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Meteorological droughts in part of southeastern Brazil: Understanding the last 100 years

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Abstract: Droughts have negatively influenced tropical regions on the planet with southeastern Brazil standing out. The objective of this study was to analyze droughts with different magnitudes since the ending of 19th and beginning of the 20th centuries based on the Standard Precipitation Index (SPI) and Standard Precipitation Evapotranspiration Index (SPEI), in the locations of São Paulo city (SP - city), metropolitan regions of Belo Horizonte (MR-BH) and Campinas (MR-Campinas), Lavras (South-MG), and Piracicaba (ME-SP). Two different periods were considered: i) wet period (SPI6 and SPEI6) and; ii) summer period (SPI4 and SPEI4). Considering the SPI indexes, the hydrological year of 2013/2014 was the driest observed for South-MG, ME-SP and MR-Campinas, while for MR-BH and SP-city, 1970/1971 and 1962/1963 were the driest, respectively. MR-BH and SP city showed different variability of 1970/1971 and 1962/1963, respectively. We could detect three periods with several consecutive droughts: 1908/1918; 1968/1981 and 2013/2019. Based on SPEI, the 2013/2014 hydrological year was the driest for all the regions, except for SP city, for which 1998/1999 and 1962/1963 were the driest, and MR-BH for which 1970/1971 and 2000/2001 were the driest. Precipitation might be the main factor to evaluate the occurrence of droughts in the studied locations, which indicates SPI is a satisfactory drought indicator for the region.

Key words: climate variability, droughts occurrences, water resources, drought indexes.

INTRODUCTION

Meteorological droughts have been defined as the absence of or insufficient precipitation volume over a region in a given period, combined or not with anomalous greater temperatures (Das et al. 2016, Chanda & Maity 2015). It can also be described as a natural short-time unbalance between water availability and water demand, affecting the agriculture, human supply, hydroelectricity, and tourism, among other economic actives (Caloiero et al. 2016). Importantly, droughts differ from an arid climate, which is a permanent condition with low precipitation and high evapotranspiration (WMO & GWP 2016).

Between 2013 and 2015, it was reported in the literature that the east of southeastern Brazil faced a very intense and unusual drought period. In analyzing data from more than 1500 weather stations in Brazil from 1981 and 2019, Cunha et al. (2019) pointed out that the severity of the drought between 2013-2015 in southeast Brazil was unprecedented and generated a water crisis of high impact. In addition to the precipitation anomalies, the average temperatures were higher than normal, which increased the effect of the atmosphere conditions that blocked the passage of cold fronts and the moisture from the Amazon region (Nobre et al. 2016). Using datasets from weather stations that compound an extensive area of the metropolitan region and surroundings, Coelho et al. (2016a) demonstrated that the hydrological year of 2013/2014 was the driest observed between 1961 and 2016 in the São Paulo Metropolitan region, especially over the main system that supplies SP city (Cantareira reservoir), which reached the lowest level in the studied period (Marengo et al. 2015).

The Standard Precipitation Index (SPI) has been capable of modelling the frequency of droughts, as well as its intensity over time (Hayes et al. 2011). This index was suggested by the World Meteorological Organization (WMO & GWP 2006) as the main statistical indicator because of its simplicity and the wide range application (Hayes 2002). The main SPI features are: (i) only precipitation data is required, which made its use wider than other indexes that require more detailed meteorological data; (ii) it is adapted to several time scales (monthly, wet and dry periods, summer and winters, etc.); (iii) it can be used to understand the hydrology, the weather and their impacts; (iv) it allows to compare droughts in different regions, regardless of the climate pattern (Zargar et al. 2011). However, as a precipitation-based index, SPI may not be always recommended for regions which are highly vulnerable to climate changes (Le et al. 2019).

Some studies have applied the SPI methodology in Southeast Brazil. Blain & Kayano (2011) analyzed 118 years of precipitation data (1890-2007) for the city of Campinas, state of São Paulo, and concluded that there is no evidence of the influence of the El Niño/La Niña over drought events in the city. In the same perspective, Sobral et al. (2019) used SPI to analyze the impact of droughts in the Rio de Janeiro state and the results did not show correlation with either the increase or reduction of rainfall.

In addition to being one of the most applied drought indexes, the SPI only accounts for precipitation, which can reduce its sensibility to extreme droughts, mainly whether the event is marked by anomalous temperatures. Adding the temperature to its calculation, the SPEI index was proposed as an alternative to SPI (by means potential evapotranspiration) to characterize drought events (Vicente-Serrano et al. 2009, Begueria et al. 2014).

These indexes have proven to be good indicators to measure the severity of the droughts. Parente et al. (2019) applied them to study the occurrence of large wildfires in Portugal related to the drought regimes and concluded that the droughts play a fundamental role in such events. Comparing the SPI and SPEI to analyze long-term drought severity in Botswana, Byakatonda et al. (2018) demonstrated that the SPEI was a better index to characterize drought in semi-arid regions. Shiru et al. (2019) evaluated the drought events in Nigeria throughout the period of 1901-2010 using the SPEI and they observed a decrease in the return period of moderate droughts, which can lead to losses in agricultural production in the following decades. Gozzo et al. (2019) observed a linear trend of increasing drought events in central and western regions of São Paulo state, and a decreasing tendency in the eastern region.

Due to the severity of the event observed in 2013/2014, it is indispensable to detail how the droughts behaved in the past and after 2016, which can be relevant to subsidize climate change studies. Thus, in order to clarify the drought variability in parts of southeast Brazil, we attempted to answer the following questions: (i) Were the droughts observed in 2013/2014 and 2014/2015 hydrological years the driest over the last 100 years in southeastern Brazil? (ii) Have these events occurred in a similar severity in different regions of southeastern Brazil? (iii) Is it possible to characterize severe droughts using both the SPI and SPEI? (iv) How severe were the events observed prior to the 1960's and what is the frequency occurrence of the droughts? (v) Was the dry period of 2013/2015 extended to the present? In this sense, this study presents a novel long-term drought study (from the end of XIX or beginning of the XX Centuries to 2019), exploring four different locations of southeastern Brazil, as well as São Paulo city, using the SPI and SPEI indexes, which will enabled answering the questions raised, improving the comprehension of this phenomenon in tropical and subtropical regions of southeast Brazil.

MATERIALS AND METHODS

Datasets

Five locations were chosen to be analyzed in this study. Lavras and Nova Lima, in Minas Gerais State, and the cities of Campinas, São Paulo and Piracicaba, in São Paulo State. There are meteorological rainfall stations with great length of the precipitation datasets and their availability in these municipalities, which allowed us to attain the purposes of our research. Thus, two periods were considered in this study: i) summer (from December to March - P4); and ii) the wet period (from October to March – P6). Figure 1 shows the geographical location of the studied cities in Southeast Brazil, and the characteristics of the weather stations and respective historical series are shown in Table I, as well as the main features of each region in which the cities are located.

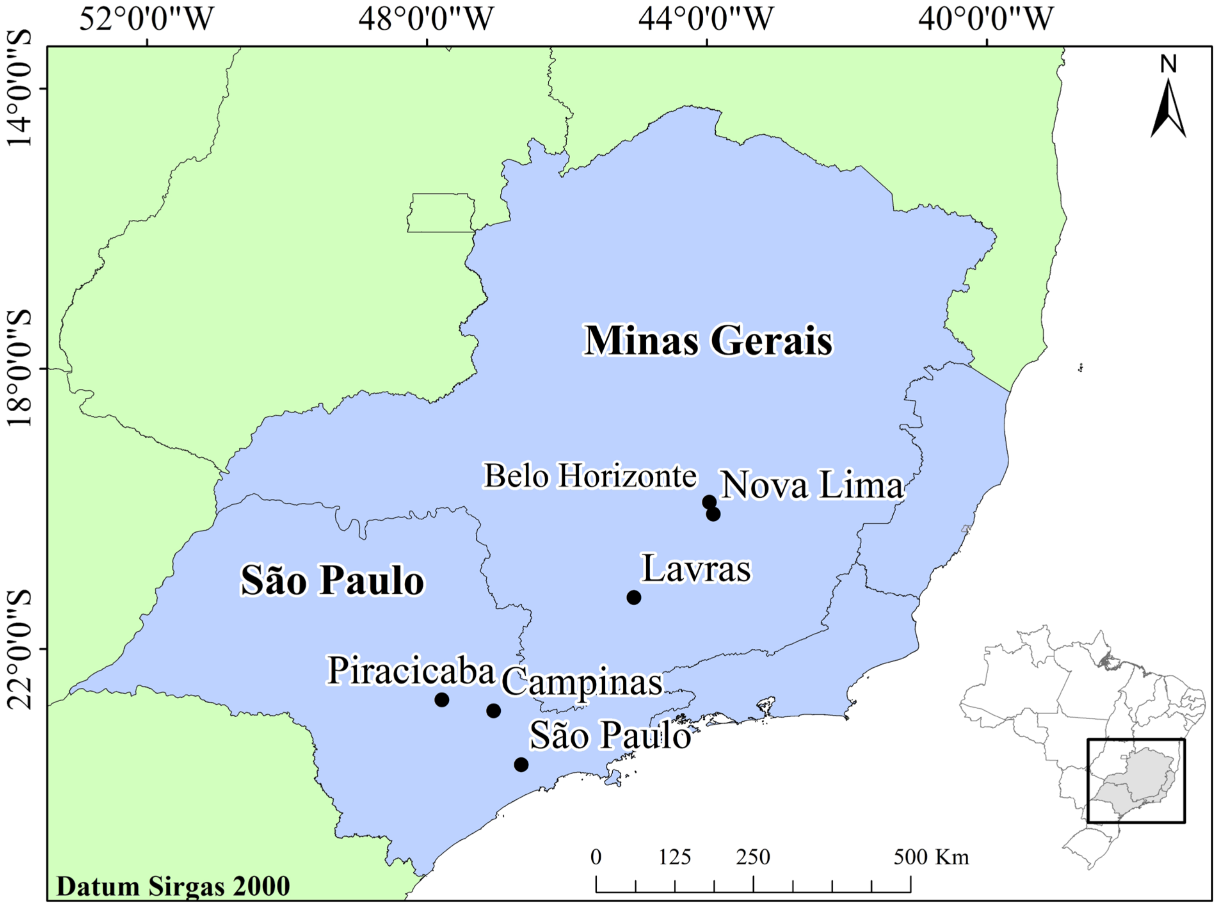

Figure 1. Location of the studied cities in Southeast, Brazil.

Table I. **Characteristics of the meteorological stations used in this study and the main features of the each region.**

Location	Variable	Latitude (South)	Longitude (West)	Elevation (m)	Agency	Historical series (SPI)	Historical series (SPEI)	Main features
Lavras (South-MG; Grande River Basin)	Precipitation	21°45'00"	45°00'00"	918.84	INMET[1] (83023)	1915 – 2019 (104 years)	1961-2019	South-MG; 4 hydropower plant reservoirs, highlighting Furnas (the largest of southeast Brazil); main region for coffee crop (*Coffee arabica*) production (CONAB 2016);
	Temperature							
Nova Lima (MR-BH; São Francisco River Basin)	Precipitation	19°57'00"	43°54"36"	770	ANA[2] (1943000)	1865 – 2019 (164 years)	1961-2019	MR-BH, the third Brazilian metropolitan region of southeast Brazil (over 5 million habitants) (IBGE 2019a);
	Temperature	19°55'48"	43°55"48"	860	INMET (83590)			
São Paulo, SP (SP) (Tietê River Basin)	Precipitation	23° 32'00''	46° 38'00''	730	DAAE[3]/SP E3-036	1888 – 2019 (131 years)	1961–2019	The largest Brazilian city, 13% of Brazilian Gross Domestic Product (GDP) (over 10 million habitants) (IBGE 2019b);
	Temperature	23°36'00"	46°24"00"	819	INMET (83004)			
Piracicaba, SP (ME-SP; Piracicaba/ Tietê River Basin)	Precipitation	22°42'30"	47°38"00"	546	ESALQ/ USP[4] (83720)	1902 – 2019 (117 years)	1961-2019	Middle east São Paulo State; the largest region for bioenergy production (sugar cane and ethanol) (CONAB 2016);
	Temperature							
Campinas, SP (MR Campinas; Tietê River Basin)	Precipitation	22º54"00"	47º4'48"	669	IAC[5]/ INMET (83729	1890 – 2019 (129 years)	1961-2019	Fourth metropolitan region of southeast Brazil, intense economic incomes and one of the greatest technological regions of Latin America (IBGE 2019b);
	Temperature							

[1]Instituto Nacional de Meteorologia, [2]Agência Nacional das Águas e Saneamento Básico, [3]Departamento de Águas e Energia Elétrica [4]Universidade de São Paulo, [5]Instituto Agronomico de Campinas.

Main aspects of the datasets

The long-term precipitation series of Piracicaba, São Paulo, Lavras and Campinas do not have gaps, however, Nova Lima presented some concentrated between 2002 and 2016. Therefore, a consistency analysis of the dataset was carried out to verify its homogeneity in relation to two other rain-gauge stations belonging to *ANA* , located close to Nova Lima: Ibirité (20° 00’00”S; 44° 00”00”W; 814 m) and Belo Horizonte (19° S; 43°W; 915 m). Linear regressions between Nova Lima and these rain-gauges series were fitted and used to fill the gaps.

Studies developed by Begueria et al. (2014) and McEvoy et al. (2012) comparing Thornthwaite and Penman–Monteith methods found similar results for SPEI calculations. Thus, monthly average temperatures from October to March were applied in this study to calculate potential evapotranspiration using the Thornthwaite method (equations 1 to 8), according to Vicente-Serrano et al. (2009). São Paulo, Piracicaba, and Campinas do not have gaps in their respective series. However, Lavras and Nova Lima had some gaps in the 1980’s and 1990’s, which were subsequently filled using PGECLIMA_R software and meteorological stations in the respective neighborhood (Kist & Filho 2014). Afterwards, monthly potential evapotranspiration series from 1961 to 2019 were then structured for each studied location.

$$ETp = 16K * \left(\frac{10T}{I}\right)^m \quad (1)$$

where is Ti is the average monthly temperature (°C) i, and I is calculated by the monthly sum of I, according to equation 2:

$$I = \sum_{i=1}^{12} \left(\frac{Ti}{5}\right)^{1,514} \quad (2)$$

where m is a coefficient calculated according to equation 3:

$$m = 6.75*10^{-7}*I^3 - 7.71*10^{-5}*I^2 + 1.79*10^{-2}*I + 0.49239 \quad (3)$$

where k is a coefficient related to latitude:

$$K = \left(\frac{N}{12}\right)*\left(\frac{NDM}{30}\right) \quad (4)$$

where NDV is the number of days for each month and N is the maximum number of sun light, calculated by:

$$N = \left(\frac{24}{\pi}\right)\varpi \quad (5)$$

where ϖ in sun angulation, calculated by:

$$\varpi = arcos\left(-tan\varphi tang\delta\right) \quad (6)$$

where φ is a latitude, in radians, and δ is the sun declination, in radians, calculated by:

$$\delta = 0.4093sen\left(\frac{2\pi J}{365} - 1.405\right) \quad (7)$$

where J is the average Julian day of the month.

Standard Precipitation Index (SPI)

SPI was calculated fitting the Gamma two parameters Probability Density Function (PDF) (equation 9) (Coelho et al. 2016a, McKee et al. 1993) and its adherence was tested by the Anderson-Darling test (Anderson & Darling 1952). This test is more appropriate than others since it is focused on the tail of the PDF. This feature is relevant because of the greatest uncertainty (the sensitivity of the PDF) in the tail of the PDFs where the lowest values are found, with a more robust test being required. This PDF was applied to model the non-exceedance frequencies of the precipitation series of 4 (summer) and 6 months (wet period) (respectively, SPI4 and SPI6).

$$PDF : f(x) = \frac{1}{\beta^\alpha * \Gamma(\alpha)} * x^{\alpha-1} * e^{\frac{-x}{\beta}} \quad (8)$$

where β and α are the Gamma PDF parameters, Γ is the gamma function, and x are precipitation values.

Table II. SPI classification (adapted from NOAA 2019).

SPI	Classification
-0.80 ≥ SPI < 0.51	Abnormally Dry (AD)
-1.30 ≥ SPI < -0.80	Moderately Dry (MD)
-1.60 ≥ SPI < -1.30	Very Dry (VD)
-2.0 ≥ SPI < -1.60	Severely Dry (SD)
SPI < -2.0	Exceptionally Dry (ED)

SPI is defined by the application of the inverse of the standard normal distribution using the estimated frequencies from Gamma 2P PDF. The classification proposed for the National Climate Data Center (NCDC) and National Oceanic and Atmospheric Administration (NOAA) can be observed in Table II.

Standard Precipitation Evapotranspiration Index (SPEI)

The SPEI calculation is based on precipitation accumulated in a given period and air temperature effects by potential evapotranspiration. Thus, the SPEI is calculated based on an atmosphere water budget (P - ET) (Vicente-Serrano et al. 2009), which has been relevant when temperature has an anomalous variability.

The Thornthwaite method is suggested by Vicente-Serrano et al. (2009) for potential evapotranspiration estimates as it only considers the average monthly temperatures instead of other meteorological variables. Similar results for SPEI were found when both the Thornthwaite and Penman-Monteith methods were applied, thus, justifying the use of the former method, mainly for regions with minimum monitoring in terms of climate variables (Begueria et al. 2014, McEvoy et al. 2012).

A historical series of water budget (P - ET) was then developed for the P6 (SPEI6) and P4 periods (SPEI4). Thus, Generalized Extreme Values (GEV) PDF (equation 10) were fitted to calculate the frequencies of P - ET series, as Gamma PDF is limited to positive data (Stagge et al. 2014).

$$PDF = \frac{1}{\sigma} * \left[1 - \varepsilon * \left(\frac{x-\mu}{\sigma}\right)\right]^{\left(\frac{1}{\varepsilon - 1}\right)} * exp\left\{-\left[\frac{x-\mu}{\sigma}\right]^{\frac{1}{\varepsilon}}\right\} \tag{9}$$

where ε, σ and μ are the PDF parametes, and x is the P-ET values.

The same procedure presented for SPI is applied to calculate the SPEI. Classification classes for SPEI as suggested by the NOAA for the SPI are not suggested by Vicente-Serrano et al. (2009), however, a comparison between SPI and SPEI events can be made. In this study, we considered the same SPI classification proposed by the NOAA, comparing the indexes under the same drought magnitude events.

RESULTS

SPI temporal variability

Figure 2 presents the goodness of fit of Gamma 2P PDF for P6 and P4 precipitation historical series for Lavras (South-MG) (a), Nova Lima (MR-BH) (b), Piracicaba (ME-SP) (c), SP city (d), and Campinas (MR-Campinas) (e). The Anderson-Darling test indicates that this PDF was adequate to model the occurrence frequency of the studied historical series, which can also be observed in the graphs of Figure 2. It is relevant to highlight that historical series longer than 100 years were used since the main objective was to evaluate the temporal variability of the droughts.

Figure 3 depicts the SPI variability throughout the time for the studied locations of southeastern Brazil. Figure 3a shows both SPI6 and SPI4 for South-MG in the last 104 years. It could be observed that the lowest SPI6 values were observed in 1974/1975 (-2.47), 2013/2014 (-2.37), and 1949/1950 (-2.05), whereas the lowest

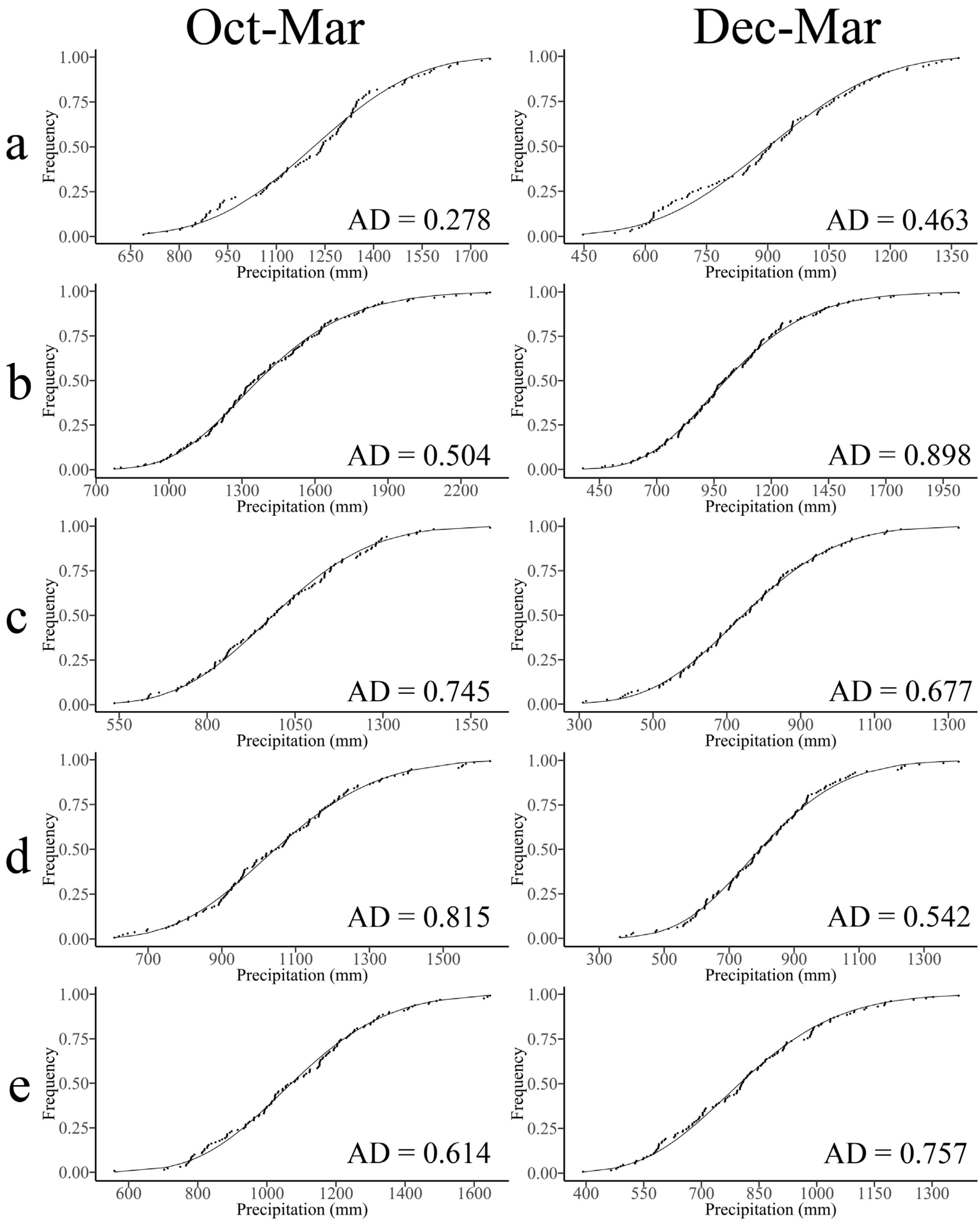

Figure 2. Goodness of the fit of the Gamma 2P PDF to the P6 and P4 precipitation historical series using Anderson-Darling test (a. South-MG; b. MR-BH; c. ME-SP; d. SP city; e. MR-Campinas).

SPI4 values were observed in 2013/2014 (-2.56) and 2016/2017 (-2.00). These values enabled establishing the occurrence of an "exceptionally dry" event in all these hydrological years, and that the summer of 2014 (P4 period) was the driest observed in South-MG over 104 years.

MR-BH (Figure 3b) showed the lowest values of SPI6 and SPI4 in the five studied locations of southeast Brazil in the last 165 years. These indexes in the 1970/1971 hydrological year were -2.46 and -2.94, respectively. A SPI6 value of -1.58 ("Very Dry") and SPI4 of -1.19 ("Moderately Dry") were observed by looking at the 2013/2014 hydrological year, far from the lowest values (1970/1971). However, it is important to point out that six consecutive droughts were observed from 2012/2013 to 2018/2019.

The lowest SPI6 for the Piracicaba region (ME-SP) (Figure 3c) was calculated for 1983/1984 hydrological year, being -2.54 ("exceptionally

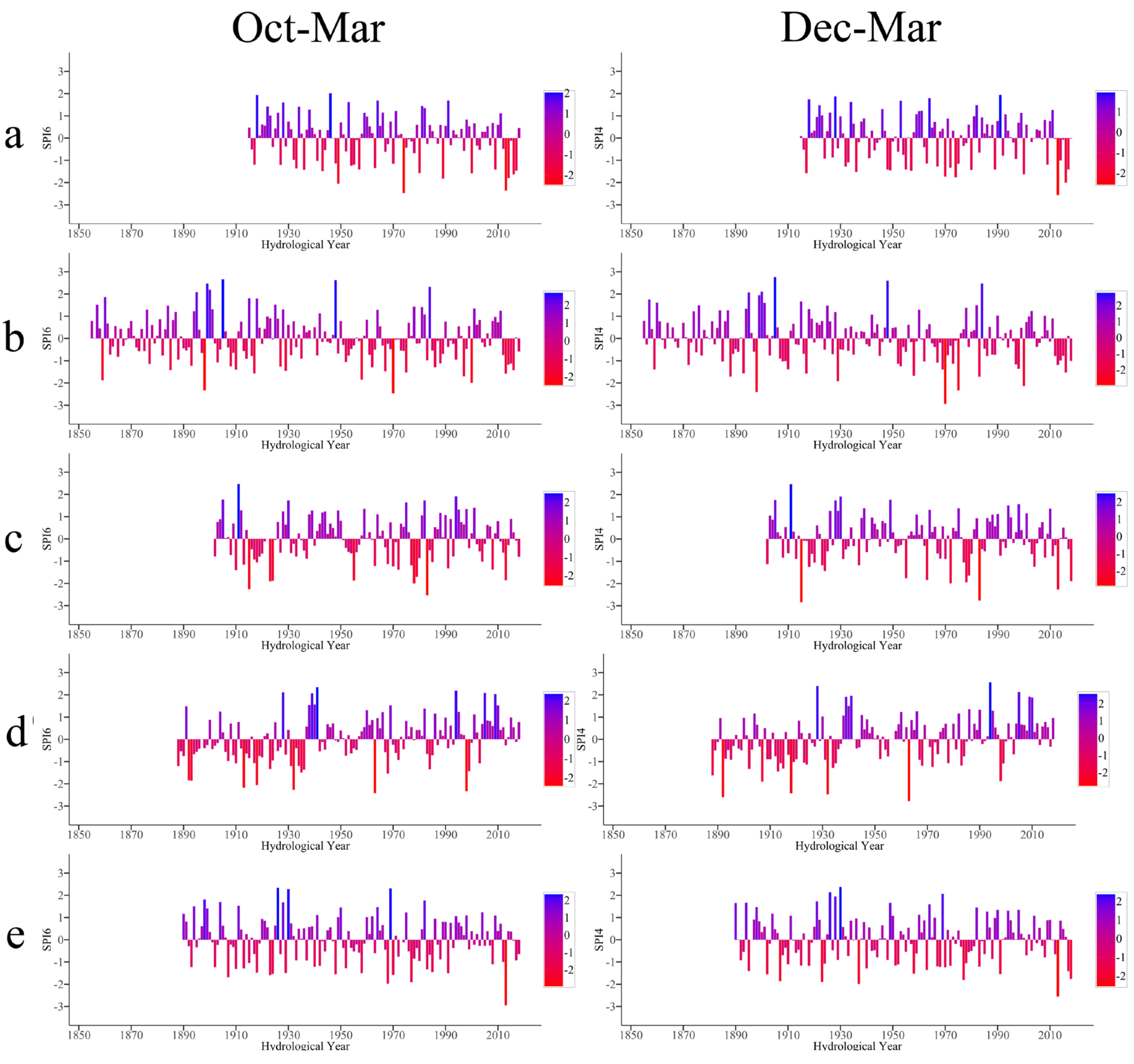

Figure 3. Temporal variability of the SPI6 and SPI4 for the studied locations of southeastern Brazil (a. South-MG; b. MR-BH; c. ME-SP; d. SP city; e. MR-Campinas).

dry"), while the lowest SPI4 (driest summer) was calculated for 1915/1916 (-2.84). The SPI6 and SPI4 in the 2013/2014 hydrological year were -1.80 and -2.27, respectively. Based on these indexes, the years of 1915/1916 and 1983/1984 were the driest from meteorological point of view.

SP - city (Figure 3d) presented the most significant droughts before 1965, with 1963/1964 hydrological year displaying the lowest SPI values of -2.41 and -2.78, respectively, for SPI6 and SPI4 ("exceptionally dry"). In addition, we could observe other intense droughts, such as in the 1892/1893, 1913/1914, 1918/1919, 1932/1933, and 1998/1999 hydrological years. Thus, the 2013/2014 hydrological year was not the driest in São Paulo city when the SPI indexes were calculated using a secular historical series.

MR-Campinas (Figure 3e) presented the lowest SPI6 and SPI4 values of -2.92 and -2.58 for the 2013/2014 hydrological year, respectively, with this year being the driest ever observed in the last 129 years.

SPEI temporal variability

Figure 5 shows the SPEI6 and SPEI4 temporal variability for the studied locations of southeastern Brazil. South-MG (Figure 5a) shows that the lowest SPEI6 and SPEI4 values were found for the 2013/2014 hydrological year of -2.10 and -2.15, respectively. Comparatively, the lowest SPI4 and the second lowest SPI6 were also observed in this hydrological year, which demonstrated to be the driest observed in this location in the last 104 years.

Figure 5b presents the SPEI6 and SPEI4 values for MR-BH, respectively showing values of -2.30 and -2.84 obtained for the 1970/1971 hydrological year, with the lowest values observed between 1961 to 2019. The lowest SPI6 and SPI4 were also estimated for this hydrological year, with it being possible to state that 1970/1971 was the driest hydrological year for this location. This variability contrasts with that obtained for South-MG.

The lowest SPEI values for ME-SP (Figure 5c) were found for 2013/2014 of -2.24 and -2.28, respectively, for SPEI6 and SPEI4. In contrast, the lowest SPI indexes were obtained for the 1983/1984 and 1915/1916 hydrological years, however the second lowest SPI4 and the third lowest SPI6 were detected for the 2013/2014 hydrological year. Therefore, it is plausible that 2013/2014 was the driest hydrological year in this location.

SP-city (Figure 5d) displayed the lowest SPIE6 for 1998/1999 and 1962/1963 (respectively, -2.40 and -2.30), whereas the lowest SPEI4 was obtained for 1962/1963 (-2.85). We could observe that the lowest SPI values were also found for the 1962/1963 hydrological year, which demonstrates that it was the driest hydrological year observed in the last 131 years considering only SP city.

MR-Campinas (Figure 5e) presented -2.98 and -2.72, respectively, for SPEI6 and SPEI4 in the hydrological year of 2013/2014, which was also observed for the SPI indexes. Similar to South-MG, the 2013/2014 was the driest hydrological year observed in the Campinas region in the last 129 years.

DISCUSSION

SPI variability

Based on the SPI secular historical series, the 2013/2014 hydrological year was not the driest ever recorded in ME-SP, MR-BH and SP-city, while this was the driest year observed for South-MG and MR-Campinas in the last 104 and 129 years, respectively, mainly for the summer period (P4). The use of exceptionally long historical series enabled fitting a more robust Gamma PDF detecting other periods drier than 2013/2014. However, the South-MG and MR-BH showed that the precipitation volume goes on lower than the average, being a continuous anomaly period between 2013-2019 (Figure 3a, b). This situation could also be observed in ME-SP (Piracicaba) and MR-Campinas, however, with some positive SPI values between 2015/2017 hydrological years. SP-city had only "abnormally dry" events which were observed in the 2013/2014 and 2017/2018 hydrological years. The other hydrological years in the period of 2013/2019 exhibit positive SPI values in both summer and wet period.

Negative and consecutive SPI values such as those observed in the 2013-2019 period indicates extended drought periods, which deeply increased the drought impacts, transferring them to the hydrological variability of the basins. Melo et al. (2016) observed a reduction of -20 to -60% of precipitation over the Furnas reservoir in 2014. According to *Operador Nacional do Sistema Elétrico* (ONS 2019), the volume of the Furnas reservoir went from 71.29% in June of 2013 to less than 10% in January of 2015. A similar analysis can be made for the Camargos reservoir, whose levels went from 97.5% in June of 2013 to less than 5% in October of 2014. In both cases, the anomaly summer of the 2013/2014 hydrological year directly impacted the levels of the reservoirs as the precipitation was not enough to bring back the levels in the wet period.

Some isolated dry hydrological years can be highlighted over the studied periods. An intense drought episode in the summer of 1963/1964 hydrological year (SPI4) which hit all the five studied locations could be observed. According to the São Paulo State Department of Water Resources, two of the most important reservoirs, Billings and Guarapiranga, only reached 17.72% and 37.88%, respectively, of their capacities in 1969, which almost led to a water and energy shortage.

The 1983/1984 hydrological year can be highlighted because of the regions affected (all the five studied) and the severity of the drought, despite being concentrated in the summer. The main causes of this drought were the atmospheric circulation over the equatorial Pacific Ocean that underwent a reversal, going to extreme warm El-Niño (1982/1983) to a La Niña (1983/1984), which led to a reversal in the wind direction, in turn causing a reduction of precipitation in the east of Southeast Brazil (Horel et al. 1986). Tanaka & Nishizawa (1985) also pointed out that the hydrological year was generally warmer than normal in all southern Brazil. The combination of negative anomalies of precipitation and positive anomalies of temperature are usually connected, characterizing stronger droughts.

A different variability of SPI indexes was also observed for SP city (Figure 3d) in relation to the other studied locations. Most of the intense drought events are observed from 1880s to the 1930s; after that, the negative anomalies of precipitation become less common, while wet years seem to become more frequent. Droughts in the metropolitan region of São Paulo using the SPI from 1961 to 2015 were analyzed by Coelho et al. (2016a) and the lowest SPI values were observed in 2013/2014 hydrological year (SPI6 = -2.71), which is different from the present study (SPI6 = -0.25). Some differences can be pointed out between the studies: (i) Coelho et al. (2106a) focused their study in a larger region than SP-city, expanding towards the east of SP state and South-MG (both regions presented one of the lowest SPI6 in 2013/2014); (ii) we analyzed rainfall series from DAEE-SP located in São Paulo city, which accounts 131 years (1888-2019); thus, a different Gamma PDF fitting was obtained, leading to different SPI variability. Importantly, we tested the fittings of this PDF by the Anderson-Darling adherence test (Figure 2), and this model was adequate for all of the

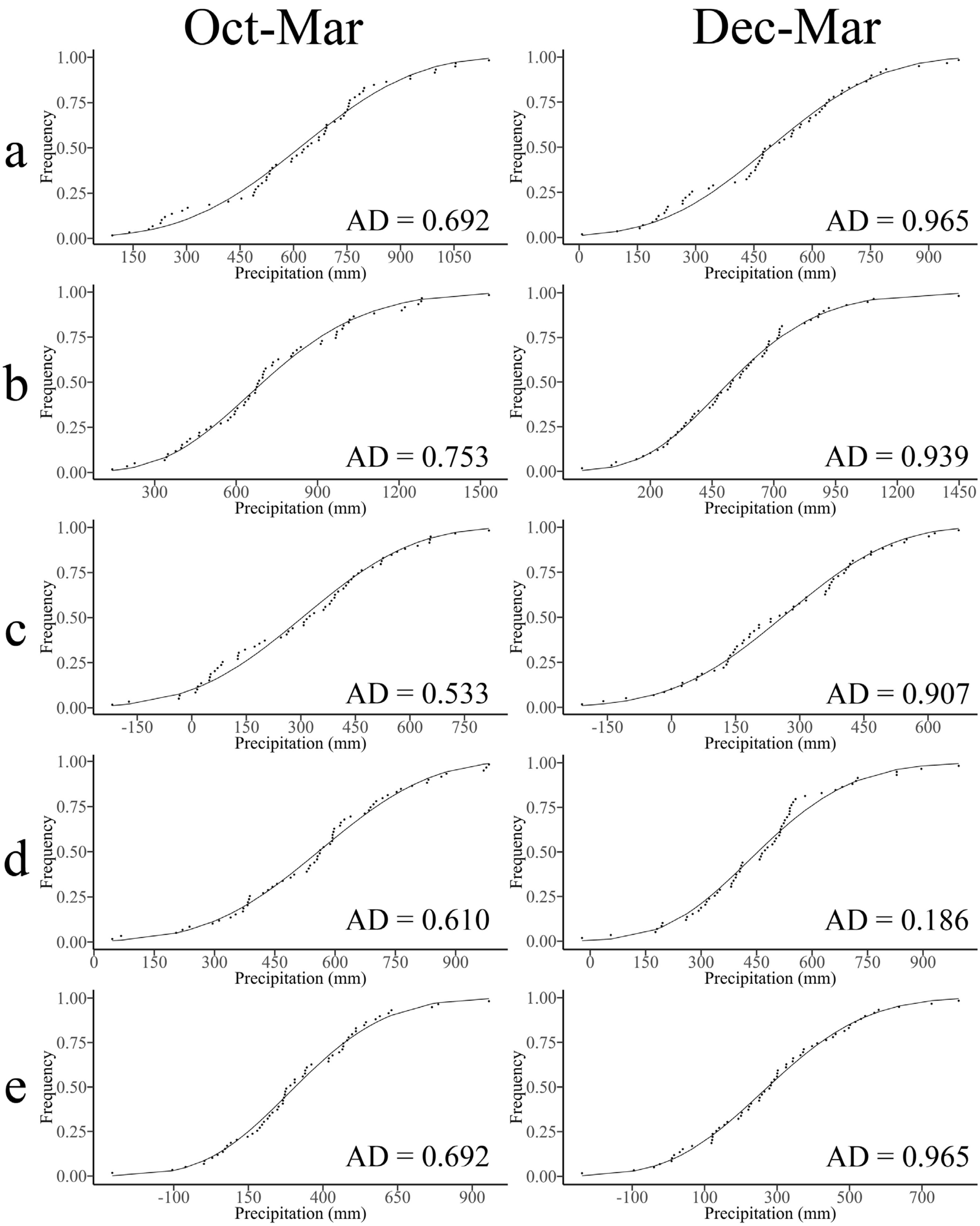

Figure 4. Goodness of the fit of the GEV PDF to P – ETp historical series for the studied locations of southeastern Brazil tested by the Anderson-Darling test (a. South-MG; b. MR-BH; c. ME-SP; d. SP; e. MR-Campinas).

studied historical series. Carbone et al. (2018) studied the effects of different lengths of the historical series for estimating SPI in Italy. They concluded that series shorter than 30 years have a tendency to generate instability on the Gamma 2P parameters, increasing the uncertainties, especially regarding the lowest SPI values (the most severe droughts). In addition, these authors verified that the fitting of this PDF to series longer than 60 years (the case of this study) tends to generate greater stability, reducing the uncertainties, mainly for those values in the tail of the PDF.

An increase in the precipitation in the metropolitan region of São Paulo in the last century has been observed by several authors (Liebman et al. 2004, Vicente-Serrano et al. 2009, Raimundo et al. 2014, Lima et al. 2018). With the development of what is called a "megacity', the formation of urban heat islands (UHI) was intensified in MR-SP, having an impact on atmospheric humidity by increasing temperature and causing changes in atmospheric stability, leading to the development of deep clouds (such as Cumulonimbus) and intense rain events (Lima et al. 2018). This might lead to the difference observed between MR-SP and the other locations.

MR-Campinas observed one "exceptionally dry" event over 129 years (-2.95, for 2013/2014 hydrological year) considering SPI6. Nevertheless, eleven "very dry" events (return period of 11.7 years) and fourteen "moderately dry" events (return period of 8.6 years) were found, showing that important droughts are frequent in the Campinas region. Social impacts of droughts were observed in Campinas during the 2013/2014 hydrological year. According to the "*Sociedade de Abastecimento de Água e Saneamento*" (SANASA 2014) of São Paulo, water rationing was necessary in the city as the Cantareira System, one of most affected, was responsible for 31 m^3/s of water. This volume was first reduced to 15.7 m^3/s, and then to only 3 m^3/s during the drought.

SPEI variability

Extreme negative values of SPEI indexes in Lavras (South-MG), Piracicaba (ME-SP) and Campinas (MR-Campinas) were observed in 2013/2014, enabling to classify this hydrological year as "extremely dry" and the driest in the last 58 years (Figure 4). The lowest SPEI4 was also recorded for the 2013/2014 year, showing that this summer presented both the greatest atmospheric water demand (higher temperatures and solar radiation) and the least precipitation, being the driest summer since 1961.

Coelho et al. (2016b) studied the anomaly precipitation over Southeast, Brazil, in this period, which can be summarized as follows: (i) the increased sea surface temperatures in the coast of Southeast Brazil was negatively correlated with the precipitation occurrences; (ii) a strong and persistent activity of the South Atlantic Anti-Cyclone in low level of the atmosphere, changing the direction of the moisture from Amazon region to Paraguay, north Argentina and south Brazil; (iii) and a subsidence of the air forcing moisture downward, which impeded convective activity mostly over Southeast Brazil. In addition, the authors also indicated that climate events such as the Pacific Decadal Oscillation (PDO), the South Atlantic Convergence Zone (SACZ) activity linked with Madden-Julian Oscillation, and the Atlantic Sea Surface Temperature (SST) might directly correlate with the increase in precipitation in MR-SP. Thus, the combination of continuous growth of the population; the high amount of water lost (~20%) in the distribution systems (DAEE/SP 2018); and the increased temperatures were the main elements which lead to one of the most critical water supply crises in the MR-SP between 2013 and 2015.

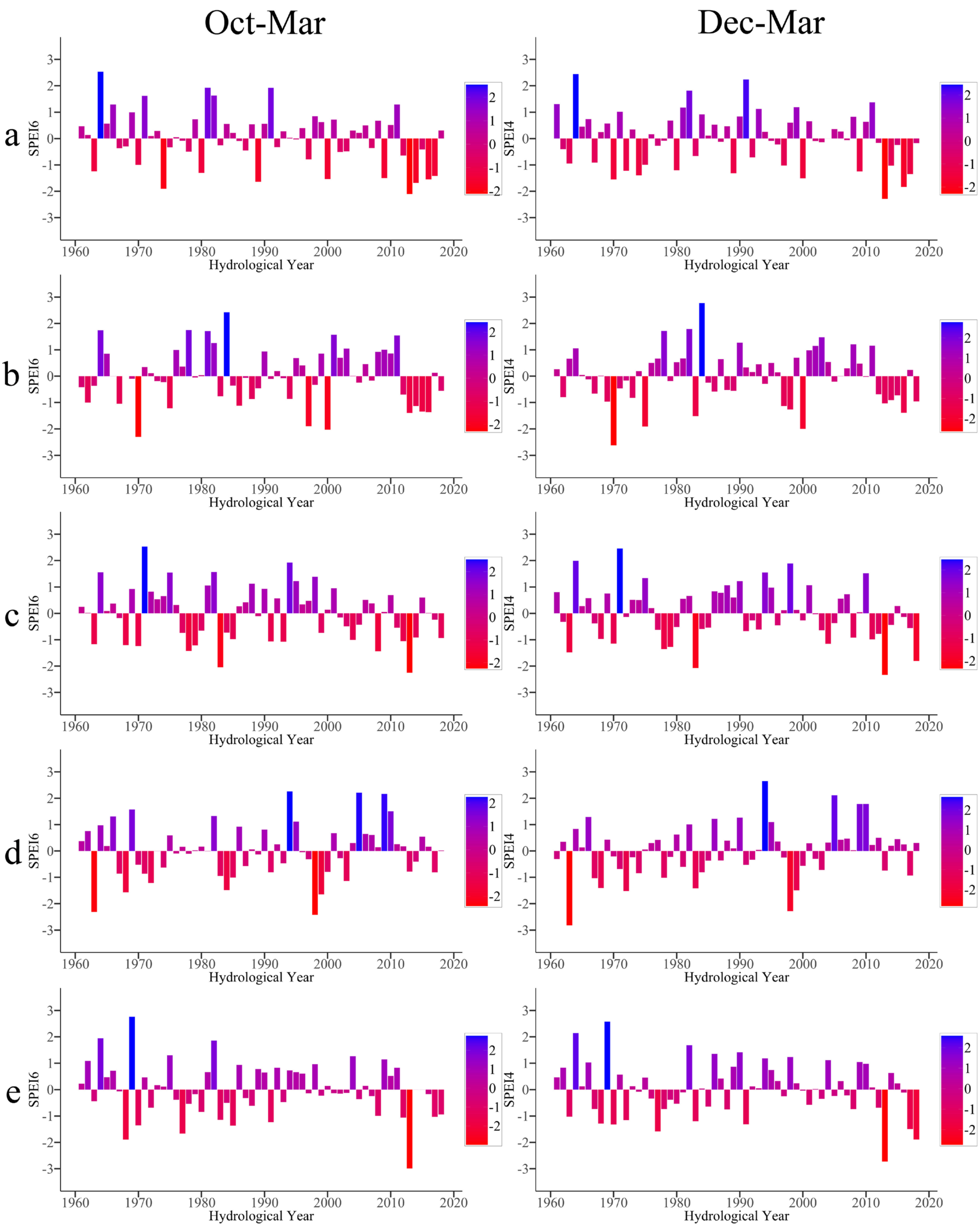

Figure 5. Temporal variability of the SPEI6 and SPEI4 for the studied locations of southeastern Brazil (a. south-MG; b. MR-BH; c. ME-SP; d. SP-city; e. MR-Campinas).

The drought observed in the 2013/2014 hydrological year severely impacted Southeast Brazil. It is necessary to point out some aspects in order to fully understand such impacts in the water supply, energy production, agriculture, and over society in general. There was an exponential growth of the population of the region, especially impacting the metropolitan regions. SP city was affected by severe droughts in 1910s, 20s, 30s, and 70s, and its population jumped from 579,033 habitants in 1920 to 11,253,503 in 2010.

Furnas Hydropower Plant is the main reservoir for southeastern Brazil and has two main purposes (Mello et al. 2021): streamflow regularization and hydroelectricity generation. The first has been fundamental in acute drought periods for supplying downstream reservoirs (there are 11 hydropower plants that are fed by outflows from Furnas). According to Furnas Administration (2015), the hydroelectricity supply in the country was not affected during 2013/2014 because of the interconnection of electric energy system in Brazil and the thermic facilities operation, increasing the costs of generation and the greenhouse gases emissions. Thus, the effects of several drought years as observed between 2013 and 2019 can deeply harm the Brazilian electric energy system, increasing the hydrological risk involved with the hydroelectricity generation.

Different from the above mentioned locations, MR-BH and SP-city showed that 2013/2014 was not the driest hydrological year. The most severe drought observed in Oct-Mar and Dec-Mar periods using SPEI indexes for MR-BH (Figure 4b) was in the 1970/1971 hydrological year (SPEI6 = -2.3; SPEI4 = -2.6). The driest Oct-Mar and Dec-Mar periods observed in SP city referred to the 1962/1963 hydrological year, following the same variability of the SPI indexes (SPEI6 = -2.30; SPEI4 = -2.80).

The combination of negative anomaly of precipitation and positive anomalies of temperature also influenced the water supply for MR-BH, ME-SP and Mr-Campinas. Data from the Companhia Sanitária de Minas Gerais (2020) has shown that the lowest levels of the three main reservoirs of the MR-BH (Serra Azul, Rio Manso, and Paraopeba) were observed in the 2013/2014 hydrological year. The Serra Azul reservoir reached a volume of 5.8% of its total capacity. In the middle east of São Paulo State (ME-SP), Piracicaba river had the lowest runoff in at least 30 years, with an average depth of 0.79 m (DAEE/SP 2018). Furthermore, the Piracicaba River increased the concentration of pollutants and increased the prices of water treatment by 20% (SABESP 2014). Thus, droughts are the main abiotic stress constraining sugarcane production (Vital et al. 2017), and consecutive years of drought as observed in 2013-2019 period can directly impact the production of the region. The metropolitan region of Campinas (MR-Campinas) was harmed by many days with water shortage, as the Atibaia river had the lowest runoff in decades, causing an increase of 500% in chloride amount need for water treatment (SANASA 2014).

CONCLUSION

a) SPEI and SPI showed that SP city was hit by more severe droughts than that observed for the 2013/2014 hydrological year; they occurred for the hydrological years of 1962/1963 (based on SPI) and 1998/1999 (based on SPEI).

b) The hydrological year of 2013/2014 was the driest observed in southeastern Brazil, considering SPI and SPEI for Lavras (South-MG), Nova Lima (MR-BH), Piracicaba (ME-SP) and Campinas (MR-Campinas);

importantly, this drought for these regions was prolonged up to 2018/2019, with several years varying from "exceptionally dry" and "moderately dry". Lavras (South-MG) was the most affected region by droughts between 2013/2019.

c) It is possible to point out that several events hit the studied regions of southeastern Brazil. The hydrological years within the periods of 1908/1918, 1968/1983 and 2013/2019 can be highlighted. It is important to understand that the increase of population, water demand, and economic development directly affected how the drought severity was faced over the last 100 years.

d) SPI showed to be an effective drought index for almost all studied regions in southeastern Brazil; the fitting of Gamma 2P PDF showed great performance for all of the studied stations, especially due to the use of longer series than previous related studies, resulting in more robustness for the estimated parameters.

e) It is plausible to affirm that the precipitation is the main factor of droughts in the study regions. Thus, the authors recommend the SPI for further studies of droughts in Southeast Brazil. According to SPI6, "Severe drought" and "Extreme Drought" occur on average once in 31 and 64 years, respectively; considering SPI4, once in 43 and 52 years, respectively.

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