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ORIGINAL PAPER

Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil

Caio A. S. Coelho[1] · **Denis H. F. Cardoso**[1] · **Mári A. F. Firpo**[1]

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Abstract The State of São Paulo in Brazil experienced in 2014 and early 2015 an expressive precipitation deficit, leading to drought conditions with impacts in water availability for public consumption, hydropower generation, and agriculture, particularly during austral summer. This study performs a detailed diagnostics of the observed precipitation during 2014 and early 2015 over a particular region of São Paulo State, which includes the massively populated metropolitan region of São Paulo. The diagnostic was designed to provide answers to a number of relevant questions for the activities, decisions, and strategic planning of several sectors (e.g., general public, media, and high-level governments). Examples of questions such diagnostics can help answer are: How much precipitation has the region received? Has the region experienced drought conditions in the past? When have similar drought conditions been observed in the past? What has been the observed precipitation pattern in the last years? How severe/rare were the 2014 and 2015 droughts? When does the rainy season typically start/end in the region? What happened during the 2013/2014 and 2014/2015 rainy seasons? The performed diagnostics based on historical 1961/1962–2014/2015 records revealed that the 2013/2014 austral summer was a very rare event classified as exceptionally dry. Similar drought events were previously recorded but with smaller magnitude in terms of precipitation deficits, making the 2013/2014 drought event the driest on the examined record. In fact, the region has been experiencing a precipitation deficit pattern since 1999/2000. One of the contributing factors for the expressive precipitation deficit in 2014 was the abnormally early end of the 2013/2014 rainy season in the region.

✉ Caio A. S. Coelho
caio.coelho@cptec.inpe.br

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

1 Introduction

The State of São Paulo in Brazil suffered a major drought in 2014 and early 2015, leading to a number of impacts in several socioeconomic sectors. Reservoirs around the metropolitan region of São Paulo, the largest city in Latin America, with a population of around 20 million people, reached unprecedented low levels. The largest reservoir (Cantareira), which normally supplies most of São Paulo's population, reached in January 2015 the level of just 5 % of storage capacity. This situation led the local government to install a pumping system capable of extracting water from deep reservoir levels never reached in the past for mitigating the water deficit for human consumption (Porto et al. 2014). The established water crisis had impacts not only in water availability for public consumption, but also for agricultural production and hydropower generation. Given the impacts generated by this major drought event, this paper aims to perform a diagnostics of the observed precipitation conditions over a particular region of São Paulo State. This region is defined by the continental area between 22.5° S, 25° S, 47.5° W, 45° W, as illustrated by the squares in Fig. 1, and includes the metropolitan region of São Paulo. Precipitation variability over São Paulo and southeastern South America has been documented in a number of studies (Kousky 1988; Liebmann et al. 2001; Carvalho et al. 2002, 2004; Dufek and Ambrizzi 2008; Sugahara et al. 2009; Silva Dias et al. 2013). The wet season in this region is influenced by the South American monsoon system (Vera et al. 2006;

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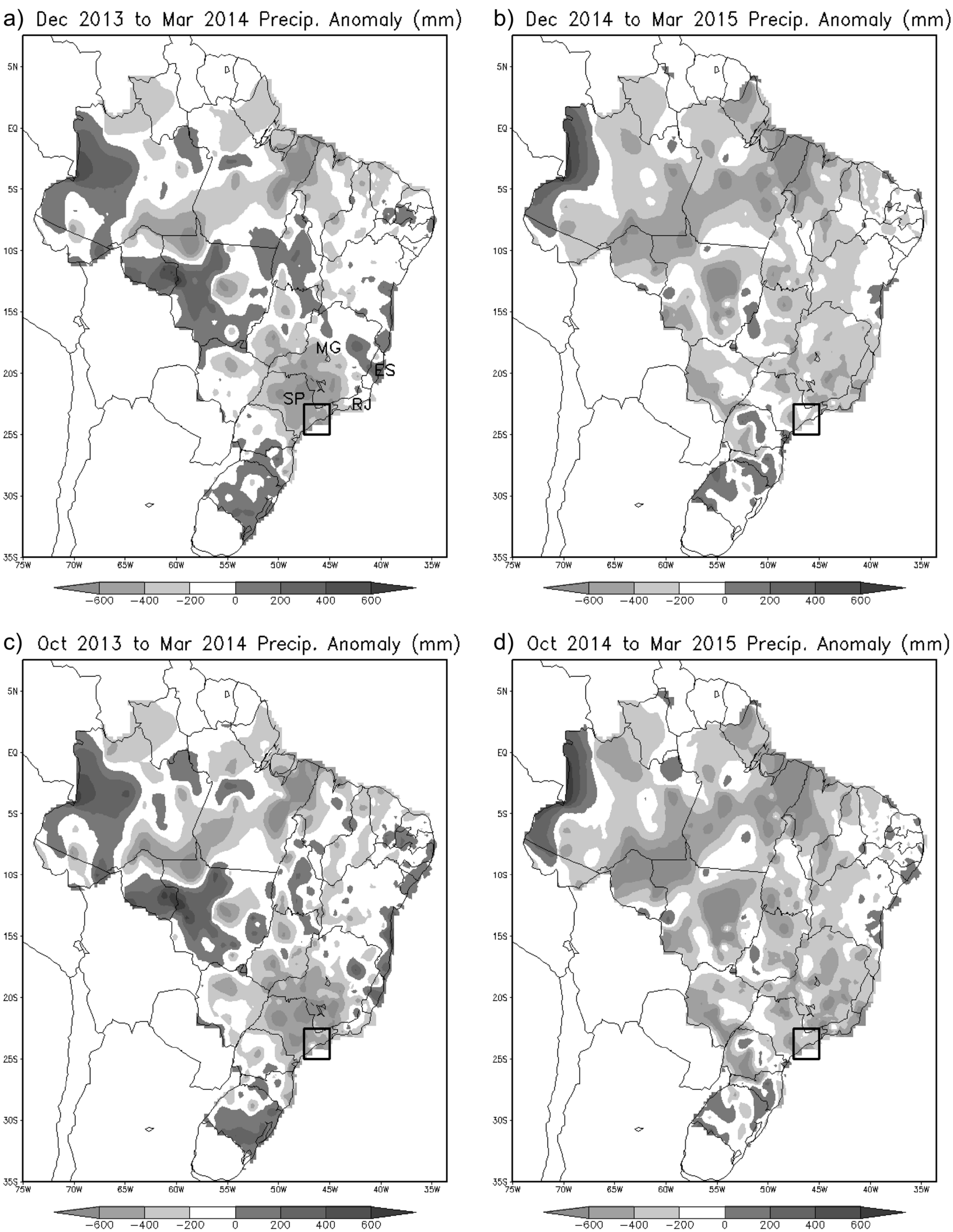

a) Dec 2013 to Mar 2014 Precip. Anomaly (mm)
b) Dec 2014 to Mar 2015 Precip. Anomaly (mm)
c) Oct 2013 to Mar 2014 Precip. Anomaly (mm)
d) Oct 2014 to Mar 2015 Precip. Anomaly (mm)
MG
ES
SP
RJ
5N
EQ
5S
10S
15S
20S
25S
30S
35S
75W
70W
65W
60W
55W
50W
45W
40W
35W
−600 −400 −200 0 200 400 600

◀ **Fig. 1** Precipitation anomalies over Brazil with respect to 1981–2010 climatology for the period **a** December 2013 to March 2014, **b** December 2014 to March 2015, **c** October 2013 to March 2014, and **d** October 2014 to March 2015. The *black square* delimiting the area between 22.5° S, 25° S, 47.5° W, and 45° W represents the continental region of São Paulo State used in the precipitation diagnostics. The two letter acronyms of the four southeast Brazil States mentioned in the text [São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ), and Espírito Santo (ES)] are indicated over their geographical locations in **a**. These four figure panels 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 around Brazil, interpolated to a regular 0.25° grid in latitude and longitude

Marengo et al. 2012). In 2001, this region of São Paulo also experienced an important precipitation deficit leading to an unprecedented energy crisis due to water shortage for hydropower production. The 2001 drought event was documented by Drumond and Ambrizzi (2005).

A detailed precipitation diagnostics for 2014 and early 2015 as performed in this study is likely to help the general public, the media, applied sectors (e.g., agriculture and water resources), and high-level governments to answer a number of climate-related questions relevant to their activities, decisions, and strategic planning. Examples of questions such diagnostics can help answer are: How much precipitation has the region received? Has the region experienced drought conditions in the past? When have similar drought conditions been observed in the past? What has been the observed precipitation pattern in the region in the last years? How severe/rare were the 2014 and 2015 droughts? When does the rainy season typically start/end in the region? And what happened during the 2013/2014 and 2014/2015 rainy seasons? Providing answers to these challenging questions is likely to help several socioeconomic sectors to better manage the risks of climate variability over the region of São Paulo State here investigated. Addressing climate-related questions of direct relevance for impact sectors (e.g., water and agriculture) is aligned with the priority areas of the Global Framework for Climate Services (GFCS, Hewitt et al. 2012).

The paper is organized as follows. Section 2 describes the precipitation data used in this study, the climatological precipitation features over the investigated region of São Paulo and the observed conditions in 2014 and early 2015. Section 3 puts the 2014 and 2015 austral summer droughts in São Paulo in historical context by examining the observed 1961–2015 precipitation time series. Section 4 classifies the severity of the 2014 and 2015 drought events using a standardized index. Section 5 examines the austral summer 2013/2014 and 2014/2015 rainy season characteristics including an indication of how anomalous were the onset and demise dates during these investigated summers. This rainy season investigation is performed using the available historical daily precipitation data from the same data sources described in Sect. 2 for the period 1998-2015. Section 6 summarizes the main findings and concludes the paper.

2 Precipitation climatology in São Paulo and observed conditions in 2014 and early 2015

The 1961–2015 precipitation time series used in this study is composed by 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 around Brazil. All available station data were first interpolated to a regular 0.25° grid in latitude and longitude. Next, for the detailed diagnostics over the continental region of São Paulo here investigated, the interpolated data was averaged over the area between 22.5° S, 25° S, 47.5° W, and 45° W illustrated by the squares in Fig. 1. The interpolation and area average procedure applied to this precipitation dataset resulted in a complete time series for the entire 1961–2015 period.

Figure 1 shows the observed precipitation anomalies over Brazil with respect to 1981–2010 climatology for the extended austral summer period (December to March) 2013/2014 (panel a) and 2014/2015 (panel b), and also for the traditionally wettest 6 months of the year (October to March) 2013/2014 (panel c) and 2014/2015 (panel d). The comparison of these panels reveals that São Paulo State suffered larger precipitation deficits in 2013/2014 than in 2014/2015. In terms of spatial extent, the core of the 2013/2014 precipitation deficit was over São Paulo (SP) and western/southern Minas Gerais (MG) States, while in 2014/2015, the core precipitation deficit was over northern/eastern São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ), and Espirito Santo (ES) States.

Figure 2a shows that the region of São Paulo here investigated (and illustrated by the squares in Fig. 1) has a well-defined wet period during the austral summer (December–January–February) and a well-defined dry period during the austral winter (June–July–August). This figure also shows that during autumn (March–April–May) and spring (September–October–November), the region presents intermediate precipitation amounts between the typical values observed in summer and winter. The mean precipitation amount during summer months is 236.9 mm, contrasting with 55.6 mm during winter months. During autumn and spring months, the mean precipitation amounts are 139.3 and 131.5 mm, respectively. The larger length of the boxes in the box and whiskers plots (also known as boxplots) of Fig. 2a shows a larger range of monthly precipitation amounts during summer, early autumn, and spring, when compared to winter. This represents a larger interannual variability during

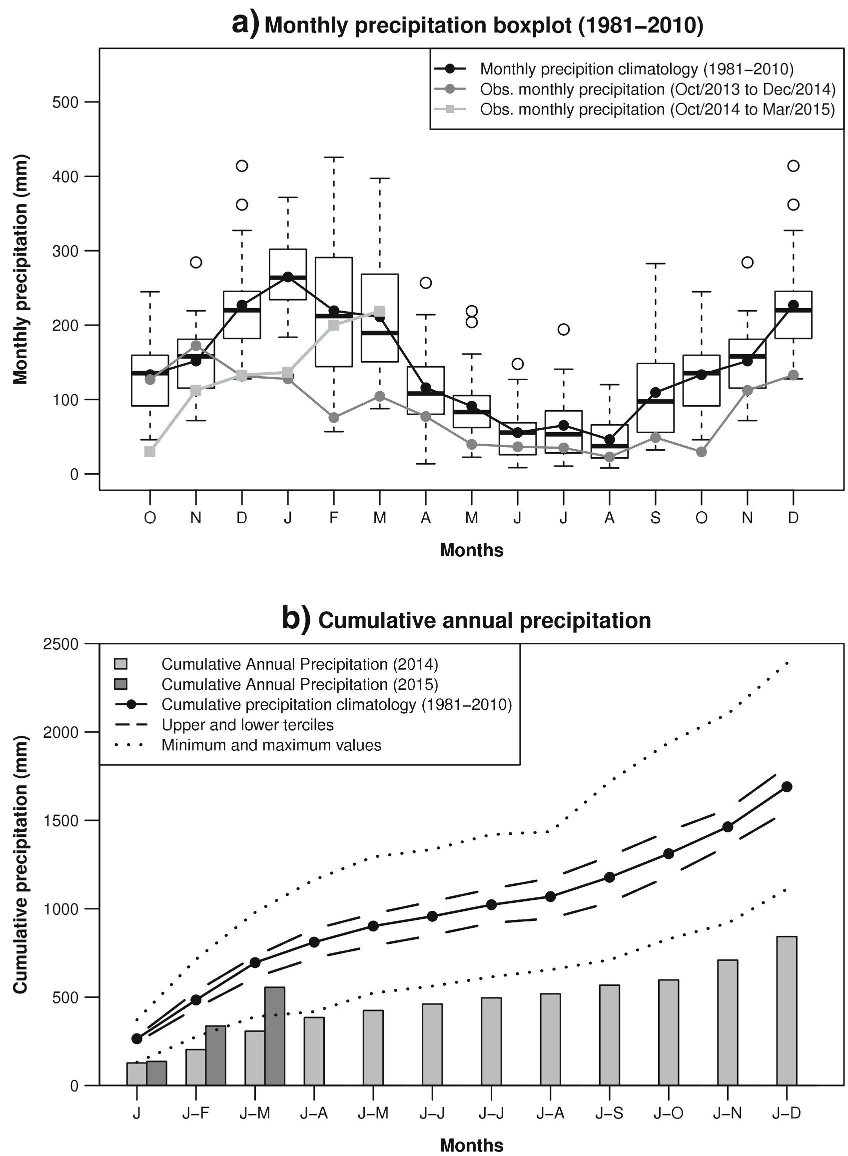


Fig. 2 **a** *Box and whiskers plots* (also known as boxplots) of monthly precipitation (mm) for the region of São Paulo marked by the square in Fig. 1 constructed using historical data for the period 1981–2010. The *central horizontal line in the box* represents the median p_{50} (50th percentile). The *upper border of the box* represents the upper quartile p_{75} (75th percentile). The *lower border of the box* represents the lower quartile p_{25} (25th percentile). The whiskers at the top of each box extend to the largest monthly value below $p_{75}+1.5IQR$, where IQR is the interquartile range given by p_{75}-p_{25}. The *whiskers at the bottom of each box* extend to the lowest monthly value above p_{25}-1.5IQR. Values outside the *whiskers* exceed the range from p_{25}-1.5IQR to p_{75}+1.5IQR, are considered extreme events, and are plotted with *open circles*. The *black solid line* is the monthly 1981–2010 climatological mean. The *dark gray solid line* is the observed monthly precipitation from October 2013 to December 2014. The *light gray solid line* is the observed monthly precipitation from October 2014 to March 2015. **b** Cumulative precipitation (mm) observed during 2014 (*light gray bars*) and early months of 2015 (*dark gray bars*). The first *light gray bar* is the observed precipitation in January 2014, the second *light gray bar* is the observed cumulative precipitation in January and February 2014. The third *light gray bar* is the observed cumulative precipitation in January–February–March 2014, etc. *The solid black line* is the 1981–2010 climatological mean cumulative precipitation. The *dashed black lines* are the 1981–2010 cumulative precipitation upper and lower terciles. The *dotted black lines* are the 1981–2010 cumulative precipitation maximum and minimum values

summer, early autumn, and spring months associated with convective precipitation systems, particularly during summer. Convective systems during austral summer (Nunes et al. 2009) are more frequent and produce much larger precipitation amounts compared to frontal systems during the winter (Cavalcanti and Kousky 2009).

Figure 2a shows that the observed precipitation in October and November 2013 (first two dark gray dots) was close to the 1981–2010 climatological mean values of 133.3 and 151.7 mm (first two black dots), respectively. During December 2013 and all 2014, the observed monthly precipitation was much lower than the monthly 1981–2010 climatological mean (solid black line), particularly during the extended austral summer period (from December 2013 to March 2014). During December 2013 and January, February, and March 2014, the observed precipitation was 131.3, 127.7, 75.7, and 104.3 mm, respectively, while the climatological mean values for these months are 226.8, 264.7, 219.3, and 211.1 mm, respectively. This represents precipitation deficits of 95.5, 137.0, 143.6, and 106.8 mm in December 2013, January, February, and March 2014, respectively. Figure 2a also shows the observed monthly precipitation from October 2014 to March 2015 (light gray solid line). The comparison with the observed precipitation from October 2013 to March 2014 reveals that October and November were much drier in 2014 than in 2013, with October 2014 recording the largest deficit (103.7) since 1981. December and January recorded similar precipitation deficits in 2013/2014 and 2014/2015. On the other hand, February and March 2015 were much different from 2014. While during February and March 2014 deficits of more than 100 mm were recorded in the region, during February and March 2015, the region experienced precipitation amounts close to the 1981–2010 climatological mean values of 219.2 and 211.1 mm, respectively.

The South Atlantic Convergence Zone (SACZ) (Kodama 1992 and 1993; Herdies et al. 2002) is the most important convective system that brings precipitation for the region during austral summer. The SACZ is a northwest-southeast oriented band of clouds that extends from the Amazon to the southeast regions of Brazil. The location of this diagonal band of convective clouds oscillates meridionaly, reaching the region of São Paulo State here investigated. However, according to the monthly climate reports of the Center for Weather Forecast and Climate Studies (CPTEC/INPE), the austral summers of 2014 and 2015 were atypical with very few reports indicating the presence of the SACZ. The reduced number of SACZ cases during these summers was therefore an important factor contributing to the precipitation deficit observed in the region of São Paulo State here investigated, particularly during the months of December and January.

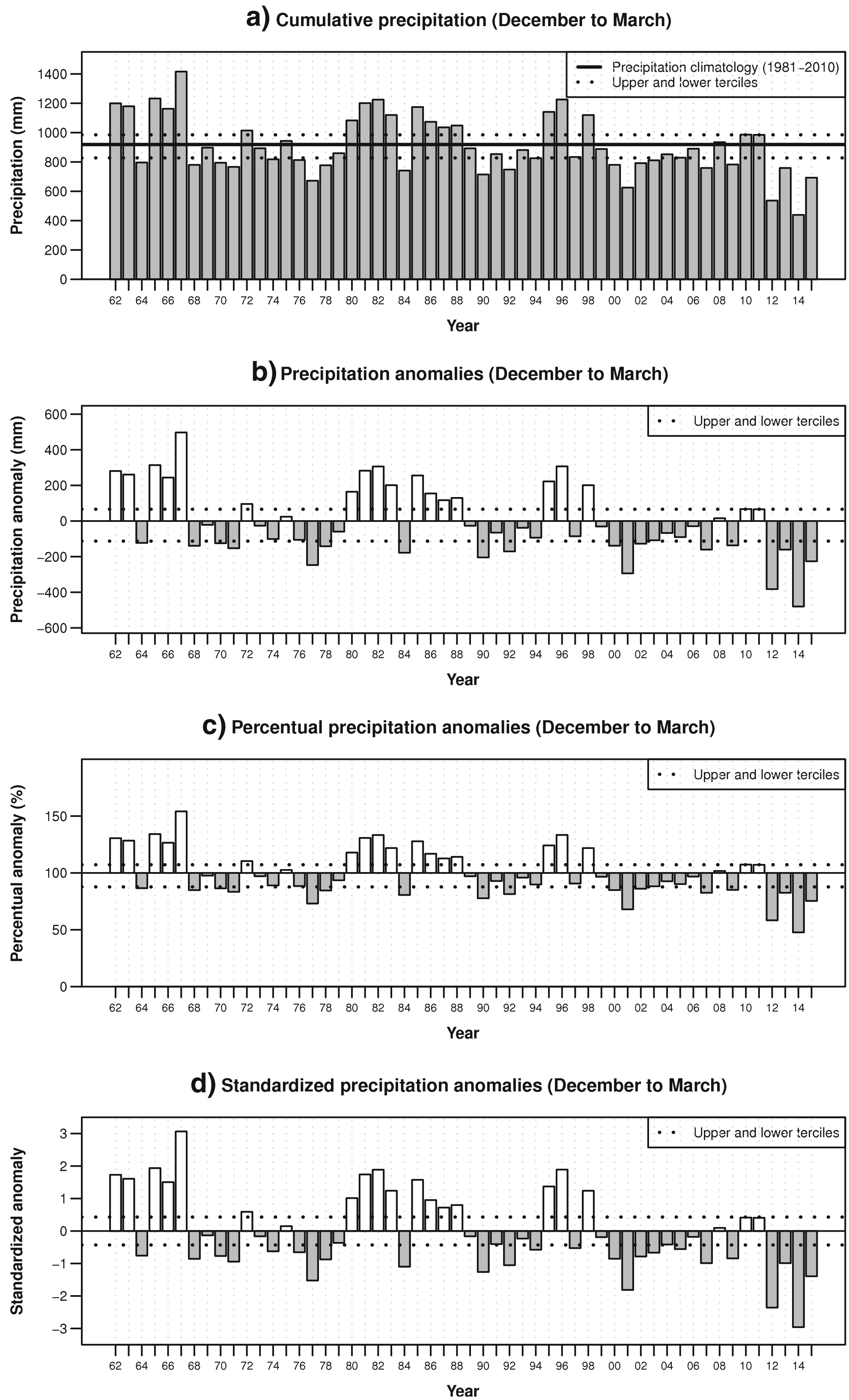
The observed precipitation in October 2014 of 29.6 mm was the lowest value of the 1981–2015 record. The second lowest October value of 45.9 was recorded in October 1999. The observed precipitation in December 2014 of 132.9 mm was the second lowest value of the 1981–2015 record. The lowest December value of 127.8 mm was recorded in 1990. The observed precipitation in January 2014 of 127.7 mm was the lowest value of the 1981–2015 record. The second lowest January value of 131.5 mm was recorded in January 2001, and the third lowest January value of 136.4 mm was recorded in January 2015. The observed precipitation in February 2014 of 75.7 mm was the second lowest value of the 1981–2015 record. The lowest February value of 56.8 mm was recorded in 1992 and is represented in the lower end of the whisker in the box and whiskers plot for February in Fig. 2a. The observed precipitation in March 2014 of 104.3 mm was the second lowest value of the 1981–2015 record. The lowest March value of 87.1 mm was recorded in 2012. After April 2014, when monthly precipitation is typically reduced, the region continued to experience below normal precipitation (i.e., precipitation amounts below the 1981–2010 monthly climatological mean precipitation shown as a solid black line in Fig. 2a). Even during winter 2014, precipitation amounts were below the traditionally dry conditions. During spring 2014, precipitation amounts remained well below normal, reinforcing the water crisis in the region initiated earlier in the year and extended until early 2015.

Figure 2b shows the cumulative precipitation observed during 2014 (light gray bars) and early months of 2015 (dark gray bars). The comparison of the light gray bars with the lines in Fig. 2b reveals that 2014 was an unprecedented year in the examined record with well below the cumulative precipitation climatology (solid black line), falling below the minimum historical 1981–2010 records marked by the lower dashed line. January 2015 (dark gray bar) was as dry as January 2014 (light gray bar). However, due to the larger precipitation amounts observed in February and March 2015 when compared to the same months in 2014, the cumulative precipitation in 2015 was considerably different from 2014.

3 The 2014 and 2015 droughts in historical context

The previous section illustrated important precipitation deficits over the region of São Paulo here investigated during the 2014 and 2015 austral summers. In order to put these events in historical context, this section presents an analysis of the observed cumulative precipitation for the extended austral summers (December to March 2013/2014 and 2014/1015) and also the wettest 6 months of the year (October to March 2013/2014 and 2014/1015) in this region during the 1961/1962–2014/2015 period.

Figure 3a shows the December to March 1961/1962–2014/2015 cumulative precipitation time series (gray bars) for the region of São Paulo marked in Fig. 1. The observed precipitation during December 2013 to March 2014 of 439.0 mm (second last bar in Fig. 3a) is well below both the climatological mean (solid black line) and lower tercile (dashed black line), representing an expressive precipitation deficit for the region. The observed precipitation during December 2014 and March 2015 of 692.8 mm (last bar in Fig. 3a) is less expressive but is also below the lower tercile. Examining the historical record since 1961, Fig. 3a shows that other years, such as 1976/1977, 1983/1984, 1989/1990, 1991/1992, 2000/2001, and 2011/2012, also experienced important deficits. As discussed in the previous section, two of these years, 1992 and 2012, recorded the lowest precipitation amounts in the 1981–2014 period in February and March, respectively.



Another interesting feature is that not only in 2013/2014 and 2014/2015 the region experienced important precipitation deficit. Figure 3a shows that in the previous 2 years, the regions also experienced below normal precipitation. In

◀ **Fig. 3** **a** December to March 1961/1962–2014/2015 cumulative precipitation time series (*bars*) for the region of São Paulo marked by the square in Fig. 1 expressed in mm. The first bar represents the accumulation for the period December 1961 to March 1962 and the last bar for the period December 2014 to March 2015. *The solid black line* is the 1981–2010 climatological mean of 918.7 mm. *The dashed black lines* are the 1981–2010 upper and lower terciles of 984.8 and 827.6 mm, respectively. **b** Corresponding December to March 1961/1962–2014/2015 precipitation anomaly time series. **c** Corresponding December to March 1961/1962–2014/2015 percentual precipitation time series. **d** Corresponding December to March 1961/1962–2014/2015 standardized precipitation anomaly time series. Anomalies and percentual precipitation in panels **b** and **c** are computed with respect to the 1981–2010 climatological mean. Standardized precipitation anomalies in **d** are computed with respect to the 1981–2010 climatological standard deviation of 162.2 mm. The *dashed lines* in panels **b**, **c**, and **d** are the upper and lower tercile values

2011/2012, the observed precipitation was 536.3 mm and in 2012/2013 758.5 mm, both values below the lower tercile. Similar features are also noticed for the wettest 6 months of the year (October to March) as shown in Fig. 4a.

Figure 3b shows the December to March 1961/1962–2014/2015 precipitation anomaly time series. Positive precipitation anomalies (i.e., precipitation excess) are shown with white bars. Negative precipitation anomalies (i.e., precipitation deficit) are shown with gray bars. December 2013 to March 2014 (second last bar) shows the largest negative precipitation anomaly of −479.7 mm with respect to the 1981–2010 climatological mean value of 918.7 mm. This illustrates the expressive magnitude of the 2013/2014 drought event over the region. December 2014 to March 2015 (last bar) presented negative precipitation anomaly of −225.9 mm. The analysis for the October to March period (Fig. 4b) indicated an important precipitation deficit of −465.6 mm for 2013/2014 (second last bar) and −369.0 mm for 2014/2015 (last bar). Complementing the previous finding of Fig. 3a, Fig. 3b shows that the region experienced important precipitation deficits not only in 2013/2014, but also in 2011/2012 and 2012/2013. The observed negative precipitation anomalies in 2011/2012 and 2012/2013 were −382.3 and −160.2 mm, respectively. Figure 3b also reveals that after 1999/2000, predominantly negative precipitation anomalies were observed over the region. This indicates that not only that the last 4 years were anomalously dry. Over the last 16 years, the region is experiencing important precipitation deficit. This feature is also noticed for the wettest 6 months of the year (October to March) shown in Fig. 4b.

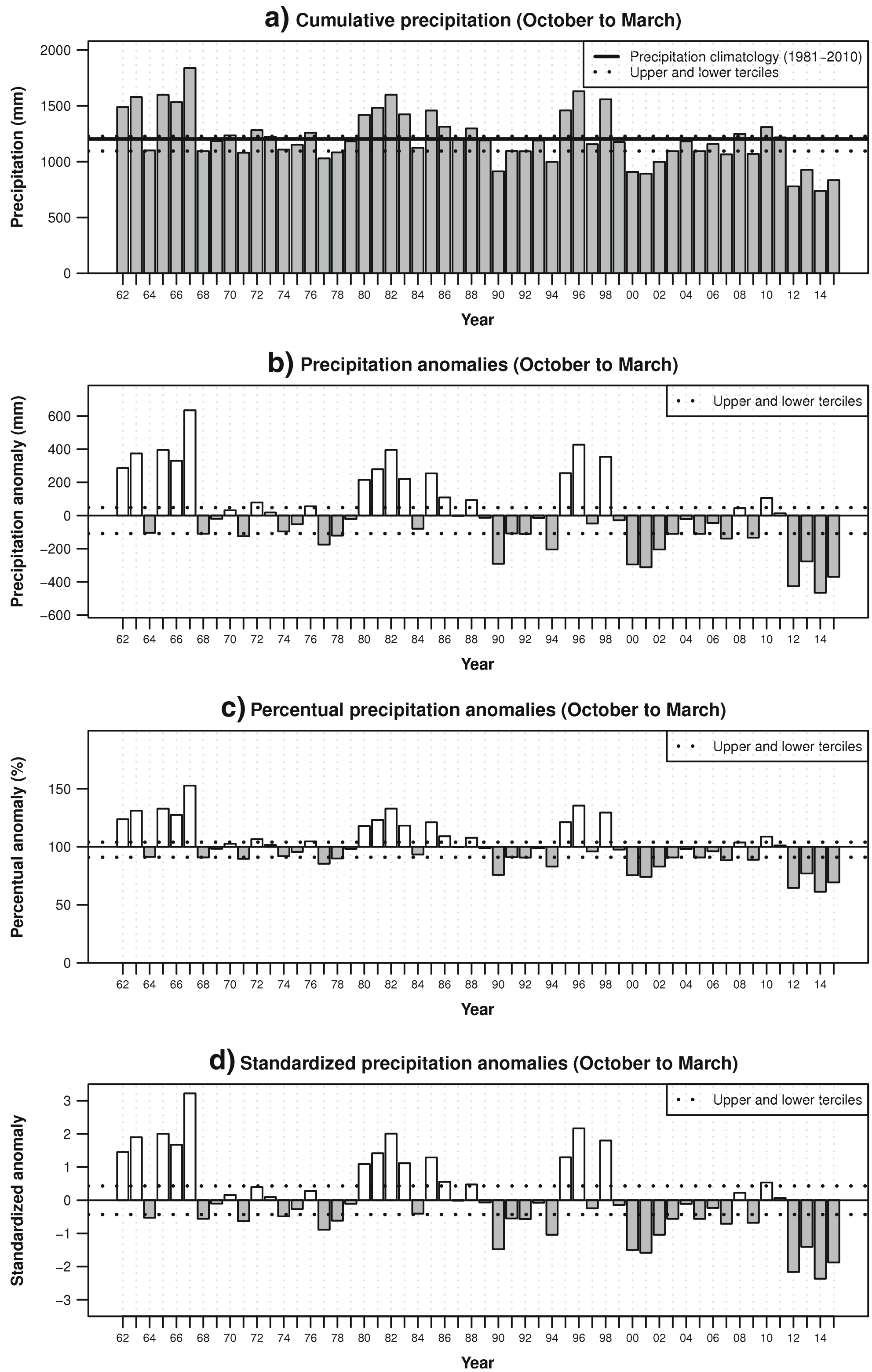
Figure 3c shows the percentual December to March 1961/1962–2014/2015 precipitation time series. In 2013/2014, only 47.8 % of the 1981–2010 climatological mean of 918.7 mm was observed in the region. This represents a remarkable percentual deficit anomaly of 52.2 %, the largest in this historical record. In 2014/2015, 75.4 % of the climatological mean was observed, representing a percentual deficit anomaly of 24.6 %. In 2011/2012, only 58.4 % of the climatological mean was observed in the region, representing the second largest percentual deficit anomaly of 41.6 % in this historical record. In 2012/2013, 82.6 % of the climatological mean was observed in the region, representing a percentual deficit anomaly of 17.4 %. Figure 3c also reveals that in 2000/2001, only 68 % of the climatological mean was observed, representing the third largest percentual deficit anomaly of 32 % in this historical record. In the analysis of the wettest 6 months of the year (October to March) 2013/2014 (second last bar) and 2014/2015 (last bar) shown in Fig. 4c, 61.3 and 69.3 % of the climatological mean (1203.7 mm) were observed in the region, respectively, representing percentual deficit anomalies of 38.7 and 30.7 %.

Figure 3d shows the December to March 1961/1962–2014/2015 standardized precipitation anomaly time series. This time series was obtained dividing the precipitation anomalies of Fig. 3b by the climatological 1981–2010 standard deviation of 162.2 mm. December 2013 to March 2014 (second last bar) shows the smallest standardized precipitation anomaly of −2.96. This indicates that the observed December 2013 to March 2014 amount represents a deficit of 2.96 times the known precipitation variability of the region estimated from the historical 1981–2010 record. This result suggests the extended austral summer 2013/2014 as an extreme event placed well into the tail of the precipitation distribution for this region. In contrast, December 2014 to March 2015 (last bar) shows a standardized precipitation anomaly of just −1.39, much less extreme than the previous summer. The standardized precipitation anomalies for the wettest 6 months of the year (October to March) 2013/2014 (second last bar) and 2014/2015 (last bar) of Fig. 4d revealed deficits of 2.36 and 1.87 times the known precipitation variability of the region (197.0) estimated from the historical 1981–2010 record.

4 Classification of the 2014 and 2015 droughts

The previous section suggested that both December to March and October to March 2013/2014 were extreme events placed in the tail of the historical precipitation distribution. This section analyzes these events in the context of the 1981–2010 precipitation distribution for the region of São Paulo State here investigated with the aim of classifying the severity of these events. A comparison with December to March and October to March 2014/2015 is also presented.

Figure 5a shows the empirical cumulative distribution for December to March precipitation (gray line) constructed with the 1981–2010 historical time series shown in Fig. 3a. This distribution indicates the probability of observing a precipitation value inferior or equal to any observed record in the 1981–2010 period. Figure 5a also shows the Gamma cumulative distribution fit to this historical record (black curve), which



represents an appropriate approximation for the empirical distribution. The shape parameter α and inverse scale parameter β of the Gamma distribution function $f(x)=\beta^{\alpha}x^{\alpha-1}e^{-\beta x}/\Gamma(\alpha)$ for any December to March precipitation value x estimated with the moment method are $\alpha = \overline{x}^2/s_x^2 = 32.1$ and $\beta = \overline{x}/s_x^2 = 0.03$, where $\overline{x}$ and s_x^2 are the 1981–2010 cumulative December to March precipitation mean and variance values, respectively. Figure 5a shows that

◀ **Fig. 4** **a** October to March 1961/1962–2014/2015 cumulative precipitation time series (*bars*) for the region of São Paulo marked by the square in Fig. 1 expressed in mm. The first *bar* represents the accumulation for the period October 1961 to March 1962 and the last bar for the period October 2014 to March 2015. The *solid black line* is the 1981–2010 climatological mean of 1203.7 mm. The *dashed black lines* are the 1981–2010 upper and lower terciles of 1095.0 and 1227.2 mm, respectively. **b** Corresponding October to March 1961/1962–2014/2015 precipitation anomaly time series. **c** Corresponding October to March 1961/1962–2014/2015 percentual precipitation time series. **d** Corresponding October to March 1961/1962–2014/2015 standardized precipitation anomaly time series. Anomalies and percentual precipitation in panels **b** and **c** are computed with respect to the 1981–2010 climatological mean. Standardized precipitation anomalies in panel **d** are computed with respect to the 1981–2010 climatological standard deviation of 197.0 mm. The *dashed lines* in panels **b**, **c**, and **d** are the upper and lower tercile values

the observed December to March 2013/2014 precipitation amount of 439.0 mm (black dot) is indeed placed in the far tail of the historical distribution. Figure 5a also shows that the observed December to March 2014/2015 precipitation amount of 692.8 mm (black square) is not placed in the far tail of the historical distribution as the 2013/2014 amount, indicating that the 2014/2015 was not as extreme as the 2013/2014 event. Figure 5c shows that the probability of observing a precipitation value inferior or equal to the December to March 2013/2014 value of 439.0 mm is extremely low (0.0001 or 0.01 %), illustrating how rare this event was. Figure 5e shows that the probability of observing a precipitation value inferior or equal to the December to March 2014/2015 value of 692.8 mm is 0.0713 or 7.13 %, illustrating that this event was much less rare than the 2013/2014 event.

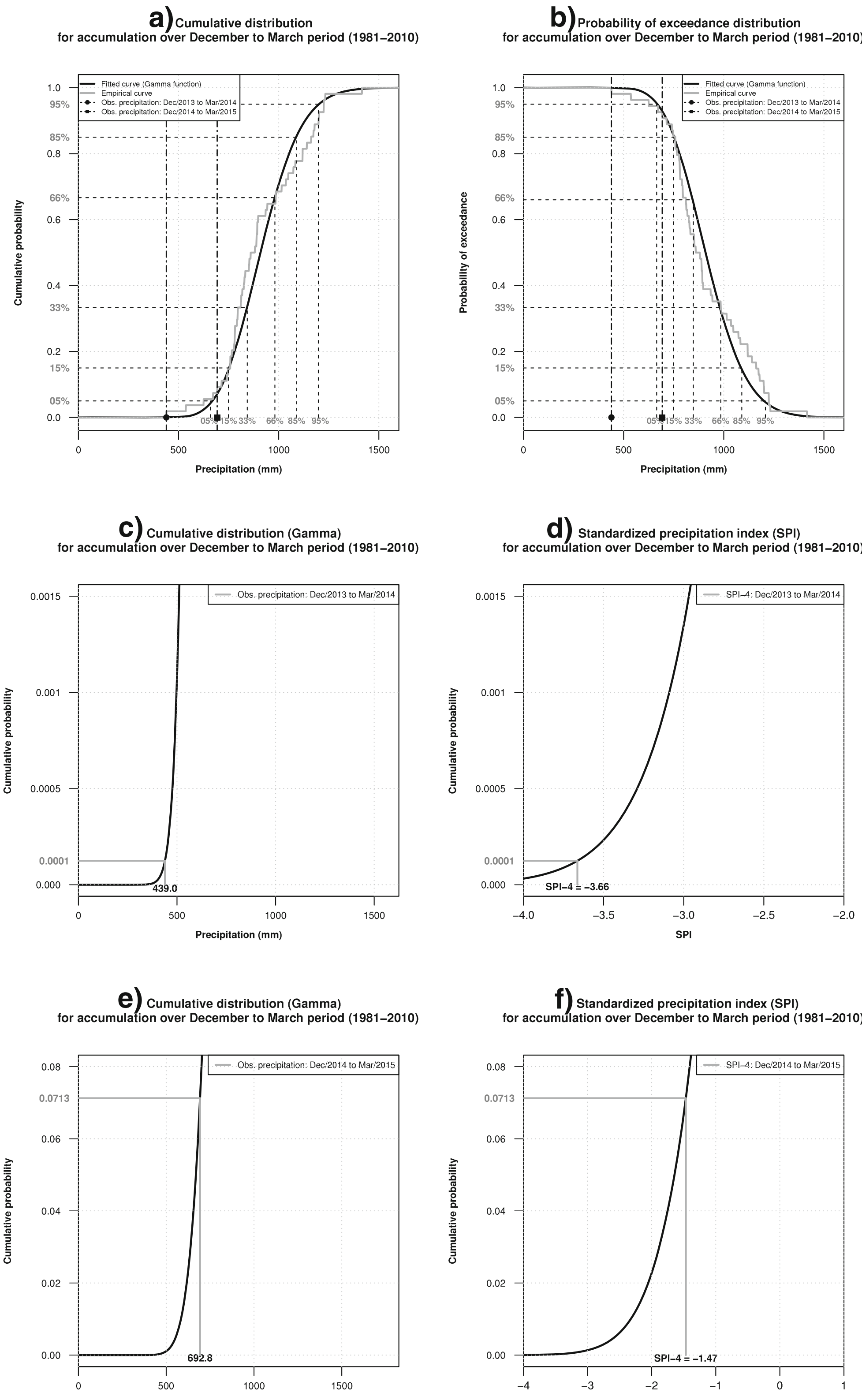
Figure 5b shows the empirical probability of exceedance distribution for December to March 1981–2010 precipitation (gray line). This distribution indicates the probability of observing a precipitation accumulation value that exceeds this value and is therefore the complementary counterpart of the empirical cumulative distribution shown in Fig. 5a. The black curve in Fig. 5b is the Gamma probability of exceedance distribution fit to this historical record. This distribution is given by 1-f(x) and also represents the complementary counterpart of the Gamma cumulative distribution shown in Fig. 5a. Figure 5b shows that the probability of observing precipitation that exceeds the December to March 2013/2014 value of 439.0 mm is extremely high (0.9999 or 99.99 %), highlighting how easy in the historical record was to observe precipitation values exceeding the rare 2013/2014 record. Figure 5b also shows that the probability of observing precipitation that exceeds the December to March 2014/2015 value of 692.8 mm is 0.9287 or 92.87 %, again illustrating that this event was much less rare than the 2013/2014 event.

The severity of the observed precipitation deficit in São Paulo during 2013/2014 and 2014/2015, leading to drought conditions can be classified using the so-called standardized precipitation index (SPI, McKee et al. 1993 and 1995). The SPI is a consistent index for monitoring and classifying precipitation deficits or excesses in different temporal scales. It is generally computed for different accumulation periods, ranging from 1 to several months. The index is the percentile mapping of a particular precipitation value obtained from a Gamma fit to the historical records for the accumulation period of interest into a normal (Gaussian) distribution with zero mean and unit variance. Positive SPI values therefore represent greater than median precipitation. Conversely, negative SPI values represent less than median precipitation. Figure 5c shows that the December to March 2013/2014 precipitation value of 439.0 mm is in the 0.01st percentile of the Gamma distribution fit to the 1981–2010 historical record. Mapping this percentile in the normal (Gaussian) distribution with zero mean and unit variance of Fig. 5d leads to a SPI of −3.66. As this value corresponds to the December to March accumulation (i.e., 4 months), it is labeled SPI-4. The severity of droughts can be classified according to the magnitude of the SPI. The National Climate Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) classifies droughts according to Table 1. Using the ranges defined in Table 1, the severity of the December to March 2013/2014 drought event in São Paulo is classified as exceptionally dry. Following the same procedure, Fig. 5e, f shows that the December to March 2014/2015 event has an SPI of −1.47 and is classified as very dry, a two level weaker classification when compared to the 2014/2015 event according to Table 1.

In order to put the 2013/2014 and 2014/2015 drought events in historical context, Fig. 6 shows 1961/1962–2014/2015 SPI indices for 4 months of accumulation from December to March (SPI-4) and 6 months of accumulation from October to March (SPI-6). For both accumulation periods, 2013/2014 stands out as the most intense event classified, according to Table 1, as an exceptionally dry with SPI values well below the −2 threshold. During the 2013/2014 drought event, the largest SPI values of −3.66 and −2.71 were found for the 4 and 6 months of accumulation, respectively (second last bars in Fig. 6a, b). The SPI values for 4 and 6 months of accumulation for the 2014/2015 event (last bars in Fig. 6a, b) were found to be −1.47 and −2.05, respectively, illustrating that this event was less severe than the 2013/2014 event.

5 The 2013/2014 and 2014/2015 rainy season characteristics

The previous sections provided answers to questions raised in the introduction about the 2014 drought in São Paulo based on monthly precipitation records. This section will provide specific weather-within-climate information about this drought event using daily precipitation records. Here, we are particularly interested in diagnosing the 2013/2014 and 2014/2015 rainy season characteristics, namely the onset and demise



dates for these events. Additionally, historical daily records are used to obtain the climatological distributions of these dates. The computation of climatological distributions for the onset and demise dates of the rainy season in São Paulo

◀ **Fig. 5** **a** Empirical (*gray line*) and Gamma (*black curve*) cumulative distribution functions for December to March 1981–2010 precipitation for the region of São Paulo marked by the square in Fig. 1. **b** Corresponding empirical (*gray line*) and Gamma (*black curve*) probability of exceedance distribution functions for December to March 1981–2010 precipitation. The *black dots* in panels **a** and **b** represent the observed December 2013 to March 2014 precipitation value of 439.0 mm and the *black squares* represent the observed December 2014 to March 2015 precipitation value of 692.8 mm. The 5th, 15th, 33rd, 66th, 85th, and 95th percentile values of the Gamma distribution are marked with *dashed lines* in panels **a** and **b. c** Gamma cumulative distribution function for December to March 1981–2010 precipitation (*black*) with the observed December 2013 to March 2014 precipitation and associated probability (*gray*). **d** Standardized precipitation curve (*black*) given by a normal (Gaussian) cumulative distribution function with zero mean and unit variance, and associated standardize precipitation index (SPI-4) for December 2013 to March 2014 (*gray*). **e** Gamma cumulative distribution function for December to March 1981–2010 precipitation (*black*) with the observed December 2014 to March 2015 precipitation and associated probability (*gray*). **f** Standardized precipitation curve (*black*) given by a normal (Gaussian) cumulative distribution function with zero mean and unit variance, and associated standardize precipitation index (SPI-4) for December 2014 to March 2015 (*gray*)

will help answer questions about when the rainy season typically starts and ends, and where the observed start and end dates for the 2013/14 and 2014/2015 seasons fit into this climatological context.

Figure 7a shows the cumulative daily precipitation from the 1st of July 2013 to the following 30th June for the region of São Paulo State here investigated and illustrated by the squares in Fig. 1. The gray-shaded area, located between the cumulative climatology (thick black solid line) and the cumulative precipitation observed in 2013/2014 (thin black solid line), highlights the magnitude of the precipitation deficit observed in the region during this period. The gray shading shows that since August 2013, the region experienced precipitation deficit, which was further aggravated after December 2013. The observed cumulative precipitation in 2013/2014 is well below the normal range defined by the upper and lower terciles for the period 1998/1999 to 2012/2013 represented by the thick black dashed lines. In fact, the observed cumulative precipitation in 2013/14 computed with 12 months of daily data until 30th June 2014 was inferior to the historical minimum accumulation for the period 1998/1999 to 2012/2013 represented by the inferior thick black dotted line. This illustrates the expressive magnitude of the observed precipitation

Table 1 National Climatic Data Center (NCDC)/National Oceanic and Atmospheric Administration (NOAA) drought severity classification

SPI values	Classification
SPI<−2	Exceptionally dry
−1,99<SPI<−1,60	Severely dry
−1,59<SPI<−1,30	Very dry
−1,29<SPI<−0,80	Moderately dry
−0,79<SPI<−0.51	Abnormally dry

deficit experienced in the region in 2013/2014. Figure 8a shows the cumulative daily precipitation from the 1st of July 2014 to the following 5th May for the region of São Paulo State here investigated and illustrated in Fig. 1. The comparison of this figure with Fig. 7a reveals that July to December 2014 was much drier than the July to December 2013. The accumulation after January 2014 was smaller than the accumulation after January 2015, illustrating the fact that the 2013/2014 rainy season was drier than the 2014/2015 rainy season.

Figure 7b shows the daily precipitation from the 1st of July to the following 30th June. The thick gray solid line represents the daily climatology for the period 1998/1999 to 2012/2013. The thin gray vertical bars represent the daily precipitation values observed in 2013/2014 (i.e., from 1st July 2013 to 30th June 2014). Figure 7b shows that precipitation was observed below the daily climatology in several days, particularly during the peak of the wet season in December 2013, January, and February 2014. Figure 8b shows similar features particularly during December 2014 and January 2015. This suggests that some characteristics of the wet rainy season such as onset and demise dates might have been affected in 2013/2014 and 2014/2015. In order to find if these characteristics have been affected, a climatological analysis of the onset and demise dates is necessary. For this analysis, one needs to use a criterion for identifying onsets and demises dates. Here, we selected the criterion proposed by Liebmann et al. (2007). This criterion is based on the analysis of the so-called anomalous daily precipitation accumulation, starting a few months earlier than the typical onset of the rainy season period and finishing a few months later than the typical end of the rainy season period. Knowing that the rainy season in São Paulo occurs during austral summer (see Fig. 2a), in this study, the accumulation was chosen to start in July and end in June of the following year. The anomalous daily precipitation is defined as the difference between the observed daily precipitation and the climatological mean daily precipitation for all days of the year. This climatological mean is computed using all available daily historical records, in this study from 1998 to 2012. After computing the anomalous daily precipitation, the anomalous daily precipitation accumulation time series for the period from July to June of the following year is obtained by summing at daily time steps the computed anomalous daily precipitation over this period.

Figure 9a shows the anomalous daily precipitation accumulation (gray curve) for the period from July 2013 to June 2014 for the region of São Paulo illustrated by the squares in Fig. 1. The dotted line represents the smoothed anomalous accumulation obtained applying a 21-day centered moving average. The 2013/2014 rainy season onset date is estimated looking for the minimum of the smoothed curve within the period from 1st July to 31st December 2013. This procedure is slightly different from Liebmann et al. (2007) that defines the onset on the day after the minimum of the

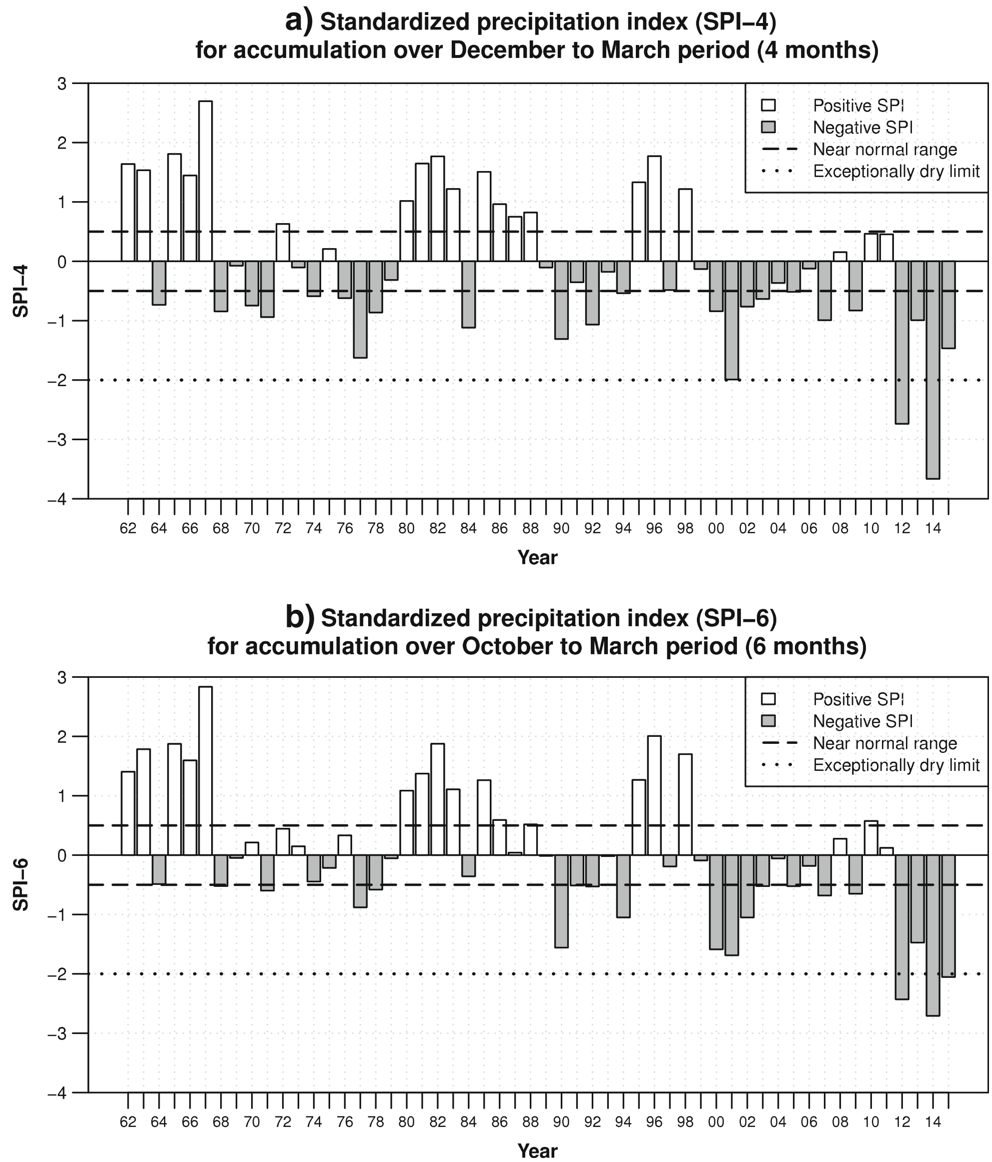


Fig. 6 Time series (1961/1962–2014/2015) of the SPI for **a** 4 months of accumulation from December to March (SPI-4) and **b** 6 months of accumulation from October to March (SPI-6). The first *bar* represents the SPI for the period December (or October) 1961 to March 1962 and the last *bar* for the period December (or October) 2014 to March 2015. The *long dashed lines* are the normal range SPI bounds of −0.5 and +0.5. The *short dashed line* is the exceptionally dry SPI limit of −2

anomalous daily accumulation. However, as the present study uses instead a smoothed daily accumulation curve, the minimum of this smoothed curve is considered an appropriate estimate of the onset, providing a reasonable indication of the approximate onset date. The first vertical solid line in Fig. 9a locates the estimated rainy season onset date around the second week of November 2013. The 2013/2014 rainy season demise date is estimated looking for the maximum of the smoothed curve within the period from 1st January to 30th June 2014. The second vertical solid line in Fig. 9a locates the estimated rainy season demise date in mid-January 2014. Figure 9b shows the anomalous daily precipitation accumulation for the period from July 2014 to May 2015. The onset and demise dates of the 2014/2015 rainy season are estimated to have occurred around the second week of December 2014 and last week of March 2015, respectively. The black vertical thick lines in both panels of Figs. 7 and 8 also mark the estimated onset and demise dates for the 2013/2014 and 2014/2015 seasons, respectively.

Repeating the procedure described above for all years of the period from 1998/1999 to 2012/2013, one can determine the historical (climatological) distribution of onset and demise dates for the region of São Paulo State here investigated. The solid lines in Fig. 10 show climatological probability density functions (pdf) of rainy season onset and demise dates determined using historical dates for the period from 1998/1999 to 2012/2013. Gray circles represent historical dates for this period obtained with the procedure describe above and illustrated in Fig. 9. Figure 10a shows that the earliest rainy season onset in the region was estimated to have occurred in early September, and the latest onset was estimated to have occurred in early December (not considering 2014/2015). The

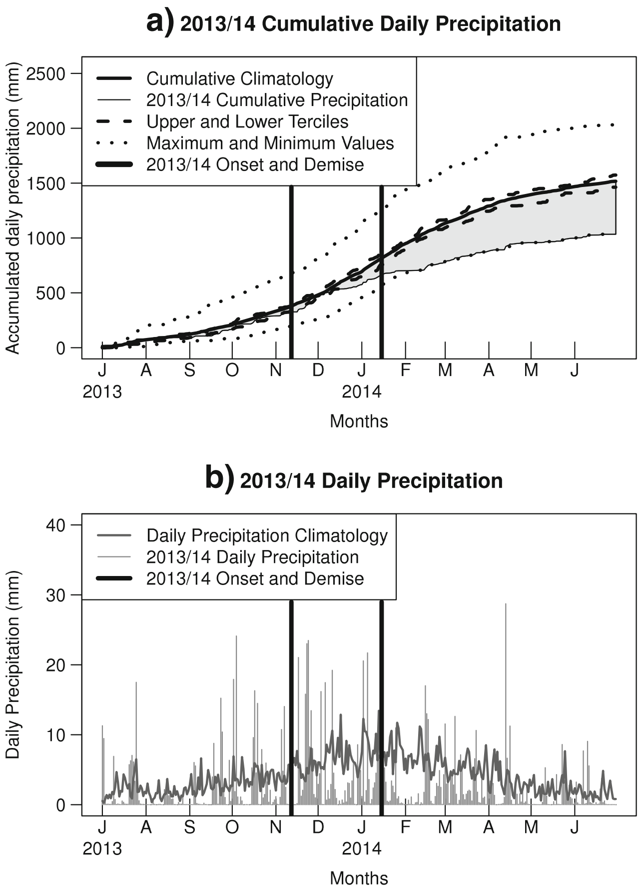


Fig. 7 **a** Cumulative daily precipitation from the 1st of July to 30th June. The *thick black solid line* is the cumulative climatology for the period 1998/1999 to 2012/2013. The *thin black solid line* is the cumulative precipitation observed in 2013/2014 (i.e., from 1st July 2013 to 30th June 2014). The *thick black dashed lines* are the upper and lower terciles for the period 1998/1999 to 2012/2013. The *thick black dotted lines* are the maximum and minimum values for the period 1998/1999 to 2012/2013. **b** Daily precipitation from the 1st of July to 30th June. The *thick gray solid line* is the daily climatology for the period 1998/1999 to 2012/2013. The *thin gray vertical bars* are the daily precipitation values observed in 2013/2014 (i.e., from 1st July 2013 to 30th June 2014). The *black vertical thick lines* in both panels mark the estimated onset and demise dates for the 2013/2014 season

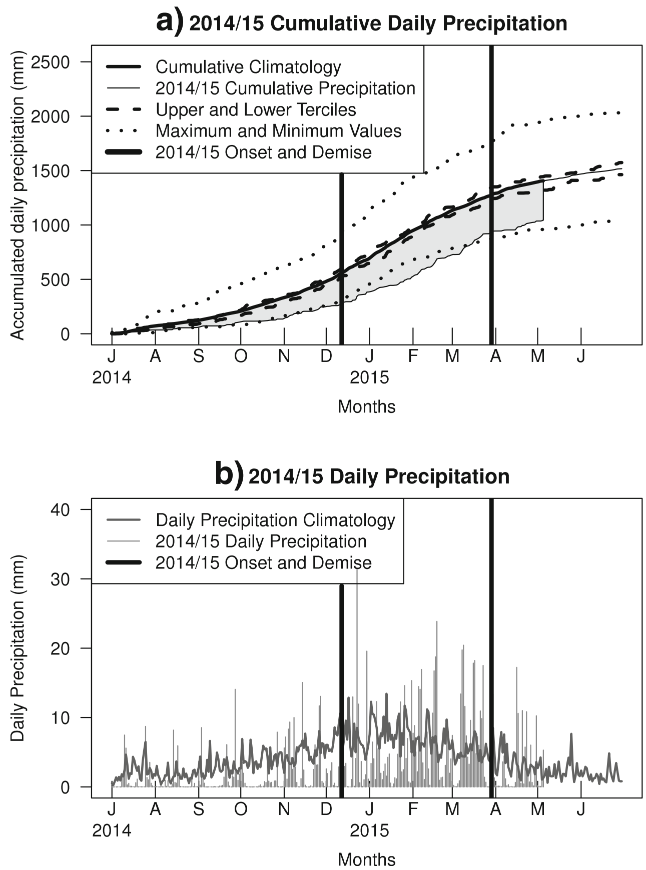


Fig. 8 **a** Cumulative daily precipitation from the 1st of July to 30th June. The *thick black solid line* is the cumulative climatology for the period 1998/1999 to 2012/2013. The *thin black solid line* is the cumulative precipitation observed in 2014/2015 (i.e., from 1st July 2014 to 5th May 2015). The *thick black dashed lines* are the upper and lower terciles for the period 1998/1999 to 2012/2013. The *thick black dotted lines* are the maximum and minimum values for the period 1998/1999 to 2012/2013. **b** Daily precipitation from the 1st of July to 30th June. The *thick gray solid line* is the daily climatology for the period 1998/1999 to 2012/2013. The *thin gray vertical bars* are the daily precipitation values observed in 2014/2015 (i.e., from 1st July 2014 to 5th May 2015). The *black vertical thick lines* in both panels mark the estimated onset and demise dates for the 2014/2015 season

mean onset date was estimated to be late October, and the most likely onset was estimated to be early November. These onset estimates are in accordance with previous studies (e.g., Liebmann et al. 2007; Franchito et al. 2008; references therein). Figure 10b shows that the earliest rainy season demise (not considering 2013/2014) was estimated to have occurred in early February, and the latest demise was estimated to have occurred in early May. The mean and most likely demise dates were estimated to be around early April.

The climatological pdfs and derived statistics described above provide a reference for putting the 2013/2014 and 2014/2015 drought events in perspective. The black dot in Fig. 10a illustrates that the estimated onset for the 2013/2014 rainy season was near the most likely date and a few days later than the mean date. The black dot in Fig. 10b illustrates that the estimated demise for the 2013/2014 rainy season was much earlier than both the most likely and mean dates. These results suggest that the rainy season 2013/2014 had a near normal start date but ended abnormally early. The early end of the rainy season was an important factor contributing to the exceptionally dry conditions during austral summer 2013/2014 in the region of São Paulo State here investigated. The black square in Fig. 10a illustrates that the estimated onset for the 2014/2015 rainy season was around the second week of December 2014 (i.e., the latest onset in the investigated record). The black square in Fig. 10b illustrates that the estimated demise for the 2014/2015 rainy season was very close to both the most likely and the mean demise dates. These

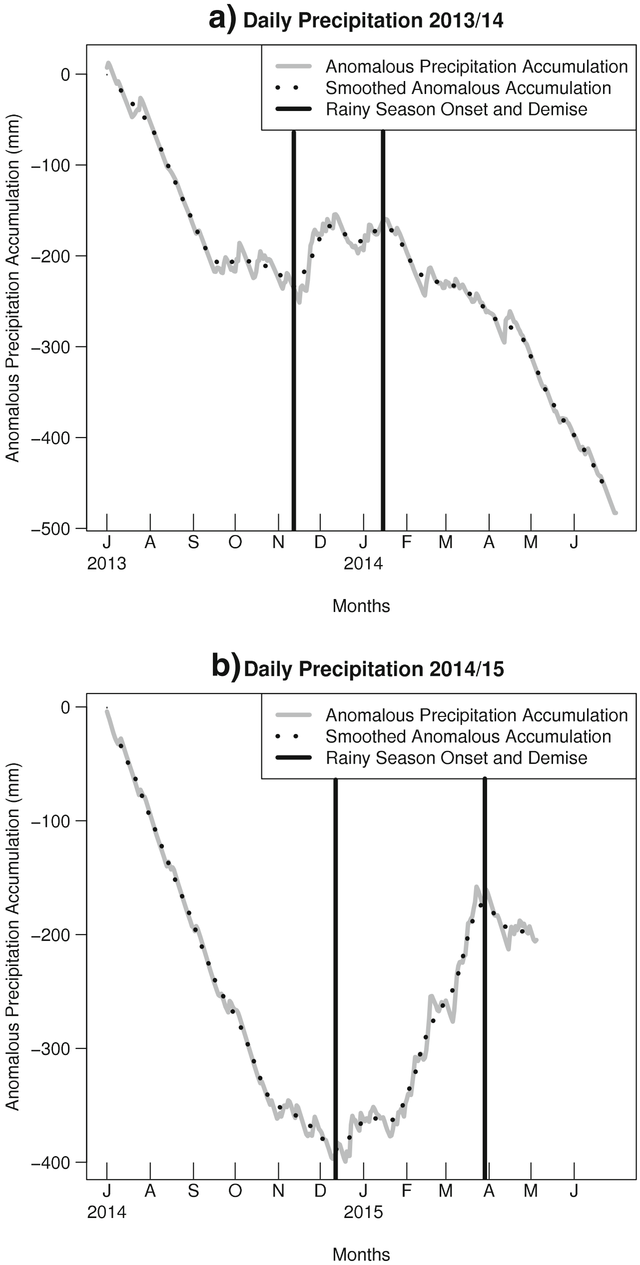


Fig. 9 Anomalous daily precipitation accumulation in mm (*gray curve*) for the period from **a** July 2013 to June 2014 and **b** July 2015 to May 2015 for the region of São Paulo illustrated in Fig. 1. The *dotted line* is the smoothed anomalous accumulation obtained applying a 21-day centered moving average. The first *vertical solid line* locates the estimated rainy season onset date. The *second vertical solid line* locates the estimated rainy season demise date

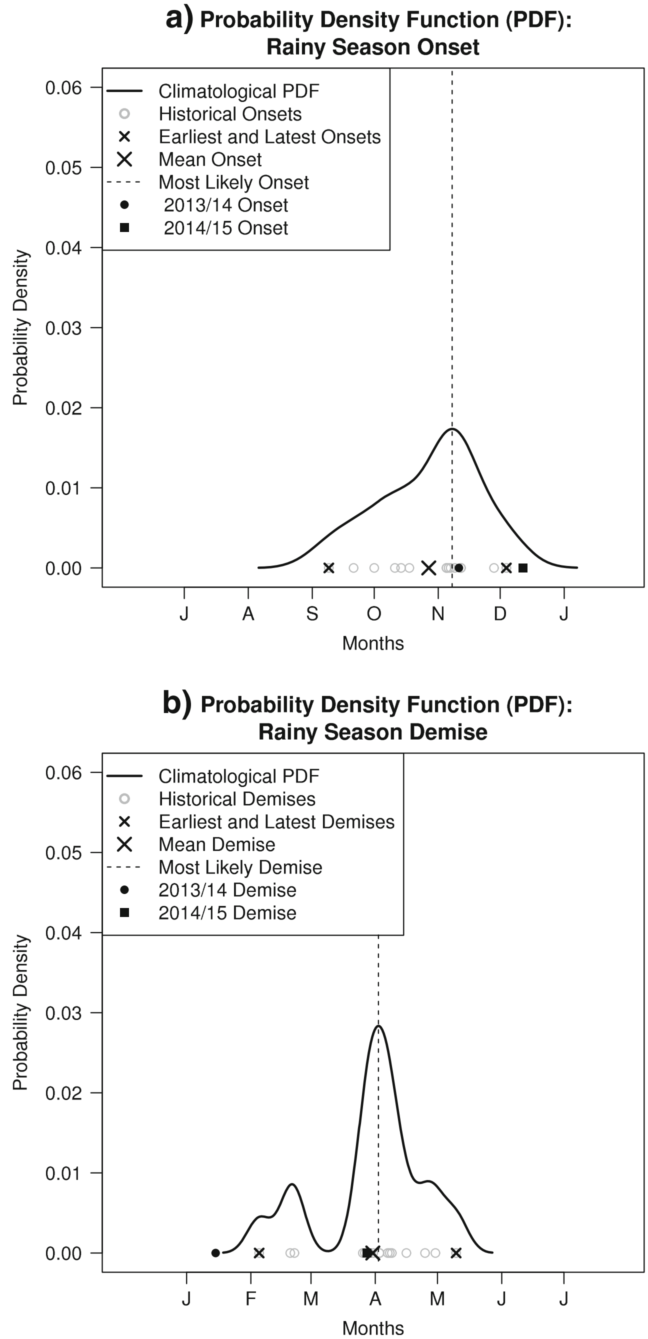


Fig. 10 Probability density functions (pdf) of rainy season **a** onset and **b** demise dates for the region of São Paulo State illustrated in Fig. 1. *Gray circles* are historical dates for the period from 1998/1999 to 2012/2013. The *solid line* is the kernel pdf for the historical dates (*gray circles*). The large cross is the historical mean date for the period from 1998/1999 to 2012/2013. The small crosses are the earliest and latest onset and demise dates occurred in the period from 1998/1999 to 2012/2013. The *vertical dashed lines* locate the estimated most likely onset and demise dates in the maximum of the kernel pdfs. The *black dots* locate the estimated onset and demise dates for the 2013/2014 rainy season. The *black squares* locate the estimated onset and demise dates for the 2014/15 rainy season

results suggest that the rainy season 2014/2015 had a very late start date and a near normal end date.

6 Summary and conclusions

This study presented a detailed diagnostics of the observed precipitation over a region of São Paulo that experienced major drought conditions, particularly during the austral summer 2013/2014, leading to an important water crisis with impacts for human consumption, agriculture, and hydropower generation. The investigation was performed using daily, monthly, and annual precipitation accumulations. The diagnostics helps answering a number of climate-related questions relevant to the activities, decisions, and strategic planning of several sectors including the general public, the media, applied sectors (e.g., agriculture and water resources), and high-level governments. A summary of the addressed questions and answers is presented below.

The first addressed question refers to the amount of precipitation observed in the investigated region of São Paulo during austral summers 2013/2014 and 2014/2015. The analysis revealed that during 2013/2014, the region received only 47.8 % of the total extended austral summer accumulation, representing an expressive precipitation deficit leading to drought conditions. Extended austral summer 2014/2015 was less dry than 2013/2014, as the investigated region received 75.4 % of the total accumulation. In terms of annual accumulation, 2014 stands out as the driest year of the 1981–2014 record. The second question refers to whether or not the region experienced similar drought conditions in the past. The examination of the historical 1961/1962–2014/2015 records revealed that the region indeed experienced similar drought conditions to 2013/2014 in previous years, but with reduced magnitude. The third addressed question, which was closely related and complementary to the previous question, was about when the region experienced drought conditions in the past. The historical record analysis revealed that not only the 2013/2014 and 2014/2015 austral summers were marked by important precipitation deficits in the region. Six other summers (1976/1977, 1983/1984, 1989/1990, 1991/1992, 2000/2001, and 2011/2012) also presented important and similar precipitation deficits, but 2013/2014 stands out as the driest summer of the 1961–2015 record.

The forth question refers to the observed precipitation pattern in the region in the last years. The performed investigation revealed that the region has been experiencing predominantly dry conditions since 1999/2000, indicating a prevailing precipitation deficit pattern during the last 16 years. An important feature to be highlighted is that for the first time in the 1961–2015 record, the region experienced expressive precipitation deficit in four consecutive years (2011/2012, 2012/2013, 2013/2014, and 2014/2015). The fifth question is concerned with the severity/rarity of the observed drought during austral summers 2013/2014 and 2014/2015. The diagnostic analysis revealed that the 2013/2014 summer drought was a very rare event placed well into the tail of the historical precipitation distribution (the lowest precipitation value recorded in the period 1961–2015) with very low probability for the occurrence of precipitation values below the amount observed in 2013/2014 (439.0 mm). Based on the standardized precipitation index, the 2013/2014 drought event was classified as exceptionally dry. The 2014/2015 summer drought was much less severe than 2013/2014, and therefore, based on the standardized precipitation index was only classified as very dry (two levels less severe than the 2013/2014 event).

The sixth question refers to specific weather-within-climate information about the 2013/2014 and 2014/2015 summer drought events, particularly addressing their rainy season characteristics, namely the typical (climatological) onset and demise dates and what happened with these characteristics during the 2013/2014 and 2014/2015 rainy seasons. A criterion was applied to determine the climatological distributions of onset and demise dates, which were then used to place the 2013/2014 and 2014/2015 events in historical context. This rainy season characteristics analysis for the region of São Paulo here investigated revealed that the 2013/2014 rainy season started around its typical onset date but ended much earlier than the typical demise date. The early end of the rainy season was an important factor contributing to the exceptionally dry conditions in the region of São Paulo State here investigated during austral summer 2013/2014. Another important factor contributing to the expressive precipitation deficit was the reduced number of SACZ cases during the 2013/2014 austral summer over the investigated region as discussed in Sect. 2. In fact, the region was under influence of a high pressure system, which impeded deep cloud formation and precipitation during most the 2013/2014 austral summer. A dynamical description of the atmospheric circulation features during this event is beyond the scope of this paper and will be presented in another study. The 2014/2015 rainy season was marked by a very late onset date and a near normal demise date. One of the main differences between these two events was that February and March 2015 were much wetter than February and March 2014.

Providing answers to the list of challenging general interest questions addressed here is only possible with a data-driven science-based type of regional climate service as documented in this study. These answers have great potential to guide several socioeconomic sectors (e.g., water management and agriculture) to better manage the risks of climate variability over the region of São Paulo State here investigated, by developing adaptation strategies to cope with the currently observed climate conditions.

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