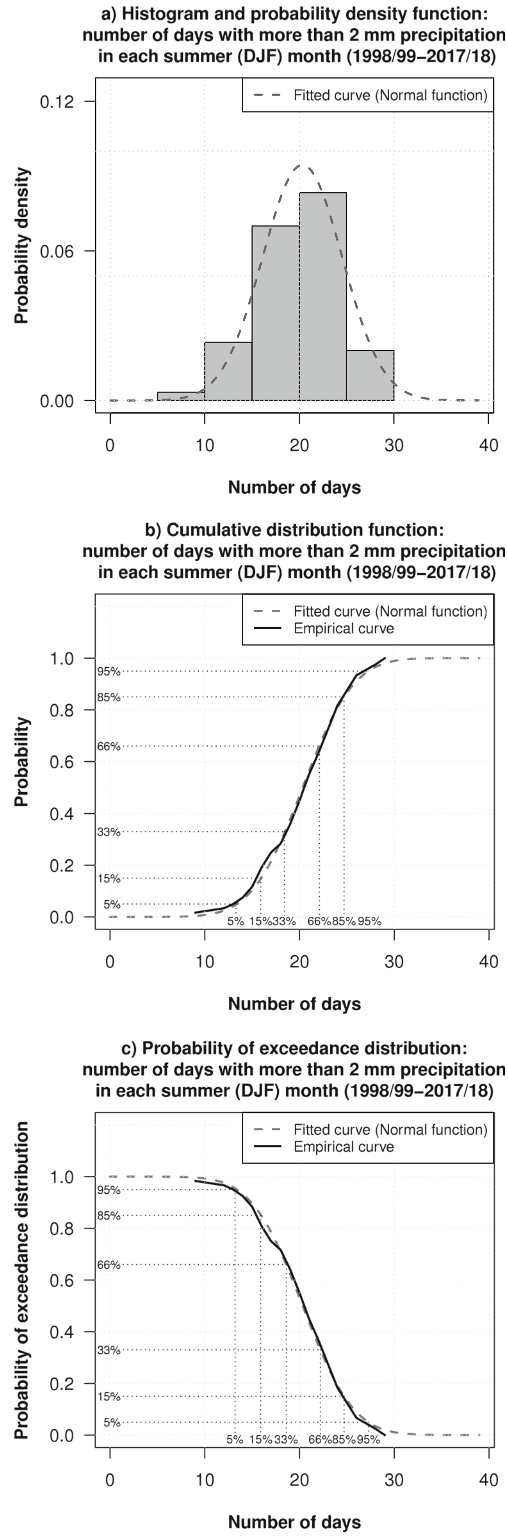

Fig. 4 Number of days with more than 2 mm precipitation in each summer (DJF) month (1998/1999–2017/2018). **a** Histogram and probability density function of number of days with more than 2 mm precipitation in each summer. **b** Empirical (black line) and normal (gray curve) cumulative distribution functions in DJF for 1998/1999–2017/2018, number of days with more than 2 mm precipitation for the region of São Paulo here investigated. **c** Corresponding empirical (black line) and normal (gray curve) probability of exceedance distribution functions in DJF for 1998/1999–2017/2018, number of days with more than 2 mm precipitation. The 5th, 15th, 33rd, 66th, 85th, and 95th percentile values of number of days distribution are marked with dashed lines in (**b**) and (**c**). The data of each of the three summer months were aggregated resulting in a sample of 60 values, corresponding to 20 values for each month

station located within the investigated region. Section 5 presents the time series anomalies of the number of wet days. Section 6 characterizes the number of wet days for 2013, 2014, and 2015, which were highlighted as dry years in the region. Finally, Section 7 presents a summary of the main findings and the conclusions.

2 Daily precipitation time series and climatological distribution

This study used daily precipitation time series from December 1998 to February 2018. This is the same dataset used by Coelho et al. (2015), which comprises observational data from the meteorological station of the Center for Weather Forecast and Climate Studies (CPTEC) of the Brazilian National Institute for Space Research (INPE), the National Institute of Meteorology (INMET), and from regional meteorological centers. The stations available were initially interpolated to a regular grid (0.25° in latitude and longitude). The diagnostic analysis of the present study was conducted using the mean daily precipitation values over a region located in the southeastern portion of the state of São Paulo, Brazil (coordinates—22.5°S, 25°S, 47.5°W, and 45°W), as indicated by the box drawn in figure 1 of Coelho et al. (2015). This procedure resulted in a 20-year-long mean daily time data series for this region, which allows the performance of the climatological assessment proposed in this study. As this study is an extension of the analysis presented in Coelho et al. (2015), it is therefore natural to use the same dataset used by these authors.

Table 3 Mean, minimum (min), maximum (max), median, and standard deviation (SD) of number of days with more than 2 mm precipitation, for the 1998/1999–2017/2018 period: December 1998–2017, January 1999–2018, February 1999–2018, and DJF 1998/1999–2017/2018

	Mean	Min	Max	Median	SD
Dec	19.5	14	26	20	3.64
Jan	23.25	17	29	23	3.30
Feb	18.25	9	25	19	4.11
DJF	20.33	9	29	21	4.22

Figure 1 shows the daily precipitation time series for the months of December 1998–2017 (panel a), January 1999–2018 (panel b), February 1999–2018 (panel c), and for the

Table 4 Mean, minimum (min), maximum (max), median, standard deviation (SD), kurtosis, asymmetry, and percentile values of the number of days with more than 2 mm precipitation for the DJF 1998/1999–2017/2018 period

	Mean	Min	Max	Median	SD	Kurtosis	Asymmetry
DJF	20.33	9	29	21	4.22	1.26	− 0.23
Percentile		5%	15%	33%	66%	85%	95%
		13.95	16	19	22.94	25	26.1

December–January–February (DJF) 1998/1999–2017/2018 season (panel d). For the analyses of the following sections, the value of 2 mm (horizontal line) was selected as the threshold for identifying rainy (or wet) days (see additional information about the reasoning for the selected threshold value in the beginning of Section 3). Therefore, days were classified as "wet" when the daily precipitation exceeded this value. December presented the highest value when compared to the other 2 months. The maximum precipitation value 68.73 mm (Table 1) was recorded on December 17, 2000. This value was recorded over a period when the South Atlantic Convergence Zone (SACZ) phenomenon manifested over the investigated region (Climanálise 2000). The maximum value for the month of February was 45.43 mm (Table 1), recorded on February 23, 2004. This month was characterized by a reduction in the intensity of daily precipitation when compared to the other two investigated months. In the time series shown in Fig. 1d, where daily data for the months of DJF were grouped, large daily precipitation values occurred in 2000, 2003, 2004, 2005, 2007, 2009, and 2010. A sharp decrease in daily precipitation values was also observed from mid-2013 until 2014.

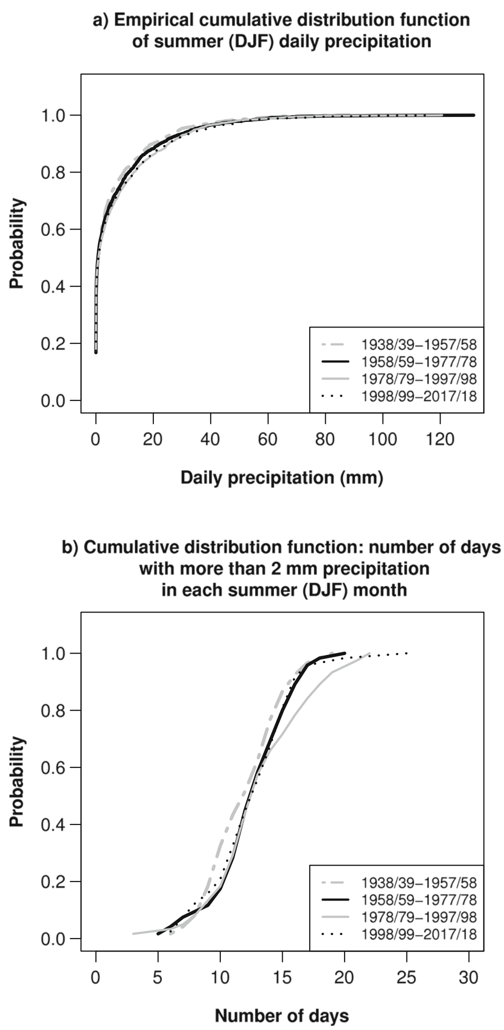

Fig. 5 Empirical cumulative distribution functions for four 20-year periods (1938/1939–1957/1958, 1958/1959–1977/1978, 1978/1979–1997/1998, and 1998/1999–2017/2018) of **a** summer (DJF) daily precipitation (mm), **b** the number of days with more than 2 mm precipitation in each summer month, based on IAG/USP meteorological station data, located in the city of São Paulo, Brazil

Figure 2 shows the daily precipitation climatological distribution for austral summer months (DJF) for the 1998/1999 to 2017/2018 period. In other words, this figure illustrates the distribution obtained from the daily data shown in Fig. 1d. Figure 2a shows the daily precipitation histogram displayed as probability density. The highest probability density is located in the lowest precipitation intervals, between 0 and 5 mm, with decreasing probability density toward the maximum value (68.73 mm), as shown in Table 1, at the tail of the empirical distribution. Note also that the histogram presents sizable probability density values until approximately 20 mm, decreasing to values close to zero at the tail of the distribution. Figure 2b shows the corresponding empirical cumulative distribution function (solid black line) of the historical daily precipitation time series for the 1998/1999–2017/2018 summer (DJF) months. This distribution indicates the probability of observing a precipitation value lower or equal to a certain value. For example, the value of 2.05 mm, which refers to the 33rd percentile, represents the precipitation amount that places one third of the data below this limit, meaning that the probability of observing a precipitation value lower than or equal to 2.05 mm is 33%. Another example for further illustrating the utility and interpretation of the proposed diagnostics for improving climate monitoring is for the average daily precipitation recorded in DJF 2013/2014 (3.49 mm), representing a deficit of 3.27 mm with respect to the climatological mean value of 6.76 mm (Table 1). According to the empirical distribution shown in Fig. 2b, the probability of observing 3.49 mm or less during the summer days is 45%.

Figure 2c shows the empirical exceedance probability distribution (solid black line). This distribution indicates the probability of observing a precipitation value that exceeds a pre-defined precipitation amount. Therefore, this distribution complements the cumulative distribution shown in Fig. 2b as it represents one minus the cumulative distribution. For example, the probability of observing a precipitation value higher than (or exceeding) the value of 2.05 mm is 66%. Figure 2b

Table 5 Mean, minimum (min), maximum (max), median, standard deviation (SD), kurtosis, and asymmetry of daily precipitation (mm) of IAG-USP station data in the city of São Paulo, Brazil, for DJF for four 20-year periods

DJF period	Mean	Min	Max	Median	SD	Kurtosis	Asymmetry
1938/1939–1957/1958	6.08	0	88.3	0.7	11.54	2.14	0.79
1958/1959–1977/1978	6.95	0	131.6	0.7	13.16	1.87	0.83
1978/1979–1997/1998	7.58	0	120.6	0.8	13.45	1.91	0.83
1998/1999–2017/2018	7.73	0	117.1	0.8	14.35	1.88	0.83

Kurtosis was computed using the Moors statistics $(p_{0.875} - p_{0.625}) + (p_{0.375} - p_{0.125})/(p_{0.75} - p_{0.25})$ and asymmetry (skewness) using the Yule Kendal statistics $(p_{0.25} - 2p_{0.5} + p_{0.75})/(p_{0.75} - p_{0.25})$, p_p are the p-th percentiles of the daily precipitation time series p

and c (vertical dashed lines) and Table 2 also show the values of the 33rd, 66th, 85th, and 95th percentiles. For the previous example for the average daily precipitation recorded in DJF 2013/2014 (3.49 mm), according to the empirical distribution shown in Fig. 2c the probability of observing 3.49 mm or more during the summer days is 55%.

3 Time series of wet days and climatological distribution

The previous section presented the daily precipitation time series and climatological distribution. This section presents the climatological analysis of the number of rainy (or wet) days. The counting of the number of rainy (or wet) days was conducted by using the 2-mm threshold, as indicated in Section 2. This threshold was chosen because it is considered a consistent value for the study area (22.5°S, 25°S, 47.5°W, and 45°W) and also adequately represents the precipitation regime over the region.

Figure 3 shows the time series of the number of wet days for the austral summer months, December, January, and February (panels a, b, c), and for the entire season (DJF) (panel d), over the 1998/1999–2017/2018 period. January presented the highest climatological mean value for the 1999–2018 period, with approximately 23 wet days (Table 3), as opposed to February that presented a mean of 19 wet days (Table 3). February 2014 presented an expressive reduction in the number of wet days, with only 9 wet days recorded. In turn, in December 2013 and January 2014, approximately 16 wet days were recorded. Figure 3d shows that since DJF 1998/1999, the number of wet days have been close to the climatological mean value. However, in 2011/2012, 2013/2014, and 2014/2015, an important reduction in the number of wet days was observed in the region. More specifically, an evident decrease was observed during DJF 2013/2014. This was the key period of the drought recorded in the southeastern region of the state of São Paulo, as documented by Coelho et al. (2015).

Figure 4 shows the histogram illustrating the climatological empirical distribution of the number of wet days in each month of the austral summer (DJF), representing a sample with 60 values, along with the adjusted normal distribution density function (dashed gray line), for the 1998/1999–2017/2018 period. The Kolmogorov–Smirnov statistical test was performed to investigate the adequacy of the normal distribution in representing a reasonable approximation of the empirical distribution. The Kolmogorov–Smirnov test provides the probability (p value) for rejecting the null hypothesis (the empirical distribution is equal to the adjusted normal distribution) in favor to the alternative hypothesis (the empirical distribution is different from the adjusted normal distribution). This test revealed no evidence for rejecting the null hypothesis in favor to the alternative hypothesis, indicating that the normal distribution was a good approximation to the empirical distribution.

Figure 4a presents the histogram and the probability density function of the number of wet days in each month of the austral summer (DJF). The highest probability density values were found between 15 and 25 wet days. Values between 5 and 30 wet days were also recorded over the analyzed period. Figure 4b shows the number of wet days cumulative empirical distribution (solid black line) and the corresponding cumulative normal distribution (dashed gray line) fit to the 60 sample

Table 6 Mean, minimum (min), maximum (max), median, standard deviation (SD), kurtosis, and asymmetry of number of days with more than 2 mm precipitation for IAG-USP meteorological station data in the city of São Paulo, Brazil, for DJF for four 20-year periods

DJF period	Mean	Min	Max	Median	SD	Kurtosis	Asymmetry
1938/1939–1957/1958	11.88	6	19	12	2.89	0.73	− 0.05
1958/1959–1977/1978	12.48	5	20	12	3.01	1.46	0.38
1978/1979–1997/1998	13.05	3	22	12.5	3.82	1.79	0.29
1998/1999–2017/2018	12.48	6	25	13	3.41	0.93	0

Table 7 Percentile values of the empirical distribution of daily precipitation of IAG-USP data in the city of São Paulo, Brazil, for DJF for four 20-year periods

DJF period	5%	15%	33%	66%	85%	95%
1938/1939–1957/1958	0	0	0	3.2	14.44	29.36
1958/1959–1977/1978	0	0	0	4.1	15.40	34.24
1978/1979–1997/1998	0	0	0	4.9	18.50	34.78
1998/1999–2017/2018	0	0	0	4.6	18.24	37.74

values representative of the DJF 1998/1999–2017/2018 summer period. This cumulative distribution indicates the probability of observing at least a certain amount of wet days. For example, Fig. 4b and Table 4 show that the probability of observing at least 19 wet days in the southeastern region of the state of São Paulo, in each month of the austral summer (DJF) here investigated, is 33%. Another example for further illustrating the utility and interpretation of the proposed diagnostics for improving climate monitoring is for the lowest number of wet days recorded in February 2014 (9 days). According to the empirical distribution shown in Fig. 4b, the probability of observing at least 9 wet days in each summer month is 1.66%. Figure 4c shows the empirical exceedance probability distribution (solid black line) and the corresponding curve obtained by fitting a normal distribution (dashed gray line) to the number of wet days during each month of the austral summer. This distribution indicates the probability of observing a number of wet days higher than a certain value. In other words, it indicates the probability of exceeding this value, therefore being complementary to Fig. 4b. For example, Fig. 4c shows that the probability of observing more than (or exceeding) 19 wet days, in each month of the austral summer (DJF), is 66%. Figure 4b and c also shows the values of the 5th, 15th, 33rd, 66th, 85th, and 95th percentiles. For the previous example for the lowest number of wet days recorded in February 2014 (9 days), according to the empirical distribution shown in Fig. 4c the probability of observing more than 9 wet days in each summer month is 98.34%.

Table 8 Percentile values of the number of days with more than 2 mm precipitation for the IAG-USP meteorological station data in the city of São Paulo, Brazil, for DJF for four 20-year periods

DJF period	5%	15%	33%	66%	85%	95%
1938/1939–1957/1958	7.95	9	10	13	15	16.05
1958/1959–1977/1978	6.95	10	11	14	16	17
1978/1979–1997/1998	7.95	9.85	11	14	17	19.1
1998/1999–2017/2018	7	9	11	14	15	17

4 Representativeness assessment using an independent daily precipitation time series

The analysis presented in the previous two sections was performed using a 20-year-long time series covering the most recent historical period (1998/1999–2017/2018), which could be considered short for climate studies, and also be affected by decadal variability and climate change. Grimm and Saboia (2015) reported that precipitation variability over the southeast region of Brazil is modulated by multidecadal modes of variability. Besides, the precipitation distribution might also be changing over the region due to the effect of global warming. One of the main impacts of a warmer atmosphere on the precipitation distribution is increasing its variability, which usually translates in broadening of the distribution curve as discussed in Pendergrass and Hartmann (2014a, b). There is therefore the need for investigating if these aspects are affecting the representativeness of the analysis performed in the previous two sections by examining a longer daily precipitation time series to make inference about the obtained results based on the 20-year-long time series.

In order to assess the representativeness of the performed regional precipitation analysis of Sections 2 and 3, daily data from the conventional historical meteorological station of the Institute of Astronomy, Geophysics and Atmospheric Sciences of University of Sao Paulo (IAG-USP), located in the city of São Paulo, which is within the southeast portion of the State of São Paulo here investigated, has also been used. This meteorological station is active and started to record data in 1934. Therefore, it allows splitting its long historical time series in four 20-year austral summer periods (1938/1939–1957/1958, 1958/1959–1977/1978, 1978/1979–1997/1998, and 1998/1999–2017/2018) for evaluating the robustness of the regional analysis for the area averaged daily precipitation using the dataset described in Section 2, and for the investigation of possible changes in daily precipitation that may have occurred in these four periods.

Figure 5 shows the empirical cumulative distribution functions of summer (DJF) daily precipitation and the number wet days (days with more than 2 mm precipitation) in each summer month, for the four 20-year periods mentioned above, based on IAG/USP meteorological station data. Figure 5a illustrates that the daily precipitation distributions for the four periods are similar, presenting a great degree of overlap particularly for precipitation values less than 5 mm and over 40 mm. The statistics for the four periods shown in Table 5 reveals that the mean and median daily precipitation is slightly larger for the two most recent periods (1978/1979–1997/1998 and 1998/1999–2017/18) when compared to the other two earlier periods (1938/1939–1957/1958 and 1958/1959–1977/1978). Table 5 also shows that the daily precipitation standard deviation is slightly reduced for the early period (1938/1939–

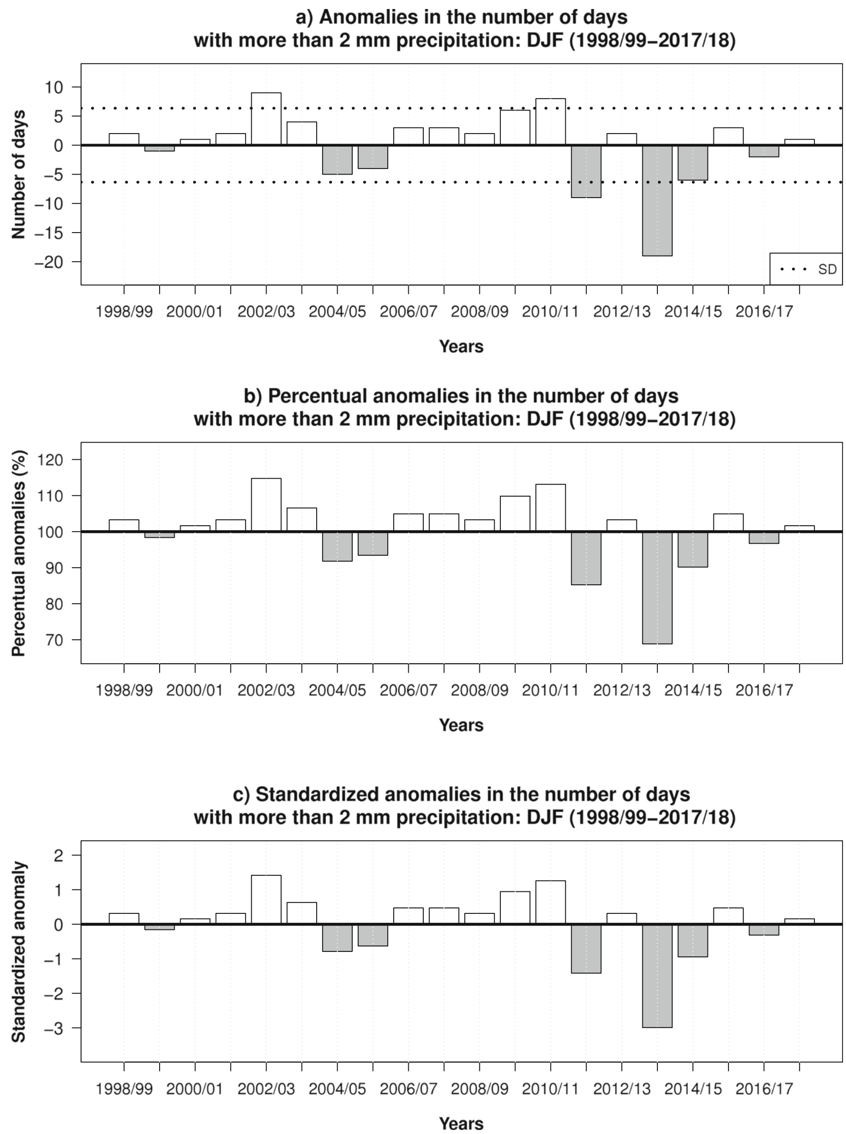

Fig. 6 DJF (1998/1999–2017/2018) wet days anomaly time series—number of days with more than 2 mm precipitation for the region of São Paulo marked by the square in figure 1 of Coelho et al. (2015). **a** Anomalies in the number of wet days with the dotted lines representing one climatological standard deviation (± 6.34 wet days). **b** Percentual anomalies in the number of wet days. **c** Standardized anomalies in the number of wet days. Anomalies and percentual precipitation in (**a**) and (**b**) are computed with respect to the 1998/1999–2017/2018 climatological mean of 60.95 wet days. Standardized precipitation anomalies in (**c**) are computed with respect to the 1998/1999–2017/2018 climatological standard deviation of 6.34 wet days

1957/1958) when compared to the other three periods, and for the latter period (1998/1999–2017/2018) the standard deviation is slightly larger when compared to the other three periods. Table 5 still reveals that the kurtosis and asymmetry parameters of the daily precipitation distribution are similar for the four investigated periods, suggesting little change in the characteristics of daily precipitation distribution. Figure 5b and the statistics shown in Tables 6 and 8 for the four investigated periods also reveal little changes in the characteristic of the distribution of the number wet days in each summer month, particularly when comparing the most recent period (1998/1999–2017/2018) with the second period (1958/1959–1977/1978). In fact, Fig. 5b shows that the distribution of the number of wet days for the three most recent periods are largely overlapping, except for the upper tail for the third period (1978/1979–1997/1998) where one can note changes in the characteristics for extremes (large number of wet days). It is also worth noting that the first period (1938/1939–1957/1958) has slightly less wet days than the other three periods.

This assessment based on an independent dataset supports the representativeness and robustness of the analysis performed for the southeast region of the State of São Paulo here investigated. Although the assessment did not reveal major changes in the main characteristics of the distributions, for some periods it was possible to diagnose changes in the characteristics of the upper tail of the distribution (Tables 5, 6, 7, and 8), where large extreme events are represented. However, overall, emphasizing that the analysis performed in this study is valid for the most recent 20-year period (1998/1999 to 2016/2017) and that large (extreme) values are more sensitive to changes, the obtained results for the southeast portion of the State of São Paulo can be considered representative, providing a robust diagnostics without the need to raise major concerns about the impacts of climate change and decadal variability in the obtained results.

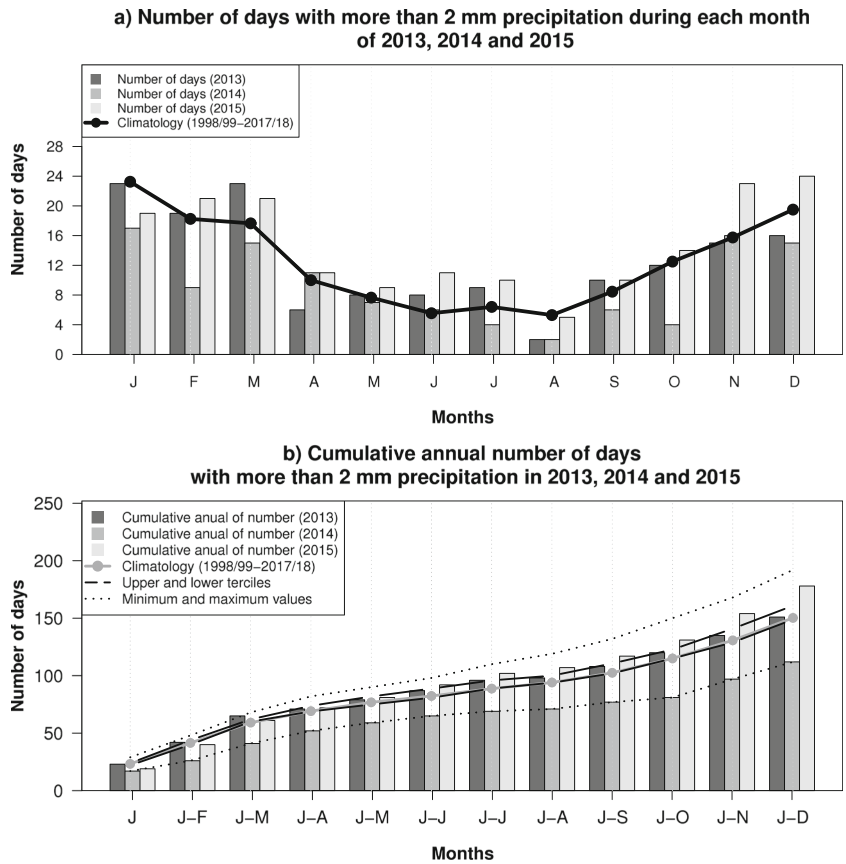

Fig. 7 Observed wet days during each month of 2013, 2014, and 2015 for the region of São Paulo marked by the square in figure 1 of Coelho et al. (2015). **a** Number of days with more than 2 mm precipitation during each month of 2013, 2014, and 2015. **b** Cumulative annual number of days with more than 2 mm precipitation in 2013, 2014, and 2015. The solid gray line is the 1998/1999–2017/2018 climatological mean cumulative wet days. The dashed black lines are the 1998/1999–2017/2018 cumulative wet days upper and lower tertiles. The dotted black lines are the 1998/99–2017/18 cumulative wet days maximum and minimum values

5 Time series of wet day anomalies

With the objective of expanding the time series analysis presented in the previous Sections 2 and 3 for the southeast region of the state of São Paulo, this section presents a time series analysis of the anomalous number of wet days for the austral summer months (DJF) for the same region through three different approaches, all for the 1998/1999 to 2017/2018 period. In the first approach, Fig. 6a shows the anomalies for the number of wet days. These anomalies were calculated as the difference between the number of wet days recorded for each austral summer season of the 1998/1999 to 2017/2018 period, and the climatological mean number of wet days for the same period. Positive anomalies (white bars) show seasons when an excessive number of wet days were observed with respect to the climatological mean number of wet days (61 days). Negative anomalies (gray bars) represent seasons when deficient number of wet days were observed. The most important deficits were recorded from 2011/2012 onwards, with the highest deficit recorded in 2013/2014 (approximately − 19 wet days). Note also that in 2014/2015 a less intense deficit was recorded (− 6 wet days).

The second approach is illustrated in Fig. 6b. This figure shows the percentual anomaly of the number of wet days during the austral summer months (DJF), which was calculated as the ratio between the number of wet days recorded in each DJF season of the 1998/1999 to 2017/2018 period and the climatological mean number of wet days for this period (61 days). Four out of the last 6 years presented important percentual deficits in the number of wet days: in 2011/2012, only 85% of the climatological number of wet days was observed; in 2013/2014, only 70% of the climatological number was observed; in 2014/2015, only 90%; and in 2016/2017, 97% of the climatological number of wet days was observed. These values represent percentual anomalies of 15%, 30%, 10%, and 3%, respectively.

Finally, in the third approach (illustrated in Fig. 6c), standardized anomalies for the number of wet days in the DJF season were calculated as the ratio between the anomalies shown in Fig. 5a and the standard deviation of the number of wet days (6.34 days) computed for the DJF 1998/1999–2017/2018 period. The years 2011/2012, 2013/2014, and 2014/2015 were particularly relevant among the last 6 years, presenting negative standardized anomalies of − 1.4, − 3, and − 0.94, respectively. The deficits in the number of wet days shown in Fig. 5, in particular for the years 2013/2014 and 2014/2015, corroborate the conditions of expressive precipitation deficits recorded in the southeastern region of the state of São Paulo, as documented by Coelho et al. (2015).

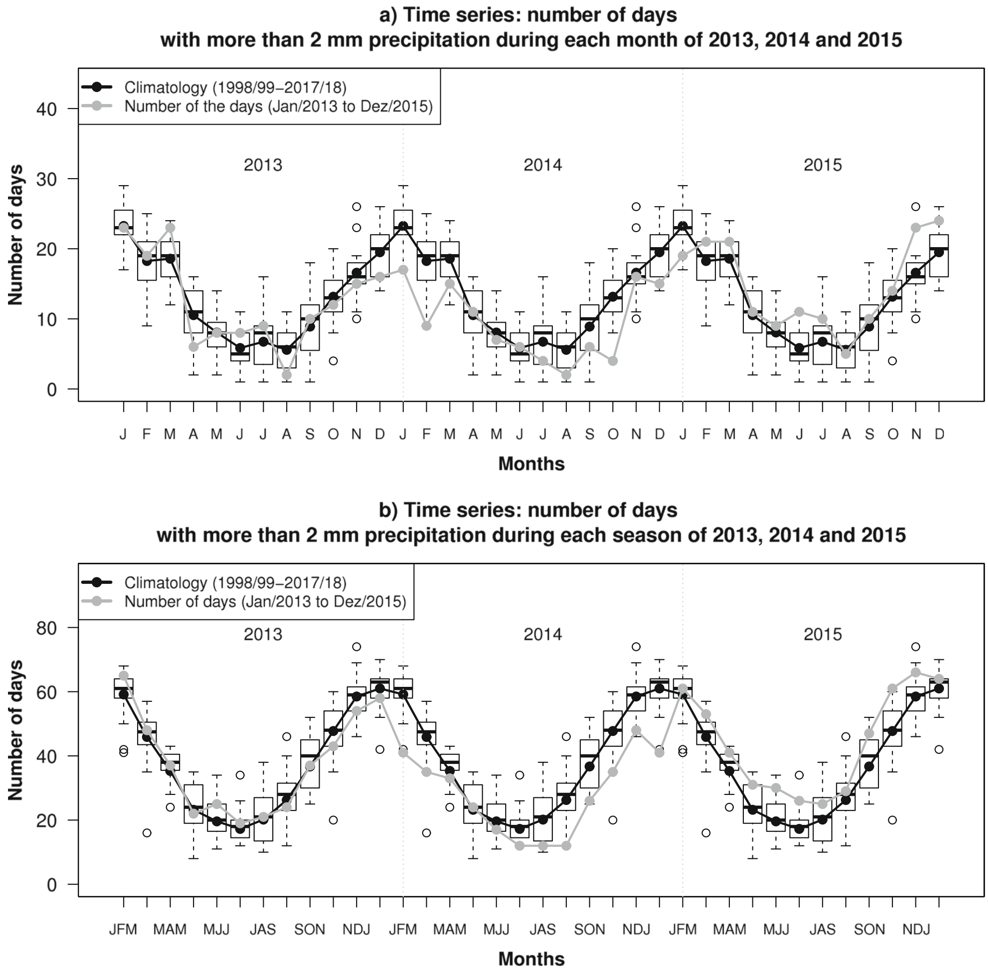

Fig. 8 Time series of number of days with more than 2 mm precipitation during each month and season of 2013, 2014, and 2015 for the region of São Paulo marked by the square in figure 1 of Coelho et al. (2015). The central horizontal line in the box represents the median p50 (50th percentile). The upper border of the box represents the upper quartile p75 (75th percentile). The lower border of the box represents the lower quartile p25 (25th percentile). The whiskers at the top of each box extend to the largest monthly value below p75 + 1.5IQR, where IQR is the interquartile range given by p75–p25. The whiskers at the bottom of each box extend to the lowest monthly value above p25 − 1.5IQR. Values outside the whiskers exceed the range from p25 − 1.5IQR to p75 + 1.5IQR, are considered extreme events, and are plotted with open circles. The black solid line is the monthly 1998/1999–2017/2018 climatological mean. The dark gray solid line is the observed number of wet days from January 2013 to December 2015. **a** Time series of number of wet days during each month. **b** Time series of number of wet days during each season

6 Observed wet days during 2013, 2014, and 2015

As described in the previous section, the austral summers (DJF) of 2013/2014 and 2014/2015 were characterized by deficits in the number of wet days. These summers were also characterized by important precipitation deficits, as described by Coelho et al. (2015). Thus, this section presents an analysis of the wet days observed over the 2013 to 2015 period, in the southeastern region of the state of São Paulo investigated in the present study. Figure 7a shows the monthly evolution of the number of wet days over 2013, 2014, and 2015. During most months of 2013, the number of wet days remained close to the climatological mean (black line), with an important reduction in the number of wet days in December 2013. During the initial months of 2014, and during most months of the second semester of the same year, the condition of reduced number of wet days remained. Finally, 2015 started January with a reduced number of wet days. However, the remaining months of the year were marked by either close to or even above the climatological mean number of wet days. Figure 7b shows the annual cumulative number of wet days for 2013, 2014, and 2015. The year 2014 presented a cumulative number of wet days well below the climatological mean (black line), representing the lowest values on record as illustrated by the lower dotted line. In the previous and following years (2013 and 2015), the annual cumulative values were near and slightly above the climatological mean, respectively.

Figure 8 shows the time series of the number of wet days during each month and season of 2013, 2014, and 2015. The black line represents the climatological mean (1998/1999–2017/2018). The box plots illustrate the behavior of the climatological distribution of the number of wet days in each month/season of the year. During the austral winter months, an important reduction in the number of wet days was noticed compared to the austral summer months. The gray line represents the number of wet days observed in each month/season of 2013, 2014, and 2015. Figure 8a shows that the number of wet days observed during a large portion of 2014 was below the climatological mean. February and October 2014 presented an important decrease in the number of wet days (9 and 4 wet days, respectively) compared to the climatological mean values (approximately 19 and 13 wet days for February and October, respectively). Figure 8b shows the overlapping 3-month season time series of the number of wet days. Close to the climatological mean wet days were observed during the early seasons of 2013. An important deficit in the number of wet days was observed during the late seasons of 2013 and the early seasons of 2014, characterizing a period when the studied region experienced an expressive precipitation deficit. This wet day deficit extended throughout the second half of 2014. Above the climatological mean, wet day conditions prevailed during 2015.

7 Summary and conclusions

This study presented a characterization of austral summer months (DJF) daily precipitation conditions for the southeastern region of the state of São Paulo within the climatic context over the 1998/1999 to 2017/2018 period. More specifically, classical statistical climatology methods were used for quantifying the climatological characteristics of daily precipitation and the number of rainy (or wet) days for producing complementary information to improve climate monitoring. This information is useful for various societal sectors that demand better temporal climatic information detailing. A summary of the main findings for the questions addressed in the present study is presented below.

The first question addressed the behavior of the daily precipitation in the southeastern region of the state of São Paulo during the past two decades. When daily precipitation data for individual austral summer months were analyzed, December and January presented homogeneous and somewhat similar precipitation time series characteristics with the largest variability over the studied season. February presented reduced daily precipitation values compared to December and January. This month in particular also recorded the lowest value among the three analyzed months (9 mm), suggesting that February presents slightly different daily precipitation characteristics from the other two months. The daily precipitation time series analysis aggregating the data from the austral summer months (DJF) presented important variability throughout the investigated period (1998/1999–2017/2018). A sharp decrease in daily precipitation values was observed in mid-2011, and this situation was maintained until 2014.

The second question addressed the typical daily precipitation distribution during the austral summer months (DJF) for the studied region. The study revealed a distribution with higher probability density around the lowest values (between 0 and 5 mm) and a decrease in probability density toward the maximum value (approximately 70 mm), resembling the shape of the distribution commonly found for daily precipitation.

The third question addressed the typical number of wet days observed in the southeastern region of the state of São Paulo during the austral summer months (DJF). When analyzed separately, January was the month that presented the highest climatological mean among the three investigated months (approximately 23 wet days), followed by December (approximately 20 days) and February (approximately 18 days). Over the two investigated decades, February was the month that presented the highest variability and the lowest value (9 wet days in February 2014) among the three austral summer months investigated. On the other hand, January was the month that presented the lowest variability and the highest value (29 wet days in January 2003).

The fourth question addressed the number of wet days observed during the past couple of decades. The analyses conducted for the austral summer months (DJF) indicated that until 2010/2011 the number of wet days remained close to the climatological mean (approximately 61 days). However, from 2011 onwards, an important reduction in the number of wet days was observed over the austral summer months, when, for example, only 52 wet days were recorded in DJF 2011/2012, 42 wet days in DJF 2013/2014, and 55 wet days in 2014/2015. The austral summer (DJF) 2013/2014 was considered one of the driest over the investigated region. These results corroborate the findings of Coelho et al. (2015), who documented the expressive precipitation deficit recorded in this region during this period from a climatic point of view.

The fifth question addressed the typical distribution of the number of wet days during the austral summer months (DJF) for the southeastern region of the state of São Paulo. The study revealed higher probability density between 15 and 25 wet days. The Kolmogorov–Smirnov test revealed that the normal distribution adequately represented the empirical distribution of wet days during the austral summer months for the studied region.

The sixth question addressed how atypical the past years were regarding the number of wet days during the austral summer. The performed analyses indicated that the austral summers (DJF) of 2013/2014 and 2014/2015 were particularly deficient in terms of wet days in the southeastern region of the state of São Paulo, corroborating with the findings of Coelho et al. (2015). Another important aspect of this study was the investigation of the representativeness of the obtained results for the southeast region of the state of São Paulo using a relatively short time series in the light of climate change and decadal climate variability. This aspect has been addressed by performing an analysis of a much longer daily precipitation time series for a conventional meteorological station (IAG/USP), located in the city of São Paulo, which is within the southeast portion of the State of São Paulo investigated in this study. By splitting the long historical time series of this meteorological station in four 20-year austral summer periods (1938/1939–1957/1958, 1958/1959–1977/1978, 1978/1979–1997/1998, and 1998/1999–2017/2018), it was possible to evaluate and confirm the representativeness and robustness of the regional analysis conducted for the area averaged daily precipitation based on a shorter time series and also investigate possibly changes in daily precipitation that may have occurred in these four periods. Although this assessment did not reveal major changes in the main characteristics of the daily precipitation and wet days distributions, for some periods it was possible to diagnose changes in the characteristics of the upper tail of the distribution, where large extreme events are represented, as previously reported by Zilli et al. (2017). However, overall, emphasizing that the analysis performed in this study is valid for the most recent 20-year period (1998/1999 to 2016/2017) and that large (extreme) values are more sensitive to changes, the obtained results for the southeast portion of the State of São Paulo can be considered representative, providing a robust diagnostics without the need to raise major concerns about the impacts of climate change and decadal variability in the obtained results.

By using daily precipitation data, the present study conducted a detailed analysis of the number of rainy (or wet) days for a region of the state of São Paulo that is of great socioeconomic importance for Brazil. Therefore, this study contributed to climate monitoring development and improvement for this region by taking an observed data-driven approach that characterized the number of wet days during the austral summer months for the past couple of decades. This approach therefore allowed the conduction of a relevant, simple, and innovative climatological analysis with great beneficial potential for sectors, such as agriculture, water resource management, and energy production, in line with the priority areas of the Global Framework for Climate Service (GFCS) of the World Meteorological Organization (WMO) (Hewitt et al. 2012).

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